Construction Planning, Modelling, and Analysis of Rainwater Harvesting System in Rural Scenario

THESIS

Submitted in partial fulfilment
of the requirements for the degree of
DOCTOR OF PHILOSOPHY
by
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2017PHXF0040P
Under the Supervision of
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BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE, PILANI

2022

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE, PILANI-333031, RAJASTHAN (INDIA)

CERTIFICATE

This is to certify that the thesis entitled **"Construction Planning, Modelling, and Analysis of Rainwater Harvesting System in Rural Scenario"** and submitted by **Mr. Raya Raghavendra Kumar**, ID No. **2017PHXF0040P** for the award of Ph.D. of the Institute embodies original work done by him under my supervision.

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ACKNOWLEDGEMENTS

Firstly, I wish to express a deep sense of gratitude and sincere thanks to my supervisor, Prof. Rajiv Gupta, Senior Professor, Department of Civil Engineering, BITS Pilani, Pilani Campus, for his valuable guidance and suggestions throughout my doctoral study. His immense knowledge of the subject has improved my research work during ups and downs. His words of motivation and positivity during the current pandemic never let me off the track. I consider it a privilege for being his student and worked under his supervision. I am grateful to Birla Institute of Technology and Science, Pilani, and the Department of Science & Technology, India, for providing all the necessary facilities and financial support for conducting my research.

I would like to take this opportunity to express my gratefulness to Prof. Ravi Kant Mittal, Professor, Department of Civil Engineering, BITS Pilani, Pilani Campus and Dr. G. Muthukumar, Assistant Professor, Department of Civil Engineering, BITS Pilani, Pilani campus, the members of Doctoral Advisory Committee (DAC), for their kind suggestions and assistance.

My special thanks to Prof. Souvik Bhattacharya, Vice-Chancellor of the University, Prof. Ashok Kumar Sarkar (former director), BITS Pilani and Prof. Sudhirkumar Barai, Director of BITS Pilani, Pilani Campus, for allowing me to pursue my research work successfully. I also express my gratitude to Prof. M. B. Srinivas, Dean, Academic - Graduate Studies & Research Division and Dr. Jitendra Panwar, Associate Dean, Academic - Graduate Studies & Research Division, for providing valuable support throughout the program.

I sincerely thank Dr. Anshuman, Associate Professor (& former Head), Department of Civil Engineering and Dr. NVM Rao, Chief of Centralised Purchases Unit, BITS Pilani, for providing me with all the materials required for carrying out my research work successfully. Special thanks are extended to Prof. Anupam Singhal, Head, Department of Civil Engineering and Dr. Nishant Roy, Assistant Professor, Department of Civil Engineering, BITS Pilani, for providing me with the software and their cooperation in my doctoral study.

I would like to express my gratitude for the encouragement and support from eminent faculty members, notably Prof. S. B. Singh, Prof A. P. Singh, Dr. Manoj Kumar, Dr. Dipendu Bhunia, Dr. Kamalesh Kumar, Dr. Durgesh Vikram, Dr. Rajesh Kumar and Dr. Sayantan Chakraborty for their supportive ideas at different stages of my work in BITS Pilani. I appreciate the assistance extended by non-teaching staff Mr. Ramesh Kumar in the field visits and data collection phase of my research and Mr. Shiv Ratan Sharma, Mr. R. D. Soni, Mr. Kamal, as well as Mr. Sultan for their timely support.

The greatest gift of life is friendship and I received it in the form of Dr. Gaurav Kumar, Ms. Soumya Kar, Dr. Vummadisetti Sudhir, Mr. Rama Krishna, Dr. Satya Pritam, Dr. Harish Puppala, Dr. V. Satheesh Varma, Dr. Vasanth Keshav, Dr. Makrand Wagale, Dr. Rahul Dandautiya, Dr. Vidhi Vyas, Mr. Kiran Gudladona, Mr. Chetan, Mr. Rishab Bajpai, Mrs. Somya Agarwal, Mr. Vishal Singh, Mr. Bhaskar, Mr. Danish, Mr. Anuj, Mr. Siva Shankar, Mr. Akshay Kumar, Mr. Dhanesh Kumar, Ms. Shrishti, Mr. Anant, Mr. Desh Bhushan Patil, Mr. Anil, Mrs. Priya, Mr. Rajesh and Mr. Abhishek. Thank you all for making a wonderful and enjoyable life at BITS Pilani campus.

Last but not least, I am thankful to my father, Mr. Raya Narasimha Kumar, and my mother, Mrs. Raya Naga Padmaja, for their constant motivation and unconditional love throughout my life. Besides, I am lucky to have my wife, Mrs. Raya Jyoshna Sreevalli, for her care, affection, and moral support during my final stages of PhD completion. Finally, I thank almighty God, who made all circumstances to keep me in this great work state.

RAYA RAGHAVENDRA KUMAR

ABSTRACT

Developing countries have a large population in rural areas. Water, an essential need for rural people's survival, is depleting in naturally available forms. Rural areas are more prone to water deficiency subjected to multiple factors. Moreover, water storage is becoming a confronting task in recent times. Simultaneously, infrastructural challenges in rural areas are distinct compared to urban areas. Domestic rainwater harvesting (RWH) and human-made water structures achieved significance because of water paucity, confined to factors such as geographic location, poorly created water infrastructures, unawareness among rural habitats, and human negligence. The rural areas need to be facilitated with functional water infrastructures by bringing constructive coordination among the local communities. The thesis considers the planning, modelling, and analysis of RWH system. This study identifies and adopts construction management principles to surpass the encountered challenges and acquire efficient construction deliverables.

RWH is the easiest and most widely accepted water-saving technique. The study highlights the factors and issues related to rural water infrastructure (RWI) development and focuses on India's RWH structures. Despite multiple efforts from various agencies and Governments, the rural areas lack incorporation of planning, coordination, and monitoring techniques on RWI. Minimal applied decision-making at lower levels leads to the inefficiency of rural water sources. Methods followed in the literature are found limited to household rainwater collection. Low water security and inadequate alternative sources for excess water storage have been observed in the various practising RWH methods, which create a research gap to construct RWH system for abundant water storage. Besides, contemporary, and advanced technology applications must address rainwater storage functioning for a community. The study represents an innovative rainwater storage structure named directional tunnel, placed in a declined position below the ground level. It reduces evaporation and temperature, thus stores rainwater for longer days. It collects runoff and rainwater from the rooftop of multiple houses in a rural community. Combined with the engineering geological characteristics, the directional tunnel's stability is affected as the whole structure interacts with the soil. The study also focuses on the behaviour of directional tunnel concerning sandy soil using PLAXIS 3D software, and the results have been interpreted for practical feasibility.

The practical execution of any rural infrastructure (RI) typically involves multiple stakeholders. Simultaneously, RI projects face multiple obstacles, such as unavailability of materials and machinery, poor estimation, failure in documentation, and cost overrun during their operations. The literature study infers that the techniques used in solving RI issues lack a professional construction management approach. Building Information Modelling (BIM) has been one of the pioneering processes in this field because of its numerous deliverable benefits during the planning, design, build, and operation phases. BIM is utilised in establishing and managing physical and functional features of any structure or place using virtual representations. Previous research works concentrated on enhancing and applying the BIM tools and framework for infrastructure projects in urban areas such as airports, bridges, highways, and tunnels, called Infrastructure BIM (I-BIM). However, the application of BIM in a rural scenario is minimal, and its execution to overcome the challenges faced in RI projects remains a gap.

This study enhances the existing concept of BIM from a rural viewpoint, as Rural BIM (R-BIM), by incorporating essential attributes based on previously performed rural studies and water infrastructure development strategies to get over the uncertainties. The concept aims to overcome the RI execution challenges by focusing on a water management scenario. In this conjunction, the R-BIM framework has been developed and explored through various dimensions, from second dimension (2D): planning to seventh dimension (7D): safety management. The various dimensions in the R-BIM correspond to planning with the incorporation of participatory management, visualisation, schedule, cost, capacity and safety management. The framework has been applied and discussed through a case study emphasising rural water management (RWM) project involved with the directional tunnel execution. The selected area is a village in Rajasthan, India. The complete RWM operation utilises the working scheme of BIM cloud by the rural stakeholders. Finally, the obtained results of the study have been validated through a project management principle, Earned Value Analysis (EVA). The scenario of implementing the complete RWM concept without the effect of R-BIM framework has also been considered in order to compare both results and recommend the developed method.

Keywords: Building Information Modelling (BIM), Construction management, Infrastructure challenges, Rainwater harvesting, Rural water infrastructure

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List of Abbreviations

AC - Actual Cost
AHP - Analytic Hierarchy Process
ASTM - American Society for Testing and Materials
BIM - Building Information Modelling
CV - Cost Variance
CPI - Cost Performance Index
CST - Compressive Strength Test
EVA - Earned Value Analysis
EV - Earned Value
FEM - Finite Element Method
GRP - Glass fibre Reinforced Plastic
I-BIM - Infrastructure Building Information Modelling
IFC - Industry Foundation Classes
IoT - Internet of Things
OSHA - Occupational Safety and Health Administration
PERT - Program Evaluation and Review Technique
PV - Planned Value
RI - Rural Infrastructure
R-BIM - Rural Building Information Modelling
RWH - Rainwater Harvesting
RWI - Rural Water Infrastructure
RWM - Rural Water Management
SPI - Schedule Performance Index
SV - Schedule Variance
TST - Tensile Strength Test
UTM - Universal Testing Machine
2D - Second dimension
3D - Third dimension
4D - Fourth dimension
5D - Fifth dimension
6D - Sixth dimension
7D - Seventh dimension

CHAPTER 1: INTRODUCTION

1.1 Chapter overview

This chapter defines the problem on which the current thesis is focused. A concise introduction on the concept adopted for solving the research problem is discussed. The outline of all chapters compiled in the thesis is also mentioned.

1.2 Water and challenges in rural areas

Water, a basic need for livelihood, has a declination in its availability globally because of the increase in the water demand by about 1.8% per year over 100 years (Wada et al., 2016). Consequently, water unavailability might arise in the future if necessary actions are refused. The deprived societies in rural areas fall short in access to secured water supply and safe sanitation, which causes health adversities, economic imbalance, gender, and social inequalities (UNESCO 2021). The absence of effective community engagement to manage comprehensive solutions from the production of raw water and to distribute water across the community is rather reason for the water scarcity. Any approach to mitigate the situation of water scarcity must consider water conservation as a crucial component. At present villagers face not only water shortages but also water quality-related problems. Rural people have insufficient access to pure drinking water due to the consequences of low income, technological capabilities, community internal management, water contamination from agricultural chemicals, industry, and waste disposal (UN Water 2015). The recommendations have to be comprehended addressing the issues and self-created solutions for reducing costs and improving sustainability.

1.3 Rainwater harvesting

The selected study is in the domain of rural areas, where several methods such as sand bores, johads, ferrocement tanks, rooftop RWH, joy pumps, and cycle run water pumps have been adopted for storing water among various RWIs (Bhoomi Magazine 2017). Out of which, RWH is an age-old concept and has paramount importance; besides, it has been considered a superior alternative to the commonly adopted piped water supply system in rural areas. The working system of RWH can be broadly classified into surface and rooftop collection. In general, a RWH system has five components: a) Catchment – a surface at which the rainwater is collected and stored, which could be a landscaped space, a rooftop, or a paved flooring surface; b) Gutters and downspouts – these connections convey water from the catchment area to the storage tank; c) Filters and first flush device – help in separating the suspended particles and pollutants in the rainwater; d) Storage tanks – usually constructed above or below the ground for storing the harvested rainwater; e) Delivery system – a water distribution system that transfers rainwater from the collection area to the place of utilisation (India Water Portal 2021). The conceptual representation of domestic RWH system has been demonstrated in Figure 1.2.

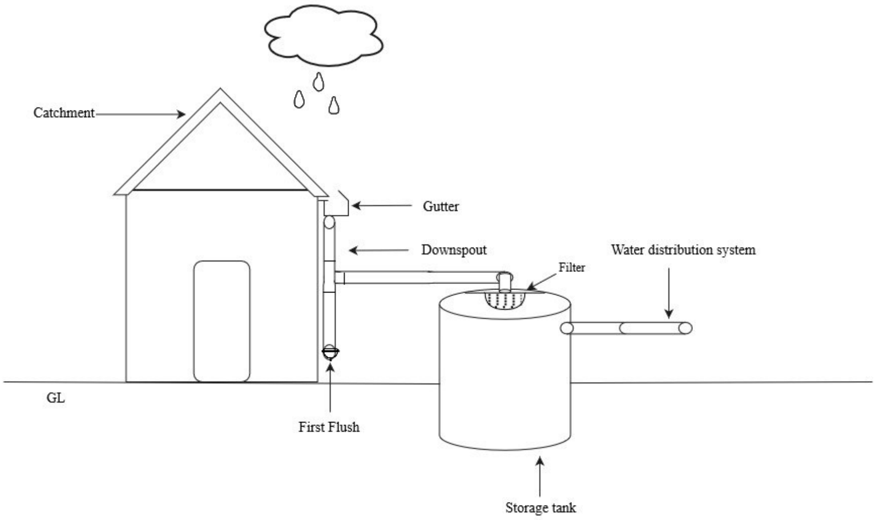


Figure 1. 1 Components of a RWH system

1.4 Infrastructures

The construction of infrastructures in rural as well as urban scenarios have been in different perspectives. However, any infrastructure is created as a primary source for better and multiple outcomes of the dwellers in a community. Well-established infrastructures in aviation, communication, bridges, power and energy, railways, roadways, water, waste and recreation facilities, shown in Figure 1.1, lead to a nation’s economic growth and affluence (Puentes 2015). Simultaneously, infrastructures have the potential to bring people together and strengthen communities, which would also encourage local businesses and companies to expand and flourish. Connecting these advantages, civil engineers play a vital role in the planning and design phases of new infrastructures. The concept of project management is directly involved in the planning, design, construction, operation, and maintenance of an intended facility. The process of identifying acceptable measures and decision-making is significant in attaining success through project management.

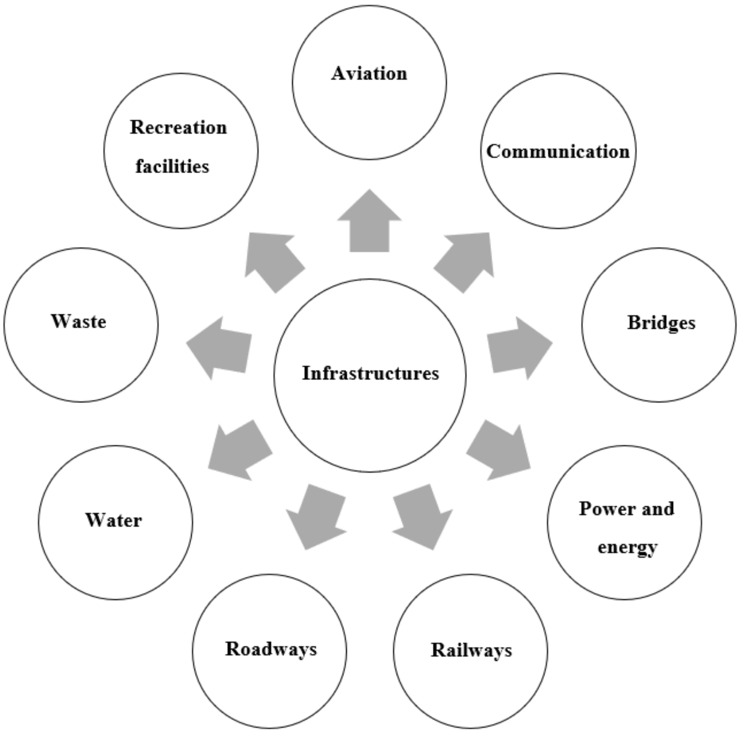


Figure 1. 2 Different domains of infrastructures

1.4.1 Rural Infrastructure

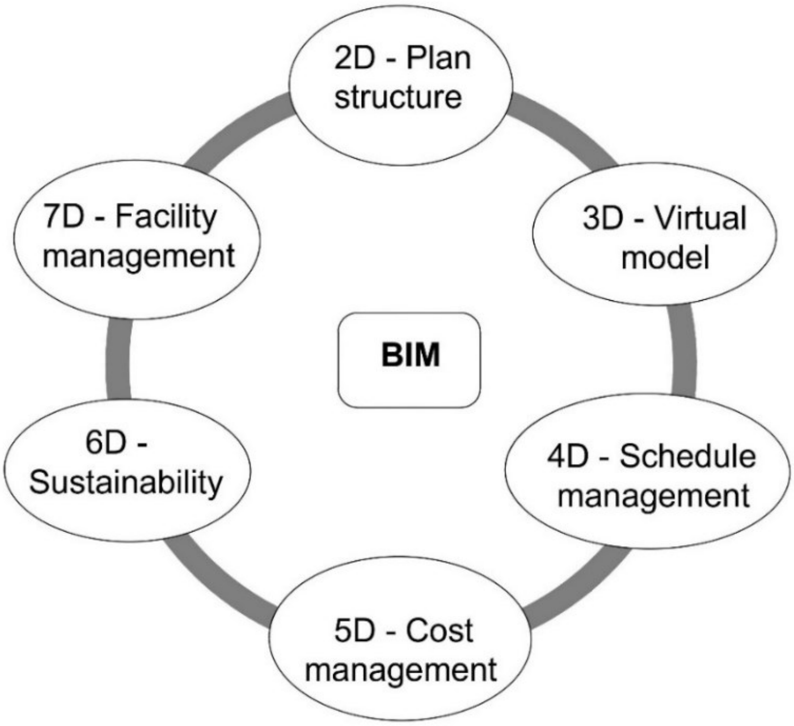
The infrastructures in urban areas have been well-established. Whereas in another scenario, RI is basically defined as a physical component targeted at a community for reaping the benefit of standard living (Memon and El Bilali 2019). Well planned and constructed RI can transform society by refurbishing improved markets for rural dwellers and producers in the villages. According to International Labour Organization (2021), the RIs are linked to the services such as roads, tracks, bridges, irrigation schemes, water supplies, schools, health centres and markets. A balanced execution of all these infrastructures leads to sustained economic development in a village. However, rural areas are often neglected, and the infrastructures which bring upliftment in their associated societies have not been given the required attention. Furthermore, private investors are reluctant to invest in rural atmospheres since those areas are less densely inhabited than urban areas, resulting in low returns (Liu and Yamauchi 2014). The existing infrastructures in rural areas might not solve the difficulties or shortcomings faced in the daily life of people. Eventually, new infrastructures must be built as the solution. Therefore, research techniques must address the impediments and maintain equity by enforcing infrastructural projects in rural areas. As a result, people living in villages would experience a prosperous life and avoid migration to cities for livelihood.

The RI intended in enhancing rural areas' standards must incorporate new technologies. Comprehensively, new systems must be well perceived before on-field initiation. Multiple techniques have been followed for the enhancement of RI operation. Some approaches include participatory technique, decentralised planning and implementation, Grey-Analytical Hierarchy Process (AHP) method, and expert systems (Benard and Iminza 2020; Wong et al., 2013; Yin et al., 2014; Olanrewaju and Olabanjo 2020). However, the prevailing issues in RI projects execution have not been averted.

1.5 Building Information Modelling

The thesis has been focused on the RI management. The background study identified construction management aspect as the potential for solution. In this area, the implementation of BIM gives the scope of defining a concept or technology coherently before construction (Joblot et al., 2017). BIM is the process of virtually interpreting a structure's functional and physical features. It is a forward move in developing computer-aided design, which integrates documentation, architectural and landscape design, construction and installation models, bill of quantities and cost estimates into a single database accessing all the above data (Li et al., 2017).

Czmoch and Pękala (2014) have stated that effective implementation of BIM by experienced engineers or designers generates profits and reduces the time of large-scale infrastructure projects. Over the years, BIM has progressed in different dimensions, emphasising the efficacy of using multiple data types for practical execution. The creation and modifications of a structural plan, known as 2D in BIM, eventually lead Mechanical-Electrical-Plumbing engineers to efficiently plan and design their corresponding tasks. Visualisations (3D) of a location help in comprehending the actual site conditions; subsequently, a project's on-site execution becomes simpler. The usage of BIM tools identifies clashes among structural members, pipelines, and ducts in building construction. Successively, schedule (4D) and cost (5D) of a project could be managed (United BIM 2020). 6D signifies sustainability, where a structure's energy consumption and efficiency during the operational stage would be assessed beforehand. Finally, 7D denotes facility management pertaining to a building's assets' maintenance and management (Intelligent HQ 2021). Figure 1.3 depicts the dimensions in BIM from 2D to 7D.



(D: Dimension)

Figure 1. 3 Dimensions of BIM

Advanced countries, such as the United States, China, Canada, and the United Kingdom, have adopted BIM in numerous fields. Life Cycle Assessment (LCA) in contemporary research helps in analysing the environmental impact of construction materials in their life cycle. Sobhkhiz et al. (2021) have emphasised the use of semantic web technologies in the construction industry for the integrated application of BIM-LCA. Furthermore, advancements in BIM have widened the scope of complex engineering projects' design, construction, operation, and maintenance phases. (Cao et al., 2015; Zhou et al., 2017). Previous researchers have preferred BIM in the urban infrastructure accomplishments for broad outreach and application (Marzouk and Ahmed 2019; Pavón et al., 2020; Alshorafa and Ergen 2021). Eventually, the employment of BIM for RI issues could act as an effective tool for the solution.

1.6 Problem statements

Modern infrastructures are increasing day by day in urban areas, considering the unprecedented rate of urbanisation. However, rural communities experience multiple confronts such as inadequate daily life facilities, poor infrastructure, water and transport inaccessibility (National Conference of State Legislatures 2020). RI projects remain unfinished or unoccupied by many users in developing countries (UK Essays 2018). Complexity in construction, unavailability of materials and machinery, poor estimation, low-grade quality, improper coordination, cost overruns, local protests, political instability, changes in governance or policies, and a lack of skilled workers are some of the factors that cause RI projects to be disrupted and delayed (Suárez et al., 2021). The enforcement of construction management strategies results in overcoming hurdles such as improper communication, unorganised documentation, staff mismanagement, site investigation delays, cost discrepancies, and resource wastage in RI projects (Tran et al., 2015).

As discussed earlier, RWH in rural areas has been preferred since it gives the decision-makers a cutting edge over the other water supply systems in rural areas because of the advantages such as i) feasibility in construction, operation and maintenance, ii) adaptability for irrigation activities, iii) decrement in over-dependency on groundwater, iv) cost-effectiveness in water bills, v) utility for non-potable purposes and vi) declination in flood and soil erosion. However, this system has disadvantages such as a) unreliability in rainfall, b) initial high capital investment, c) regular maintenance and d) limitation in the storage capacity e) surface water evaporation (Misra 2019).

The resolution of the problems lies in handling strategies and research-oriented applications. All the challenges, barriers, and issues must be well understood and addressed depending on the regional factors. Hence, the research problem generated a focus on the RWH intended for communities in rural areas. Simultaneously, the thesis explores overcoming RI projects' challenges by applying construction management techniques for quality-oriented accomplishments.

1.7 Motivation for the study

Alarming factors in rural areas of India such as four out of ten rural households travelling every day for drinking water, 10.5 per cent rural households spending over 30 minutes to get water every day have been concerning (Shagun 2019a). Only 11.3 per cent households receive potable water directly at homes in rural parts of India. Moreover, hand pumps, the most relied principal source of drinking water, accounted for 42.9 per cent usage (Shagun 2019b). The United Nations (UN) set the agenda of 2030 as Sustainability Development Goals (SDG). 17 goals have been framed, where SDG-6 corresponds to "accessing safe and pollution-free drinking water by enforcing integrated water resources management". Based on the current demographics in India and UN set SDG, the present study focus has been towards RWI sector. Hence, a resolution for the existing challenges through the development of a community-targeted water management in rural areas has been concentrated. Besides, the existing studies reflect common obstacles in RI projects such as lack of detailed construction models, unskilled workforce, prefabrication and haulage issues, poor decision-making, and deficiency in communication platform. BIM, a powerful tool in construction management has been applied in urban infrastructure projects for various capabilities. However, the rural aspect of BIM needs investigation. Considering the latest developments of BIM, this thesis focused on development of BIM concept adoptable for RI projects.

1.8 Scope of the study

The outcomes of the present study will have an impact on the RWI sector, especially in RWH applications. The novel concept of directional tunnel developed in this study is highly adoptable for RWH in rural areas. The feasible materials of jute fibre as well as GRP have been explored. Simultaneously, GRP has been recommended through experimental as well as analytical study. The results obtained from analytical model gives good agreement of feasible angle for installation of directional tunnel.

Considering the distinct challenges in RI projects, R-BIM framework has been enhanced in the rural perspective, which is helpful in developing skill and safety of the existing workforce. The R-BIM framework validation through the RWH system has been performed with the help of a case study. The EVA application in the study, by the reflection of with and without the effect of R-BIM on RWH system, reinforces the developed framework. Also, "Effect of R-BIM framework on transportation projects", "Enhancement of R-BIM framework to nD", "Application of eco-friendly materials on directional tunnel" are some of the studies which can be done in the future to enhance the focused industry.

1.9 Outline of thesis

The thesis work is structured into seven different chapters. An overview of the upcoming chapters, from Chapter 2 to Chapter 7, has been mentioned ahead:

Chapter 2: Literature review

This chapter presents a thorough review of challenges faced in RIs' construction and management. Various RWI studies and BIM concepts concerning urban as well as rural areas have been considered in identifying the research gaps.

Chapter 3: Fundamental techniques employed in the water infrastructure management and integration of BIM for rural infrastructures

This chapter emphasises the established techniques for water infrastructure development. The role of I-BIM and developments in BIM pertaining to water infrastructure have been highlighted. The concept of R-BIM has been developed based on the obstacles concerning RI execution and improvements in water infrastructure management.

Chapter 4: Planning an efficient water management system by Directional Tunnelling method and analysing its stability in soil conditions

This chapter discusses about development of an innovative RWH method, named Directional tunnel. Different alternatives in the fabrication of the directional tunnel have been highlighted. Besides, the study explores the practical feasibility of this method by analysing its stability and failure in underground soil conditions. PLAXIS 3D software has been used for analysing and interpreting the results.

Chapter 5: Development of Rural BIM framework and its implementation

This chapter considers the development of the R-BIM framework aiming at multiple dimensions. The framework has been adopted and discussed through a case study on RWM held at a village in Rajasthan (India). The planning phase of the application through R-BIM has been discussed.

Chapter 6: Execution of R-BIM and its validation by Earned Value Analysis

This chapter discusses the developed R-BIM framework's execution in the study area and various stakeholders' management in a BIM cloud platform. The method of EVA, a project management principle, validates the obtained results. The implementation of RWM without the effect of the R-BIM framework has been considered and compared with the acquired results.

Chapter 7: Conclusions and Future Scope

This chapter concludes with the findings of the research work based on the methodology and validations carried out. Besides, the chapter outlines the study's limitations and future scope.

1.10 Summary of the chapter

An introduction concerning the problem statements in the current thesis has been highlighted. BIM, a construction management process, has the potential in solving the execution challenges of urban infrastructure projects. However, RI projects need a broadened approach. Among the various types of infrastructures, the study has been focused on RWI. A brief discussion on the method of RWH and its components have been portrayed. Since this method pose disadvantages, an in-depth literature review regarding the selected study has been discussed for identifying the research gaps in the next chapter.

References

Alshorafa, R. and Ergen, E., 2021. Determining the level of development for BIM implementation in large-scale projects: A multi-case study. Engineering, Construction and Architectural Management, 28 (1), 397–423.

Benard, M.M. and Iminza, R.M., 2020. Effective Project Management for Sustainable Rural Development in Africa. International Journal of Academic Research in Business and Social Sciences, 10 (8), 788–806.

Bhoomi Magazine, 2017. Traditional and Innovative Water Conservation Methods in India [online]. Available from: http://bhoomimagazine.org/2017/04/01/traditional-and-innovative-water-conservation-methods-in-india/ [Accessed 3 Mar 2020].

Cao, D., Wang, G., Li, H., Skitmore, M., Huang, T., and Zhang, W., 2015. Practices and effectiveness of building information modelling in construction projects in China. Automation in Construction, 49, 113–122.

Czmoch, I. and Pękala, A., 2014. Traditional design versus BIM based design. Procedia Engineering, 91, 210–215.

India Water Portal, 2021. Components of a rainwater harvesting system [online]. Available from: https://www.indiawaterportal.org/special-page/chapter-2-components-rainwater-harvesting-system [Accessed 20 Jan 2022].

Intelligent HQ, 2021. BIM Dimensions: 3D, 4D, 5D, 6D & 7D BIM - Explained [online]. Available from: https://www.intelligenthq.com/bim-dimensions-3d-4d-5d-6d-7d-bim-explained/ [Accessed 10 Jan 2021].

International Labour Organization, 2021. Developing rural infrastructure [online]. Available from: https://www.ilo.org/asia/WCMS_099466/lang--en/index.htm [Accessed 10 Oct 2021].

Joblot, L., Paviot, T., Deneux, D., and Lamouri, S., 2017. Literature review of Building Information Modeling (BIM) intended for the purpose of renovation projects. IFAC-PapersOnLine, 50 (1), 10518–10525.

Li, X., Xu, J., and Zhang, Q., 2017. Research on Construction Schedule Management Based on BIM Technology. Procedia Engineering, 174, 657–667.

Liu, Y. and Yamauchi, F., 2014. Population density, migration, and the returns to human capital and land: Insights from Indonesia. Food Policy, 48, 182–193.

Marzouk, M. and Ahmed, R., 2019. BIM-based facility management for water treatment plants using laser scanning. Water Practice and Technology, 14 (2), 325–330.

Memon, J.A. and El Bilali, H., 2019. Rural Infrastructure and Food Security. Zero hunger encyclopedia of the UN sustainable development goals, Springer, 1–10.

Misra, A.K., 2019. Rainwater Harvesting and Artificial Recharge of Groundwater. Groundwater Development and Management, Springer, 421-439.

National Conference of State Legislatures, 2020. Challenges Facing Rural Communities [online]. Available from: https://www.ncsl.org/research/agriculture-and-rural-development/challenges-facing-rural-communities.aspx [Accessed 5 Jul 2021].

Olanrewaju, O.A. and Olabanjo, A.G., 2020. An Expert System for Rural Water Supply Management. International Journal of Innovative Research and Development, 9 (8), 19–27.

Pavón, R.M., Arcos Alvarez, A.A., and Alberti, M.G., 2020. BIM-based educational and facility management of large university venues. Applied Sciences, 10 (22), 1–28.

Puentes, R., 2015. Why Infrastructure Matters: Rotten Roads, Bum Economy [online]. Available from: https://www.brookings.edu/opinions/why-infrastructure-matters-rotten-roads-bum-economy/ [Accessed 16 Sep 2019].

Shagun, 2019a. News report: Rural households' challenges for drinking water [online]. Available from: https://www.downtoearth.org.in/news/water/4-out-of-10-rural-households-travel-every-day-for-drinking-water-67935 [Accessed 3 Mar 2022].

Shagun, 2019b. News report: Nearly 80 per cent Indian households without piped water connection [online]. Available from: https://www.downtoearth.org.in/news/water/nearly-80-per-cent-indian-households-without-piped-water-connection-67928 [Accessed 3 Mar 2022].

Suárez, D., Díaz-Puente, J.M., and Bettoni, M., 2021. Risks identification and management related to rural innovation projects through social networks analysis: A case study in Spain. Land, 10 (6), 1-23.

Tran, D.Q., Hallowell, M.R., and Molenaar, K.R., 2015. Construction Management Challenges and Best Practices for Rural Transit Projects. Journal of Management in Engineering, 31 (5), 1-9.

UK Essays., 2018. Why Many Projects Fail At Rural Areas Construction Essay [online]. Available from: https://www.ukessays.com/essays/construction/why-many-projects-fail-at-rural-areas-construction-essay.php#citethis [Accessed 5 Jul 2021].

UNESCO, 2021. Rural water development [online]. Available from: https://en.unesco.org/themes/water-security/hydrology/water-human-settlements/rural-development [Accessed 5 Oct 2021].

UN Water, 2015. Sustainable Approaches for Drinking Water in Rural Area [online]. https://www.un.org/waterforlifedecade/waterandsustainabledevelopment2015/pdf/Noppawan_Boontham_CaseGDG.pdf [Accessed 25 Apr 2021].

United BIM, 2020. Benefits of BIM implementation [online]. Available from: https://www.united-bim.com/5-benefits-of-bim-implementation/ [Accessed 20 Jun 2020].

Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., Van Vliet, M.T.H., Yillia, P., Ringler, C., Burek, P., and Wiberg, D., 2016. Modeling global water use for the 21st century: The Water Futures and Solutions (WFaS) initiative and its approaches. Geoscientific Model Development, 9 (1), 175–222.

Wong, H.L., Luo, R., Zhang, L., and Rozelle, S., 2013. Providing quality infrastructure in rural villages: The case of rural roads in China. Journal of Development Economics, 103 (1), 262–274.

Yin, S.X., Li, H.M., Wang, A.J., and Sha, M., 2014. The evaluation research on the rural infrastructure construction of Shaanxi based on Grey-AHP. Advanced Materials Research, 869–870, 172–177.

Zhou, W., Qin, H., Qiu, J., Fan, H., Lai, J., Wang, K., and Wang, L., 2017. Building information modelling review with potential applications in tunnel engineering of China. Royal Society Open Science, 4 (8), 1-16.

CHAPTER 2: LITERATURE REVIEW

2.1 Chapter overview

The literature review in this chapter describes the common challenges during the execution of RI projects. A focus on the water infrastructures' status and their management in India have been emphasised. The concept of BIM in the urban scenario and its history at the rural level has been discussed. Finally, the research gaps and objectives have been mentioned at the end of the chapter.

2.2 Introduction

A well-accomplished RI can transform the living standards of rural habitats. Infrastructural development acts as a boosting factor to eradicate or lessen the gap between cities and villages. Scoones (2009) inferred that potential spots for rural development must be identified to distinguish the area for development. Available funding sources for infrastructural development must be recognised since economic growth and financial resources have two–way effects on each other. Policymakers and governments need to invest more in infrastructure development. Subsequently, it passes the message that developed infrastructure is crucial in every country, and governments put efforts towards infrastructure development for achieving socio-economic developmental goals (Kumari and Sharma 2017).

2.3 Challenges in the execution of rural infrastructure projects

Infrastructures in urban areas have been equipped with sophisticated facilities and energy-efficient architecture (Szolomicki and Golasz-Szolomicka 2019). Moreover, integrated planning and management of urban infrastructure have been explored based on future climate predictions (Caprario et al., 2022). However, rural areas lag the application level of new policies, technologies, and approaches compared to cities with strong administration and planning measures (Zheng 2014). Governments and agencies taking part in the plan implementation should focus on intensified supervision and community planning in rural areas and elude mismanagement and wrong decisions during construction. For instance, Government of India initiated Rural Infrastructure Development Fund (RIDF) under National Bank for Agricultural and Rural Development (NABARD) in 1995-96, which works as a financial source to gain prosperity in the RI projects of agriculture, social and rural connectivity (NABARD 2021).

Many researchers argue that the RI projects' challenges have been distinct from urban infrastructural projects. Eventually, RI uncertainties have to be resolved effectively. In this connection, two case studies were initially reviewed for absorbing various obstacles in the RI projects' execution.

I. Zamfara state, Nigeria

The study conducted by Kaura et al. (2018) considered procedures followed by craftsmen and their consequences in the rural areas of Nigeria. Their study reveals that technically trained and untrained craftsmen exhibited similar practices during building construction planning and foundation work. Some of the irregular routines observed were misinterpretation of plans, poor selection of construction materials, and inconsistency in the adoption of specifications for the assigned activities. Besides, soil's bearing capacity at the locations was never determined before construction. Building codes were often ignored for construction works in rural areas, which misled to building collapses in numerous cases. The absence of supervision was also a significant cause in remote locations, which led to mismanagement in construction sites. Simultaneously, planning practices such as selection of equipment, preparation of ground, measuring accurately the parameters of plan, application of technical information in building construction as well as various works in different stages were moderately adopted by the workforce. Negligence in placing foundation according to specification, reinforcement for foundation and laying foundation for preventing unequal settlement were observed. Moreover, rare practice in establishing width of foundation trenches, driving in pegs uniformly for determining thickness of foundation concrete and conducting site tests on foundation materials. It was also noticed that there was no significant difference between the master craftsmen with qualification and those without qualification concerning construction practices in the state. Conclusively, the Nigerian case study implicates the lack of technical training, dismissal of guidelines/building codes and human resource mismanagement as setbacks for construction in rural areas.

II. Hainan province, China

Liang and Yue (2021) studied wastewater treatment systems' construction and operation failure in Dala village of Hainan province, China. The village had 275 families with an overall population of 1500. A wastewater treatment system was constructed in 2010 for treating approximate sewage of 250 m^3/day. Simultaneously, the initial investment of entire wastewater treatment system costed 870,000 yuan, which was provided by the county governments. The operation and maintenance cost were covered by the village committee, whose revenues were derived from land rentals. Because the treatment system mainly comprised the wetland, the O&M cost is not very high. An outlay of 2,800 yuan per month covered the payment for three women who clean the wetland of 600 yuan each per month and payment for one external technician of 1,000 yuan per month. As the village committee was not a professional service institute, the treatment system stopped working in 2016. The construction of the treatment systems had technical defects; therefore, those systems could not handle the village's sewage seven years after its inception. The complete project management lied in the hands of four stakeholders, such as local government, town government, village committees and farmers. Lack of technical knowledge, management skills and incompetent decentralised management led to obstacles that finally had an operational breakdown. Eventually all these factors give insights to enhance construction practices in rural areas by avoiding technical flaws, properly administered decentralisation, and well managed sustainable operation for a long duration.

Skilled labour force shortage persists in India and Nigeria. India ranks 129 among the 162 countries concerning availability of skilled labour (Times of India 2020). Simultaneously, a survey conducted in Nigeria exhibited that around 80.6% of labour in construction industry of Nigeria were unskilled. India and China are densely populated countries. Therefore, the challenges faced in the construction sector have the potential to behave as a reference develop a research solution. Considering these factors, the case studies from India and Nigeria have been considered in the context of current study.

The problems associated with restructuring rural areas might be addressed by drawing on experiences and achievements from other countries, which may have experienced similar developmental stages as part of their progression. Long and Liu (2016) aimed to advance the contemporary rural restructuring in China by focusing on spatial restructuring, economic restructuring and social restructuring, and the key challenges for rural areas. Suárez et al. (2021) classified challenges in rural innovative infrastructure projects into five categories: social, technical, economic, political, and environmental. The detailed types of challenges associated with various categories in rural level projects have been listed in Table 2.1.

Table 2. 1 Classification of challenges in rural infrastructure projects

Category	Type of challenge
Social	Local protests
	Lack of knowledge and experience
Technical	Poor machine operation
	Contractor performance
	Poor construction methods
	Poor communication and coordination
	Material shortage
Economic	High energy and water costs
	Cost overrun
	Payment delays
	Inflation and interest rate variance
Political	Political instability
	Changes in policies and regulations
	Corruption
	Governance conflicts
Environmental	Climate change
	Adverse weather conditions
	Risks prone to droughts, cyclones, floods, and storms
	Loss of habitats and landscapes

2.4 Building water management in societies

Considering a wide range of RIs in villages, this thesis focuses on the domain of RWI. Water management in the villages has been one of the significant defying tasks over the years. The fundamental elements to be considered for a well-planned water management system involves coordinated national and international strategies, a competent technical workforce, effectively sized and structured infrastructure, priority investment in technology and innovation (Shamir and Howard 2012). Investments in multi-purpose water management strategies increase governance and management of water resources. These strategies help in controlling water demand irrespective of the season (Bernier et al., 2016). A study conducted by Lund et al. (2012) in California recommends two valuable methods: a) encouraging groundwater and

b) improving water transfers for the prospects of water management. Increased groundwater storage was economical compared to the construction of new water infrastructures. Moreover, improvements in water transfer reduced water demand. According to their study, the lack of groundwater basins and local resistance to water sale were considered significant challenges. However, this thesis recommends that the increase in groundwater storage and new water infrastructures must go parallel in a rural scenario since water demand rises with population and the need could be met with the combined effect.

The increase in water demand must be satisfied by maintaining sufficient per capita water (Kumar and Ballabh 2000). In order to meet the demand, water available from natural sources is being retracted in an immature way which affects the status of rivers and other natural streams (Jain 2019). Upsurge in the water demand is connected to various purposes. These include the combined effect of growth in population and food grains, multiple water users across families, increased energy demand, frequent droughts, limited water infrastructure, uncontrolled groundwater extraction, and inadequate groundwater extraction water supply (Multipure 2021). Carter et al. (1999) have identified the adoption of sustainability as one of the most promising steps to overcome difficulties for a community water supply. The main components of achieving sustainability are motivation, regular maintenance, cost recovery, and continuous support. The responsibility of motivating the residents for implementing a new water source system and its maintenance, collecting user fees, upholding regular meetings could be assigned to different committees in a community (Wichman et al., 2016).

The dynamics of water management are not happening through a faster approach. The groundwater level is declining throughout many parts of the world (Basu 2021). At the end of 2020, around 784 million people globally do not have access to better quality water (Lifewater 2020). Groundwater unavailability could occur if appropriate steps are not taken. Therefore, recharging the groundwater or creating water resources for human sustenance has turned imperative. Water can be reserved in water storage structures, and it can be achieved by constructing sufficient water infrastructures. Eventually, Everard et al. (2020) highlighted that any engineered infrastructure in a rural domain could meet the growing population’s demand by incorporating engineered solutions and natural sources.

2.4.1 Declining status of RWI’s performance

Population rise across countries has been leading to restrained water availability. Consequently, water-saving methods gained importance. This thesis considers Indian scenario, hence the enforcement of RWI’s policies and the factors for better outcomes are studied. In coordination with the different state governments, the Government of India has been pushing towards accomplishing Sustainable Development Goal 6, i.e., “ensure availability and sustainable management of water and sanitation for all”, set by the United Nations General Assembly. Policies such as National Rural Drinking Water Program (2009), National Water Framework Law (2016), Accelerated Urban Water Supply Program (1994), Namami Gange (2014), National Water Policy strive for the objective of clean water and sanitation for all by 2030 (Ahmed and Araral 2019).

Updating water sources with new technology and methods would benefit the people during unforeseen circumstances (Hutchings et al., 2016). India’s population close to 1.4 billion, bears an expected water demand of 910 billion cubic metres by 2025 and 1072 billion cubic metres by 2050 (Statista 2021). According to the National Institution for Transforming India (NITI) Aayog report 2018, nearly half of India’s population suffers from water conundrums. Three-fourths of rural households do not possess piped swater supply, resulting in dependencies on unhygienic sources (Chengappa 2021). With the introduction of Jal Jeevan Mission - rural, 2019, only 34 per cent of households were incorporated with the infrastructure (Abraham 2021). Despite several policies, schemes, and efforts by the various governments and water bodies in communities, India’s drinking water supply has been insufficient and do not reach people in time.

Execution of new RWI faces a significant challenge of political risk for new investments. Local administration and their objections behave adversely for the financiers or investors to come forward and take up the projects. The governments may also not take a risk on sensitive issues. The stakeholders’ concession and multiple parties' involvement in the infrastructure would help in solving the local problems concerning infrastructure construction (Tortajada 2014). Simultaneously, some governments stay reluctant to enact new technologies in rural areas since capital investment becomes enormous.

Non-Government Organisations (NGO) and women's participation in RWM have always been crucial and noteworthy in India. Organisational coordination and people participation should go hand in hand to implement rural water supply projects successfully. Besides, women’s contribution remains forever vital in sustainable water management as they involve in household water storage activities. The timely unavailability of water increases women’s mental pressure, and locating additional water sources becomes challenging (Crow and Sultana, 2002). Moreover, water inaccessibility and its quality directly impact societal development and health vulnerabilities for children (Tarrass and Benjelloun 2012). The collective action of women’s decision-making in water management slims down the barriers in a village or a community. Self Employed Women’s Association (SEWA), formed during the 1970s, portrayed women’s water management role. The SEWA personnel conducted several meetings and campaigns for finding the difficulties faced, accessibility to water sources, quality of drinking water within the native districts. The exposure to problems and challenges allowed SEWA for spreading its service across other districts in Gujarat, India. It paved the way for launching Women, Water and Work campaign on various state-level platforms. The progressive work of it had given rise to other 6 NGOs, and it worked as a state-level water recharging committee for the improvement in rural water development (Ahmed, 2000). Hence, from the extant study, it is evident that the NGOs had changed the RWM scenario and advised changes in the implementation of water policies.

Another outlook of involving people in projects can be carried out by collecting people’s opinions, involving them in decision-making, and monitoring construction work. Manikutty (1998) has highlighted the interaction methods in rural areas, such as a) direct interaction with the users, b) indirect interaction with the users with the help of representatives for obtaining feedback and opinions. According to his study, Project Advisory Groups and local staff in Karnataka were the key role players in community participation. Meanwhile, in Kerala, youth clubs and women clubs were employed to spread health awareness programs and community involvement activities. Based on the various people interaction strategies among different states in India, it can be concluded that a particular strategy may not be adaptable in another place because of the feasibility of the approach among different attitudes of people.

In a step toward active participation among rural people in India, under Mahatma Gandhi National Rural Employment Guarantee Act (NREGA), the participants of water-related schemes were made to devote an ample amount of their time for maintaining water infrastructure (Falk et al., 2019). Prokopy (2005) has stated that all types of users, including poor households in the community, were liable for capital cost contribution in a water supply project. Hence, it can be inferred that a higher active participatory contribution leads to a RWM's success.

2.4.2 Rural water management through rainwater harvesting

This thesis focuses on RWH because of its affordability in rural areas of India. Rainwater can be harvested in two types; primarily, the collection of rainwater from the roof and its storage in an underground tank and secondly for groundwater recharge (Kumar 2004). In practice, RWH is a reliable alternative for domestic use over the constrained public water supply in rural areas (Owusu and Asante 2020). The traditional structures constructed as a part of a rainwater harvesting system in rural areas of India has been discussed in Table 2.2.

Table 2. 2 Different types of traditional rainwater collection system in rural areas of India

S.No	Name of the method	Working system	Remarks
1.	Paar system (Percolation system)	Rainwater flows from the catchments and percolates into the sandy soil.	Traditional masonry technique.
2.	Kuis / Beris (Narrow opened well)	10-12m deep pits were dug near tanks to collect the seepage, and the pit gets wider as it gets deeper into the ground and creates a large surface area for water to seep.	Prevents the collected water from evaporating.
3.	Saza Kuva (Open well)	Well pit with a huge circular foundation and an elevated platform sloping away from the well.	Source for irrigation in hilly regions of Western Rajasthan.
4.	Johad (Earthen check dam)	Small earthen check dams that capture and conserve rainwater, improve percolation and groundwater recharge.	Built by brick/stone masonry.
5.	Cheruvu (Village pond)	Reservoirs to store runoff.	Supplemented with sluices, canals, and flood weirs to supply water.

6.	Baoli / Bavadi (Stepped well system)	Stone blocks lined on the walls of the trenches without mortar and created with stairs leading down to the water.	Constructed to serve water across seasonal fluctuations.
7.	Kund / Kundi	Basically, a circular underground well with a wire mesh across water-inlets prevents debris from falling into the well-pit. Sides of the well-pit are covered with lime and ash.	Harvest rainwater for drinking, usually constructed with local materials or cement. These are found in Thar Desert region in Western Rajasthan and some areas in Gujarat.

A few Prominent RWH practices in rural areas in the past two decades organised by various NGOs in the Indian scenario have been discussed further in Table 2.3.

Table 2. 3 Prominent RWH practices by various NGOs in the past two decades in India (2001-2020) (Ministry of Water Resources 2020)

S.No	Methods	Location & NGO concerned	Remarks
1.	Traditional RWH practice	Kuitasuk village - Nicobar district, Chowra island. Local people.	Circular pots were rainwater holding structures for the conservation of water.
2.	RWH and management of water on steep slopes for cultivation	Along (Aalo) - West Siang District, Arunachal Pradesh. Local farmers.	The practice of terrace cultivation in the high slope of the Arunachal Himalayas. Water is preserved for cultivation.
3.	RWH and management of water for dual fish-cum-paddy cultivation	Lower Subansiri district - Arunachal Pradesh. Local farmers.	Storing of water by traditional structures for fish-cum-paddy cultivation.

			Release and supply of water from higher to lower level areas.
4.	RWH at Mewat district in Haryana	Untka school - Mewat district.	A rooftop rainwater harvesting system was established for recharging the aquifer for drinking and food preparation. It is suggested for shallow aquifer areas.
5.	Ground Water Recharge through Rooftop RWH	St Albert's College - Ranchi. Action for Food Production (AFPRO).	Rooftop rainwater was transferred to a recharging unit, then it percolated into the ground and restored the area's water table. Enhancement in soil moisture.
6.	Rooftop RWH	Loreto Convent School - Ranchi. Action for Food Production (AFPRO)	Adopted a similar mechanism as discussed ahead in St Albert's College – Ranchi in the view of groundwater recharge.
7.	Mazhapolima -a community based open well recharge programme	Thrissur – Kerala. Arghyam.	Groundwater recharge by supplying rainwater into the open, bore wells and ponds.
8.	RWH and recharge structures	Kishori-Bhikampura and Alwar district - Rajasthan. Tarun Bharat Sang	Recharge structures and rainwater storage structures were built by community involvement. Supervisory groups were

			formed to ensure proper operation, maintenance, and desilting.
9.	Rooftop RWH	Bilaspur and Kabirdham District – Chhattisgarh. Samerth Charitable Trust	Water structures were renovated and resumed functioning. Constructed six roof RWH structures.
10.	Roof RWH and storage	Patan, Surendranagar, Kutch areas. Self Employed Women's Association	Roof RWH was implemented by diverting the rainwater to underground pucca tanks. As a result, 4000 individual tanks were constructed to harvest 88.5 crore litres of rainwater from 1995 to 2008. 10.4 crore litres of water was conserved in ponds and wells by recharging the water table.

2.4.2.1 Miscellaneous rainwater harvesting systems developed by NGOs

I. Jal Bhagirathi Foundation

The project tiled "Developing improved & sustainable sources of drinking water through RWH in 5 villages of Thar Desert in Rajasthan, India", aimed in demonstrating the applicability of decentralized cost-effective rainwater harvesting, storage and purification structures for increasing the long-term availability of improved drinking water along with improved sanitation and hygiene practices. This project focused its direct implementation efforts in 5 water distressed villages of the Marwar region in the Thar Desert. Another project titled "Adaptive Strategies Through Community Management of Natural Resources to address Climate Change in the Marwar Region", was implemented in 5 villages of Barmer and Jodhpur districts and was successful in reviving traditional rainwater harvesting systems ensuring water security (Jal Bhagirathi Foundation 2021).

II. Tarun Bharat Sangh

Among the multiple projects, the Babajiwala Johad has been a 160-meter long structure, an earthen embankment with a masonry spillway and was built by the community. The embankment was 13 meter wide at the base and 1.3 meter wide at the top. It is 4.5 meter high and has a catchment area of 10.25 sq. km. The details that have gone into the making and maintenance of the dam are etched on a stone wall, 1.3-1.6 meters in height. In its valley below, Sankhara ka Bandh, is enclosed in a narrow passage between the steep slopes of the adjoining hillsides was renovated by the community. The cemented, stone-limed embankment has been built to withstand the great force and swift flow of water. With a catchment of 9 sq. km., the crescent-shaped, convex embankment has been raised across a length of 260 meters and is 7 meters high. Its base is a strong 7-meter wide, narrowing to 2.6 meters at the top (Tarun Bharat Sangh 2022).

Based on the above discussions, the literature study highlights that various NGOs have been instrumental in constructing RWH structures in the previous twenty years. However, the structures serve the intended community for a small-time extent. The scope of advancement in the existing RWH systems lies in large scale construction for a longer duration.

2.4.3 Challenges in existing rainwater harvesting systems

The evolution of brick, cement and steel directed people to start constructing masonry structures and reinforced concrete structures for storing rainwater since these structures last longer with less maintenance. Most of the traditional RWH structures constructed have been located far from the living communities in rural areas. Women and children in rural areas invest abundant time in fetching water from remote locations (Baguma et al., 2010). Plan of action intended towards community water management in rural areas must satisfy the purpose of the nearest water source location to all the people living in a community (Onyenechere, 2004). Community water management measures need to be encouraged for overcoming these obstacles by concentrating on a complete RWH system. Thereby people living in smaller communities can save time by procuring water from a nearby location. Mwenge Kahinda and Taigbenu (2011) stated that rural communities face the problem of capital investment in labour during the implementation of the RWH system. Even though many RWH measures have been followed in India from ancient times, the progressive speed has been less because of investment in capital and time. Sanction of approvals from government/village authorities has also been a time consuming and lengthy process. Another primary challenge lies in individuals, where people do not show interest and come forward for installing a RWH system at their residence (Rumi Aijaz, 2020).

2.5 Research background of BIM

2.5.1 BIM for urban infrastructure projects

The research background of BIM ensures a broad scope of its application. It is a successful method deployed to fulfil the objectives of clients, contractors, sub-contractors, and other stakeholders involved in the execution. Table 2.3 gives a brief note on the application of BIM tools for addressing various uncertainties in urban infrastructure projects across developed countries.

Table 2. 4 Application of BIM tools in various developed countries (Sacks et al., 2018)

S.No	Case Study – Location	Key challenges	Remarks
1.	National Children's Hospital, Dublin, Ireland	➢ Avoid risks and identify clashes in the design. ➢ Reduction of repetitive manual tasks.	➢ Trained and managed multidisciplinary design teams to organise the digital system. ➢ Incorporation of BIM Execution Plan.
2.	Hyundai Motor Studio, Goyang, South Korea	➢ Complex spatial arrangement ➢ Free-form-patterned exterior panels ➢ Build mega truss structure with lessened schedule ➢ Diminish perspective differences between project participants	➢ Manage spatial design complexity using BIM-based coordination. ➢ Adopt parametric modelling for façade panelling and free-form-patterned exterior panel detailing. ➢ Implement 3D laser scanning for quality control and multi-trade prefabrication for

			minimised schedule and increased productivity for mega truss structure. ➢ Virtual reality devices and 4D simulations to assist project participants in communication.
3.	Victoria station, London underground, United Kingdom	➢ Avoid problems in the existing tunnels and surrounding buildings while constructing new tunnels. ➢ Maximise interoperability among various involved disciplines.	➢ Virtual management of a powerful jet grouting machine through data enriched information model. ➢ Development of a single and accurate information model for structural, architectural, and building service clashes by enabling time and cost reduction.
4.	Prince Mohammad Abdul Aziz International Airport, Medina, United Arab Emirates	➢ Implement early stakeholder management for appropriate asset organisation, content and element tagging.	➢ BIM-FM platform, i.e., the combined effect of BIM and facility management, integrates design and construction information with facility management workflow and systems. ➢ Adoption of Computerised Maintenance Management System and Building

			Management/Automation system.
5.	Howard Hughes Medical Institute, Chevy Chase, Maryland, United States	➢ Develop accuracy and speed in retrofitting projects.	➢ Impacts of the created facilities were determined.
6.	Stanford Neuroscience Health Centre, Palo Alto, California	➢ Lack of asset data in the models. ➢ Low work order productivity ➢ Ineffective capital planning	➢ Achievement of real-time facility information. ➢ Reduction in cost savings up to 4.5% ➢ Improved patient care and safety.

Various case studies imply that the usage of BIM tools for urban infrastructure projects is in a faster progressive stage. Multiple structural, execution and interoperability challenges have been addressed through different studies. This literature study helped in perceiving and adopting a framework for preventing RI challenges using BIM tools.

2.5.2 BIM in the rural scenario

BIM is underutilised in the rural scenario for technical applications in civil engineering, and a shift in focus on the rural aspect is essential. Wei et al. (2020) and Hassan et al. (2016) have stressed BIM usage in large landscape projects in rural areas for pre-visualisations. Abbondati et al. (2020) have applied the BIM process in the quest of assessing and managing an existing rural road infrastructure project in Italy. A series of actions like modelling the terrain surface, horizontal alignment and vertical profile of the surface, designing 3D corridors, geometric and structural modelling of viaducts and realistic 3D rendering impacted in achieving the target of rural road extension. Ma et al. (2011) studied the impact of using BIM technology to develop basic drawing plans of rural houses to obtain increased energy efficiency. The results from their study established a correlation between design components and the energy consumption of buildings. Huang et al. (2018) applied BIM to the residential housing projects in rural areas for energy estimation and cost reduction of materials. Both studies analysed BIM on existing infrastructure systems in rural areas, which led towards identifying the flaw points and generating renovated construction designs.

BIM and Geographic Information System (GIS) integration is one of the emerged mechanisms implemented in urban studies. However, Shuo and Zhen-Zhong (2020) formulated a Lightweight BIM-GIS Integration Method for its viability in the rural scenario. This method utilised the Cesium platform and multi-scale lightweight algorithm for effectively organising rural buildings' data. Simultaneously, Pontrandolfi (2020) executed the integrated BIM-GIS tools on historical monuments in Italy's villages, which resulted in a partial or complete recovery from its unstable condition. Matejka (2019) proposed three ways of value estimation for buildings in the rural areas of the Czech Republic by utilising virtual models of BIM. It comprised traditional BIM and integrated approaches. However, his study could not achieve the results because of the vague and outdated models. Hence, the inferences from all these studies denote that the application of BIM in rural areas is minimal. The full potential of BIM in rural areas has not been explored compared to the extensive research in urban areas.

A few key takeaways from the literature study on BIM for rural areas are discussed. Execution of BIM for rural projects explores all planning activities at different phases and levels of construction. The advantages of modelling and visualising the complete surrounding environment can be achieved. For a rural level project, space is not a constraint; therefore, conceptualising the neighbouring conditions of the infrastructure area gives a better scenario for civil engineers during on-site execution. Comprehensive inputs or changes received from stakeholders in a rural project can be updated at any stage of a project so that they can be reviewed and communicated.

2.6 Research gaps identified

a) The declining status of construction and management of RWI is alarming. The literature study infers that RWI development is often neglected compared to urban areas. Eventually, the methodologies required for the follow-up of RWI development need to be accentuated.

b) RWH systems available for larger water conservation and management are limited. Advancements in this area and technology aimed at acceptable solutions are required.

c) The water collected from RWH could be easily stored however it has limitations, such as such as abundant time investment in water collection from distantly placed locations and deficiency of alternatives for the excess rainwater storage at the household level. A rainwater storage tank denying the disadvantages need to be addressed.

d) The challenges in RI construction are distinct. Simultaneously, the BIM process has been enforced for overcoming infrastructure challenges in urban areas. However, BIM in rural areas for solving RI uncertainties has not been explored to complete potential.

e) The lack of detailed construction models and communication platform for stakeholders in RI projects' execution persists.

2.7 Research objectives

- Studying methodologies implemented in water infrastructure development and integrating into Building Information Modelling for rural infrastructures.
- Planning an efficient water management system for a community in a rural area.
- Visual design and implementation of directional tunnelling system for underground water storage.
- Validating obtained results by using project management techniques.

2.8 Summary of the chapter

Different obstacles during the execution of RI projects and two case studies pertaining to these issues have been broadly reviewed and discussed. RWH practices in India in the recent past and challenges in the existing RWH systems have been discussed. The application of BIM for numerous urban projects' accomplishments was highlighted. There has been limited research on BIM in the technical aspect of a rural scenario. Hence, based on the identified research gaps, four research objectives have been framed. The next chapter discusses about the inception of R-BIM concept for rural infrastructures.

References

Abbondati, F., Oreto, C., Viscione, N., and Biancardo, S.A., 2020. Rural Road Reverse Engineering Using BIM: An Italian Case Study. Proceedings of the International Conference on Environmental Engineering, Vilnius Gediminas Technical University, Department of Construction Economics & Property, ICEE, 11, 1-7.

Abraham, P., 2021. How Jal Jeevan Mission 2.0 can make India a water-rich country [online]. Available from: https://yourstory.com/socialstory/2021/02/jal-jeevan-mission-two-make-india-water-rich?utm_pageloadtype=scroll [Accessed 20 Feb 2021].

Ahmed, S., 2000. In search of a drop: women and drinking water management in rural Gujarat (India): the case of SEWA. Institute of Rural Management, Working paper, 137, 1-20.

Ahmed, M. and Araral, E., 2019. Water governance in India: Evidence on water law, policy, and administration from eight Indian states. Water, 11 (10), 1-29.

Baguma, D., Loiskandl, W., and Jung, H., 2010. Water Management, Rainwater Harvesting and Predictive Variables in Rural Households. Water Resources Management, 24 (13), 3333–3348.

Basu, J., 2021. World Water Day: Do you know the real value of water? [online]. Available from: https://www.outlookindia.com/website/story/poshan-news-world-water-day-where-are-we-and-what-can-we-do-about-it/377814 [Accessed 12 Jun 2021].

Bernier, Q., Sultana, P., Bell, A.R., and Ringler, C., 2016. Water management and livelihood choices in southwestern Bangladesh. Journal of Rural Studies, 45, 134–145.

Caprario, J., Tasca, F.A., Santana, P.L., Azevedo, L.T.S., and Finotti, A.R., 2022. Framework for incorporating climate projections in the integrated planning and management of urban infrastructure. Urban Climate, 41, 1-18.

Carter, R.C., Tyrrel, S.F., and Howsam, P., 1999. The impact and sustainability of community water supply and sanitation programmes in developing countries. Water and Environment Journal, 13 (4), 292–296.

Chengappa, R., 2021. The great Indian thirst: The story of India’s water crisis, solutions to tackle it [online]. Available from: https://www.indiatoday.in/magazine/cover-story/story/20210329-the-great-indian-thirst-1781280-2021-03-20 [Accessed 8 Apr 2021].

Crow, B. and Sultana, F., 2002. Gender, class, and access to water: Three cases in a poor and crowded delta. Society and Natural Resources, 15 (8), 709–724.

Everard, M., Ahmed, S., Gagnon, A.S., Kumar, P., Thomas, T., Sinha, S., Dixon, H., and

Sarkar, S., 2020. Can nature-based solutions contribute to water security in Bhopal? Science of the Total Environment, 723, 1-11.

Falk, T., Kumar, S., and Srigiri, S., 2019. Experimental games for developing institutional capacity to manage common water infrastructure in India. Agricultural Water Management, 221, 260–269.

Hassan, R., Saetre, F., and Ovyang, K. A., 2016. Trends and Practices Using 3D Visualisations for Large-Scale Landscape Projects in Norway. [online]. Available from: http://papers.cumincad.org/cgi-bin/works/Show?ascaad2016_029 (Accessed 20 June 2019).

Huang, M., Li, J., and Liao, C., 2018. The Role of BIM Technology in Energy-saving Reconstruction of Existing Residential Buildings in Rural Areas. Advances in Engineering Research, 7th International Conference on Energy and Environmental Protection (ICEEP 2018), 170, 627–631.

Hutchings, P., Chan, M.Y., Cuadrado, L., Ezbakhe, F., Mesa, B., Tamekawa, C., and Franceys, R., 2015. A systematic review of success factors in the community management of rural water supplies over the past 30 years. Water Policy, 17 (5), 963–983.

Jal Bhagirathi Foundation, 2021. Jal Bhagirathi Projects [online]. Available from: http://jalbhagirathi.org/Projects [Accessed 5 Sep 2022].

Jain, S.K., 2019. Water resources management in India - challenges and the way forward. Current Science, 117 (4), 569–576.

Kaura, T. H., Emmanuel, R., and Dauda, I., 2018. Assessment of Building Constitution Planning and Foundation Work Practice of Craftsmen in Rural Areas in Zamfara State, Nigeria. [online]. Available from: http://repository.futminna.edu.ng:8080/xmlui/bitstream/handle/123456789/10503/Assessment%20of%20Building%20Constitution%20Planning%20and%20Foundation%20Work%20Practice%20of%20Craftsmen%20in%20Rural%20Areas%20in%20Zamfara%20State%2c%20Nigeria.pdf?sequence=1&isAllowed=y . [Accessed 5 Jan 2021].

Kumar, M.D. and Ballabh, V., 2000. Water management problems and challenges in India: An analytical review. Institute of Rural Management Anand, 60, 1–28.

Kumar, M.D., 2004. Roof Water Harvesting for Domestic Water Security: Who Gains and Who Loses? Water International, 29 (1), 43–53.

Kumari, A. and Sharma, A.K., 2017. Physical & social infrastructure in India & its relationship with economic development. World Development Perspectives, 5, 30–33.

Liang, X. and Yue, X., 2021. Challenges facing the management of wastewater treatment systems in Chinese rural areas. Water Science and Technology, 84 (6), 1518–1526.

Lifewater, 2020. World Water Day 2020: 10 Facts About the Water Crisis [online]. Available from: https://lifewater.org/blog/world-water-day-2020/ [Accessed 25 Feb 2021].

Long, H. and Liu, Y., 2016. Rural restructuring in China. Journal of Rural Studies, 47, 387–391.

Lund, J., Hanak, E., Dinar, A., Gray, B., Howitt, R., Mount, J., Moyle, P. and Thompson, B., 2012. California Water Management Challenges. In World Environmental and Water Resources Congress 2012: Crossing Boundaries (2329-2338).

Manikutty, S., 1998. Community participation: Lessons from experiences in five water and sanitation projects in India. Development Policy Review, 16 (4), 373–404.

Ma, J.Y., Choo, S.Y., Seo, J.H., and Jeong, S.W., 2011. A Study on BIM based Energy Efficient Design Improvement for Rural Standard Drawing and Specification in South Korea: Focusing on Using Buffer-Zone. eCAADe, Information/Knowledge Architecture & BIM, 29, 430–438.

Matejka, P., 2019. Utilisation of digitised building data and information models (BIM) in value estimation of building in rural areas. Engineering for Rural Development, 18, 1693–1698.

Ministry of Water Resources, 2020. Best Practices of Ground Water Harvesting in Different Parts of India [online]. Available from: https://jalshakti-dowr.gov.in/sites/default/files/BP_NGO_0.pdf [Accessed 10 Jan 2021].

Multipure, 2021. The Increasing Demand for Water [online]. Available from: https://www.multipure.com/purely-social/science/increasing-demand-water/ [Accessed 13 Nov 2021].

Mwenge Kahinda, J. and Taigbenu, A.E., 2011. Rainwater harvesting in South Africa: Challenges and opportunities. Physics and Chemistry of the Earth, 36 (14–15), 968–976.

NABARD, 2021. Rural Infrastructure Development Fund [online]. Available from: https://www.nabard.org/content1.aspx?id=573&catid=8&mid=8 [Accessed 5 Aug 2021].

Onyenechere, E.C., 2004. Water supply measures used by the rural people of Ebonyi and Enugu, Nigeria. Journal of Water Supply: Research and Technology, 53 (6), 425–431.

Owusu, S. and Asante, R., 2020. Rainwater harvesting and primary uses among rural communities in Ghana. Journal of Water Sanitation and Hygiene for Development, 10 (3), 502–511.

Pontrandolfi, R., 2020. Multiscale GIS-BIM methodological approaches and digital systems for the knowledge of the modern architectural heritage in Italy. The rural Village "La Martella" in Matera. International Archives of the Photogrammetry, Remote Sensing and

Spatial Information Sciences, 44, 279–286.

Prokopy, L.S., 2005. The relationship between participation and project outcomes: Evidence from rural water supply projects in India. World Development, 33 (11), 1801–1819.

Rumi Aijaz, 2020. Scaling-up urban rainwater harvesting [online]. Available from: https://www.orfonline.org/expert-speak/scaling-up-urban-rainwater-harvesting-65535/ [Accessed 28 May 2020].

Sacks, R., Eastman, C., Lee, G. and Teicholz, P., 2018. BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers. 3rd Edition, John Wiley & Sons.

Scoones, I., 2009. Livelihoods perspectives and rural development. Journal of Peasant Studies, 36 (1), 171–196.

Shamir, U. and Howard, C.D.D., 2012. Water management in 2050. Toward a Sustainable Water Future: Visions for 2050, 37–45.

Shuo, L. and Zhen-Zhong, H., 2020. A Lightweight BIM-GIS Integration Method for Rural Building Design and Construction, Proceedings of the Creative Construction e-Conference 2020, 25–30.

Statista, 2021. Water demand in India in 2010-2050 by sector [online]. Available from: https://www.statista.com/statistics/1111839/india-water-demand-by-sector/ [Accessed 2 Mar 2021].

Suárez, D., Díaz-Puente, J.M., and Bettoni, M., 2021. Risks identification and management related to rural innovation projects through social networks analysis: A case study in Spain. Land, 10 (6), 1-23.

Szolomicki, J. and Golasz-Szolomicka, H., 2019. Technological advances and trends in modern high-rise buildings. Buildings, 9 (9), 1-32.

Tarrass, F., and Benjelloun, M., 2012. The effects of water shortages on health and human development. Perspectives in Public Health, 132 (5), 240–244.

Tarun Bharat Sangh, 2022. Tarun Bharat Sangh Programmes [online]. Available from: https://tarunbharatsangh.in/portfolio_page/adapting-to-climate-change-through-water-management-in-eastern-rajasthan/ [Accessed 6 Sep 2022].

Times of India, 2020. News report: With 1 in 5 workers ‘skilled’, India ranks 129 among 162 [online]. Available from: https://timesofindia.indiatimes.com/india/with-1-in-5-workers-skilled-india-ranks-129-among-162/articleshow/79769587.cms [Accessed 5 Mar 2022].

Tortajada, C., 2014. Water infrastructure as an essential element for human development. International Journal of Water Resources Development, 30 (1), 8–19.

Wei, X., Bonenberg, W., and Zhou, M., 2020. The Application of BIM in the ‘China Beautiful Rural’ Design Project–Yangyou Village River Ecological Landscape Reconstruction Design Project. Springer International Publishing, Cham, Switzerland. 135-145.

Wichman, C.J., Taylor, L.O., and von Haefen, R.H., 2016. Conservation policies: Who responds to price and who responds to prescription? Journal of Environmental Economics and Management, 79, 114–134.

Zheng, C.B., 2014. The problems and thinking of planning and construction in rural communities under new urbanisation. Applied Mechanics and Materials, 584, 399–402.

CHAPTER 3: FUNDAMENTAL TECHNIQUES EMPLOYED IN THE WATER INFRASTRUCTURE MANAGEMENT AND INTEGRATION OF BIM FOR RURAL INFRASTRUCTURES

3.1 Chapter overview

This chapter emphasises on the approaches adopted for water infrastructure enhancement. Different perspectives concerning RWI development, and the factors required in their planning and implementation have been focused. Further, the role of BIM in large scale infrastructure projects and its recent applications in the water infrastructure industry have been highlighted. The R-BIM concept has been introduced based on the identified research gaps concerning RI and the studied RWI methodologies.

3.2 Approaches for rural infrastructural enhancement

Previous researchers applied several techniques in enhancing infrastructure management in rural areas. Mishra (2001) and Brushett and John-Abraham (2006) emphasised the need to nurture rural communities by building infrastructure facilities, focusing on a broadened economy, decentralised planning and implementation, integrated regions, fostered services, and controlled private sector participation for social well-being. The study conducted by Wong et al. (2013) suggests that the rural road infrastructure in China experienced high quality and lucrative status by the organised and collaborative work of government and local leadership.

Yin et al. (2014) developed the Grey-AHP method, which merges the grey correlation method and analytic hierarchy process for evaluating older RIs in a province and obtains the best and worst order of criteria, which helps to establish a new RI. Zhou et al. (2019) have developed a model by integrating Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis and strategic vector method for emulating prefabricated construction of rural buildings. Whereas Benard and Iminza (2020) discussed the practices such as integrated endogenous and exogenous approach, natural environmental conservation, web model, green infrastructure initiatives' adoption and participatory techniques for enhanced project management in RI development. Naderpour et al. (2019) have enriched a model for project time estimation by merging risk management and fuzzy expert systems. Mishra et al. (2021) have modified Bromilow's Time-Cost model in Nepal's context for assessing time and cost components of urban and rural hospital buildings. Moreover, the incorporation of expert systems in managing a rural water supply has helped in achieving higher productivity and sustainability by developing an interactive water supply system, installing independent purifying reservoirs, sensitive reservoirs, and water tanks (Olanrewaju and Olabanjo, 2020). Apparently, Kamal and Flanagan (2014) identified a few barriers in RI expansion: lack of innovative growth, absence of strategies in new technological applications, and single ownership. The literature study infers that the management of RI lacks a framework for guiding future rural infrastructural projects.

3.2.1 Features required during planning of water infrastructures

The domain of the thesis has been confined to water management. Thereby a few prominent RWIs used in the general practice are discussed further.

a) Piped water supply: The channelled network connection between different pipes and supply through tap/pump is called as piped water supply. Access to piped water supply is 47.28 per cent of rural households in India.

b) Hand pump: Hand pumps are manually operated pumps; they use human power and mechanical advantage to move fluids or air from one place to another. They are widely used in every parts of world for a variety of activities such as industrial, marine, irrigation and leisure.

c) Power pump: A water pump is an essential tool to pump out water from the garden, pool, or under the ground.

d) Bore well: Bore wells are drilled in hard crystalline rocks. In bore wells casing pipes are used only up to the bed rock.

e) Tube well: Tube wells are drilled in soft sedimentary strata especially along the coastal stretch a well consisting of an iron pipe with a solid steel point and lateral perforations near the end, which is driven into the earth until a water-bearing stratum is reached, when a suction pump is applied to the upper end.

f) Infiltration well: Infiltration wells are generally proposed in the river bank, riverbed or lakebed to tap water from the unconfined aquifer. Infiltration wells are preferred where the minimum saturated thickness of aquifer is at least 5m. Generally, this will provide a very good supply of water throughout the year. Even if the river dries up during times of little rain, water will be available from the underground.

Based on these basic characteristics of RWIs, planning of water infrastructures has been emphasised. The primary features involved in their support have been studied further. The planning of water infrastructures has challenging aspects like precipitation, water demand and water availability in the selected location, population and spatial development, stream flows, reservoir volumes and economic growth (Pedro-Monzonís et al. 2015). The carried-out study recommends five features during the planning stages of water infrastructures, such as, a) participatory methods, b) community-based management, c) public-private partnership, d) water sensitive planning, and e) climatic conditions as depicted in Figure 3.1.

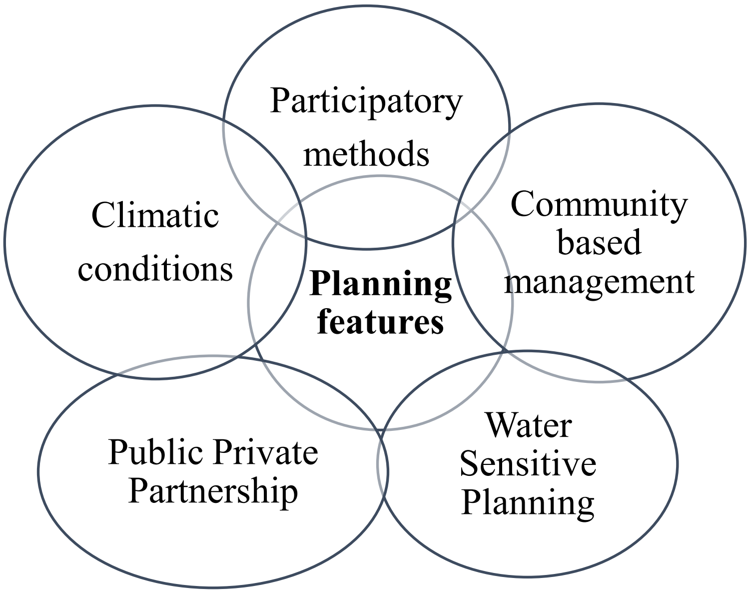


Figure 3. 1 Planning features for water infrastructures

During the implementation of RI projects, participatory methods contribute to the comprehensive model's development. The data collected by the participatory techniques have to be analysed through qualitative approaches. Public investments and user fee collection could strengthen the continual acquisition of public infrastructure and the maintenance of existing infrastructure, which create a sustainable pathway toward RI development. This would help low-income households have equal access to infrastructure without paying user fees. These aspects make any RI project more justifiable and relatable in participatory terms. Moreover, demand requirements in water can be met with two criteria, a) efficiency and b) cost-effectiveness. Community based management primarily integrates women to get involved as a part of the water infrastructure to augment the system efficiency. The people living in the community around the proposed water infrastructure project must be motivated to add the essence of participation (Ducrot, 2017). People's association for stable water supply in rural areas must possess a realistic approach rather than a conceptual one (Hutchings et al., 2016).

Many developing countries invest hugely in infrastructure projects since population growth has created a demand for fulfilling the requirements in various sectors associated with infrastructural development. This study suggests understanding the advantages of the water sensitive planning method, as it focuses on urban and regional planning. This concept comprises activities such as intensifying water resources and their quality to control stormwater's unfavourable consequences and raise the surrounding environment standards cost-effectively through people participation (Carmon and Shamir, 2010).

Gopakumar (2010) studied that water supply projects' operation based on Public-Private Partnership (PPP) in India underwent success. The induction of PPP into urban areas like Bengaluru, Chennai, and Kochi water supply got technical expertise, improved drinking water quality, and renovation of existing infrastructure. Urban scenarios' adaptation to India's rural scenario could observe considerable growth by making people engaged. Identifying and supporting capable PPPs, providing grants and financial backing, estimating detailed costs, and tariff collection can be some of the modifications to motivate better rural water supply under PPP (Kleemeier and Lockwood, 2012). Furlong et al. (2017) stressed that water infrastructure projects built by neglecting climate change factors have failed in their operation. Inadequate guidelines and procedures at the organisational level were the primary reasons for the loss. Estimation of the monsoon period and rainfall forecast performs as a crucial factor. Their study indicates that professional help, guidance, and future impact on climate change help to improve planning in water infrastructure projects.

Private parties' entry and too much commercialisation in the water infrastructure management system involves contractual risks (Marques and Berg 2011). Accepting the practical innovations and creating awareness of the technology would stimulate public expectations as well as enhance the water supply system. Water governing bodies are play a pivotal role in water resources' construction, operation, maintenance, and management in a community (Tantoh and Simatele 2018). According to the water requirement and demand in the communities, the water governing bodies must take necessary action plans. Planned water supply assists in reducing the current and future water deficiencies.

3.2.2 Evaluative techniques in the planning of water infrastructures

Generally, water infrastructure-based projects experience various risks, delays, uncertainties either directly or indirectly. Adopting mechanisms or techniques in the planning stages of water infrastructure can keep away ambiguities in the on-site execution. The current study recommends four evaluative techniques required during the planning stages of water infrastructures, a) Risk Based Estimation, b) Life Cycle Assessment, c) Capacity Factor Analysis, and d) Cost Benefit Analysis, as illustrated in Figure 3.2.

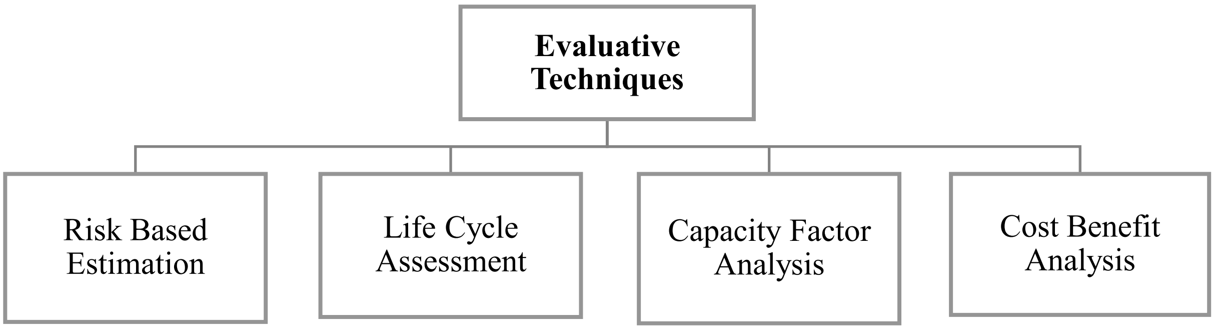


Figure 3. 2 Evaluative techniques in the planning of water infrastructures

Risk Based Estimation is a technique followed for estimating projects by designating the uncertainties or risks involved in the project. The probabilities of the risks for a project can be determined. The technique is feasible and applicable for major infrastructure projects; however, it is not viable for small projects since its accuracy is not critical due to multiple stakeholders' active participation, quantification of risks, and transformation of experience into quantitative data (Liu and Napier 2010). Extensive interviews, broad research, case studies of different countries can be performed to identify water infrastructure risks (Ameyaw and Chan, 2015).

Another superior technique, the Life Cycle Assessment (LCA) method, analyses the environmental impact of a water infrastructure system. The largest area of influence could be found after applying LCA to any selected area. Population and annual water flow used through the system act as the main functions in the analysis. LCA conducted on rural water systems proposes all life cycle stages associated: manufacture, fabrication, usage, maintenance, recycling and disposal stage of the whole infrastructure (Jones and Silva 2009).

Another critical prospect in the planning of water infrastructures is sustainability. The sustainability measure of indicators for water infrastructure is associated with technical, environmental, economic aspects. The indicators' measures can be evaluated based on positive and negative outcomes of human-related activities (Dinet et al., 2017). Bouabid and Louis (2015) highlighted the Capacity Factor Analysis model to understand water infrastructure sustainability, where service, institutional, human resources, technical, economic, financial, energy, environmental, and social factors could be considered.

RWI projects are manoeuvred as public demand-driven projects. Hutton et al. (2007) denoted the cost-benefit analysis method for establishing qualitative value to a specific community through any project. This methodology analyses a project, subsequently determines the costs and calculates the benefits. Long-run marginal costs related to water infrastructure projects identify necessary infrastructure growth costs, such as capital, maintenance, and operating costs. Moreover, the cost-benefit analysis yields water supply and sanitation investments as a potential social welfare step from a global perspective. Eventually, water infrastructure projects must satisfy environmental benefits, maximum storage, reuse, and utilisation benefits.

3.3 Concept of Infrastructure BIM

After grasping all the above-discussed methodologies pertaining to water infrastructure development and the research background of BIM from Chapter 2, this study obtained the motivation in employing the construction management concepts. Eventually, the BIM process was administered for solving the research problem of encountered challenges in RI projects from the perspective of RWH. Hence, the latest BIM tools for modern infrastructures have been discussed ahead.

BIM adoption to infrastructure projects, termed Infrastructure BIM (I-BIM), has been studied further. I-BIM has been associated with designing, constructing, and managing airports, bridges, hospitals, and university campuses (Acampa et al., 2018). Besides, previous studies explored I-BIM to existing infrastructures, such as Abbondati et al. (2020), focused on I-BIM to an existing international airport in Rome (Italy) for intelligent runway implementation, which comprised smart 3D models with smooth documentation, planning, maintenance, and monitoring the comprising materials, certifications, structural and functional parameters data. Acampa et al. (2019) highlighted the need for model verification/validation while operating I-BIM to detect coordination-related issues. Bosurgi et al. (2021) developed a method for providing and interpreting pavement condition data in an I-BIM scenario, which uses smart objects for simplifying the representation and elaboration of surveyed information. Tools like BIM Viewer, Solibri Model Viewer and Autodesk Navisworks expose the clashes, check the models and their codes, and verify the models' accordance with the standards.

A transformation in BIM application for urban infrastructure projects is visible nowadays. Vilventhan et al. (2021) successfully carried 3D visualisations of the existing subsurface utilities to determine clash detection for utility relocation in urban underground projects. Their study also inferred that the real-time interpretations of the existing utilities' on-site conditions aided the stakeholders in pursuing well-managed communication during relocation. Besides, the I-BIM approach has been extended to tunnel design by incorporating geological-geotechnical information for defining the 3D digital subsoil model in the excavation of a metro line (Fabozzi et al., 2021). In the wake of the COVID – 19 pandemic situation, Campisi et al. (2020) focused on micromobility in Italian cities by employing BIM tools, where bicycle commutation plans and designs have been developed using I-BIM. Their study emphasised decision-making considering environmental impact, cost, and viability for the designers. Simultaneously geotechnical modelling and simulation as a part of BIM caused in determining structural properties, quantity take-off, and optimisation of Italian infrastructure projects (Osello et al., 2017). Hence, the study of I-BIM implies that there has been a rapid growth of BIM in many developed countries for numerous objectives of civil engineering.

3.3.1 BIM for water infrastructures

Water infrastructures targeted on a community absorb enormous human and technical efforts. The application of BIM as a problem-solving technique in the water industry emulates comprehensive accomplishments. Zhu et al. (2019) have explored the aspect of smart water management and real-time assessment of the water situation in Shenzhen, China, by developing an overall framework incorporating the Internet of Things (IoT) and BIM. Taha et al. (2020) studied the effect of using a BIM tool, i.e., Autodesk Green Building Studio, in estimating water consumption in an Institutional project and suggested techniques like RWH and greywater reclamation for increasing water efficiency as well as annual water cost savings.

Basically, BIM models belong to Industry Foundation Classes (IFC) standards, an object-based file format that is interoperable by various designers. BIM models are distinguished by geometry, material, cost, and construction information related to scheduling or maintenance. Especially, 3D models are parametric, making the design more valuable (Biancardo et al., 2021). Söbke et al. (2018) discussed the benefits of perfect design and execution of settlement tanks in wastewater treatment plants by blending semantic data models into IFC standards. This integration of semantic models and IFCs improved the collaborative network in BIM planning (Zhao et al., 2019). Hence, BIM for water-related projects makes the stakeholders analyse the adjacent situation and comprehend the mistakes in the planning process.

Yang and Song (2015) acknowledged the advantages of visualisation, defined material properties, integration of pipe network, construction simulations and work collaboration in the BIM application of water supply and drainage design. Moreover, Qun et al. (2017) have solved energy-saving optimisation issues faced in the pumping station by employing possible simulations through BIM technology in the preliminary design stages. Usage of emerging BIM tools such as Autodesk Revit, Civil 3D, and virtual reality devices have gained weightage associated with the water sector (Kamunda et al., 2021). Marzouk and Ahmed (2019) applied point cloud images through 3D laser scanning technology connecting to facility management (7D) in BIM to maintain water treatment plant equipment. The extensive time requirement in designing and evaluating water efficiency in green buildings made Nguyen et al. (2021) establish a BIM-Green Buildings solution kit. It provided easy and early design changes in monitoring and managing water sources to comply with green building criteria, save money and optimise work conditions. Organisations such as BIM4Water and British Water strive in upholding training events for water and sewerage companies in the UK and gain successful project delivery (BIM4Water 2017).

Liu et al. (2019) established BIM based Water Efficiency (BWe) framework for providing reference for the application of BIM in water efficiency. Langar and Pearce (2017) observed a moderate implementation between of RWH technologies and strategies with the help of BIM among design firms. Moreover, Maqsoom et al. (2021) studied that BIM provides a theoretical baseline for identifying rainwater potential and its utility in different seasons. The method in that study followed a scenario of modelling houses in BIM environment for multiple sites and performed calculations. A simple methodology of the water requirements per person per day were calculated, and the potential available water was calculated from simple statistical relationships. Conclusively, the cumulative rainwater was calculated and drawn against the demand line for identifying the demand and availability of the water over the entire year. In this conjunction, enforcement of BIM for water infrastructures, especially RWH structures is a demanding aspect for the solution of obstacles. Its execution would be a step for terminating problems effectively.

3.4 Inception of R-BIM

The study developed a novel R-BIM concept based on the above discussions on I-BIM and the successful methodologies in water infrastructure development. This theory helps mitigate RI challenges by simultaneously focusing on the lack of a civil engineering perspective of BIM in a rural scenario, as discussed in section 2.5.2. Prior to the development of R-BIM, a few additional concepts have been concentrated, which helped in framing a comprehensive model. The characteristics have been discussed ahead, which could append and enhance BIM from a rural perspective.

The planning and construction of infrastructural projects without users' insights might decrease their expectation levels. Previous researchers revealed that the participatory process and its enforcement on RI, especially water management related projects, has a prominent prospect (Asthana 2010; Lamaddalena et al., 2004; Von Korff et al., 2012; Waridin et al., 2018). Limited studies dealt with the concept of merging participatory management in BIM (Turkyilmaz and Kizilkan, 2019). Hence this study induces participatory management in R-BIM at the planning stage.

Model creation with specifications and dimensions stipulated with the building codes in a selected location would be an advantage in visualising a comprehensive RI, since the first case study discussed in section 2.3 provides the evidence of ignoring detailed construction in rural areas. Prefabricated construction has been an approach for faster completion. Haghir et al. (2021) created an automated design tool to support the design and evaluation of freeform structures, which follows the 3D CAD tool and an algorithm for generating a BIM model, thereby reducing complexity, production time, and over-dependency among stakeholders. Simultaneously the prefabricated construction enhancement is essential in remote locations since high-quality construction materials are unavailable. Construction labour in rural areas had been short of technical skills in both the reviewed case studies of section 2.3. Moreover, Al-Rubaye and Mahjoob (2020) have employed the measured mile method to quantify the loss in labour productivity. Their study has recommended enhancing coordination and communication among the involved construction parties for better outputs. According to a survey conducted by Roy and Mukhopadhyay (2019), about 40.6 per cent rural male workers and 25.1 per cent female workers have been engaged in the rural non-agricultural sector in India, out of which construction sector bears the highest share. The raise in workforce demands skill development for increased efficiency. Bråthen and Moum (2016) introduced BIM-kiosks, which facilitated on-site labour in accessing BIM models for smoother operations, however the rural workers lack technical ability in advanced equipment operation. Hence, this study introduces the demonstration of the prefabrication procedure through BIM tools as capacity management. Enhancing the workforce's skills is a must, as prefabrication and modular construction have become the prospects in civil engineering. As a result, illustration of construction methods through BIM aids the workers in gaining skills and constructing in less time.

Perttula et al. (2003) reported that 32% of the accidents in Finland construction sites occurred during the haulage of construction materials. The latest researchers have proposed metaheuristic methods for material and safety management at construction sites. Wang et al. (2015) have combined the process of BIM and firefly algorithm for obtaining the best suitable tower crane layouts. Kaveh and Vazirinia (2020) have developed an upgraded sine cosine algorithm for the optimal tower crane layout in high-rise building's construction sites. Reflecting on these findings, planning proper haulage vehicles for material handling in rural areas has been deemed crucial. Urban planners deployed viable functional decision-making tools in the planning of water infrastructures (Lienert et al., 2015, Fletcher et al., 2017). As per the literature study, many RWIs are not well planned, coordinated, and monitored. Furthermore, incompetent rural water supplies are affected by poor applied decision-making at lower levels. Hence, R-BIM concept values the incorporation of efficient decision-making in planning stages of RWI.

Mismanagement of human resources has led to construction failure in the reviewed case study of section 2.3. Lukale (2018) determined that improper coordination among multiple parties in rural road infrastructure projects has a high relative index, misleading to cost overrun. Hence, the thesis highlights utilising a common shared platform for communication among the rural stakeholders thereby avoiding technical and practical miscommunication. Figure 3.3 shows all the explored feasible attributes intended for inclusion in R-BIM. As a result, organised domain knowledge and expertise for the practitioners in rural areas are made available.

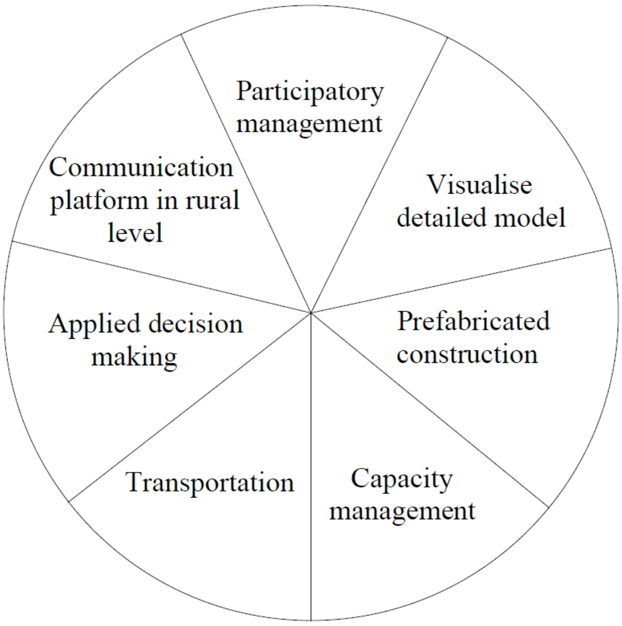


Figure 3. 3 Attributes of R-BIM

3.5 Summary of the chapter

The successful features and evaluative methodologies in water infrastructure planning have been discussed in this chapter. The notion of I-BIM, as well as current BIM breakthroughs in the water industry, have been explored for the development of a method for rural infrastructures called R-BIM. The study highlights R-BIM as a solution to the challenges in RI construction, which was produced by integrating the discussed planning and evaluative approaches for water infrastructures. The next chapter discusses about the development and stability of directional tunnel method, an innovative concept of RWH.

References

Abbondati, F., Biancardo, S. A., Palazzo, S., Capaldo, F. S., and Viscione, N., 2020. I-BIM for existing airport infrastructures. Transportation Research Procedia, 45, 596–603.

Acampa, G., Bona, N., Grasso, M., and Ticali, D., 2018. BIM: Building information modeling for infrastructures. AIP Conference Proceedings, 2040 (1), 1-5.

Acampa, G., Marino, G., and Ticali, D. 2019., Validation of infrastructures through BIM. AIP Conference Proceedings, 2186 (1), 1-10.

Al-Rubaye, Z.R.A. and Mahjoob, A.M.R., 2020. Using measured mile method to quantify the loss of labor productivity in Iraqi construction site. Asian Journal of Civil Engineering, 21 (7), 1287–1296.

Ameyaw, E.E. and Chan, A.P., 2015. Risk ranking and analysis in PPP water supply infrastructure projects: an international survey of industry experts. Facilities, 33 (7/8), 428-453.

Asthana, A.N., 2010. Is participatory water management effective? Evidence from Cambodia. Water Policy, 12 (2), 149–164.

Benard, M.M. and Iminza, R.M., 2020. Effective Project Management for Sustainable Rural Development in Africa. International Journal of Academic Research in Business and Social Sciences, 10 (8), 788–806.

Biancardo, S.A., Intignano, M., Viscione, N., Guerra De Oliveira, S., and Tibaut, A., 2021. Procedural Modeling-Based BIM Approach for Railway Design. Journal of Advanced Transportation, March, 1-21.

BIM4Water, 2017. BIM guidance for the water industry [online]. Available from: https://www.britishwater.co.uk/media/Download.aspx?MediaId51217 [Accessed 10 Mar 2019].

Bosurgi, G., Pellegrino, O., and Sollazzo, G., 2021. Pavement condition information modelling in an I-BIM environment. International Journal of Pavement Engineering, 1–16.

Bouabid, A. and Louis, G.E., 2015. Capacity factor analysis for evaluating water and sanitation infrastructure choices for developing communities. Journal of Environmental Management, 161, 335–343.

Bråthen, K. and Moum, A., 2016. Bridging the gap: Bringing BIM to construction workers. Engineering, Construction and Architectural Management, 23 (6), 751–764.

Brushett, S. and John-abraham, I., 2006. Infrastructure for Improved Rural Livelihoods. World

Bank, September, 93, 1–4.

Campisi, T., Acampa, G., Marino, G., and Tesoriere, G., 2020. Cycling master plans in Italy: The I-BIM feasibility tool for cost and safety assessments. Sustainability, 12 (11), 1-20.

Carmon, N. and Shamir, U., 2010. Water-sensitive planning: Integrating water considerations into urban and regional planning. Water and Environment Journal, 24 (3), 181–191.

Dinet, E., Racoviteanu, G., and Jercan, A., 2017. Improvement of the Water Infrastructure in Central Moldova. Procedia Engineering, 209, 156–163.

Ducrot, R., 2017. When good practices by water committees are not relevant: Sustainability of small water infrastructures in semi-arid mozambique. Physics and Chemistry of the Earth, 102, 59–69.

Fabozzi, S., Biancardo, S.A., Veropalumbo, R., and Bilotta, E., 2021. I-BIM based approach for geotechnical and numerical modelling of a conventional tunnel excavation. Tunnelling and Underground Space Technology, 108, 1-14.

Fletcher, S.M., Miotti, M., Swaminathan, J., Klemun, M.M., Strzepek, K., and Siddiqi, A., 2017. Water Supply Infrastructure Planning: Decision-Making Framework to Classify Multiple Uncertainties and Evaluate Flexible Design. Journal of Water Resources Planning and Management, 143 (10), 1-9.

Furlong, C., Brotchie, R., Considine, R., Finlayson, G., and Guthrie, L., 2017. Key concepts for Integrated Urban Water Management infrastructure planning: Lessons from Melbourne. Utilities Policy, 45, 84–96.

Gopakumar, G., 2010. Transforming water supply regimes in India: Do public-private partnerships have a role to play? Water Alternatives, 3 (3), 492–511.

Haghir, S., Haghnazar, R., Saghafi Moghaddam, S., Keramat, D., Matini, M.R., and Taghizade, K., 2021. BIM based decision-support tool for automating design to fabrication process of freeform lattice space structure. International Journal of Space Structures, 36 (3), 164–179.

Hutchings, P., Parker, A., and Jeffrey, P., 2016. The political risks of technological determinism in rural water supply: A case study from Bihar, India. Journal of Rural Studies, 45, 252–259.

Hutton, G., Haller, L., and Bartram, J., 2007. Global cost-benefit analysis of water supply and sanitation interventions. Journal of Water and Health, 5 (4), 481–501.

Jones, S.A. and Silva, C., 2009. A practical method to evaluate the sustainability of rural water and sanitation infrastructure systems in developing countries. Desalination, 248 (1–3), 500–509.

Kamal, E.M. and Flanagan, R., 2014. Key characteristics of rural construction SMEs. Journal of Construction in Developing Countries, 19 (2), 1–13.

Kamunda, A., Renukappa, S., Suresh, S., and Jallow, H., 2021. BIM in the water industry: addressing challenges to improve the project delivery process. Engineering, Construction and Architectural Management, 28 (2), 510–529.

Kaveh, A. and Vazirinia, Y., 2020. An upgraded sine cosine algorithm for tower crane selection and layout problem. Periodica Polytechnica Civil Engineering, 64 (2), 325–343.

Kleemeier, E., and Lockwood, H., 2012. Public-private partnerships for rural water services. IRC, World Bank, 4, 1-8.

Lamaddalena, N., D'arcangelo, G., Billi, A., Todorovic, M., Hamdy, A., Bogliotti, C., and Quarto, A., 2004. Participatory water management in Italy: Case study of the consortium 'bonifica della capitanata'. Participatory water saving management and water cultural heritage, 169, 159–169.

Langar, S. and Pearce, A.R., 2017. Implementation Trends for Rainwater-Harvesting Technologies and Strategies and Their Relationship with Building Information Modeling. Journal of Architectural Engineering, 23 (1), 1–9.

Lienert, J., Scholten, L., Egger, C., and Maurer, M., 2015. Structured decision-making for sustainable water infrastructure planning and four future scenarios. EURO Journal on Decision Processes, 3 (1–2), 107–140.

Liu, L. and Napier, Z., 2010. The accuracy of risk-based cost estimation for water infrastructure projects: Preliminary evidence from australian projects. Construction Management and Economics, 28 (1), 89-100.

Liu, Z., Zhang, C., Guo, Y., Osmani, M., and Demian, P., 2019. A Building Information Modelling (BIM) based Water Efficiency (BWe) Framework for Sustainable Building Design and Construction Management. Electronics, 8 (599), 1–19.

Lukale, A.M., 2018. Determinants of cost overruns in rural roads infrastructure projects in Kenya, (Thesis) Strathmore University [online]. Available from: https://su-plus.strathmore.edu/handle/11071/6118 [Accessed 15 Dec 2020].

Maqsoom, A., Aslam, B., Ismail, S., Thaheem, M.J., Ullah, F., Zahoor, H., Musarat, M.A., and Vatin, N.I., 2021. Assessing Rainwater Harvesting Potential in Urban Areas: A Building Information Modelling (BIM) Approach. Sustainability (Switzerland), 13 (22), 1-21.

Marques, R.C. and Berg, S., 2011. Risks, Contracts, and Private-Sector Participation in Infrastructure. Journal of Construction Engineering and Management, 137 (11), 925–932.

Marzouk, M. and Ahmed, R., 2019. BIM-based facility management for water treatment plants using laser scanning. Water Practice and Technology, 14 (2), 325–330.

Mishra, Y., 2001. Telecom Infrastructure in Rural India. Indian Journal of Public Administration, 47 (3), 426–433.

Mishra, A.K., Sudarsan, J.S., and Nithiyanantham, S., 2021. Assessment of time–cost model of public health buildings in Nepal. Asian Journal of Civil Engineering, 22 (1), 13–22.

Naderpour, A., Sardroud, J.M., Mofid, M., Xenidis, Y., and Rostam, T.P., 2019. Uncertainty management in time estimation of construction projects: A systematic literature review and new model development. Scientia Iranica, 26 (2), 752–778.

Nguyen, T.P., Nguyen, V.-A., Pham, D.D., and Do, H.Q., 2021. Integrating Building Information Modelling (BIM) and Tools with Green Building Certification System in Designing and Evaluating Water Efficiency of Green Building for Sustainable Buildings. IOP Conference Series: Materials Science and Engineering, 1079 (3), 1-11.

Olanrewaju, O.A. and Olabanjo, A.G., 2020. An Expert System for Rural Water Supply Management. International Journal of Innovative Research and Development, 9 (8), 19–27.

Osello, A., Rapetti, N., and Semeraro, F., 2017. BIM Methodology Approach to Infrastructure Design: Case Study of Paniga Tunnel. IOP Conference Series: Materials Science and Engineering, 245 (6), 1-10.

Pedro-Monzonís, M., Solera, A., Ferrer, J., Estrela, T., and Paredes-Arquiola, J., 2015. A review of water scarcity and drought indexes in water resources planning and management. Journal of Hydrology, 527, 482–493.

Perttula, P., Merjama, J., Kiurula, M., and Laitinen, H., 2003. Accidents in materials handling at construction sites. Construction Management and Economics, 21 (7), 729–736.

Qun, M., Wang, J., and Liu, C., 2017. Energy-Saving Optimization of Water Supply Pumping Station Life Cycle Based on BIM Technology. IOP Conference Series: Earth and Environmental Science, 100 (1), 1-7.

Roy, N.S., and Mukhopadhyay, I., 2019. Emerging Challenges of Rural Labour Market: Insights from Indian Villages. Arthaniti: Journal of Economic Theory and Practice, 18 (1), 86–103.

Söbke, H., Theiler, M., Tauscher, E., and Smarsly, K., 2018. BIM-based description of wastewater treatment plants. Proceedings of 16th International Conference on Computing in Civil and Building Engineering (ICCCBE), Tampere, Finland, 6 (5), 1-8.

Taha, F.F., Hatem, W.A., and Jasim, N.A., 2020. Utilizing BIM technology to improve sustainability analyses for Iraqi Construction Projects. Asian Journal of Civil Engineering, 21 (7), 1205–1215.

Tantoh, H.B. and Simatele, D., 2018. Complexity and uncertainty in water resource governance in Northwest Cameroon: Reconnoitring the challenges and potential of community-based water resource management. Land Use Policy, 75, 237–251.

Turkyilmaz, E. and Kizilkan, M.B., 2019. A Conceptual Idea of Participatory Design with BIM. Environment-Behaviour Proceedings Journal, 4 (11), 23-29.

Vilventhan, A., Razin, S., and Rajadurai, R., 2021. 4D BIM models for smart utility relocation management in urban infrastructure projects. Facilities, 39 (1–2), 50–63.

Von Korff, Y., Daniell, K.A., Moellenkamp, S., Bots, P., and Bijlsma, R.M., 2012. Implementing participatory water management: Recent advances in theory, practice, and evaluation. Ecology and Society, 17 (1), 1-14.

Wang, J., Zhang, X., Shou, W., Wang, X., Xu, B., Kim, M.J., and Wu, P., 2015. A BIM-based approach for automated tower crane layout planning. Automation in Construction, 59, 168–178.

Waridin, W., Dzulkhijiana, A., and Mafruhah, I., 2018. Community empowerment in rural infrastructure development program. Economic Journal of Emerging Markets, 10 (1), 8–14

Wong, H.L., Luo, R., Zhang, L., and Rozelle, S., 2013. Providing quality infrastructure in rural villages: The case of rural roads in China. Journal of Development Economics, 103 (1), 262–274.

Yang, R. and Song, W., 2015. BIM for Building Water Supply and Drainage Design. Proceedings of International Conference on Automation, Mechanical Control and Computational Engineering, AMCCE, 2094–2099.

Yin, S.X., Li, H.M., Wang, A.J., and Sha, M., 2014. The evaluation research on the rural infrastructure construction of Shaanxi based on Grey-AHP. Advanced Materials Research, 869, 172–177.

Zhao, L., Liu, Z., and Mbachu, J., 2019. An Integrated BIM–GIS Method for Planning of Water Distribution System. ISPRS International Journal of Geo-Information, 8 (8), 1-22.

Zhou, J., He, P., Qin, Y., and Ren, D., 2019. A selection model based on SWOT analysis for determining a suitable strategy of prefabrication implementation in rural areas. Sustainable Cities and Society, 50, 1-13.

Zhu, X., Yin, Z., Liu, Y., Feng, B., and Wang, Y., 2019. Study on Framework Design of Smart Water Management System in Shenzhen. IOP Conference Series: Earth and Environmental Science, 330 (3), 1-8.

CHAPTER 4: PLANNING AN EFFICIENT WATER MANAGEMENT SYSTEM BY DIRECTIONAL TUNNELLING METHOD AND ANALYSING ITS STABILITY IN SOIL CONDITIONS

4.1 Chapter overview

The current chapter discusses and highlights an innovative structure called the Directional tunnel method for RWH. This system is adoptable in rural areas, since these places experience less atmospheric pollution, an essential criterion for rooftop runoff collection (Farreny et al., 2011). The fabrication of directional tunnel with jute fibre and glass fibre reinforced plastic (GRP) materials has been discussed. The directional tunnel's stability in underground soil conditions has been analysed to define the optimum installation angle.

4.2 Inception of directional tunnelling method through rainwater harvesting

The literature study infers that previous researchers have invested their efforts and presented overhead and underground structures as community tanks for storing rainwater. Traboulsi and Traboulsi (2017) innovated a system for collecting rainwater directly on the building roofs. Moreover, some of the attempts made in underground water storage structures have been a vertical underground tank with one surface open to the atmosphere, a vertical tank with a manhole, and a vertical underground tank having an inlet through a pipe, elevated tank (Takai, 2002), and a ground tank. The main point about open vertical tanks has been that the water surface exposed to the atmosphere gets evaporated, and the next layer comes to sun exposure, by which the rate of evaporation remains the same. Simultaneously, the energy required for drawing water from a vertical tank makes the users invest in a higher monetary value. Space remains a major constraint for a large-sized community tank because of massive land occupancy. Lani et al. (2018) suggested installing a simple and cost-effective treatment system for the stored rainwater before potable use to avoid minor contaminants. In order to overcome the issues, problems, constraints faced in vertical underground tanks and cover the research gaps, this study initiated an innovative method called Directional tunnel for underground rainwater storage.

Directional tunnel as a community tank in the rural community water management set-up is a unique construction method. It has been highlighted as the solution for the water shortage among community water storage methods. The objectives of the directional tunnel through RWH are to a) reduce the rate of water evaporation in the stored structure, b) store a large volume of water using less ground space without interfering with the surrounding structures, c) consume less energy for water drawing from the stored facility.

This structure is placed in a declination below the ground level, thus gets the name directional tunnel. Since it lies in an angular position, the major advantages are that the space required for its occupancy is less, the energy required for drawing water from the structure's storage is low because of its lessened depth compared to vertical tanks. Moreover, the upper layers of the stored water do not get exposed directly to the sun, resulting in reduced evaporation. The directional tunnel method involves the practice of storing both the overflown rainwater from nearby household RWH tanks and channelised runoff near the location. A filter is placed at the inlets for accumulating clean water. A conceptual diagram of directional tunnel has been illustrated in Figure 4.1.

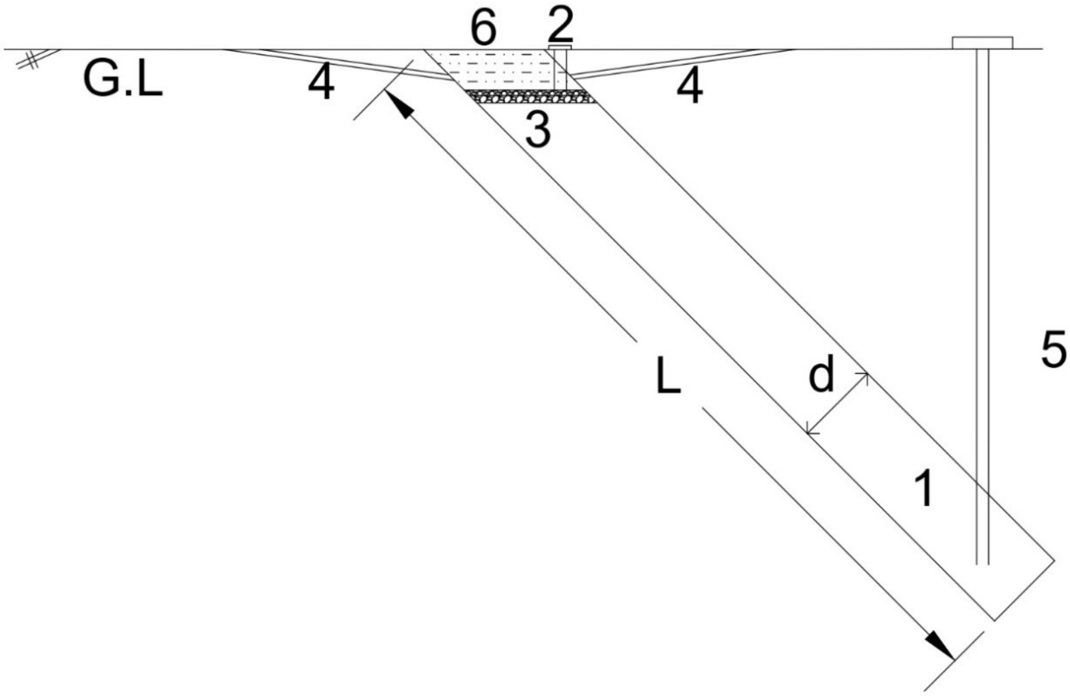


Figure 4. 1 Conceptual representation of RWH in directional tunnel

1 – Water storing directional tunnel	5 – Outlet pipe
2 – Inlet pipe from runoff	6 – Catchment area
3 – Water filter for inlet	L – Length of the directional tunnel
4 – Multiple inlets from household tanks	d – diameter of the directional tunnel

4.3 Alternate materials for fabricating directional tunnel

Many researchers have developed water storage methods by constructing and using diverse materials. Standard practices observed in the present days are Reinforced Cement Concrete (RCC) water tanks, masonry water tanks, Poly Vinyl Chloride (PVC) water tanks, and metal water tanks (Verma 2019). RCC water tanks and PVC water tanks have been the most preferred among all the mentioned types. Both RCC water tanks and PVC water tanks have their own merits and demerits. The major disadvantage in a RCC water tank is the crack propagation, leading to leakage and reduced durability. Besides, those are heavy and immovable after fixing them in one place. Their construction takes place in situ and precast, however the area required is large, thereby increasing the time consumed and risks involved.

A PVC water tank has the advantage of being easily transported and setting up. The major demerit is their low resistance to ultraviolet (UV) radiation. Most PVC water tanks tend to deteriorate due to high UV radiations (Libro 2021). Besides, they catch up fire quickly as they are less fire-resistant. Further, studies have shown the leaching of certain chemicals such as Bisphenol A and Epichlorohydrin into the water in due course of time from the tank (Al-Bahry et al., 2011).

Metal tanks prove advantageous over PVC tanks for being economical, UV and fire resistant and leaching free into the water. However, corrosion is a major demerit for metal tanks (Watts 1967). Moreover, installing metal tanks below the ground level is tedious, making the construction of underground metal water tanks challenging. After understanding all advantages and disadvantages, the study drove its focus towards the combined cause of durability and high strength for producing functional and structural prospects.

Many fibres such as hemp, coir, kenaf, sisal, ramie, broom, and jute are easily available (Das et al., 2010). Hence, two types of alternative storage water tanks' materials identified in the study are jute fibre and GRP. Among all the natural fibres, jute is considered one of the most prominent materials in the natural fibres and composite materials because of its high mechanical strength and harmless nature (Tripathy et al. 1999). The process of fabricating directional tunnel using these materials has been discussed in the following sections.

4.3.1 Development of a Jute Fibre Water Tank

The utilization of jute fibre as a composite material needs a methodical approach to maintain mechanical strength. Untreated jute fibre usually is a collection of numerous thin fibres (Ramesh et al., 2013). The collection of thin fibres should be treated and made firm. Natural jute fibre is hydrophilic, i.e., it attracts moisture, this property of jute compromises with the strength property of the composite. Increasing the overall strength of the composites can be achieved by combining jute either with epoxy resin or unsaturated polyester resin. The resin results in an exothermic reaction after bonding with a hardener and solidifies the jute composite material (Gopinath et al., 2014).

Studies reflect an improvement in mechanical properties of jute composites such as tensile strength, flexural strength, impact strength and hardness (Tripathy et al., 1999; Defoirdt et al., 2010; Mishra and Biswas 2013). Previous researchers suggested that jute fibre epoxy composites have been preferred over jute fibre unsaturated polyester resin composites (Doan et al., 2012; Gopinath et al., 2014; Gogna et al., 2019). After considering prior research studies, it has been decided to develop a Jute Fibre Water Tank, which could act as the directional tunnel component. This process followed the application of epoxy resin–hardener mixture, where jute fibre behaves as reinforcement and resin as the matrix.

Initially, two cylindrical jute fibre water tank models of small size, measuring diameter x height: 0.45m x 0.6m, with fibre thickness 0.002m and 0.010m, have been tested for quality check. Later, a major dimension of diameter x height: 3.05m x 3.05m with combined jute fibre thicknesses have been fabricated. Hand layup technique has been adopted for applying the epoxy resin-hardener mixture. A ratio of 10:1, epoxy resin and hardener, respectively, have been thoroughly weighed and mixed. In the first model, the jute fibre of thickness 0.002m has been wound on a mould. The inner coat has followed an outer coat of the mixture, and the mould has been extracted after it got cured. A base of jute fibre has been made and affixed by applying the same coat of epoxy resin-hardener mixture. A total of three coats have been applied on both inside and outside surfaces uniformly. After two days of curing, water has been filled in the models. The same process has been followed for the other jute fibre thickness of 0.010m. Both jute fibre water tank models could hold water up to its total volume. The making process of models bearing fibre thickness 0.002m and 0.010m have been represented from Figure 4.2 to Figure 4.5.

(a) Thickness of jute fibre – 0.002m

Figure 4. 2 Application of epoxy resin – hardener mixture

Figure 4. 3 Water filled after curing

(b) Thickness of jute fibre – 0.010m

Figure 4. 4 Winding jute fibre to the mould

Figure 4. 5 Water filled in the model

After successfully preparing two models in a small dimension, the jute fibre water tank with a storage capacity of 20m^3 has been prepared. Jute fibres of the thickness of 0.010m and 0.002m have been simultaneously used for the model bearing dimension, diameter x height: 3.05m x 3.05m. Initially, both the sizes of jute fibre have been wound to a hollow metal frame, as shown in Figure 4.6. A base of the same material has been prepared after the circumferential walls have been formed. Later the same combination properties of the epoxy resin-hardener mixture have been maintained for the uniform application of outer coat and internal coat, as represented in Figure 4.7. The metal frame has been extracted after the circumferential walls curing, and the base of the jute fibre water tank has been coated along and bonded. The model has been tested for water leakages. The jute fibre water tank had minor leakages from the base area, and multiple coats of epoxy resin-hardener application diminished water leakages. Figure 4.8 depicts the final jute fibre water tank.

(c) Thickness of jute fibre – **0.002m and 0.010m**

Figure 4. 6 Winding jute fibre to the frame

Figure 4. 7 Internal application of epoxy resin-hardener mixture coat

Figure 4. 8 Final jute fibre water tank

Although, the manufacturing of jute fibre water tank models has been a defying task, the haulage of the product became tedious because of its massiveness and weight. Hence, a lightweight material as GRP for directional tunnel has been considered. The next section discusses about the detailed usage of GRP material in directional tunnel.

4.3.2 Manufacturing GRP water tanks

Weston (1980) was the first researcher in introducing GRP water tanks globally. This composite material exhibits neither brittle nor ductile properties, and its behaviour lies between them. GRP used as a core material for water tanks produces benefits such as corrosion resistance, high strength, extended durability, and lightweight installation (Elmar Witten and Volker Mathes 2020). These advantages directed toward the manufacturing of GRP water tanks.

Glass fibre acts as reinforcement and epoxy resin as the matrix in GRP water tanks. The first step involved in fabrication has been the preparation of a wooden dye frame. It has been used as a mould for fabricating GRP panels. After preparing the frame, bi-directional glass fibre mats have been stacked in layers and coated with an epoxy resin-hardener mixture in the ratio of 10:1, respectively, through the hand lay-up technique, as shown in Figure 4.9. Three layers of glass fibre mats and epoxy resin-hardener mixture have been applied on the wooden dye frame surface. Curing this frame for four days attains a strengthened GRP panel, as depicted in Figure 4.10. Multiple GRP panels after curing have been considered for the fabrication and formation of the walls of a tank, as shown in Figure 4.11. The same material composition has been followed for the top cover and base of the tanks. All parts' integration produced a final GRP water tank with a wall thickness close to 5mm, as illustrated in Figure 4.12.

Figure 4. 9 Application of bi-directional glass fibre mats on dye frame along epoxy resin-hardener mix coat

Figure 4. 10 GRP panels set for curing

Figure 4. 11 Multiple GRP panels after curing

Figure 4. 12 Assembling multiple panels for GRP water tanks

The tank has been tested for leakages and defects. Minute water leakages have been observed at a few walls, which have been settled. Connecting GRP panels in longitudinal series of any desired dimension fetches the complete structure of a directional tunnel.

4.3.2.1 Determination of strength properties of GRP panels

The previous section discussed about the three-layered GRP panels for directional tunnel. Moreover, two-layered GRP panels have also been prepared under a similar manufacturing process and considered for adopting the most feasible and mechanically viable material between the two types for installing directional tunnel. The GRP panels were tested for Elasticity modulus (E), tensile strength and compressive strength. These parameters have been determined by testing the GRP specimens as per the American Society for Testing and Materials (ASTM) guidelines mentioned in ASTM D3039 (ASTM 2000), and ASTM D3410 (ASTM 2003). These tests have been conducted in a universal testing machine (UTM) of 100kN capacity, preinstalled in the advanced structural engineering laboratory, BITS Pilani.

4.3.2.2 Tensile strength test of GRP specimens

Tensile strength test has been conducted on the GRP panels by cutting the specimens in the fibre alignment directions of 0°, 45° and 90°, as per the ASTM D3039 guidelines shown in Figure 4.13. Three specimens in each direction were considered for the tensile strength test.

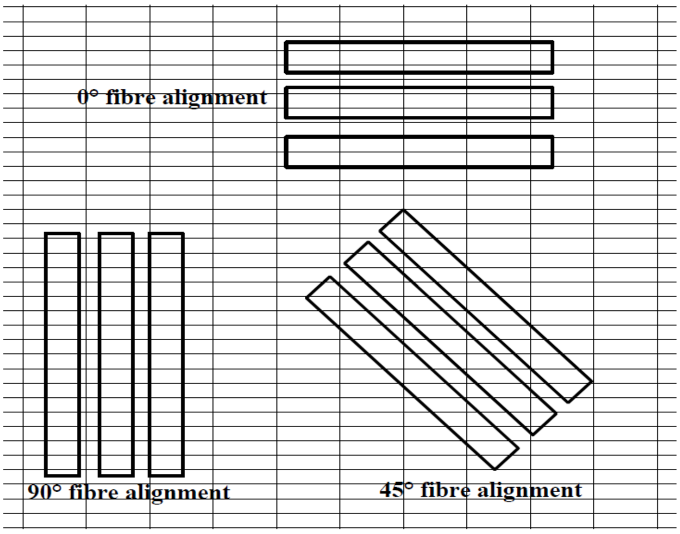


Figure 4. 13 Schematic diagram of cutting GRP specimen

Three specimens in each orientation, with a total of nine specimens have been cut and measured before the testing. The specimens' dimensions have been presented in Table 4.1.

Table 4. 1 Two-layered GRP specimen sizes for tensile strength test

S.No	Specimen code	Length (mm)	Width (mm)	Thickness (mm)
1.	TST-2-GRP-0-SP1*	250	15±0.3	3.32
2.	TST-2-GRP-0-SP2	250	15±0.3	3.27
3.	TST-2-GRP-0-SP3	250	15±0.3	3.50
4.	TST-2-GRP-90-SP1	175	25±0.3	3.22
5.	TST-2-GRP-90-SP2	175	25±0.3	3.17
6.	TST-2-GRP-90-SP3	175	25±0.3	3.60
7.	TST-2-GRP-45-SP1	190	25±0.3	3.37
8.	TST-2-GRP-45-SP2	190	25±0.3	3.52
9.	TST-2-GRP-45-SP3	190	25±0.3	3.23

***Note: Tensile Strength Test of two-layered GRP panel with 0° fibre alignment for specimen 1 and likewise for other specimens' code.**

Figure 4.14 represents the tensile strength test carried on a two-layered GRP specimen. Similarly, the test has been performed on the remaining eight specimens.

Figure 4. 14 Tensile test of the two-layered GRP specimen

The test results of all the specimens have been gathered. Stress-strain relationship curves for each case's specimens have been plotted for obtaining Young's Modulus E_1 and E_2 along orthogonal directions (i.e., 0° and 90°) and Shear Modulus (G) at 45°. Figure 4.15 represents the stress-strain relationship among the three specimens at 0° fibre alignment.

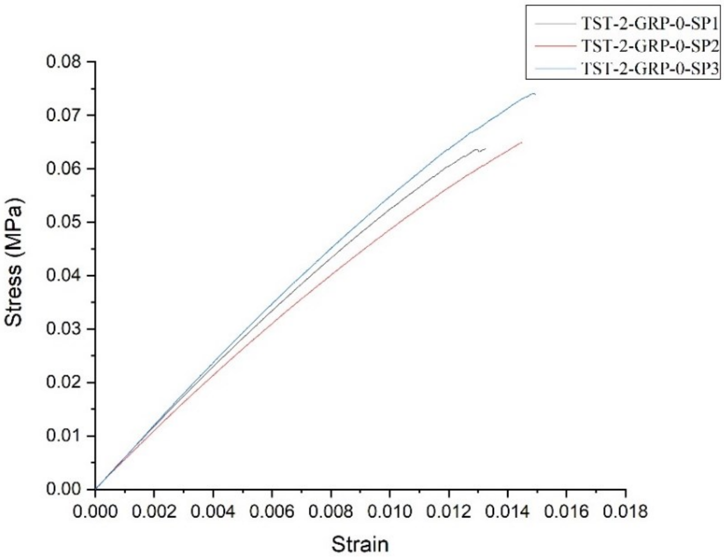


Figure 4. 15 Stress v/s Strain relationship curves of specimens at 0° fibre alignment in two-layered GRP panels

The slopes of curves TST-2-GRP-0-SP1, TST-2-GRP-0-SP2, and TST-2-GRP-0-SP3 have been 4.94, 4.52, and 5.06 respectively. Hence, the highest slope among the three curves has been taken as E_1: 5.06GPa from specimen: TST-2-GRP-0-SP3. Figure 4.16 exhibits the stress-strain relationship among the three specimens at 90° fibre alignment.

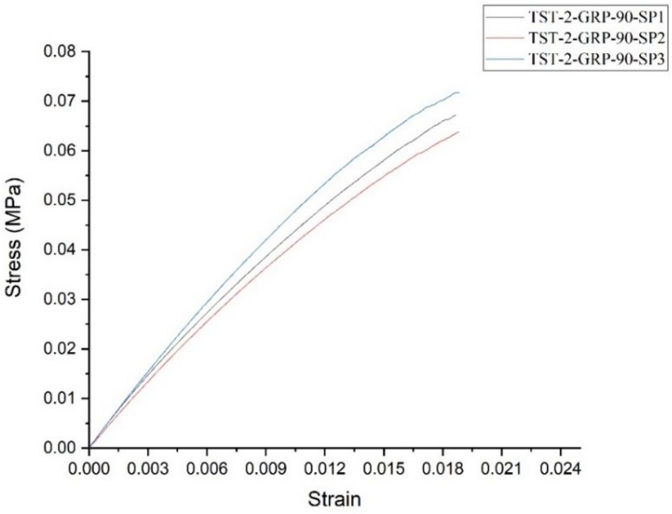


Figure 4. 16 Stress v/s Strain relationship curves of specimens at 90° fibre alignment in two-layered GRP panels

The slopes of curves TST-2-GRP-90-SP1, TST-2-GRP-90-SP2, and TST-2-GRP-90-SP3 have been 3.62, 3.42, and 3.90 respectively. As a result, the highest slope among the three comparison curves has been obtained from the specimen: TST-2-GRP-90-SP3 is 3.90GPa (E_2). Figure 4.17 illustrates the stress-strain relationship among the three specimens at 45° fibre alignment.

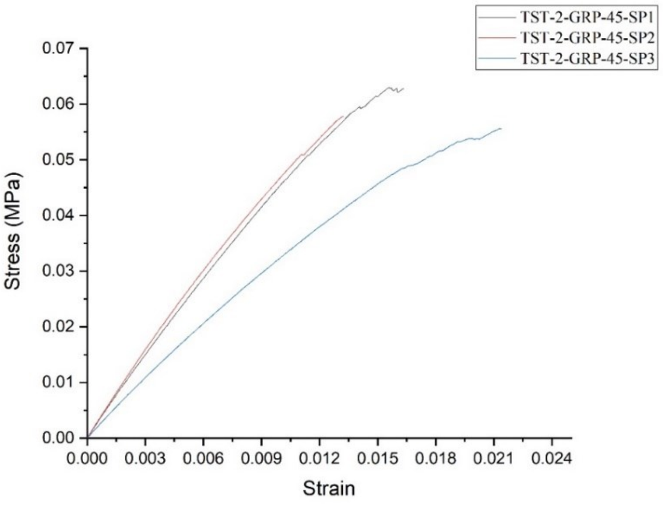


Figure 4. 17 Stress v/s Strain relationship curves of specimens at 45° fibre alignment in two-layered GRP panels

The slopes of curves TST-2-GRP-45-SP1, TST-2-GRP-45-SP2, and TST-2-GRP-45-SP3 have been 3.42, 3.86, and 3.22, respectively. The highest slope from the curve of specimen: TST-2-GRP-45-SP2 has been considered G: 3.86GPa. The ultimate tensile strength among the two-layered GRP specimen has been observed as 0.076kN/mm2. After conducting the tensile strength test on two-layered GRP panels, the following category of three-layered GRP panels has been cut for performing the tensile test. The measured specimens' dimensions have been presented in Table 4.2. Figure 4.18 shows the tensile strength test carried on a three-layered GRP specimen. Simultaneously, the test has been conducted for the other specimens.

Table 4. 2 Three-layered GRP specimen sizes for tensile strength test

S.No	Specimen code	Length (mm)	Width (mm)	Thickness (mm)
1.	TST-3-GRP-0-SP1*	250	15±0.3	4.51
2.	TST-3-GRP-0-SP2	250	15±0.3	4.55
3.	TST-3-GRP-0-SP3	250	15±0.3	4.80
4.	TST-3-GRP-90-SP1	175	25±0.3	4.46
5.	TST-3-GRP-90-SP2	175	25±0.3	4.63
6.	TST-3-GRP-90-SP3	175	25±0.3	4.71
7.	TST-3-GRP-45-SP1	190	25±0.3	4.45
8.	TST-3-GRP-45-SP2	190	25±0.3	4.48
9.	TST-3-GRP-45-SP3	190	25±0.3	4.78

Note: Tensile Strength Test of three-layered GRP panel with 0° fibre alignment for specimen 1 and likewise for other specimens' code

Figure 4. 18 Tensile test of the three-layered GRP specimen

The tensile strength test results of three-layered GRP specimens helped in producing stress-strain relationship curves and obtained E_1, E_2, and G. Figure 4.19 represents the stress-strain relationship among the three specimens at 0° fibre alignment. The slopes of curves TST-3-GRP-0-SP1, TST-3-GRP-0-SP2, and TST-3-GRP-0-SP3 have been 3.68, 4.51, and 6.54, respectively. The curve of specimen TST-3-GRP-0-SP3 has the highest slope, thus E_1 - 6.54GPa.

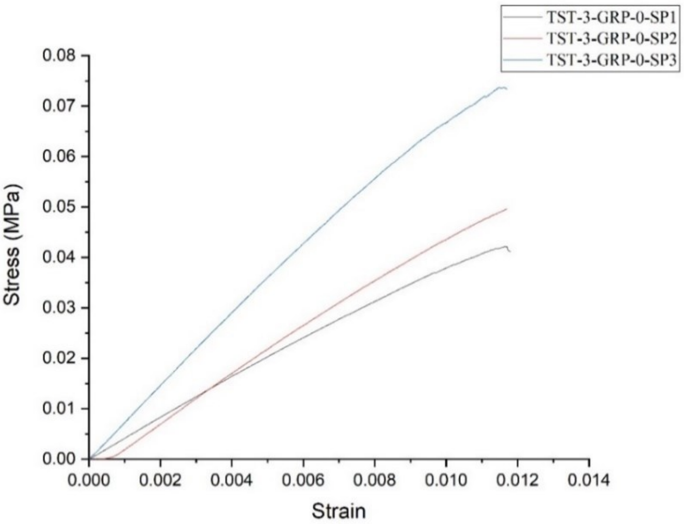


Figure 4. 19 Stress v/s Strain comparison of specimens at 0° fibre alignment in three-layered GRP panels

Figure 4.20 exhibits the stress-strain relationship among the three specimens at 90° fibre alignment. The slopes of curves TST-3-GRP-90-SP1, TST-3-GRP-90-SP2, and TST-3-GRP-90-SP3 have been 3.33, 3.06, and 4.43, respectively. The highest slope has been obtained from the curve of TST-3-GRP-90-SP3, with E_2 - 4.43GPa.

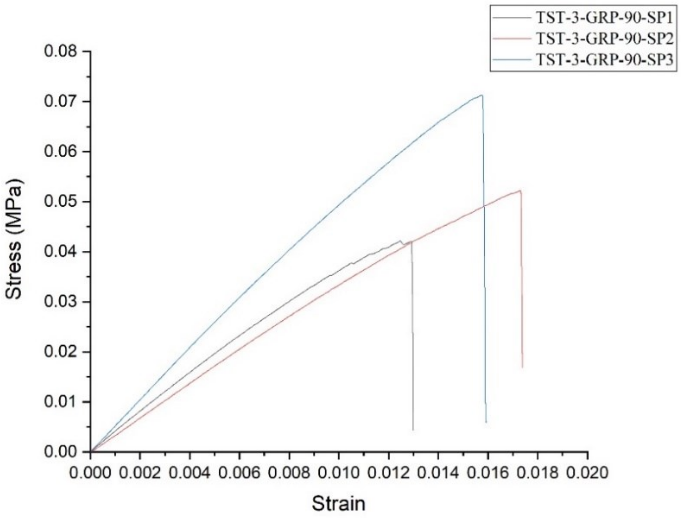


Figure 4. 20 Stress v/s Strain comparison of specimens at 90° fibre alignment in three-layered GRP panels

Figure 4.21 illustrates the stress-strain relationship among the three specimens at 45° fibre alignment. The slopes of curves TST-3-GRP-45-SP1, TST-3-GRP-45-SP2, and TST-3-GRP-45-SP3 have been 4.03, 2.68, and 4.4, respectively. The curve of specimen: TST-3-GRP-45-SP3 has the highest slope, thus G - 4.4GPa.

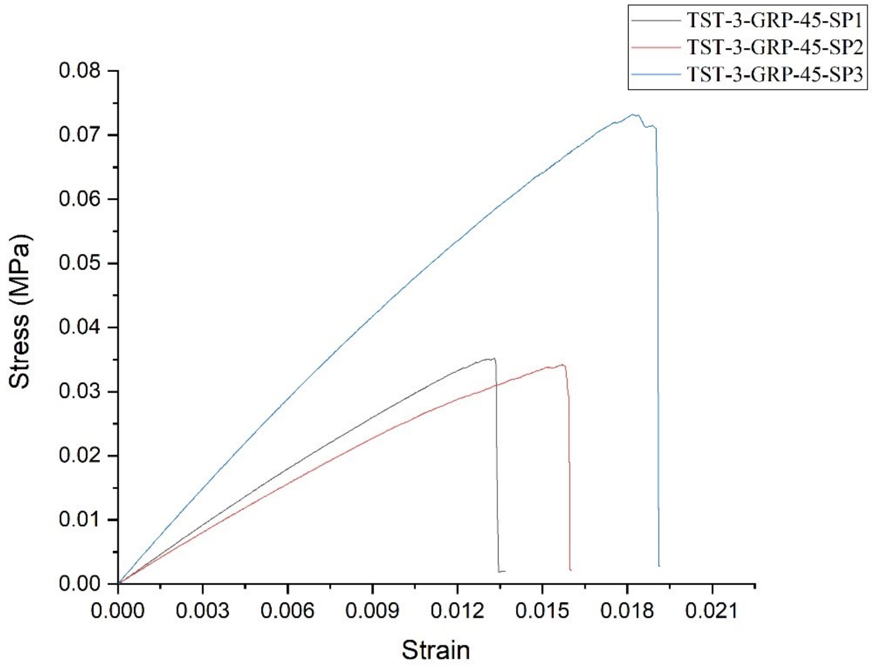


Figure 4. 21 Stress v/s Strain comparison of specimens at 45° fibre alignment in three-layered GRP panels

The ultimate tensile strength among all three-layered GRP specimen has been recorded as 0.086kN/mm^2. Based on the tensile strength test results of both types of GRP specimens, the three-layered GRP panels has high tensile strength, Young's modulus (E_1 and E_2) and shear modulus (G). Moreover, failure of the two-layered GRP panel occurred at a lower ultimate tensile strength compared with that of the three-layered GRP panel.

4.3.2.3 Compressive strength test of GRP specimens

Compressive strength test has also been performed on the GRP panels for assessing the ultimate compressive strength. The specimens have been cut in the direction of 0° and 90° of the fibre alignment, as per ASTM D3410 guidelines. Three specimens in each direction, hence a total of six specimens have been cut and measured before the testing, presented in Table 4.3. Figure 4.22 represents the compressive strength test carried on a two-layered GRP specimen. Simultaneously, the test has been conducted on the other specimens.

Table 4. 3 Two-layered GRP specimen sizes for compressive strength test

S. No	Specimen code	Length (mm)	Width (mm)	Thickness (mm)
1.	CST-2-GRP-0-SP1*	105	10±0.3	3.42
2.	CST-2-GRP-0-SP2	105	10±0.3	3.63
3.	CST-2-GRP-0-SP3	105	10±0.3	3.55
4.	CST-2-GRP-90-SP1	105	25±0.3	3.48
5.	CST-2-GRP-90-SP2	105	25±0.3	3.64
6.	CST-2-GRP-90-SP3	105	25±0.3	3.45

Note: Compressive Strength Test of two-layered GRP panel with 0° fibre alignment for specimen 1 and likewise for other specimens' code

Figure 4. 22 Compressive strength test of two-layered GRP specimen

The test results of all the specimens have been collected and represented in Table 4.4. The ultimate compressive strength among all the specimens, has been recorded as 0.057kN/mm^2.

Table 4. 4 Compressive strength results of two-layered GRP specimens

S. No	Specimen code	Compressive strength (kN/mm^2)
1.	CST-2-GRP-0-SP1	0.047
2.	CST-2-GRP-0-SP2	0.057
3.	CST-2-GRP-0-SP3	0.045

4.	CST-2-GRP-90-SP1	0.036
5.	CST-2-GRP-90-SP2	0.054
6.	CST-2-GRP-90-SP3	0.044

The compressive strength test was performed on three-layered GRP panels after the test on two-layered GRP panels. The specimens' dimensions have been presented in Table 4.5. Figure 4.23 demonstrates the compressive strength test carried on a three-layered GRP specimen. Similarly, the test has been performed on the remaining five specimens.

Table 4. 5 Three-layered GRP specimen sizes for compressive strength test

S. No	**Specimen code**	**Length (mm)**	**Width (mm)**	**Thickness (mm)**
1.	CST-3-GRP-0-SP1*	105	10±0.3	4.15
2.	CST-3-GRP-0-SP2	105	10±0.3	4.50
3.	CST-3-GRP-0-SP3	105	10±0.3	4.23
4.	CST-3-GRP-90-SP1	105	25±0.3	4.71
5.	CST-3-GRP-90-SP2	105	25±0.3	4.62
6.	CST-3-GRP-90-SP3	105	25±0.3	4.65

Note: Compressive Strength Test of three-layered GRP panel with 0° fibre alignment for specimen 1 and likewise for other specimens' code

Figure 4. 23 Compressive strength test of three-layered GRP specimen

The test results of all the specimens have been collected and represented in Table 4.6. The ultimate compressive strength among three layered GRP panels has been observed as 0.73kN/mm^2.

Table 4. 6 Compressive strength results of three-layered GRP specimens

S.No	Specimen code	Compressive strength (kN/mm^2)
1.	CST-3-GRP-0-SP1	0.06
2.	CST-3-GRP-0-SP2	0.073
3.	CST-3-GRP-0-SP3	0.058
4.	CST-3-GRP-90-SP1	0.072
5.	CST-3-GRP-90-SP2	0.07
6.	CST-3-GRP-90-SP3	0.071

Compressive strength test results on both types of GRP specimens suggest that the three-layered GRP panels have high compressive strength. The failure of two-layered GRP specimens occurred at a lower ultimate compressive strength than that of a three-layered GRP panel. Hence two-layered type has been out of consideration for the directional tunnel's practical installation based on the tensile and compressive strength test results.

4.4 Stability analysis of directional tunnel

Soil as an engineering material is non-coherent in nature. Underground construction works have always been very challenging from the civil engineering point of view. This study employs directional tunnel in underground conditions; therefore, stability analysis comes into the picture for the prior identification of stresses, strains, and deformations. Dependent factors in the underground stability are the type of tunnel section, inclination angle on tunnel stability, the effect of overlying strata, stratification of soil, and angle of repose (Kumar and Shrivastava 2017). PLAXIS, a fast and reliable Finite Element Method (FEM) based software, interprets any structure's behaviour in soil interaction. It follows a numerical modelling approach for the two-dimensional and three-dimensional analysis of deformation and stability in geotechnical engineering (Wilde 2021). Previous researchers have stated that the simulations of PLAXIS 3D have been instrumental in decision-making for the geotechnical obstacles in different infrastructures' construction (Zhao and You 2018; Aicha and Mezhoud 2021; Shinde et al., 2019). Moreover, this software contributes to the scope of BIM as well as other engineering modelling tools. Eventually, the infrastructures' execution is safe in real-time accomplishment.

4.4.1 Simulation of the directional tunnel in PLAXIS 3D

This study has been in the context of Rajasthan state, India, and the classified soil type across the state has been predominantly sandy soil. Based on this factor, the directional tunnel's stability limited to sandy soil has been analysed in the thesis. With respect to the discussions in section 4.3, the structure is placed in a declination below the ground level. Since it is an innovative structure, this thesis defines the optimal angle for the directional tunnel's execution. Initially, the soil samples collected from a location named Ramnathpura (intended study area), in Rajasthan, were tested at the geotechnical engineering laboratory, BITS Pilani for determining soil properties. The acquired soil sample's angle of repose was measured to be 31°. The determination of cohesion (C) and angle of internal friction (φ) was performed through a direct shear test (Indian Standards Institution, 1985). The results of the test have been presented in Table 4.7. Normal and shear stress outputs have been plotted for acquiring C and φ, as shown in Figure 4.24.

Table 4. 7 Results of direct shear test for the soil sample

S. No	Applied Weight (kN)	Area of shear box (m^2)	Observed reading	Least count of the dial	Normal stress (kN/m^2)	Shear stress (kN/m^2)
1	0.005	0.0036	2	0.2209944	1.389	1.228
2	0.01	0.0036	3	0.2209944	2.778	1.841
3	0.015	0.0036	4	0.2209944	4.167	2.455
4	0.03	0.0036	9	0.2209944	8.333	5.525
5	0.06	0.0036	18	0.2209944	16.667	11.05

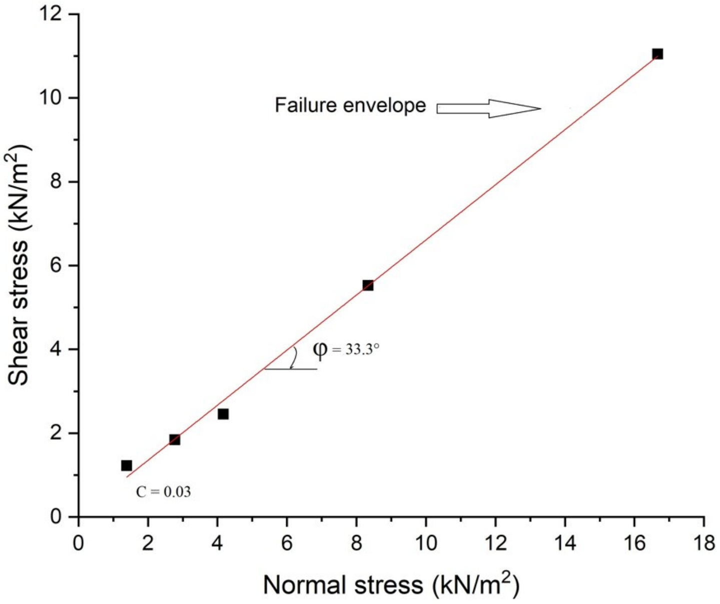


Figure 4. 24 Plotting Normal v/s Shear stress for determining C and φ

Linear fitting for the curve produced an equation (4.1). The intercept of this equation has been considered as C: 0.03 kN/m^2 and inverse tangent of the slope: 0.6574 as φ: 33.3° in the soil sample.

$$y = 0.6574x + 0.03 \qquad (4.1)$$

Successively, the stability of the directional tunnel's orientation has been analysed for five different cases. The angles of declination have been considered as 10°, 20°, 30°, 35°, and 40°. These angles are selected based on the obtained internal friction angle of the soil model. Since, the PLAXIS 3D analysis adopts FEM, a linear or nonlinear computation is one of the two alternatives (Hasançebi and Dumlupinar 2013). Linear analysis is a simple process to perform and utilise when forces applied to any part on a structure do not generate significant deformation. Simultaneously, a non-linear analysis is a more complex operation required when the forces applied on a material can cause major displacements (Valtonen 2019). The directional tunnel has been intended for positioning at a shallow depth below the ground level, therefore minor displacements were anticipated, and linear static analysis has been followed. 10-node tetrahedral elements with a conventional Mohr–Coulomb soil model using constitutive equation (4.2) and elastic plate material were considered by linear analysis through FEM in PLAXIS simulations.

$$\tau = C + \sigma \, Tan(\varphi) \qquad (4.2)$$ (Labuz and Zang 2012)

Where τ – Shear stress, σ – Normal stress

C – Cohesion

φ - Angle of internal friction

Figure 4.25 illustrates the complete methodology adopted in the study for executing stability analysis in PLAXIS 3D. The analysis was initiated by setting the geometrical boundary of the soil model with dimensions: length x width: 80mx40m and borehole depth of 30m. It consisted of the loose sand type of soil. The tunnel with a trajectory length of 21.34m and transverse dimensions of a diameter:3.05m, a thickness:0.005m, as illustrated in Figure 4.26, have been generated. The selection criteria for length and diameter of the directional tunnel have been discussed elaboratively in the upcoming Chapter 5 at section 5.4.2.3.

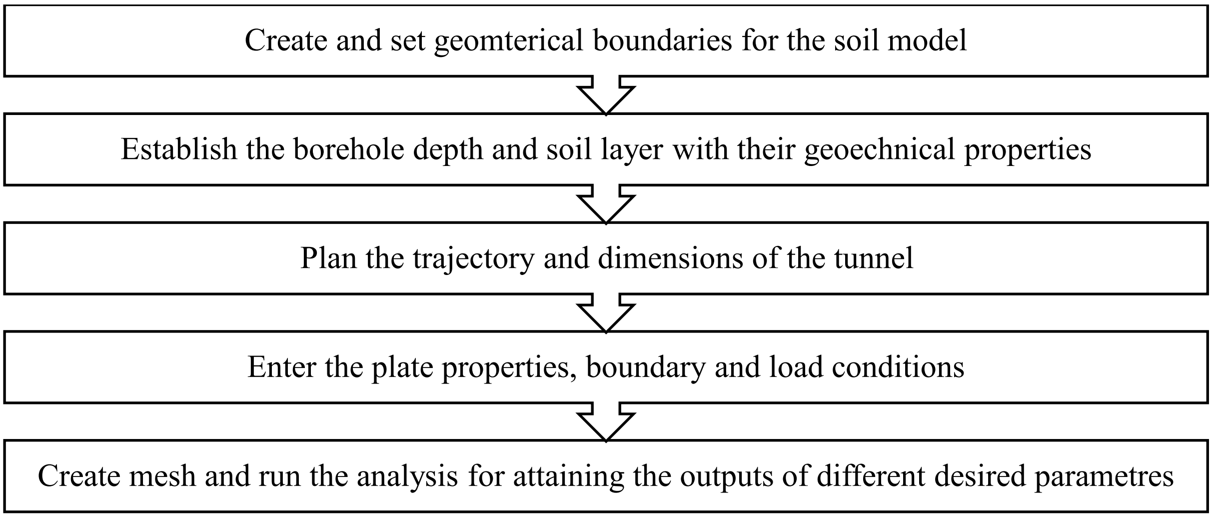
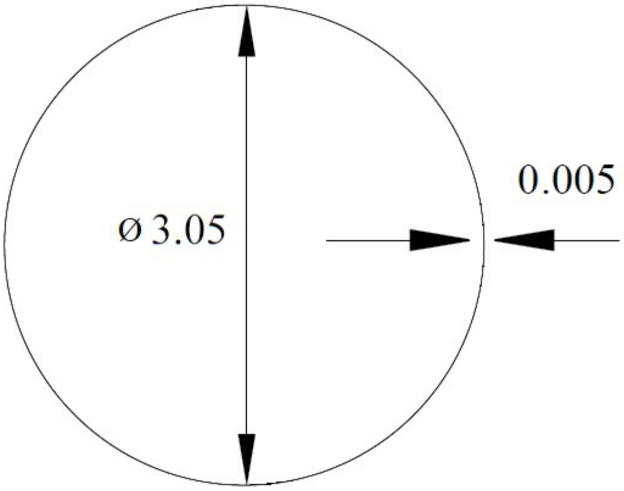


Figure 4. 25 Methodology of the conducted stability analysis through PLAXIS 3D software



(All measurements are in metres)

Figure 4. 26 Transverse dimensions of the tunnel

Inputs of geotechnical parameters for the selected loose sand have been presented in Table 4.8. Three-layered GRP plate properties have been considered for stability analysis, as indicated in Table 4.9. Properties such as Young's modulus has been based on the conducted tensile strength test, density has been measured and Poisson's ratio has been considered from an earlier study (Craig and Summerscales 1988). All inputs and fixed boundary conditions of the directional tunnel have been the same throughout all five cases. Static load condition has been created. Medium mesh for the whole model has been opted for the computation though numerical modelling. Finally, the simulations were performed for attaining the outputs of different desired parameters.

Table 4. 8 Inputs of geotechnical parameters

Property	**Unit**	**Value**
Dry unit weight (γ_{unsat})	kN/m^3	16
Saturated unit weight (γ_{sat})	kN/m^3	19
Angle of internal friction (φ)	°	33.3
Cohesion (C)	kN/m^2	0.03

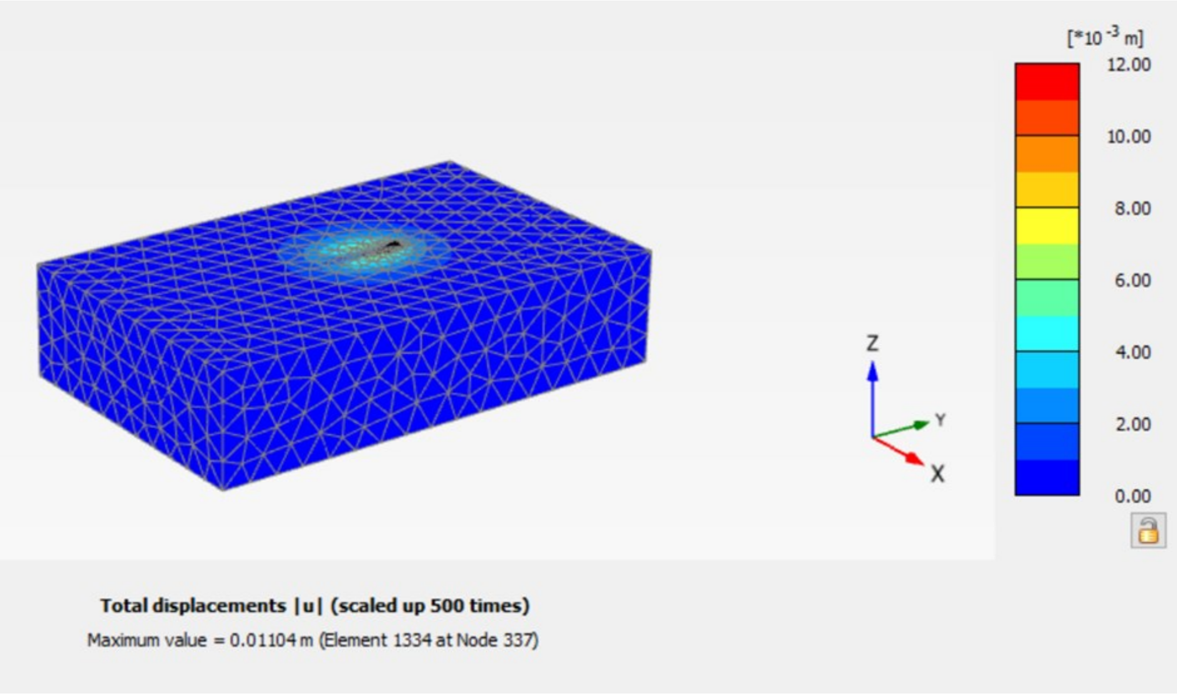
Table 4. 9 Inputs of GRP plate

Property	**Unit**	**Value**
Young's modulus	GPa	E_1: 6.54 E_2: 4.43
Density	g/cm^3	γ: 2.35
Poisson's ratio	-	υ: 0.3

Simulations of the above-mentioned five positions have been operated, and outputs of the three results, such as total displacements (u), principal stresses (σ_1, σ_2, σ_3) and principal strains (ε_1, ε_2, ε_3) have been considered for studying the response of the directional tunnel. Failure analysis by the identification of plastic points has been performed, which helped in analysing the failure along the section of directional tunnel. A few assumptions such as a) a single homogenous loose sand type of soil in the complete model, b) no effect of hydrostatic pressure in the directional tunnel, c) fixed boundary conditions and d) static load conditions have been considered in the analysis. Eventually, the simulations have been carried for the declinations of 10°, 20°, 30°, 35°, and 40° for directional tunnel.

Case 1 - Declination angle: 10°

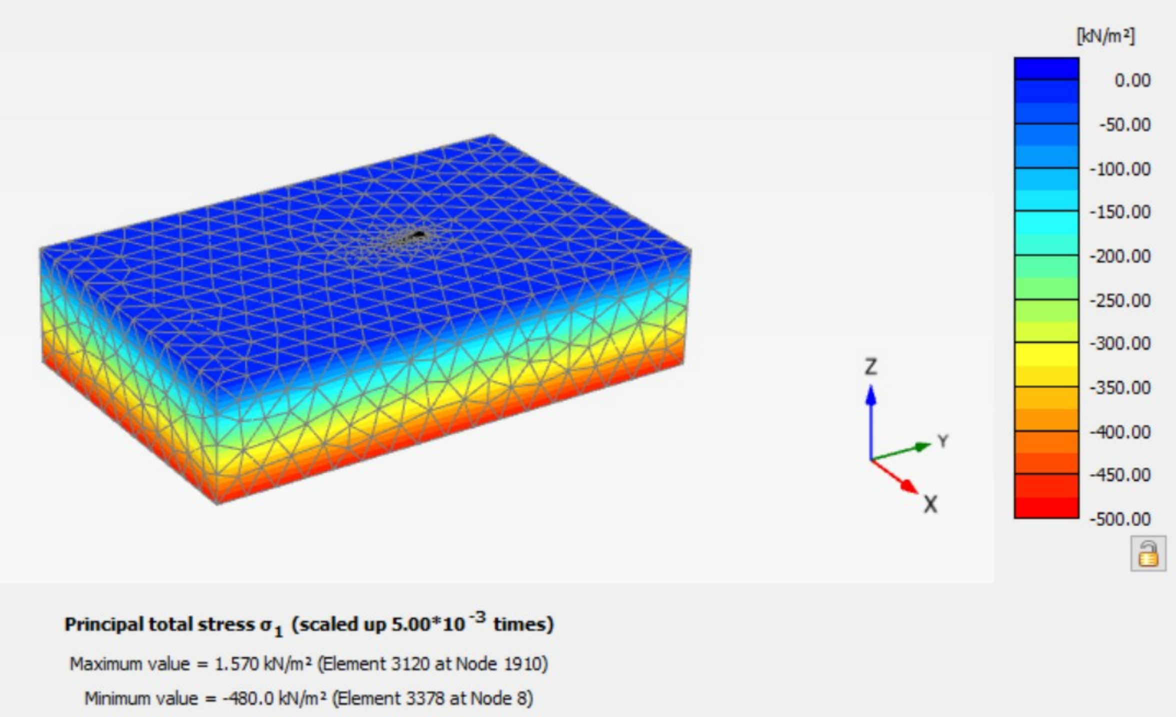
The analysis has been performed based on the fixed parameters of the directional tunnel at a declination of 10° below ground level. The outputs of total displacements, principal stresses and principal strains have been obtained and represented from Figure 4.27 to Figure 4.33.



Total displacements |u| (scaled up 500 times)

Maximum value = 0.01104 m (Element 1334 at Node 337)

Figure 4. 27 Total displacements (u) at 10°

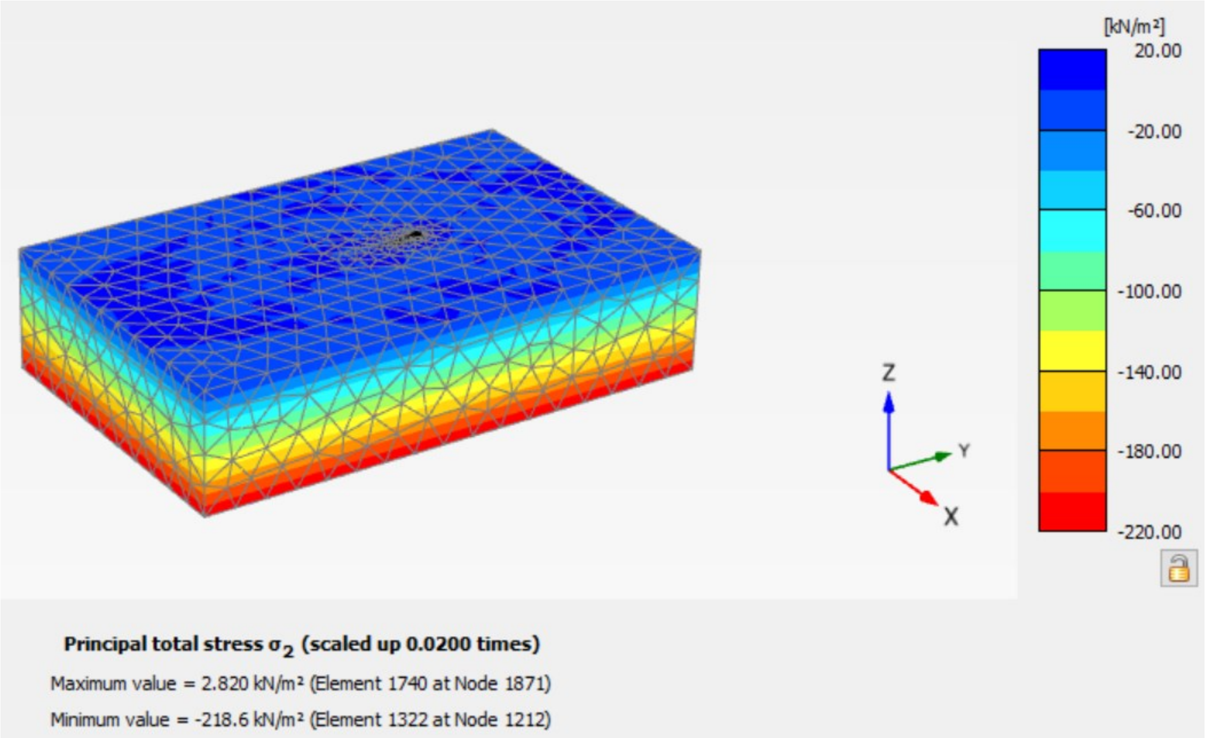


Principal total stress σ_1 (scaled up 5.00*10 $^{-3}$ times)

Maximum value = 1.570 kN/m² (Element 3120 at Node 1910)

Minimum value = -480.0 kN/m² (Element 3378 at Node 8)

Figure 4. 28 Principal total stresses (σ_1) at 10°

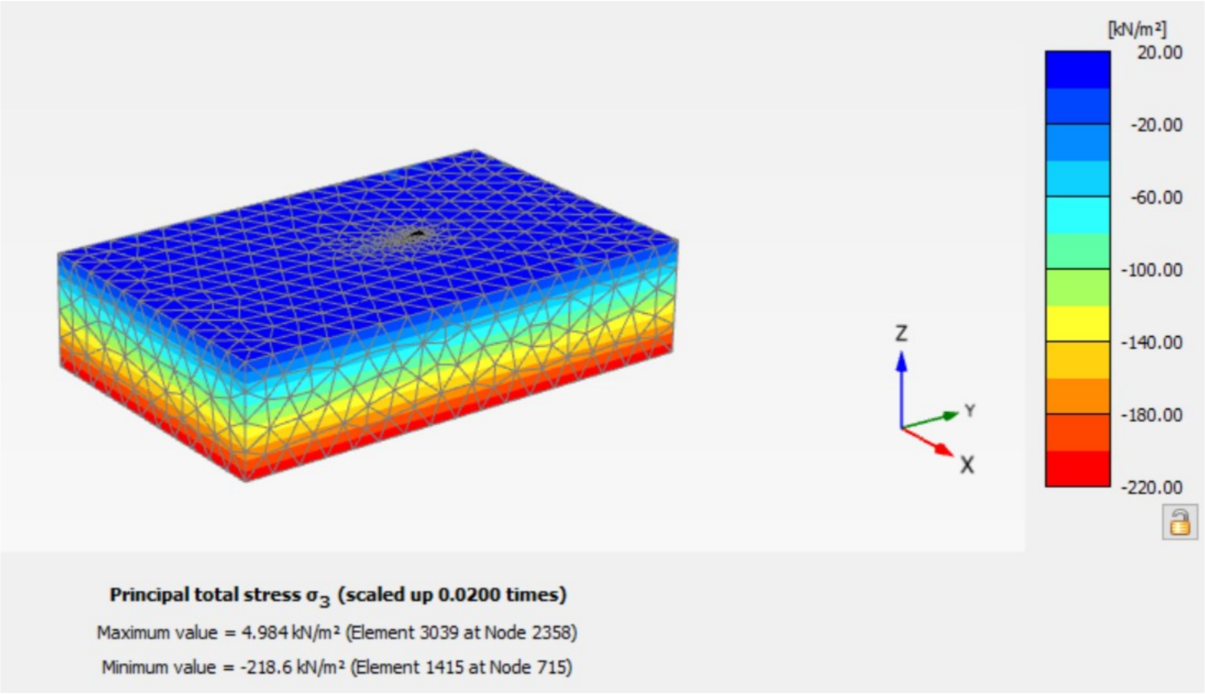


Principal total stress σ_2 (scaled up 0.0200 times)

Maximum value = 2.820 kN/m² (Element 1740 at Node 1871)

Minimum value = -218.6 kN/m² (Element 1322 at Node 1212)

Figure 4. 29 Principal total stresses (σ_2) at 10°

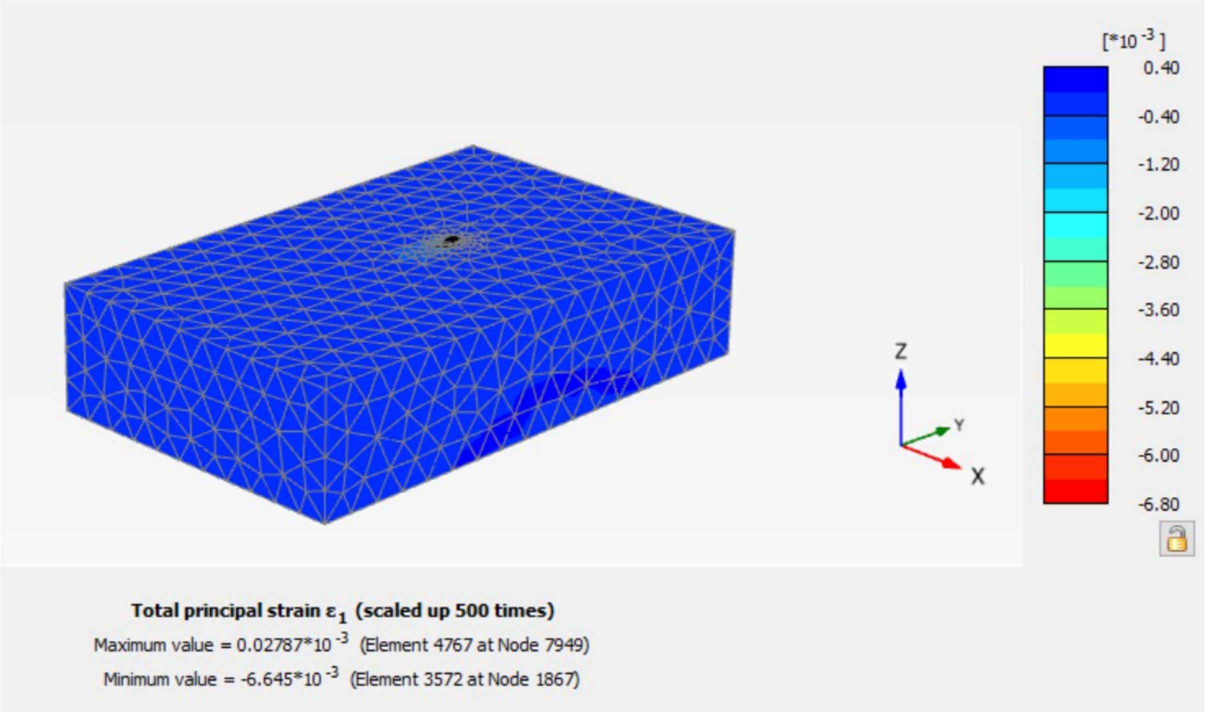


Principal total stress σ_3 (scaled up 0.0200 times)

Maximum value = 4.984 kN/m² (Element 3039 at Node 2358)

Minimum value = -218.6 kN/m² (Element 1415 at Node 715)

Figure 4. 30 Principal total stresses (σ_3) at 10°

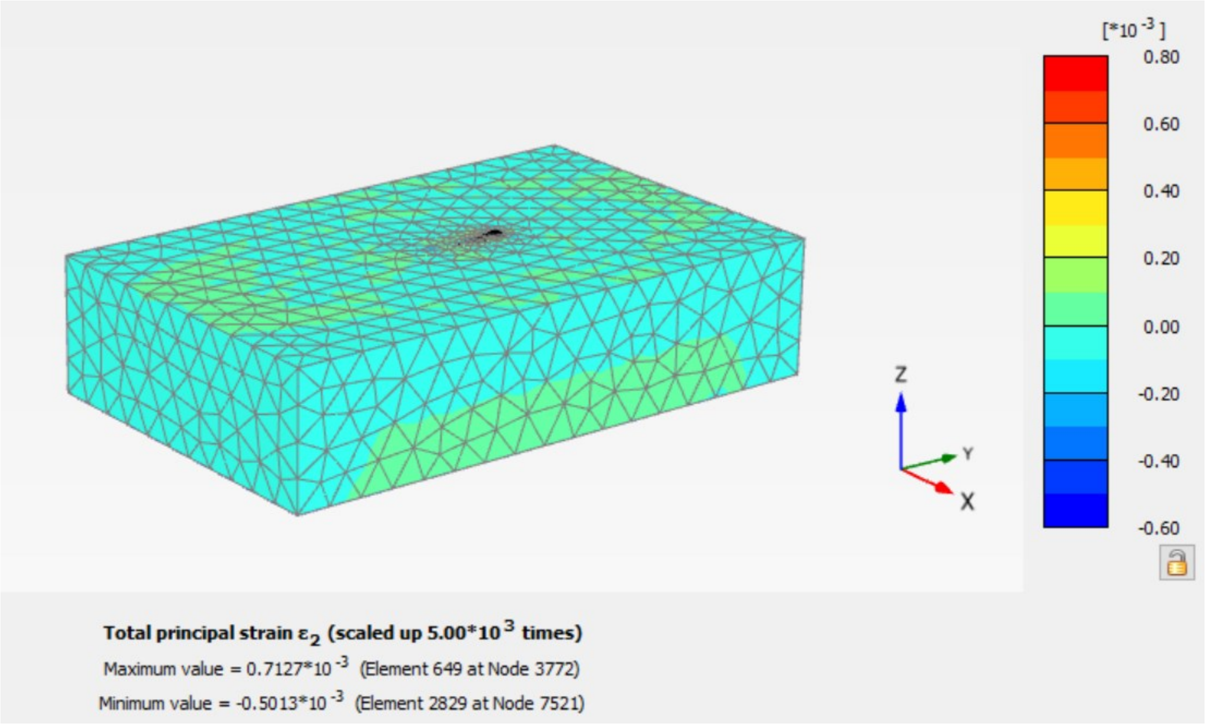


Total principal strain ε_1 (scaled up 500 times)

Maximum value = $0.02787*10^{-3}$ (Element 4767 at Node 7949)

Minimum value = $-6.645*10^{-3}$ (Element 3572 at Node 1867)

Figure 4. 31 Total principal strains (ε_1) at 10°

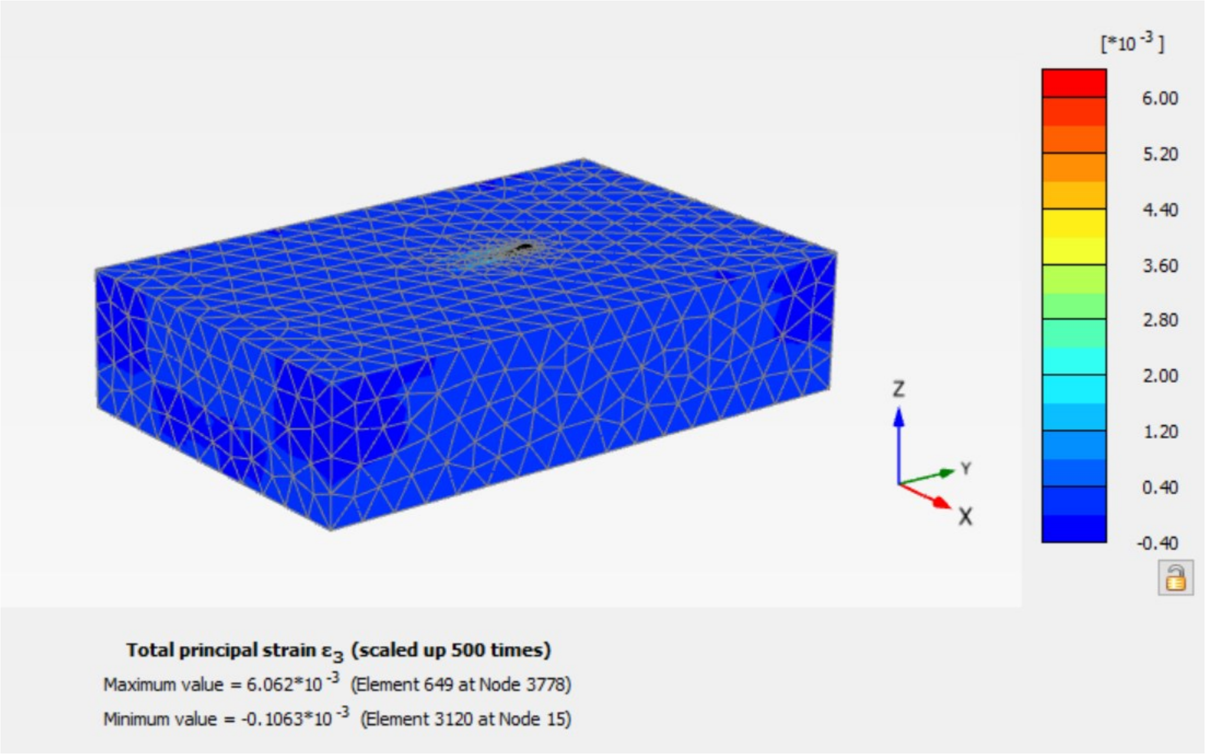


Total principal strain ε_2 (scaled up $5.00*10^3$ times)

Maximum value = $0.7127*10^{-3}$ (Element 649 at Node 3772)

Minimum value = $-0.5013*10^{-3}$ (Element 2829 at Node 7521)

Figure 4. 32 Total principal strains (ε_2) at 10°



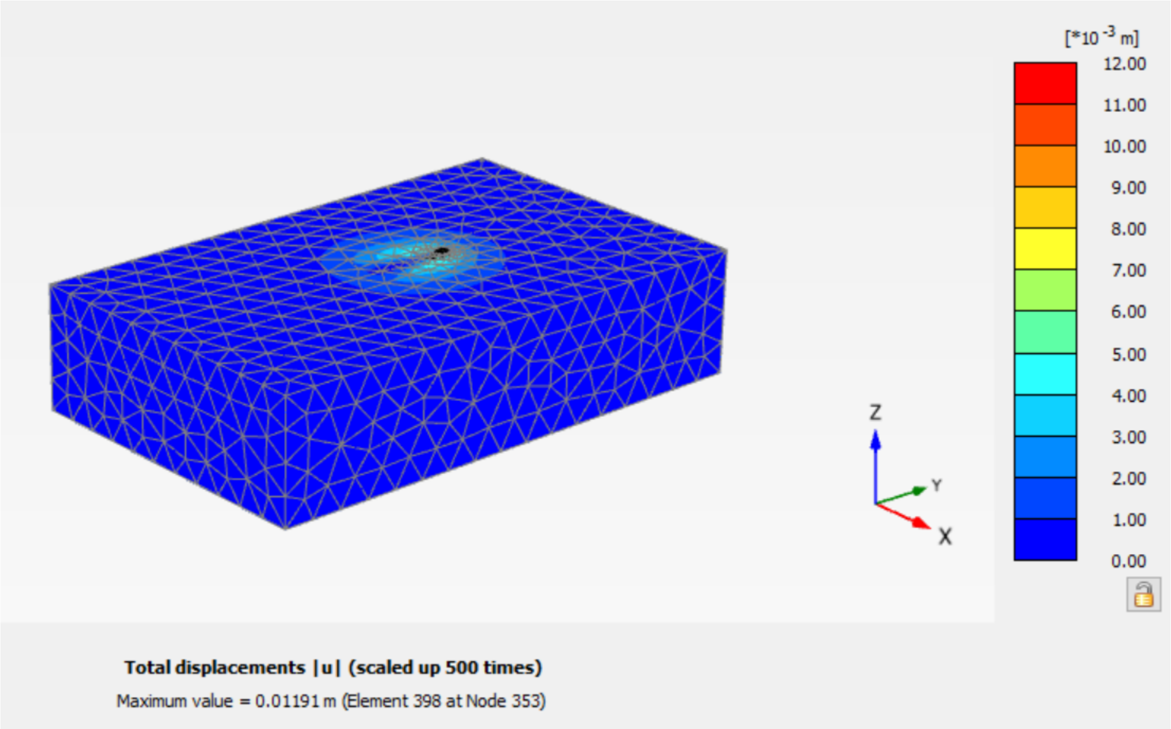
Total principal strain ε_3 (scaled up 500 times)
Maximum value = 6.062*10 -3 (Element 649 at Node 3778)
Minimum value = -0.1063*10 -3 (Element 3120 at Node 15)

Figure 4. 33 Total principal strains (ε_3) at 10°

The bottom end depth was 5.13m from the ground level for the directional tunnel in Case 1 at a declination of 10°, for which the acquired results have been maximum displacement (u): 11.04x10^{-3}m, maximum principal total stresses: 1.570kN/m^2 (σ_1), 2.820kN/m^2 (σ_2), 4.984kN/m^2 (σ_3), and maximum principal total strains: 0.0278x10^{-3} (ε_1), 0.7127x10^{-3} (ε_2), 6.062x10^{-3} (ε_3).

Case 2 - Declination angle: 20°

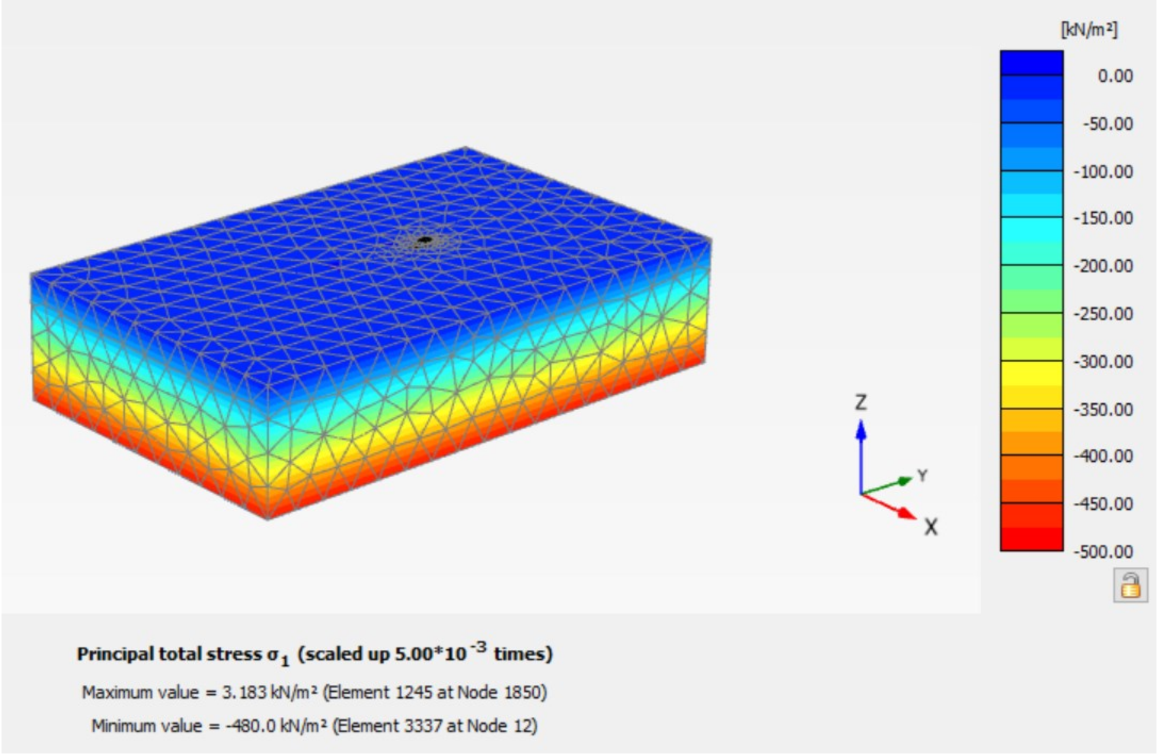
The next case of the directional tunnel at declination of 20° below ground level has been analysed for understanding the behaviour. The outputs of total displacements, principal stresses and principal strains have been obtained and illustrated from Figure 4.34 to Figure 4.40.



Total displacements |u| (scaled up 500 times)

Maximum value = 0.01191 m (Element 398 at Node 353)

Figure 4. 34 Total displacements (u) at 20°

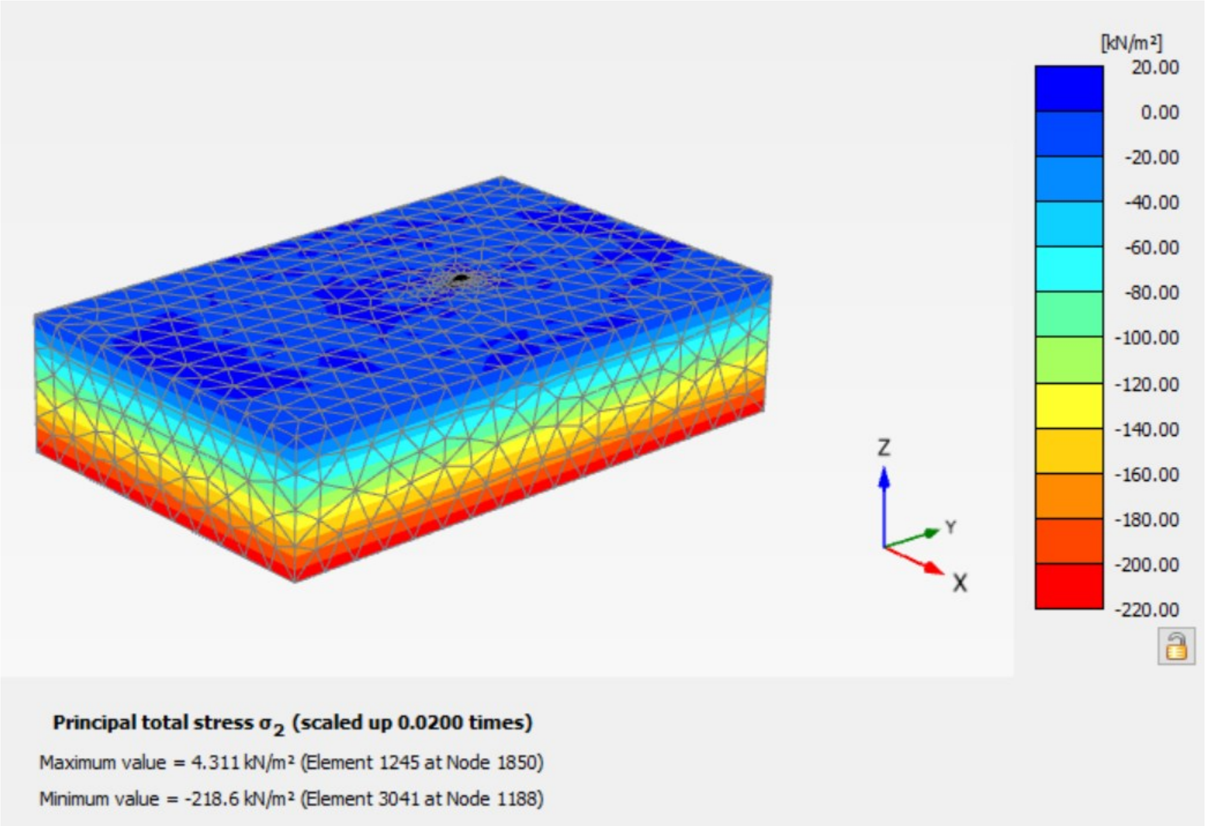


Principal total stress σ_1 (scaled up $5.00*10^{-3}$ times)

Maximum value = 3.183 kN/m^2 (Element 1245 at Node 1850)

Minimum value = -480.0 kN/m^2 (Element 3337 at Node 12)

Figure 4. 35 Principal total stresses (σ_1) at 20°

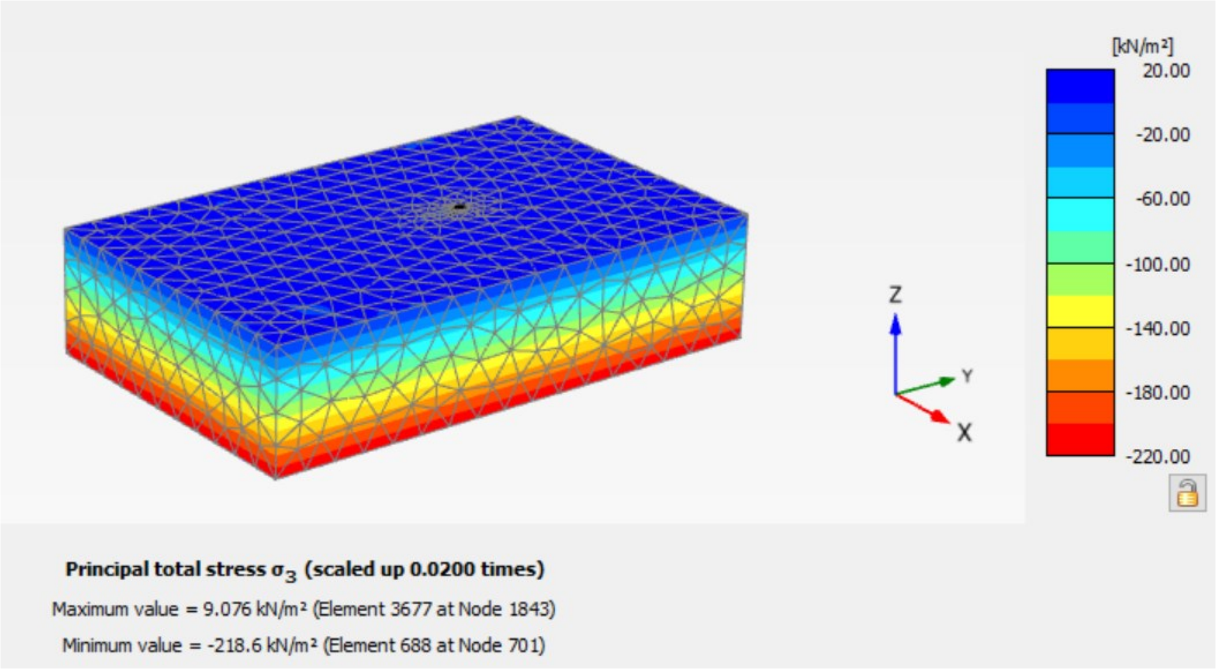


Principal total stress σ_2 (scaled up 0.0200 times)

Maximum value = 4.311 kN/m² (Element 1245 at Node 1850)

Minimum value = -218.6 kN/m² (Element 3041 at Node 1188)

Figure 4. 36 Principal total stresses (σ_2) at 20°

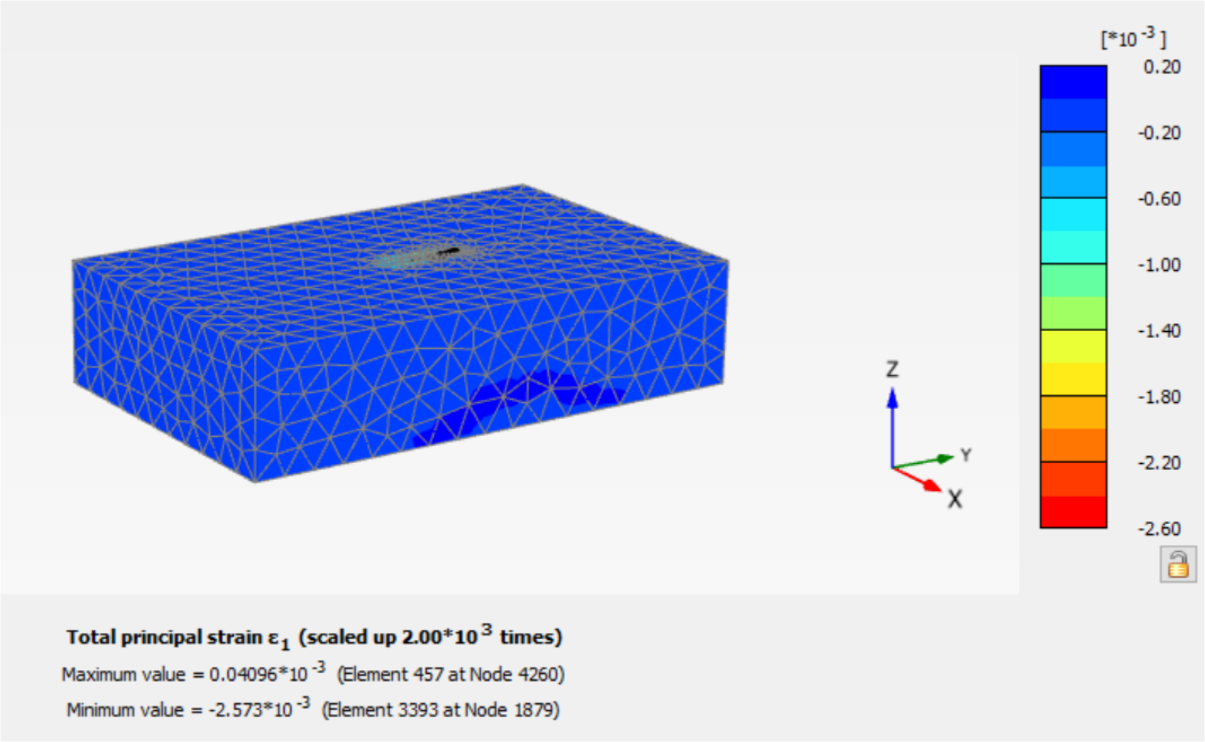


Principal total stress σ_3 (scaled up 0.0200 times)

Maximum value = 9.076 kN/m² (Element 3677 at Node 1843)

Minimum value = -218.6 kN/m² (Element 688 at Node 701)

Figure 4. 37 Principal total stresses (σ_3) at 20°

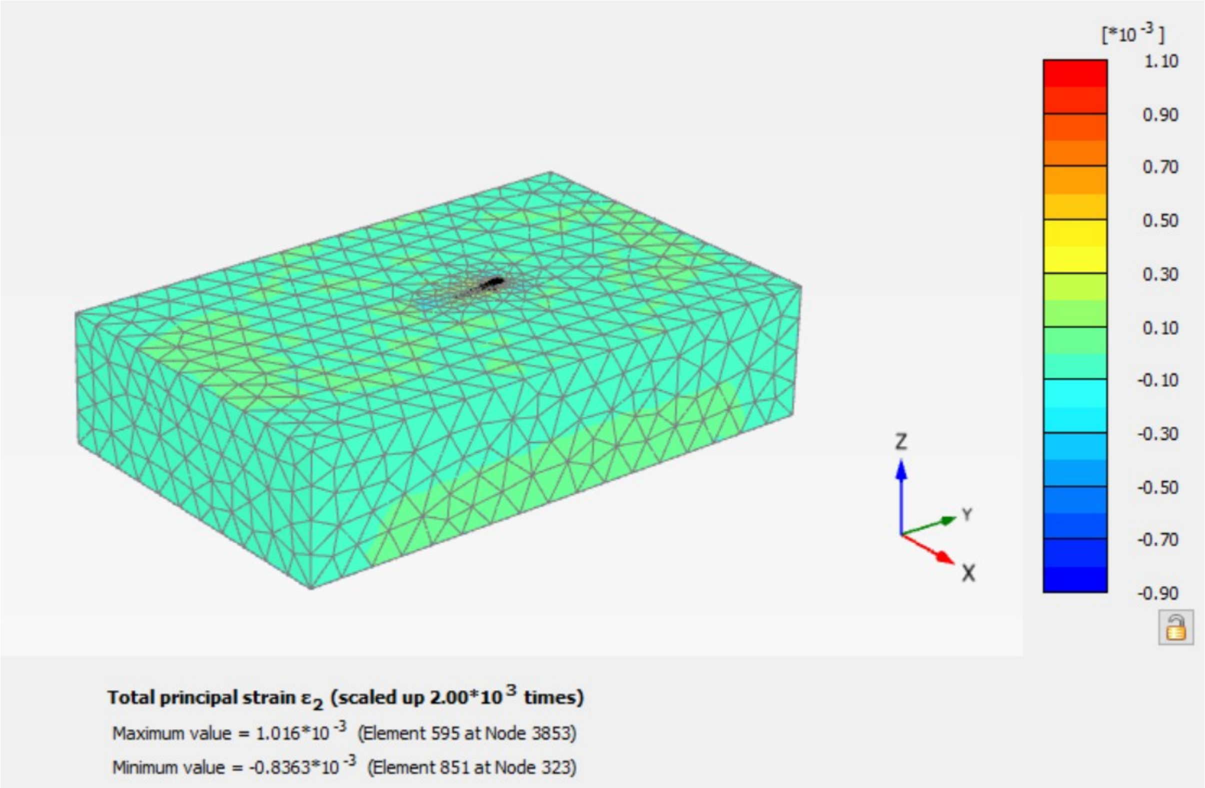


Total principal strain ε_1 (scaled up $2.00*10^3$ times)

Maximum value = $0.04096*10^{-3}$ (Element 457 at Node 4260)

Minimum value = $-2.573*10^{-3}$ (Element 3393 at Node 1879)

Figure 4. 38 Total principal strains (ε_1) at 20°

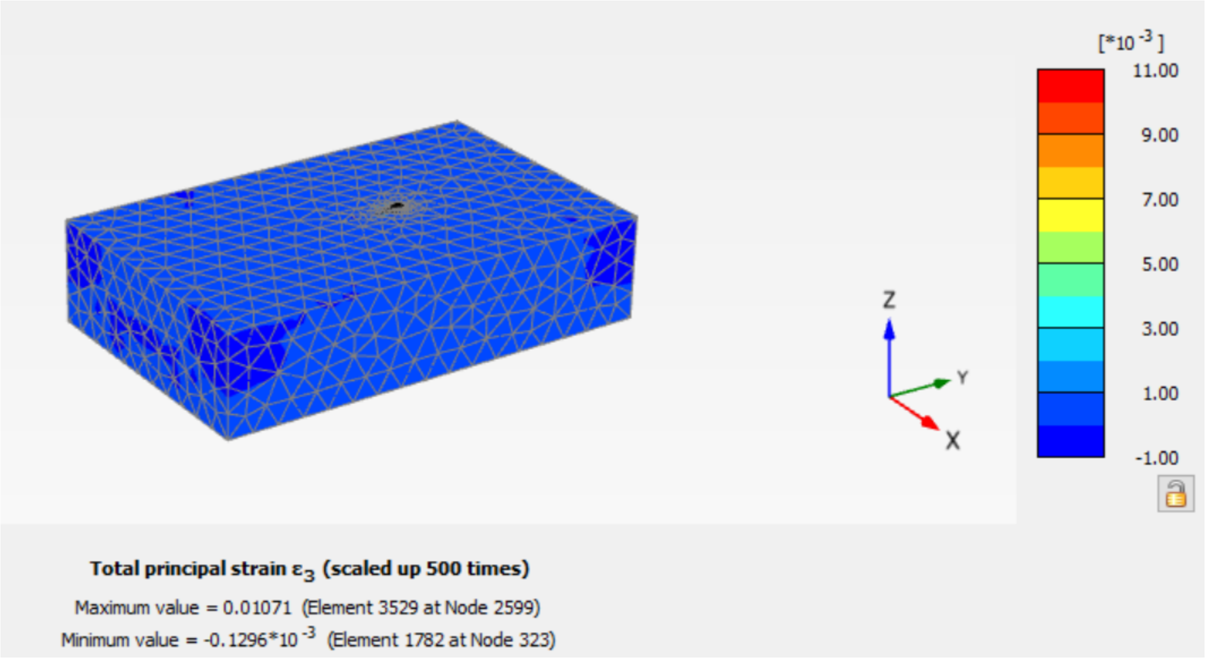


Total principal strain ε_2 (scaled up $2.00*10^3$ times)

Maximum value = $1.016*10^{-3}$ (Element 595 at Node 3853)

Minimum value = $-0.8363*10^{-3}$ (Element 851 at Node 323)

Figure 4. 39 Total principal strains (ε_2) at 20°



Total principal strain ε_3 (scaled up 500 times)

Maximum value = 0.01071 (Element 3529 at Node 2599)

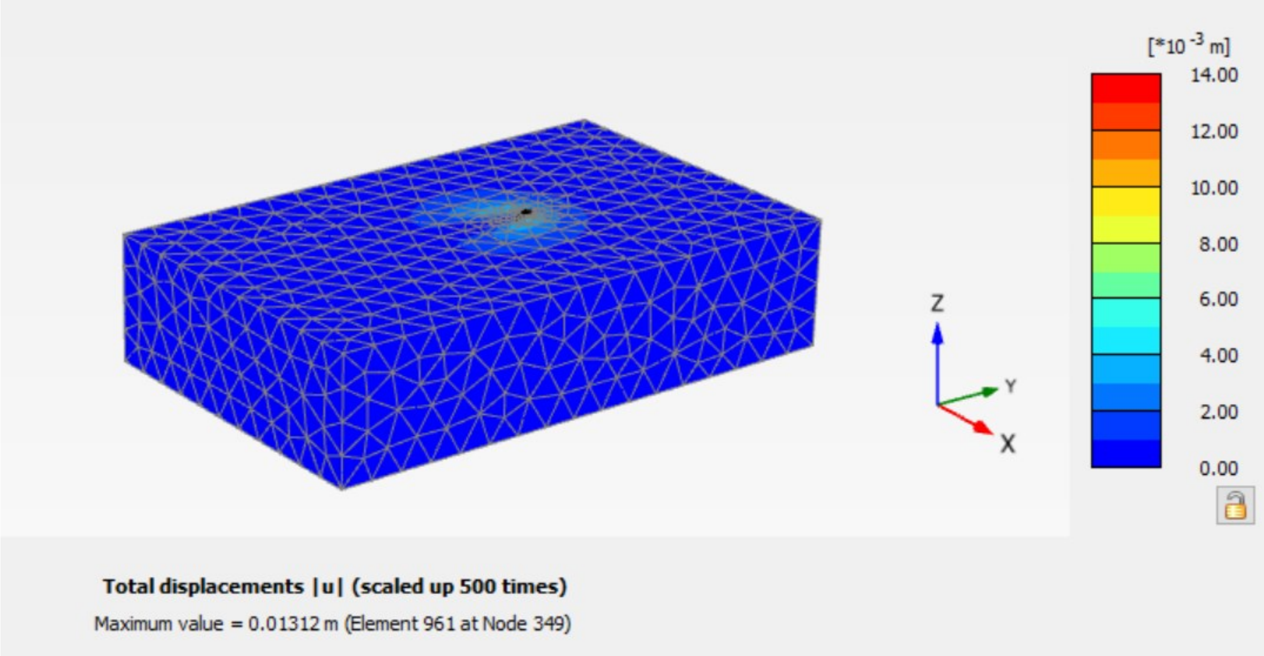
Minimum value = $-0.1296 * 10^{-3}$ (Element 1782 at Node 323)

Figure 4. 40 Total principal strains (ε_3) at 20°

The bottom end of the directional tunnel was placed at a depth of 7.3m from the ground level in Case 2 at a declination of 20°, for which the acquired results have been maximum displacement (u): 11.91×10^{-3}m, maximum principal total stresses: 3.183kN/m^2 (σ_1), 4.311kN/m^2 (σ_2), 9.076kN/m^2 (σ_3), and maximum total principal strains: 0.0409×10^{-3} (ε_1), 1.016×10^{-3} (ε_2), 10.71×10^{-3} (ε_3). An increment in the magnitude of all outputs has been observed in this orientation when compared with that of 10°. Hence, the analysis continued with a slightly higher declination of 30°.

Case 3 - Declination angle: 30°

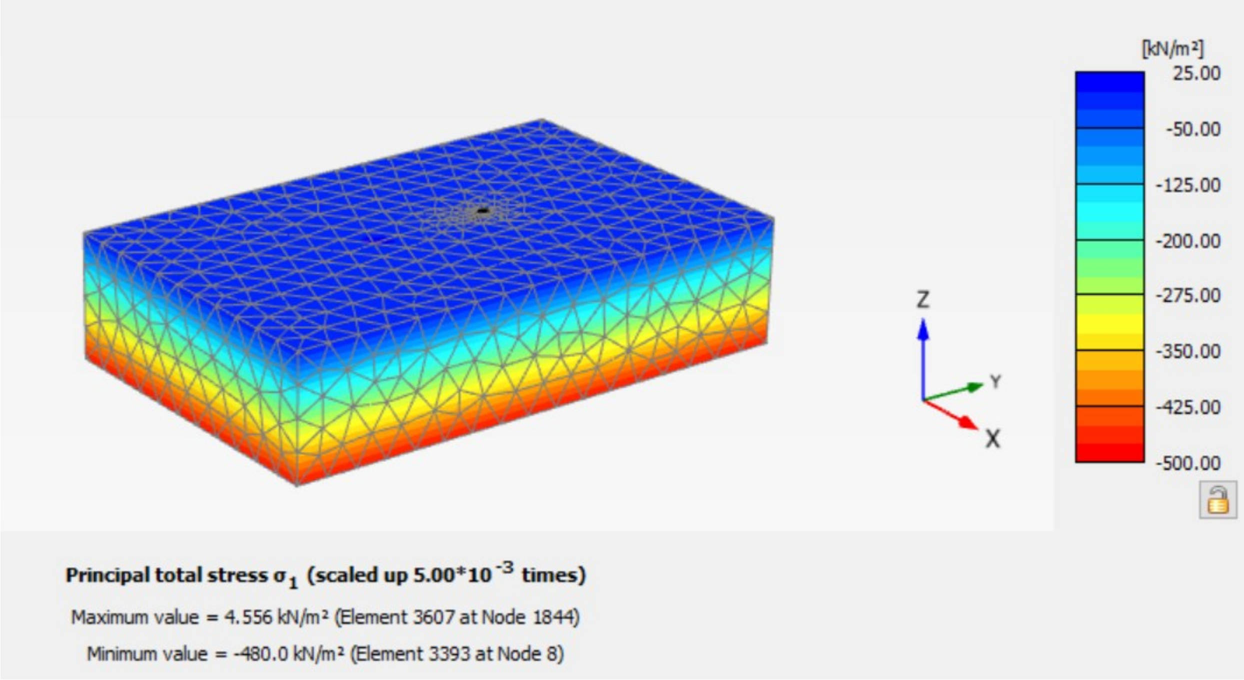
The directional tunnel's position set at 30° below the ground level has bottom end depth at 9.145m. The increase in depth helped to analyse and understand the behaviour. The outputs of total displacements, principal stresses and principal strains have been obtained and illustrated from Figure 4.41 to Figure 4.47.



Total displacements |u| (scaled up 500 times)

Maximum value = 0.01312 m (Element 961 at Node 349)

Figure 4. 41 Total displacements (u) at 30°

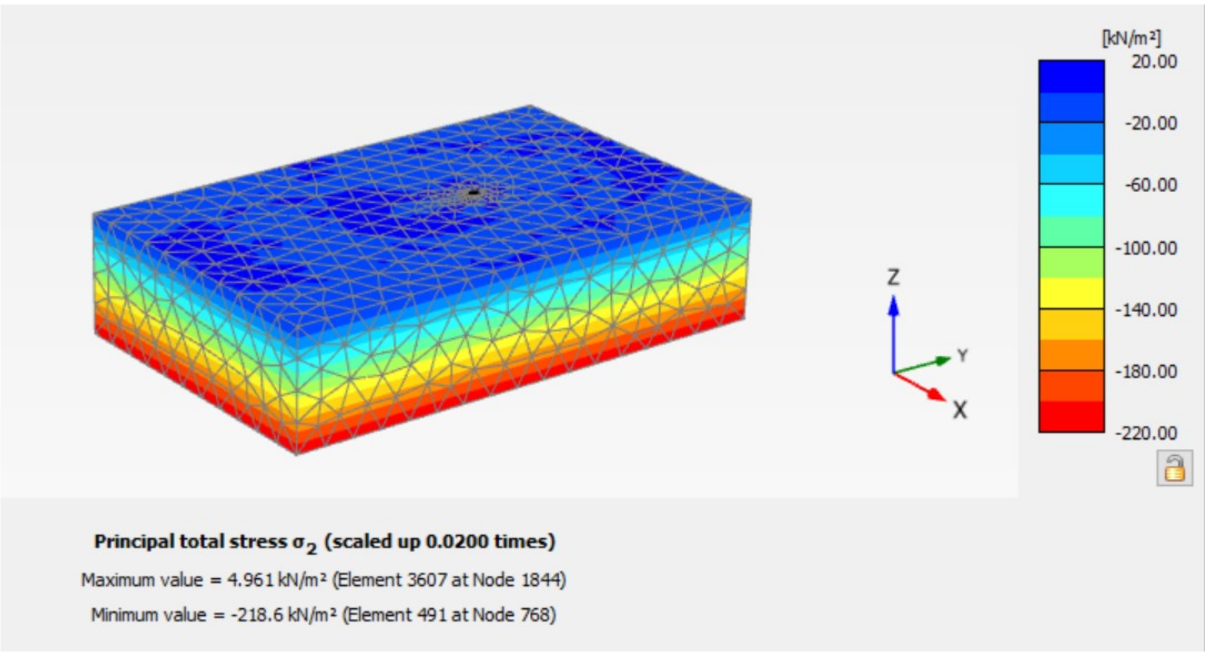


Principal total stress σ_1 (scaled up $5.00*10^{-3}$ times)

Maximum value = 4.556 kN/m² (Element 3607 at Node 1844)

Minimum value = -480.0 kN/m² (Element 3393 at Node 8)

Figure 4. 42 Principal total stresses (σ_1) at 30°

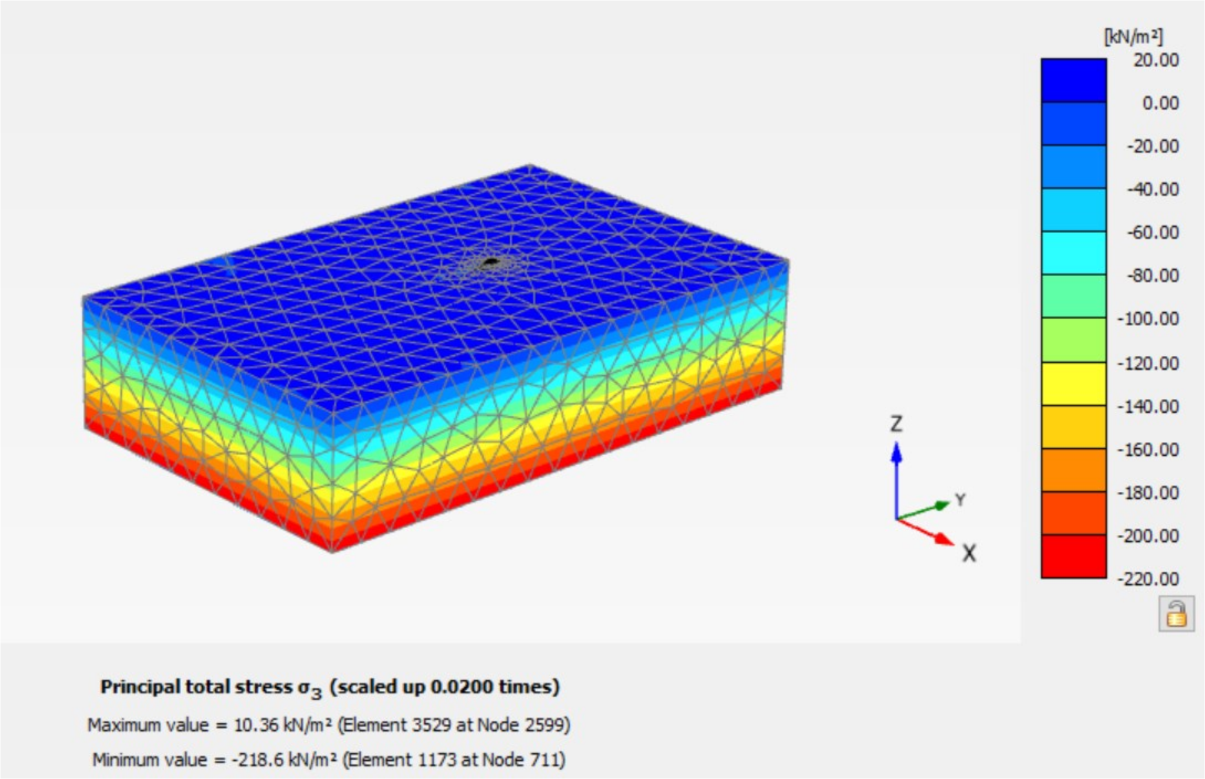


Principal total stress σ_2 (scaled up 0.0200 times)

Maximum value = 4.961 kN/m² (Element 3607 at Node 1844)

Minimum value = -218.6 kN/m² (Element 491 at Node 768)

Figure 4. 43 Principal total stresses (σ_2) at 30°

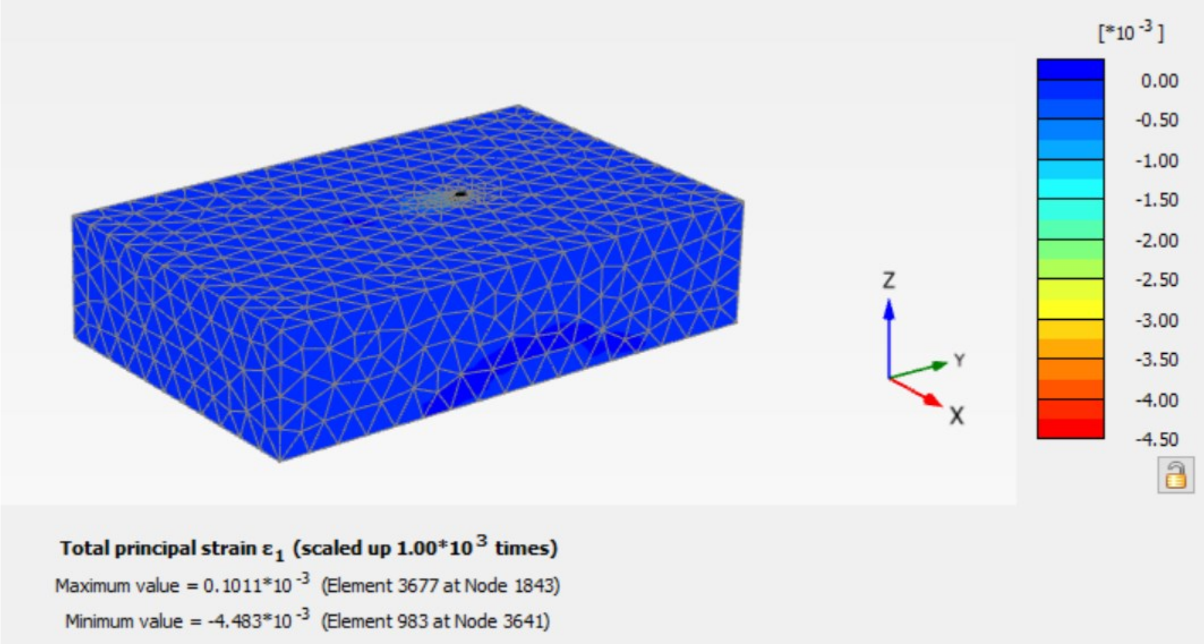


Principal total stress σ_3 (scaled up 0.0200 times)

Maximum value = 10.36 kN/m² (Element 3529 at Node 2599)

Minimum value = -218.6 kN/m² (Element 1173 at Node 711)

Figure 4. 44 Principal total stresses (σ_3) at 30°

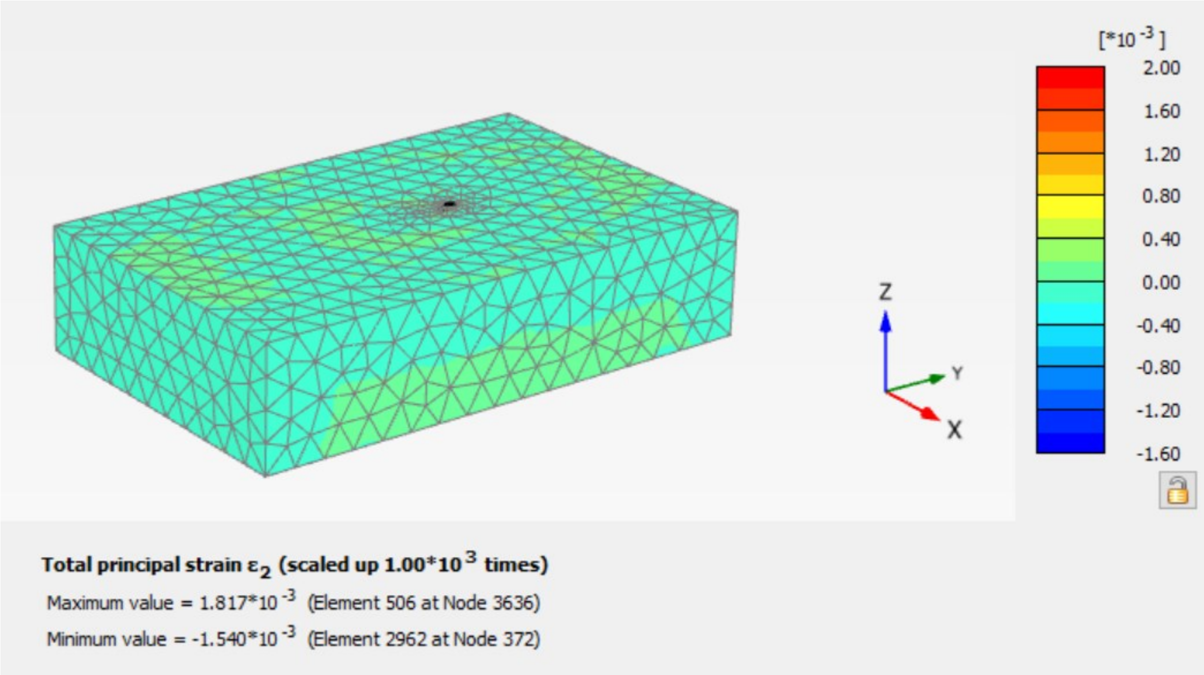


Total principal strain ε_1 (scaled up $1.00*10^3$ times)

Maximum value = $0.1011*10^{-3}$ (Element 3677 at Node 1843)

Minimum value = $-4.483*10^{-3}$ (Element 983 at Node 3641)

Figure 4. 45 Total principal strains (ε_1) at 30°

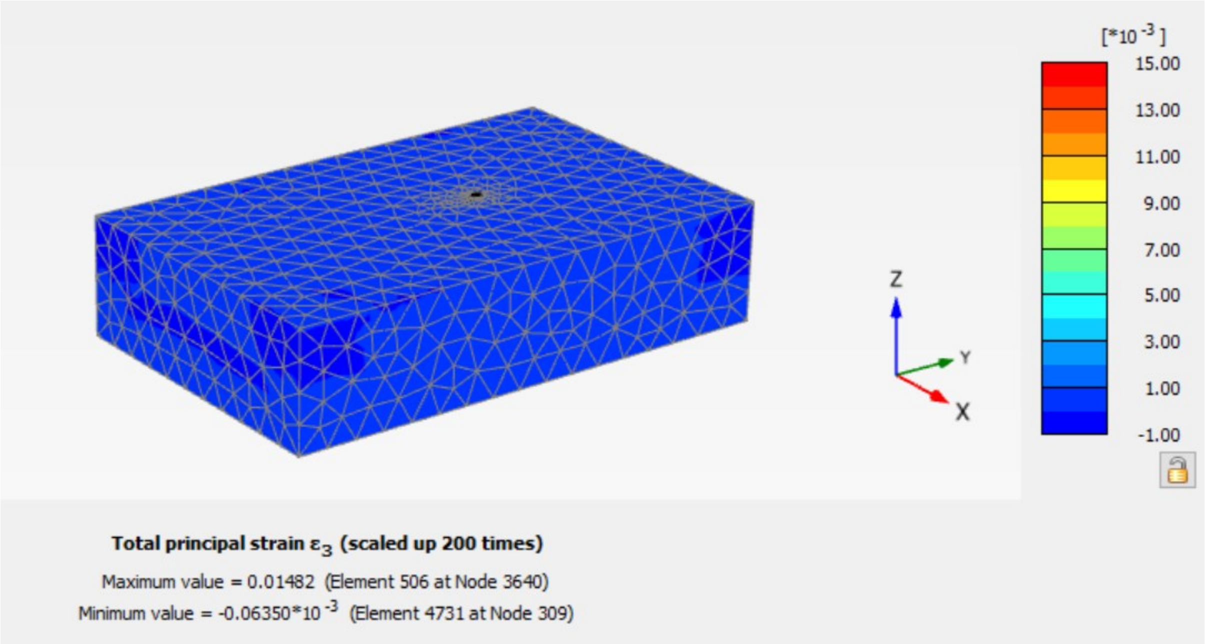


Total principal strain ε_2 (scaled up $1.00*10^3$ times)

Maximum value = $1.817*10^{-3}$ (Element 506 at Node 3636)

Minimum value = $-1.540*10^{-3}$ (Element 2962 at Node 372)

Figure 4. 46 Total principal strains (ε_2) at 30°



Total principal strain ε_3 (scaled up 200 times)

Maximum value = 0.01482 (Element 506 at Node 3640)

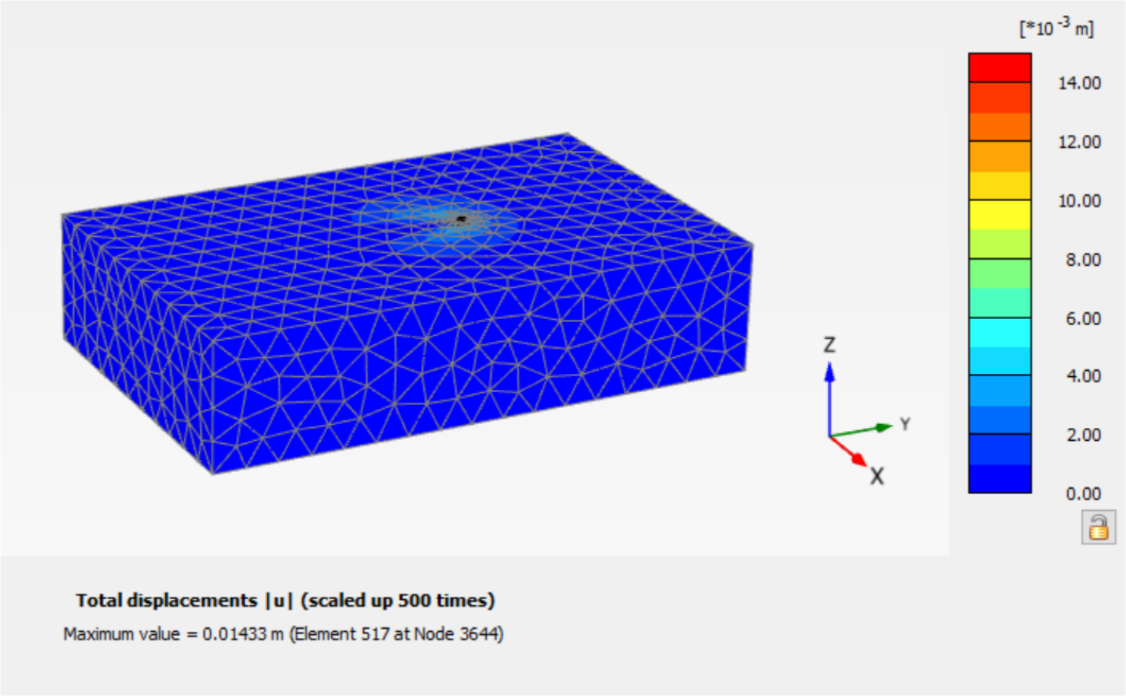
Minimum value = -0.06350*10^{-3} (Element 4731 at Node 309)

Figure 4. 47 Total principal strains (ε_3) at 30°

The obtained results in Case 3 at the position of 30° declination for the directional tunnel have been maximum displacement (u): 13.12x10^{-3}m, maximum principal total stresses: 4.556kN/m^2 (σ_1), 4.961kN/m^2 (σ_2), 10.36kN/m^2 (σ_3), and maximum total principal strains: 0.1011x10^{-3} (ε_1), 1.817x10^{-3} (ε_2), 14.82x10^{-3} (ε_3). Moreover, an increase in the magnitude of all the acquired parameters has been observed in case 3. The behaviour of the directional tunnel close to the soil model's angle of internal friction (33.3°) has been considered; hence 35° declination has been studied further.

Case 4 - Declination angle: 35°

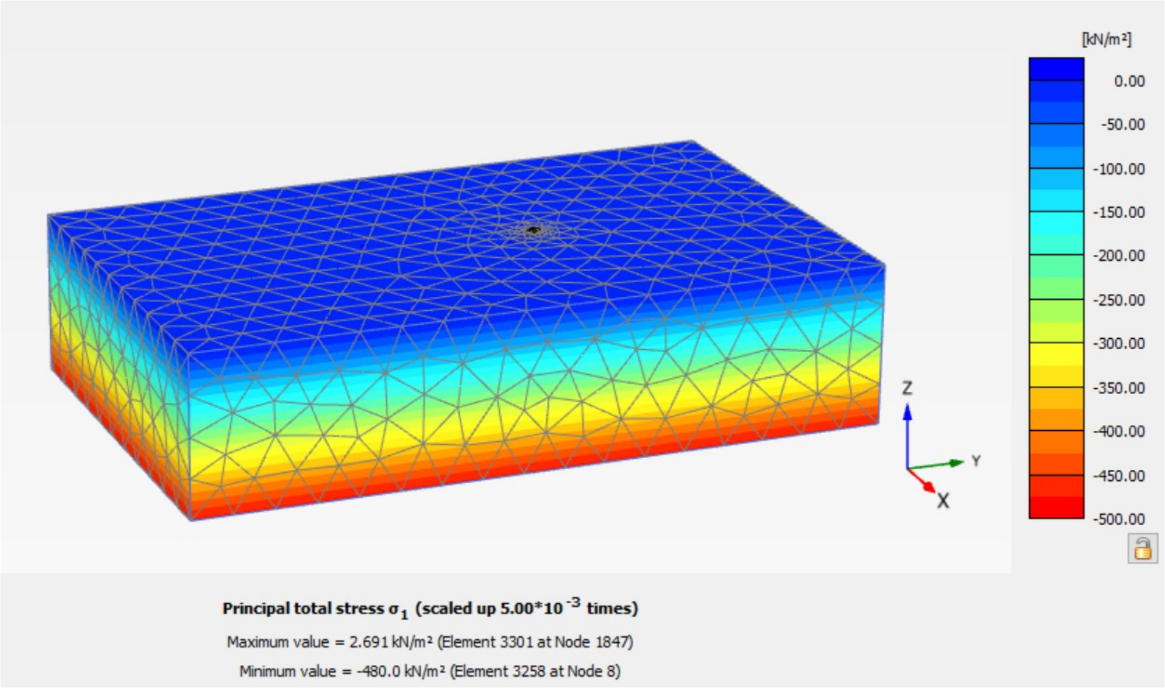
The directional tunnel's position at 35° below the ground level has bottom end depth at 10m. This condition has been analysed for understanding the stability in terms of deformations, stresses, and strains. The outputs of the conducted analysis have been depicted from Figure 4.48 to Figure 4.54.



Total displacements |u| (scaled up 500 times)

Maximum value = 0.01433 m (Element 517 at Node 3644)

Figure 4. 48 Total displacements (u) at 35°

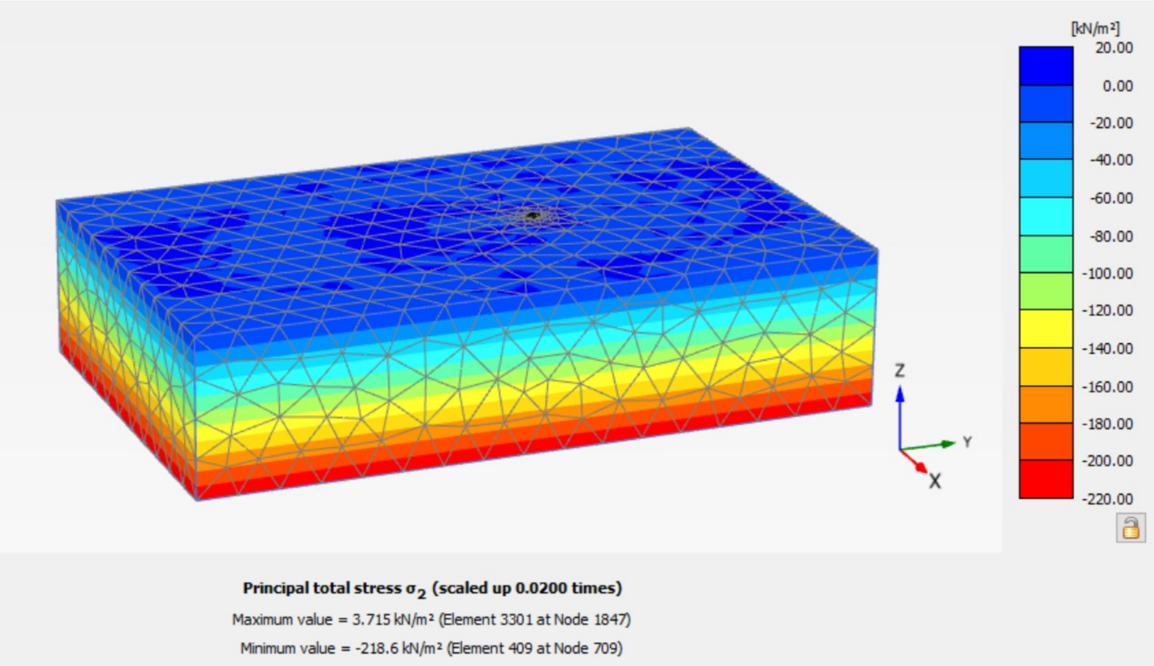


Principal total stress σ_1 (scaled up $5.00*10^{-3}$ times)

Maximum value = 2.691 kN/m² (Element 3301 at Node 1847)

Minimum value = -480.0 kN/m² (Element 3258 at Node 8)

Figure 4. 49 Principal total stresses (σ_1) at 35°

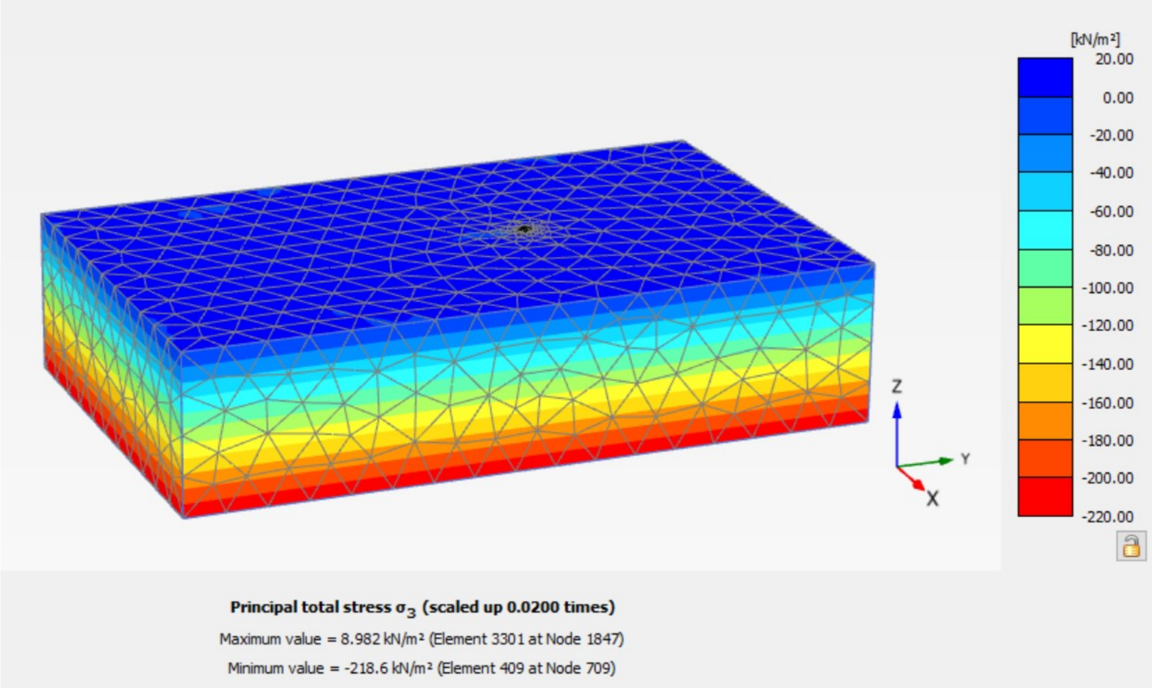


Principal total stress σ_2 (scaled up 0.0200 times)

Maximum value = 3.715 kN/m² (Element 3301 at Node 1847)

Minimum value = -218.6 kN/m² (Element 409 at Node 709)

Figure 4. 50 Principal total stresses (σ_2) at 35°

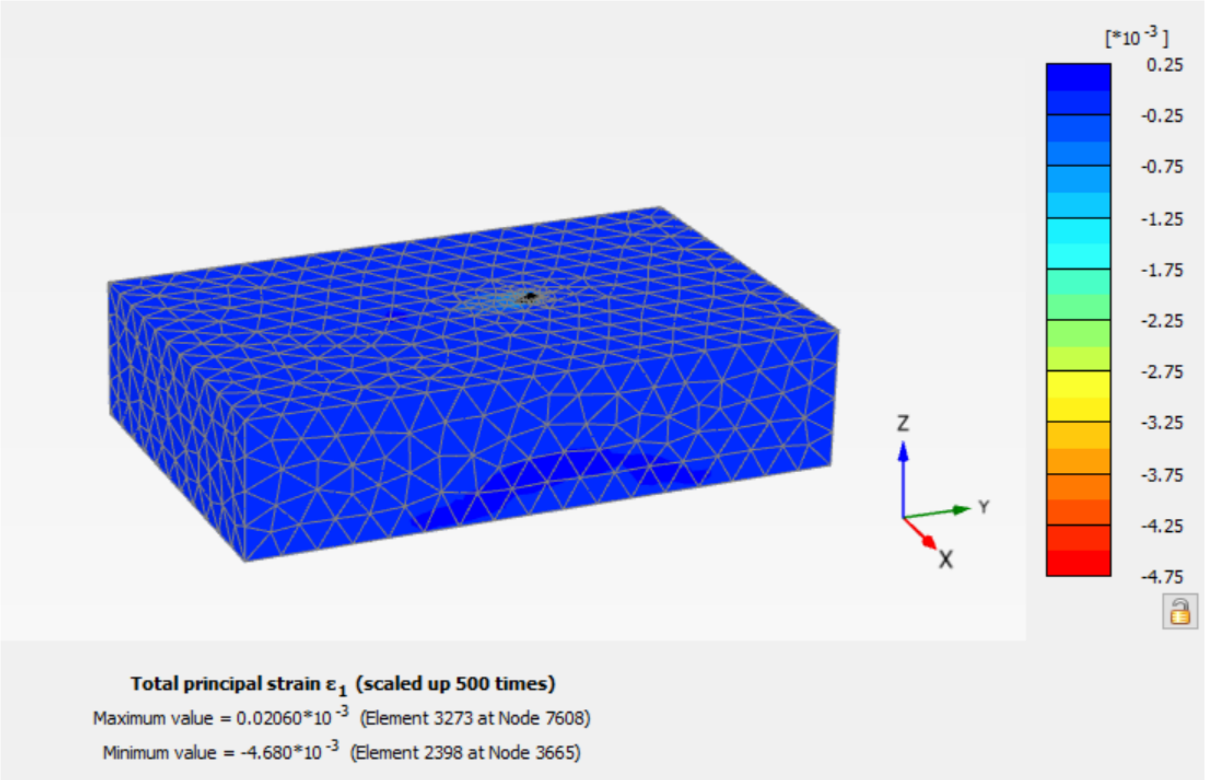


Principal total stress σ_3 (scaled up 0.0200 times)

Maximum value = 8.982 kN/m² (Element 3301 at Node 1847)

Minimum value = -218.6 kN/m² (Element 409 at Node 709)

Figure 4. 51 Principal total stresses (σ_3) at 35°

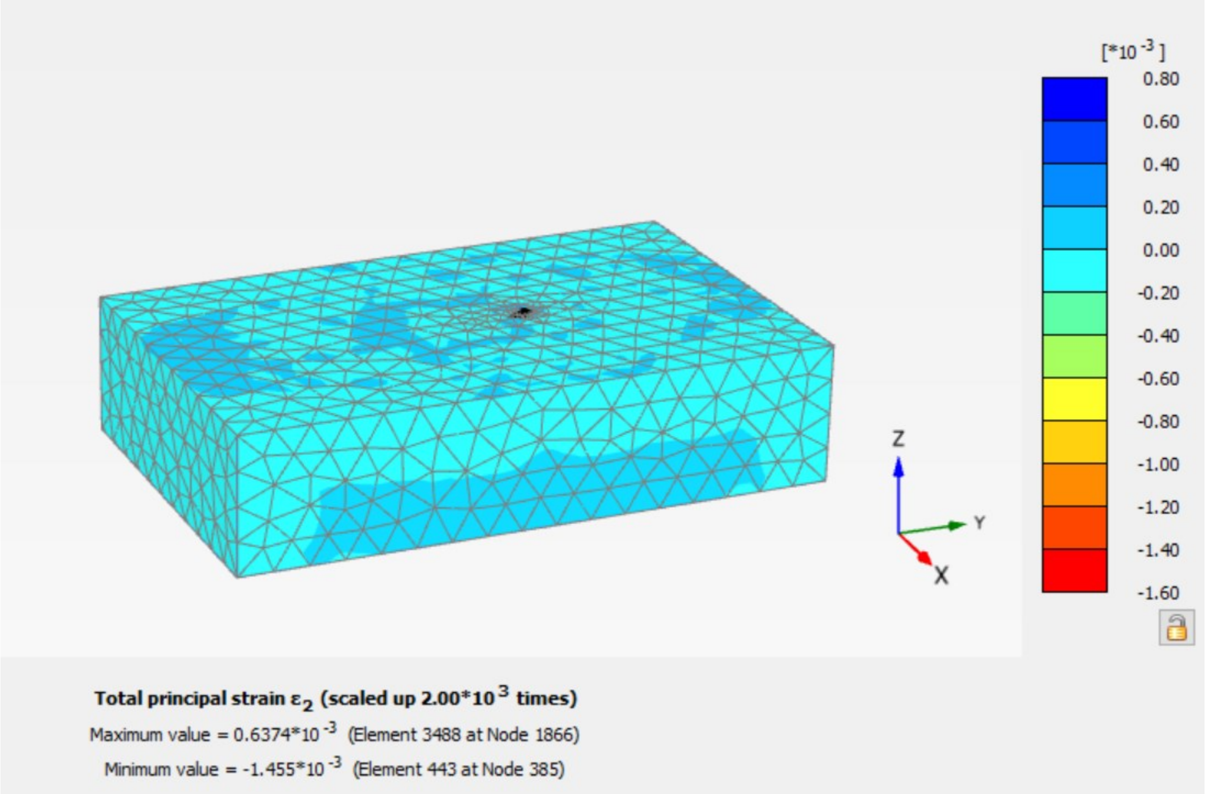


Total principal strain ε_1 (scaled up 500 times)

Maximum value = $0.02060*10^{-3}$ (Element 3273 at Node 7608)

Minimum value = $-4.680*10^{-3}$ (Element 2398 at Node 3665)

Figure 4. 52 Total principal strains (ε_1) at 35°

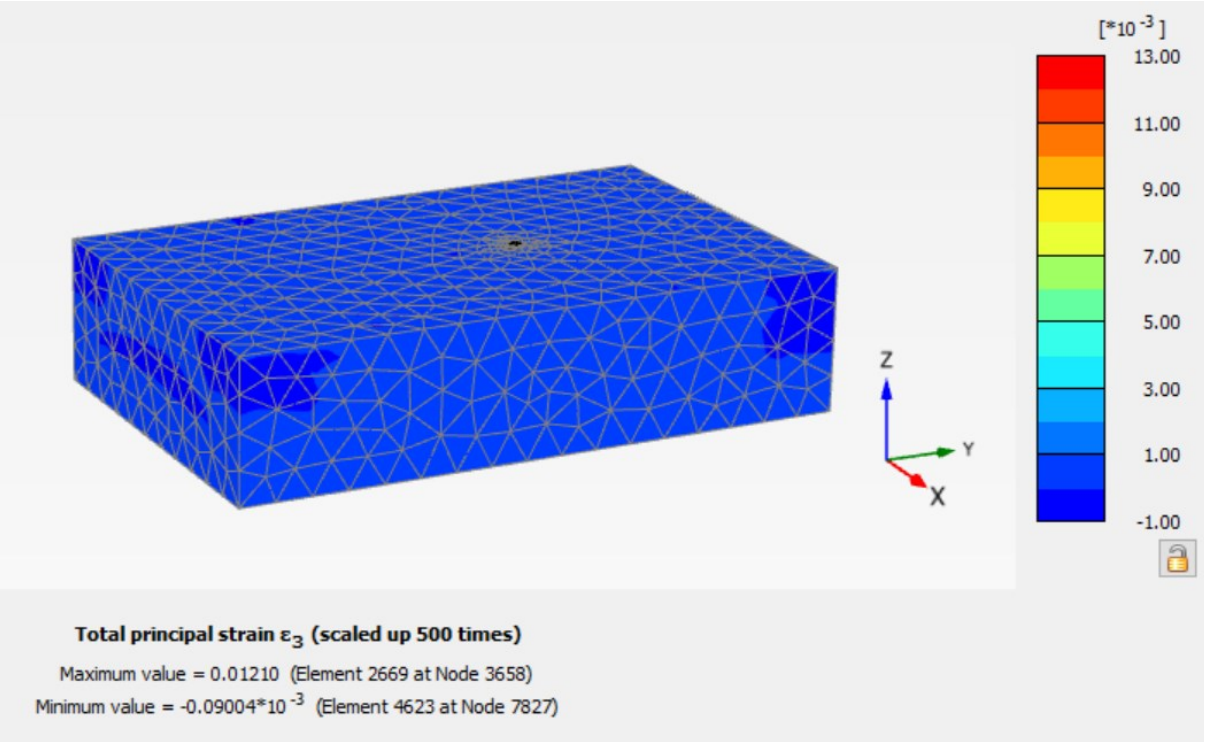


Total principal strain ε_2 (scaled up $2.00*10^{3}$ times)

Maximum value = $0.6374*10^{-3}$ (Element 3488 at Node 1866)

Minimum value = $-1.455*10^{-3}$ (Element 443 at Node 385)

Figure 4. 53 Total principal strains (ε_2) at 35°



Total principal strain ε_3 (scaled up 500 times)

Maximum value = 0.01210 (Element 2669 at Node 3658)

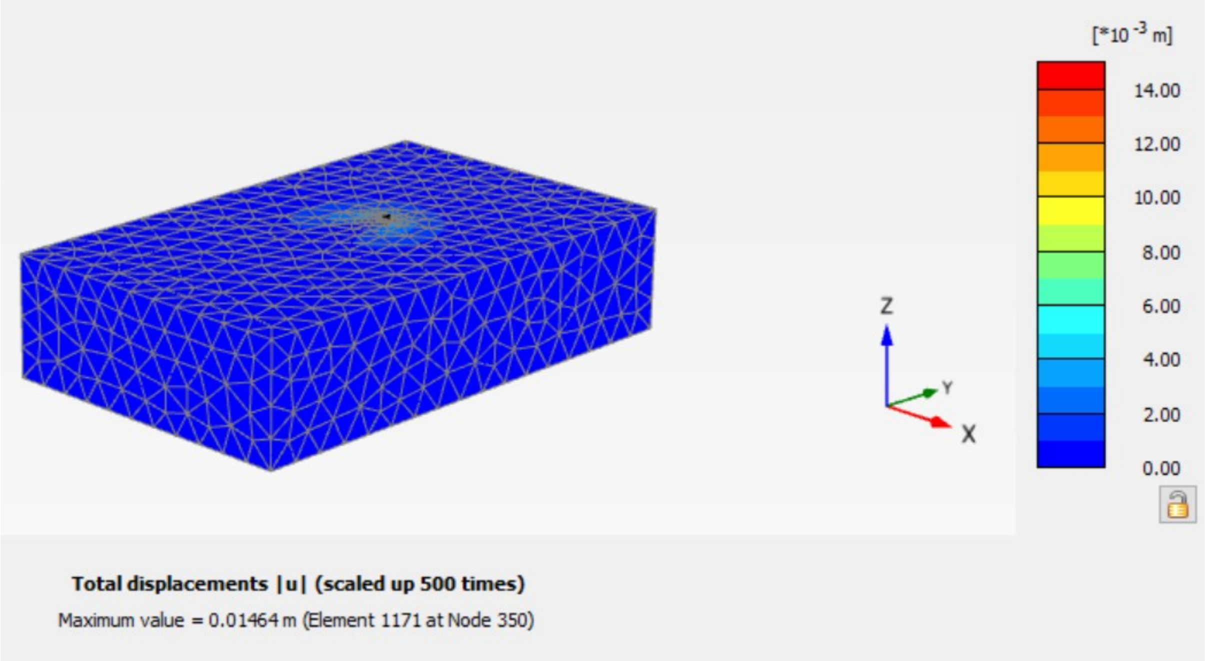
Minimum value = -0.09004*10^{-3} (Element 4623 at Node 7827)

Figure 4. 54 Total principal strains (ε_3) at 35°

The analysis of directional tunnel's 35° declination exhibits maximum displacement (u): 14.33x10^{-3}m, maximum principal total stresses: 2.691kN/m^2 (σ_1), 3.715kN/m^2 (σ_2), 8.982kN/m^2 (σ_3), and maximum total principal strains: 0.0206x10^{-3} (ε_1), 0.6374x10^{-3} (ε_2), 12.10x10^{-3} (ε_3). The magnitude of displacement has increased, simultaneously other outputs of principal stresses and principal strains have seen a decrement in this case. This factor indicates state of critical nature for the directional tunnel at 35° orientation in the soil model when compared with the other cases. Moreover, the analysis has been performed with a higher declination of 40° so that the behaviour is completely perceived.

Case 5 - Declination angle: 40°

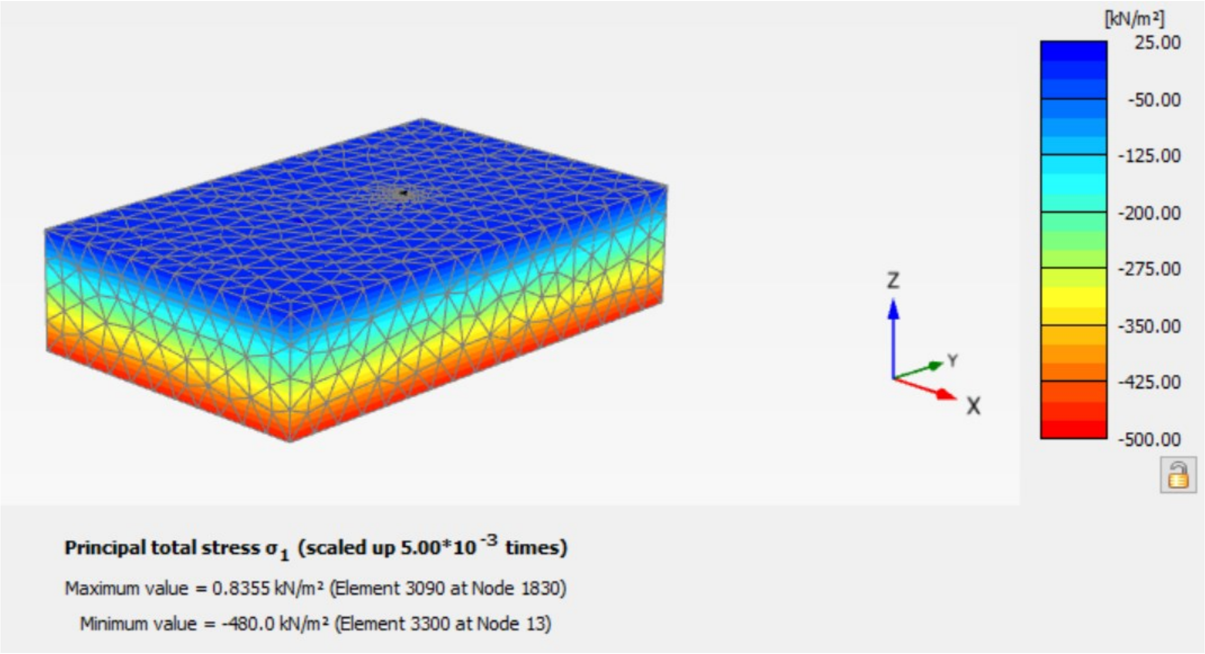
The outputs of the conducted analysis for directional tunnel's position at 40° below the ground level has been portrayed from Figure 4.55 to Figure 4.61.



Total displacements |u| (scaled up 500 times)

Maximum value = 0.01464 m (Element 1171 at Node 350)

Figure 4. 55 Total displacements (u) at 40°

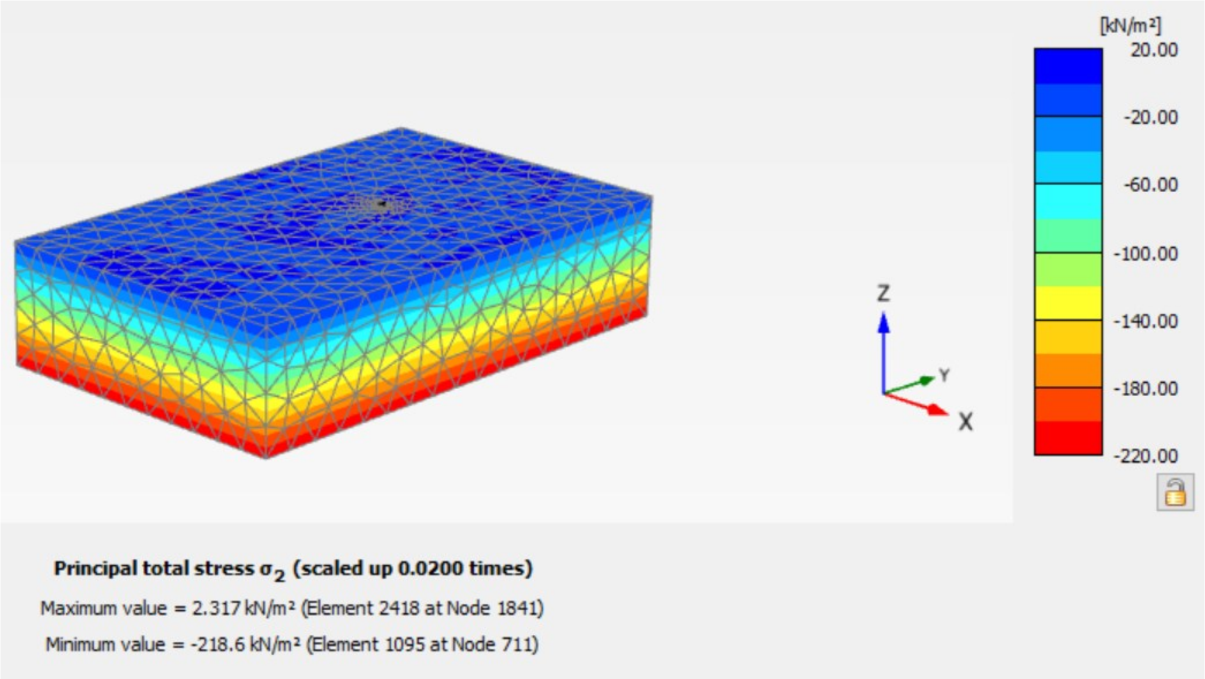


Principal total stress σ_1 (scaled up $5.00*10^{-3}$ times)

Maximum value = 0.8355 kN/m² (Element 3090 at Node 1830)

Minimum value = -480.0 kN/m² (Element 3300 at Node 13)

Figure 4. 56 Principal total stresses (σ_1) at 40°

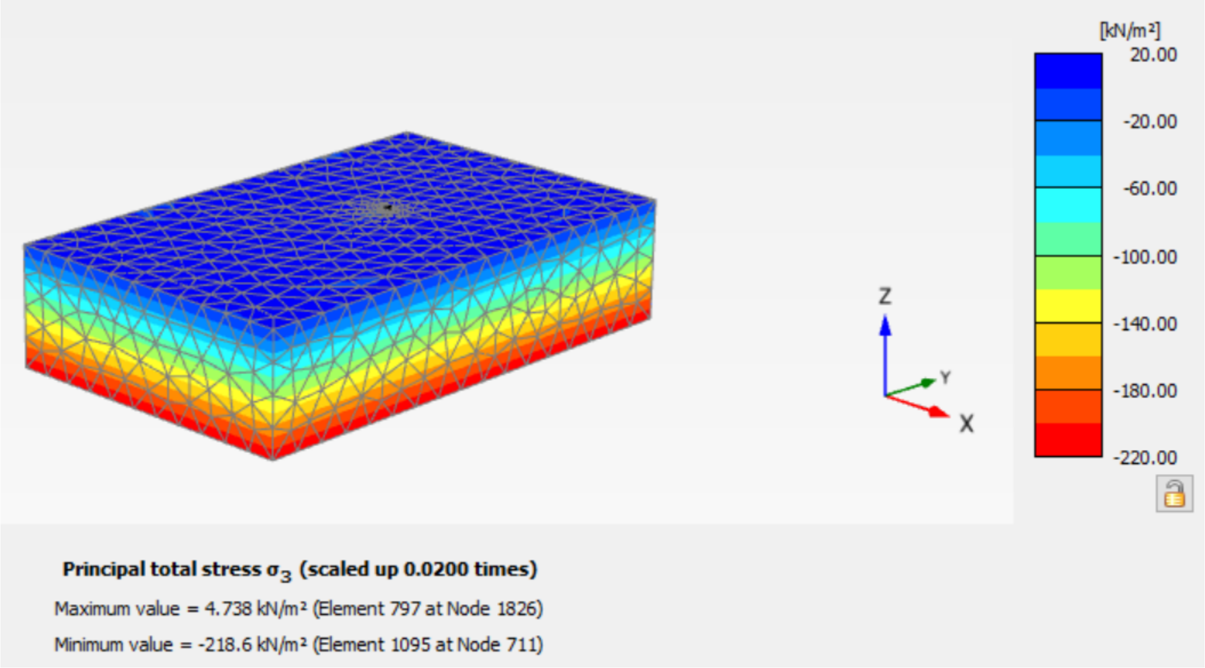


Principal total stress σ_2 (scaled up 0.0200 times)

Maximum value = 2.317 kN/m² (Element 2418 at Node 1841)

Minimum value = -218.6 kN/m² (Element 1095 at Node 711)

Figure 4. 57 Principal total stresses (σ_2) at 40°

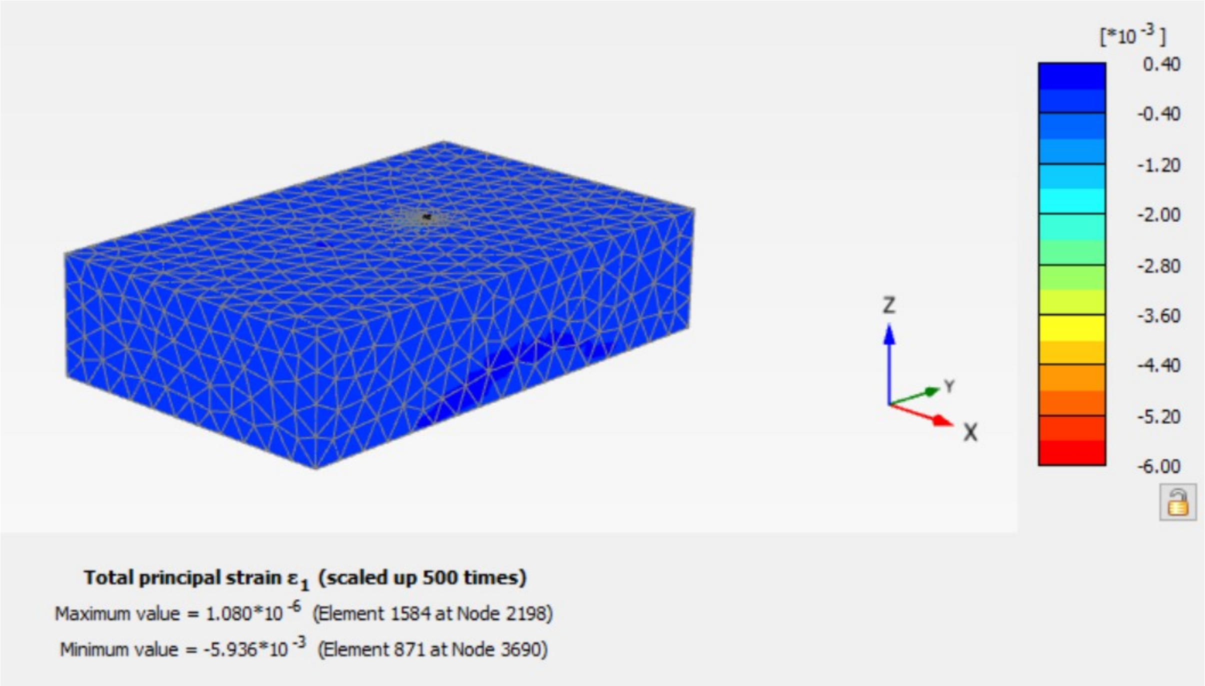


Principal total stress σ_3 (scaled up 0.0200 times)

Maximum value = 4.738 kN/m² (Element 797 at Node 1826)

Minimum value = -218.6 kN/m² (Element 1095 at Node 711)

Figure 4. 58 Principal total stresses (σ_3) at 40°

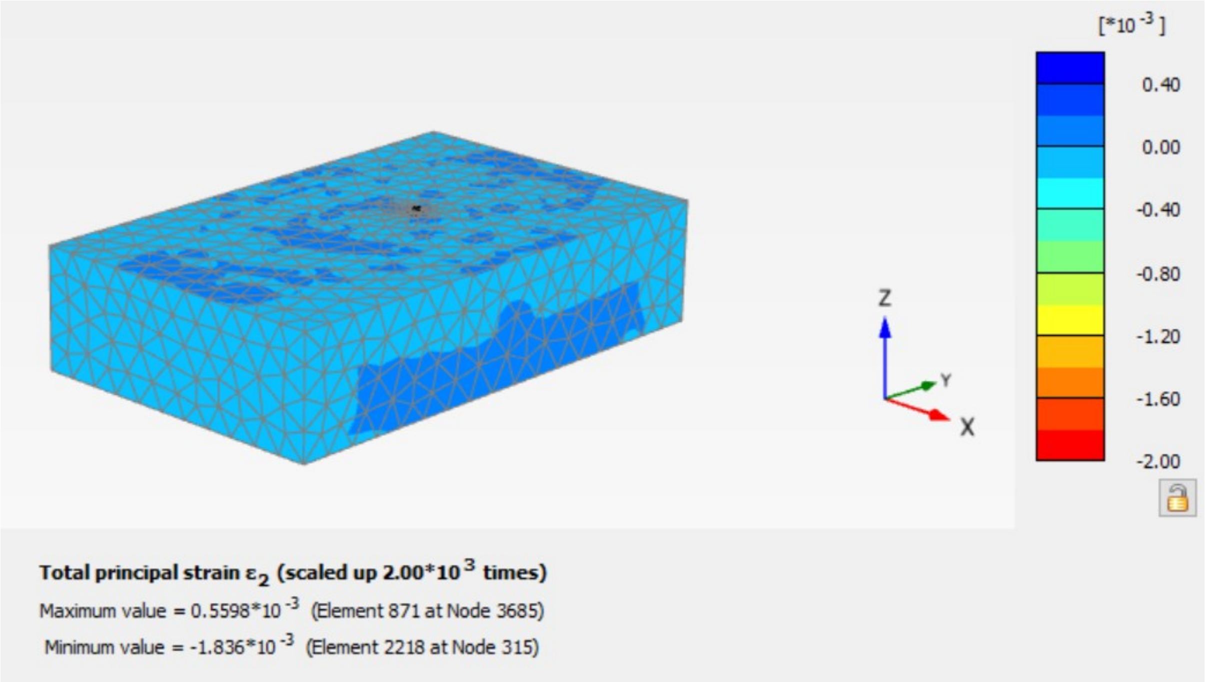


Total principal strain ε_1 (scaled up 500 times)

Maximum value = $1.080*10^{-6}$ (Element 1584 at Node 2198)

Minimum value = $-5.936*10^{-3}$ (Element 871 at Node 3690)

Figure 4. 59 Total principal strains (ε_1) at 40°

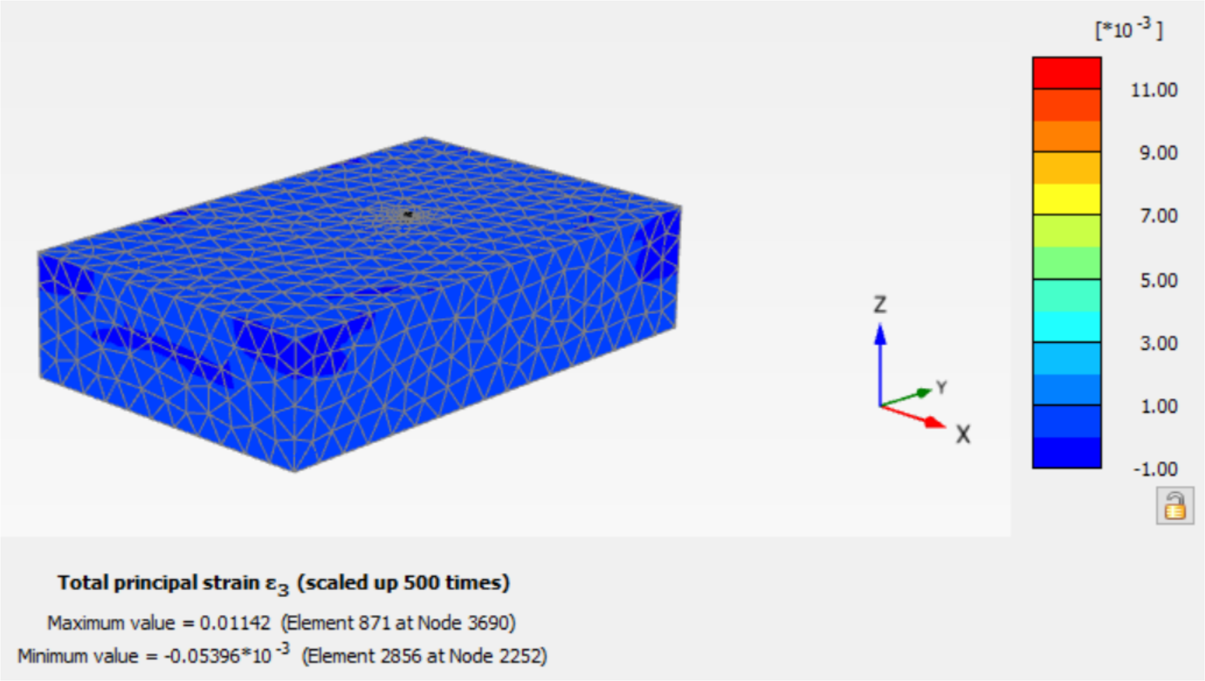


Total principal strain ε_2 (scaled up $2.00*10^3$ times)

Maximum value = $0.5598*10^{-3}$ (Element 871 at Node 3685)

Minimum value = $-1.836*10^{-3}$ (Element 2218 at Node 315)

Figure 4. 60 Total principal strains (ε_2) at 40°



Total principal strain ε_3 (scaled up 500 times)

Maximum value = 0.01142 (Element 871 at Node 3690)

Minimum value = -0.05396*10 $^{-3}$ (Element 2856 at Node 2252)

Figure 4. 61 Total principal strains (ε_3) at 40°

The directional tunnel at 40° declination has bottom edge depth at 10.95m from ground level, produced maximum displacement (u): 14.64x10^{-3}m, maximum principal total stresses: 0.8355kN/m^2 (σ_1), 2.317kN/m^2 (σ_2), 4.738kN/m^2 (σ_3), and maximum total principal strains: 0.00108x10^{-3} (ε_1), 0.5598x10^{-3} (ε_2), 11.42x10^{-3} (ε_3). Further decrement in the magnitude of principal stresses and strains has been observed which indicates failure of the soil model. Hence, the directional tunnel's result as per case 5 has been a failure. The simulated results of all five declinations have been consolidated in Table 4.10.

Table 4. 10 Simulated results for five declinations of the directional tunnel

S. No	**Angle of Declination (°)**	**Total Displacement (u) (x10^{-3} m)**	**Principal stresses (kN/m^2) (max)**			**Principal strains (x10^{-3}) (max)**		
			σ_1	σ_2	σ_3	ε_1	ε_2	ε_3
1.	10	11.04	1.570	2.820	4.984	0.0278	0.712	6.062
2.	20	11.91	3.183	4.311	9.076	0.0409	1.016	10.71
3.	30	13.12	4.556	4.961	10.36	0.1011	1.817	14.82
4.	35	14.33	2.691	3.715	8.982	0.0206	0.6374	12.10
5.	40	14.64	0.835	2.317	4.738	0.00108	0.5598	11.42

The directional tunnel at each declination has generated principal stresses in the complete model. σ_1 and σ_3 in every orientation have been considered for plotting the corresponding Mohr's circles. Initially the radius and centre of the circles have been determined, as portrayed in Table 4.11. This analysis has been compared with the failure envelope of the soil sample as per the discussions of Figure 4.24 and illustrated in Figure 4.62.

Table 4. 11 Determination of radius and centre for Mohr's circle analysis

S. No	Angle of declination (°)	Principal stresses (kN/m^2)		Radius ($\frac{\sigma_3 - \sigma_1}{2}$)	Centre ($\frac{\sigma_3 + \sigma_1}{2}$)
		σ_1	σ_3		
1.	10	1.570	4.984	1.707	3.277
2.	20	3.183	9.076	2.9465	6.1295
3.	30	4.556	10.36	2.902	7.458
4.	35	2.691	8.982	3.1455	5.8365
5.	40	0.835	4.738	1.9515	2.7865

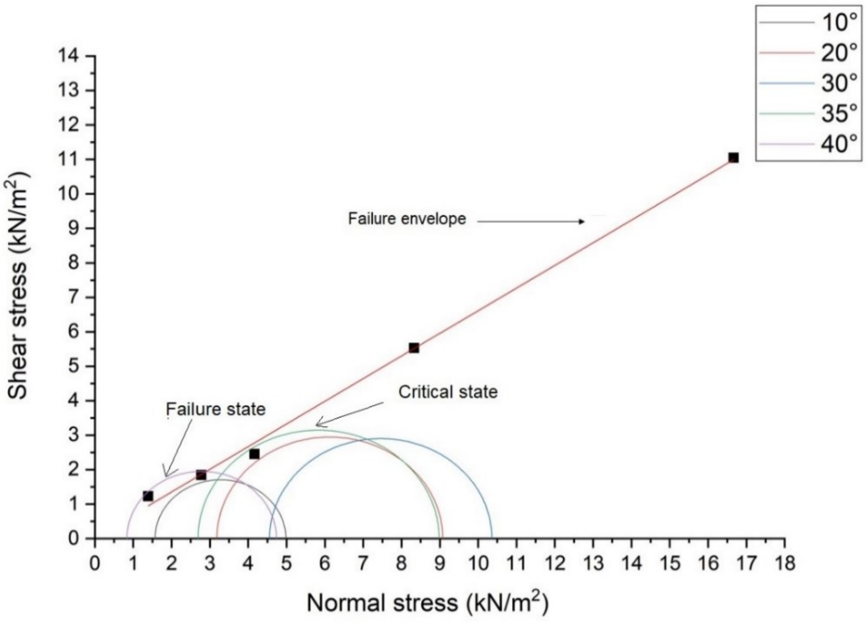


Figure 4. 62 Mohr's circle analysis at each declination and comparison with failure envelope

The depicted Mohr's circle analysis for principal stresses at 10° and 20° have been safe and lower compared with other cases. However, directional tunnel at these two declinations occupies more land surface area which could obstruct agriculture area and plant roots in the surrounding location at rural places. Moreover, at 30° declination the structure was found safe in comparison with the failure envelope and soil's internal angle of friction of 33.3°. However, the directional tunnel at 35° has the representation very close to failure envelope which turns into critical state and at 40° orientation the failure state has been detected.

4.4.2 Failure analysis of the directional tunnel

Failure analysis has been considered for three declinations of the directional tunnel, i.e., 30°, 35°, and 40° by the Mohr-Coulomb failure criterion. The positions of 10° and 20° have been not considered since the main objective of less land occupancy by the directional tunnel does not satisfy in these both cases. The performed analysis helps in observing the failure points along the ground surface and the walls of the directional tunnel. The conducted simulations in PLAXIS 3D for the declinations of 30°, 35°, and 40° have been represented from Figure 4.63 to Figure 4.65.

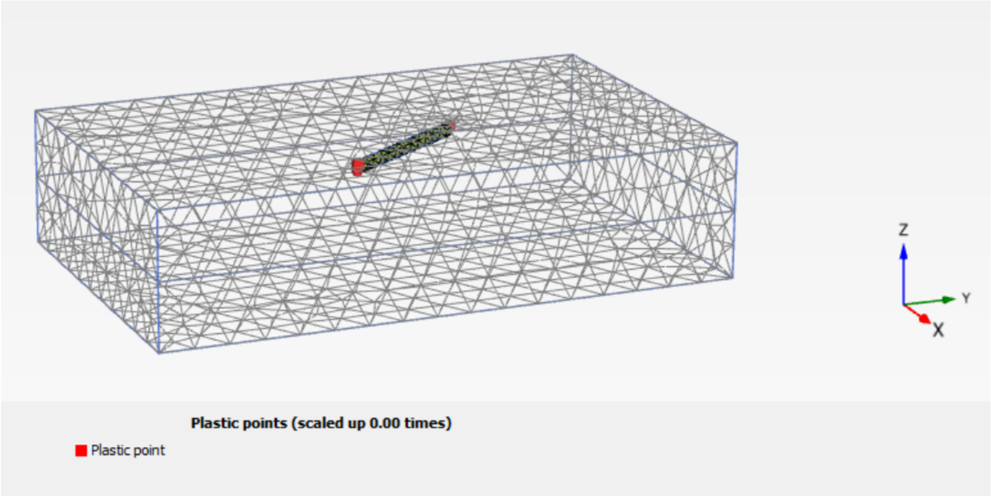


Figure 4. 63 Simulation of failure analysis in directional tunnel at 30° declination

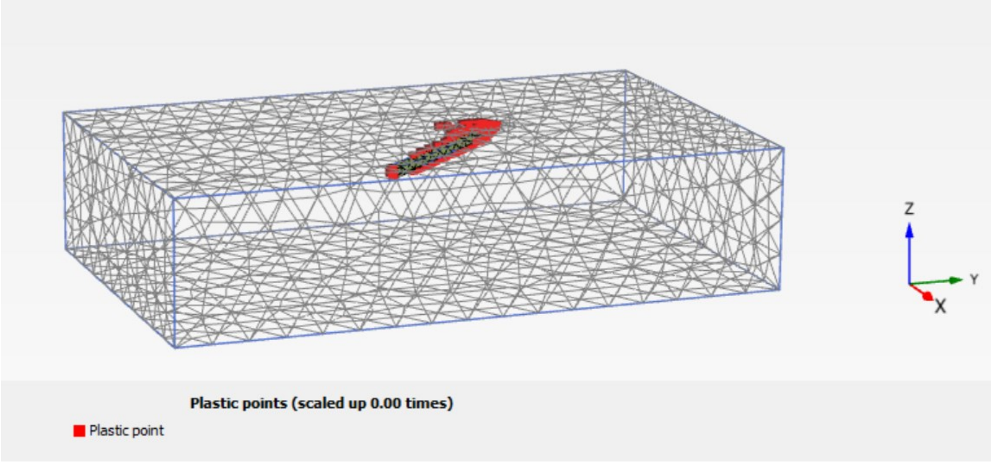


Figure 4. 64 Simulation of failure analysis in directional tunnel at 35° declination

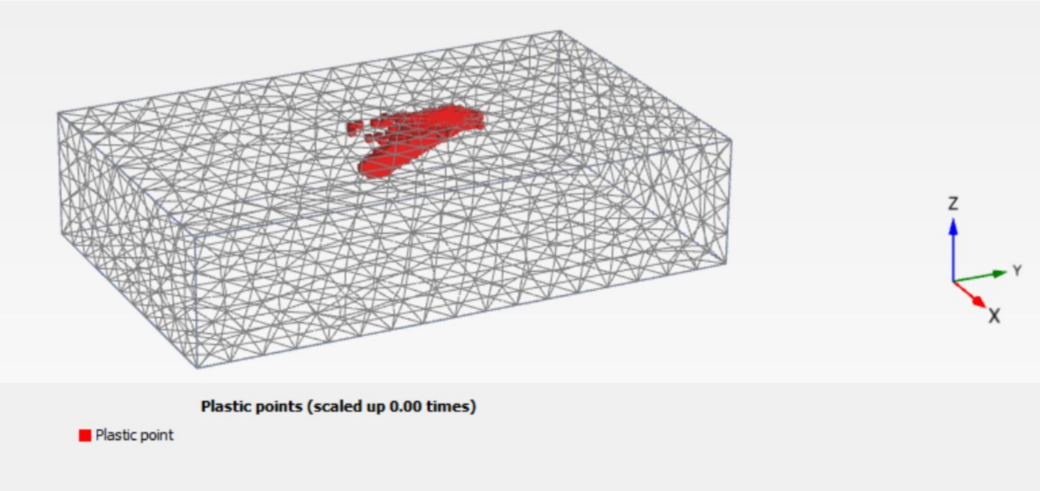


Figure 4. 65 Simulation of failure analysis in directional tunnel at 40° declination

Depending on the analysed three failure modes, the directional tunnel has been safe at 30° with minimal plastic points, which could be observed at the structure's bottom and top end portions. The situation of 35° declination has been found critical and failure could occur at any unforeseen circumstance. The 40° orientation has complete failure along with the soil model leading to failure in the directional tunnel. Hence, the 30° declination has been safe and recommended through failure analysis simulation also, which manages with the identified angle of repose (31°) and angle of internal friction (33.3°) for the selected sandy soil medium as well as avoids possible sliding. Eventually, from the two conclusions of stability and failure analysis performed in PLAXIS 3D, this thesis recommends that the directional tunnel at a declined angle range of 30° - 34° is suitable for practical implementation in sandy soils.

4.5 Summary of the chapter

This chapter disclosed an innovative RWH system through directional tunnel method, and it has been discussed at length. The advantages of this method have been highlighted. Different materials such as jute fibre and GRP for fabricating directional tunnel have been considered. Jute fibre models with different fibre thicknesses and GRP material with two cases, such as two-layered and three-layered panels for directional tunnel have been manufactured for determining the most feasible one for execution. Multiple declinations, such as 10°, 20°, 30°, 35° and 40° of the directional tunnel have been analysed for determining its stability in sandy soil conditions. The declined position of 30° - 34° for the directional tunnel’s installation has been suggested through the stability and failure analysis simulations conducted in PLAXIS 3D software.

Moreover, the attained results of PLAXIS 3D simulation have been compared with relevant results. The application of GRP in the infrastructure sector has been limited. One among them has been a leaching reactor in a zinc plant (Lindgren, 2016). Since, the concept of directional tunnelling is a modern technique, the usage of PLAXIS 3D confined to GRP in the current aspect could not be compared with the existing literature. Although previous studies with respect to conventional tunnelling method using PLAXIS have been performed. Shinde et al. (2019) have employed PLAXIS for the evaluation of soil mass deformation during tunnelling, which has been surrounded by dense and clayey sand. Their study stated that the simulated results produced a total displacement of 29.03×10^{-3}m. Hence, the present study's directional tunnel using three-layered GRP panels in the sandy soil at 30° performs better with a reduced value of 54.81% compared with the earlier study.

References

Abbood, I.S., Odaa, S.A., Hasan, K.F., and Jasim, M.A., 2021. Properties evaluation of fiber reinforced polymers and their constituent materials used in structures - A review. Materials Today: Proceedings, 43, 1003–1008.

Aicha, B. and Mezhoud, S., 2021. Numerical Modelling of the Behavior of Tunnel in Soft Surrounding Rock: A Case Study of Djebel El-Ouahch Tunnel, Algeria. Geotechnical and Geological Engineering, 39 (8), 5505–5516.

Al-Bahry, S. N., Elshafie, A.E., Victor, R., Mahmoud, I.Y., and Al-Hinai, J. A., 2011. Opportunistic pathogens relative to physicochemical factors in water storage tanks, Journal of water and health, 9(2), 382–393.

ASTM, 2000. D3039/D3039M Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. Annual Book of ASTM Standards, 15, 1–13.

ASTM, 2003. D 3410/D 3410M Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading. Annual Book of ASTM Standards, 8, 1-16.

Elmar Witten and Volker Mathes, 2020. The Market for Glass Fibre Reinforced Plastics (GRP) in 2020 [online]. Available from: https://ddfiberglass.com/sites/default/files/2021-05/AVK market report 2020.pdf [Accessed 14 Jan 2021].

Craig, P.D. and Summerscales, J., 1988. Poisson's ratios in glass fibre reinforced plastics. Composite Structures, 9 (3), 173–188.

Das, P.K., Nag, D., Debnath, S., and Nayak, L.K., 2010. Machinery for extraction and traditional spinning of plant fibres, 9, 386–393.

Defoirdt, N., Biswas, S., Vriese, L. De, Tran, L.Q.N., Acker, J. Van, Ahsan, Q., Gorbatikh, L., Vuure, A. Van, and Verpoest, I., 2010. Assessment of the tensile properties of coir, bamboo and jute fibre. Composites Part A: Applied Science and Manufacturing, 41 (5), 588–595.

Doan, T.T.L., Brodowsky, H., and Mäder, E., 2012. Jute fibre/epoxy composites: Surface properties and interfacial adhesion. Composites Science and Technology, 72 (10), 1160–1166.

Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J., and Gabarrell, X., 2011. Roof selection for rainwater harvesting: Quantity and quality assessments in Spain. Water Research, 45 (10), 3245–3254.

Fu, S.Y., Lauke, B., Mäder, E., Yue, C.Y., and Hu, X., 2000. Tensile properties of short-glass-fiber- and short-carbon-fiber-reinforced polypropylene composites. Composites Part A: Applied Science and Manufacturing, 31 (10), 1117–1125.

Gopinath, A., Kumar, M.S., and Elayaperumal, A., 2014. Experimental Investigations on Mechanical Properties Of Jute Fiber Reinforced Composites with Polyester and Epoxy Resin Matrices. Procedia Engineering, 97, 2052–2063.

Gogna, E., Kumar, R., Sahoo, A.K. and Panda, A., 2019. A comprehensive review on jute fiber reinforced composites. Advances in industrial and production engineering, 1019, 459-467.

Hasançebi, O. and Dumlupinar, T., 2013. Linear and nonlinear model updating of reinforced concrete T-beam bridges using artificial neural networks. Computers and Structures, 119, 1–11.

Indian Standards Institution, 1985. IS 11229 (1985): Specification for shear box for testing of soils, 1-10.

Kumar, P. and Shrivastava, A., 2017. Various factors affecting stability of underground structures:State of Art. Indo Rock 2017: 7th Indian Rock Conference, October, 576–580.

Labuz, J.F. and Zang, A., 2012. Mohr-Coulomb failure criterion. Rock Mechanics and Rock Engineering, 45 (6), 975–979.

Lani, N.H.M., Yusop, Z., and Syafiuddin, A., 2018. A review of rainwater harvesting in Malaysia: Prospects and challenges. Water, 10 (4), 1–21.

Libro, H., 2021. Concrete vs Plastic Water Tanks: Guide to Choose for Your Home [online]. Available from: https://www.homeslibro.com/2021/06/concrete-vs-plastic-water-tanks.html [Accessed 8 Aug 2021].

Lindgren, M., Bergman, G., Kakkonen, M., Lehtonen, M., Jokinen, J., Wallin, M., Saarela, O., and Vuorinen, J., 2016. Failure analysis of a leaching reactor made of glass-fiber reinforced plastic. Engineering Failure Analysis, 60, 117–136.

Mishra, V. and Biswas, S., 2013.Physical and mechanical properties of bi-directional jute fiber epoxy composites. Chemical, Civil and Mechanical Engineering Tracks of 3rd Nirma University International Conference on Engineering, (NUiCONE 2012), Procedia Engineering, 51, 561–566.

Ramesh, M., Palanikumar, K., and Reddy, K.H., 2013. Mechanical property evaluation of sisal – jute – glass fiber reinforced polyester composites, Composites : Part B, 48, 1–9.

Shinde, N.T., Kuwar, S.R., Khairnar, A.P., Khairnar, Y.J., and Shivde, S.R., 2019. Tunnel Analysis using Plaxis 2D, International Journal of Research in Engineering, Science and Management, 2 (4), 539–540.

Takai, S., 2002. Wide area water collection type underground water tank. U.S. Patent No. 6,382,237B1.

Tripathy, S.S., Landro, L.D.I., Fontanelli, D., Marchetti, A., and Levita, G., 1999. Mechanical Properties of Jute Fibers and Interface Strength with an Epoxy Resin, Journal of Applied Polymer Science, 75 (13), 1585–1596.

Traboulsi, H., and Traboulsi, M., 2017. Rooftop level rainwater harvesting system. Applied Water Science, 7 (2), 769–775.

Valtonen, V.M., 2019. Impacts of nonlinear vs. Linear finite element analysis on ice-strengthened primary structures. Proceedings of the 25th International Conference on Port and Ocean Engineering under Arctic Conditions(POAC), Delft, The Netherlands. 1-10.

Verma, A., 2019. Storage of water and construction of a tank as per the NBCI guideline [online]. Available from: https://www.beltecno-global.com/blog/storage_of_water [Accessed 20 Sep 2019].

Watts, F.S., 1967. Some aspects of corrosion problems associated with storage tanks. Anti Corrosion Methods and Materials, 14 (8), 8–18.

Wilde, 2021. PLAXIS 3D - Product Description [online]. Available from: https://wildeanalysis.co.uk/software/built-environment/plaxis/3d/ [Accessed 18 Jun 2021].

Weston, S. 1980 Liquid storage tank. U.S. Patent No. 4,193,510.

Zhao, L. and You, G., 2018. Stability study on the northern batter of MBC Open Pit using Plaxis 3D. Arabian Journal of Geosciences, 11 (6), 1-11.

CHAPTER 5: DEVELOPMENT OF RURAL BIM FRAMEWORK AND ITS IMPLEMENTATION

5.1 Chapter overview

This chapter discusses the development of R-BIM framework, based on the discussed R-BIM concept, which is feasible for practical application and targets surpassing the encountered challenges of RI projects discussed in section 2.3. It has been reflected through a case study focused on RWM. The various dimensions of R-BIM covering multiple facets of the study have been comprehensively emphasised.

5.2 Multiple frameworks for BIM implementation

A framework behaves as a structured procedure for any developed feature/technology in figuring out issues. The literature study indicates that from the early 2000s, researchers have been proposing various methodologies in the theoretical and practical perspectives of BIM. Succar et al. (2007) recommended following a three-node formula of policy, technology, and process for pursuing BIM knowledge and adopting visual models for construction. Jung and Joo (2011) created a conceptual BIM framework for practical implementation by integrating three aspects such as BIM technology, BIM perspective, and construction business functions. McArthur (2015) presented an improved 7D BIM framework for intensifying the existing buildings' operation, maintenance, and sustainability. His study reflected on handling information transfer between BIM models and Facility Management models, controlling the created model, managing indeterminate situations in building documentation, and determining critical information for achieving sustainability. The evolution of IoT made Tagliabue and Ciribini (2018) frame a construction site management process by extracting the real-time simulation sensors' data and interpreting them into 3D models. Hence, designing frameworks has been a prominent aspect for successfully implementing a method.

5.3 Development of R-BIM framework

The developed R-BIM concept has been proposed as the R-BIM framework, adaptable for practical execution. The study incorporates participatory management in planning, visualisation, scheduling, cost estimation, capacity enhancement, and safety management concerning multiple stages of R-BIM from 2D to 7D, shown in Table 5.1. The outputs are operated in the BIM cloud, and all the concerned stakeholders at the rural level perceive the outcomes.

Table 5. 1 Components and tasks in R-BIM

Dimension	Component	Task
2D	Planning	Planning a model by involving participatory management
3D	Visualisation	Create visualised models and render flythrough videos of the created models in multiple scenarios
4D	Schedule management	Schedule and manage various activities involved in the entire project, and transportation of materials
5D	Cost management	Estimate and manage the whole budget as well as the expenditure of the project.
6D	Capacity management	Enhancing the unskilled workers in rural areas
7D	Safety management	Risk identification and ensure safety protocols by dashboards to assist site workers' safety.

Planning (2D) a RI needs to be done with the combined effect of human interactions where all the users play a pivotal role in decision-making. At the same time, 3D is related to the virtual representation of a targeted location. 4D and 5D are connected to an intended infrastructure’s schedule and cost management, respectively. Schedule management primarily focuses on defining the required resources and interrelationships with all the activities/tasks in a project’s accomplishment. Secondly, planning a proper transport vehicle for material handling is incorporated. Cost management deals with the expenditure estimation depending on different heads of the scheduled work. The study highlights workers’ skills in rural areas; capacity management has been included as 6D in the R-BIM framework. It emphasises the skill development of workers using the BIM tools in prefabrication related tasks. Site workers are prone to risks associated with the RI execution; hence the framework adjoined 7D as safety management. All the risks are assessed beforehand for the planned activities and classified based on the risk level, which gives rise to the following up of safety protocols by dashboards. The management of the whole R-BIM process, named R-BIM framework, illustrated in Figure 5.1, can be operated on computers/android devices in a BIM cloud platform. The framework engages all the rural level stakeholders to raise any issue and review the problem for the providence of a corrected model.

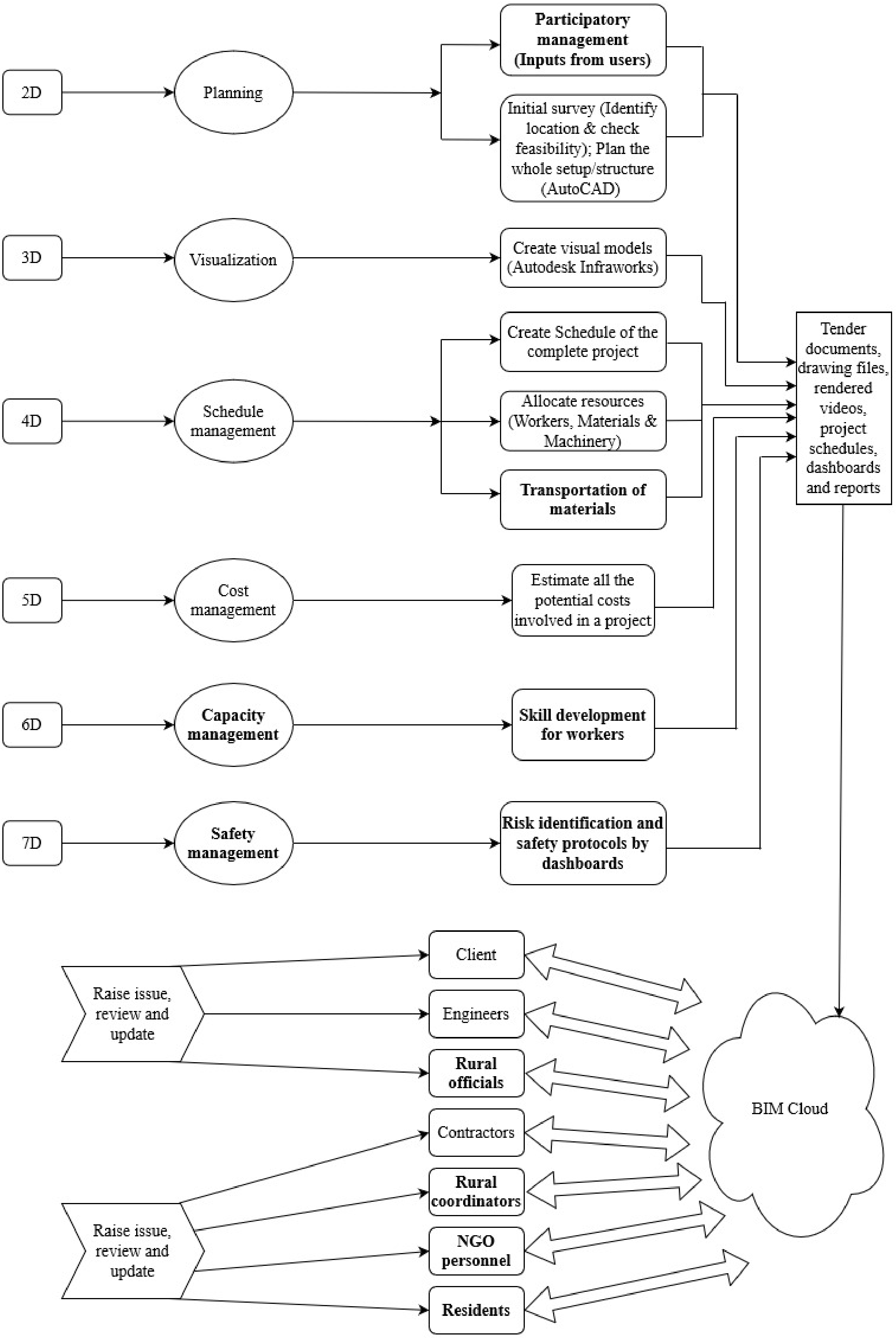


Figure 5. 1 R-BIM Framework

Note: Bold text highlights the inclusion of discussed attributes in R-BIM

5.4 Enforcement of R-BIM framework through a RWM execution

The enhanced R-BIM framework has been validated through a RWM project. The fundamental reason for selecting the water management domain is due to its complex execution in rural areas. It involves multiple stakeholders' involvement, extensive resource utilisation, and time consumption. The selected study area was at Ramnathpura, in Rajasthan, India (geographic coordinates: 28°18'38.628" N, and 75°39'43.38" E). The R-BIM practice has involved two phases; a) Planned phase and b) Actual phase. Rural stakeholders have been engaged in the entire process. The application of EVA has supported evaluating the performance of the work executed against the work planned. Finally, the scenario of RWM execution ignoring the R-BIM framework application has been considered. The EVA results of this aspect have been compared with the R-BIM study EVA results. The flowchart of the adopted methodology in the entire study has been depicted in Figure 5.2.

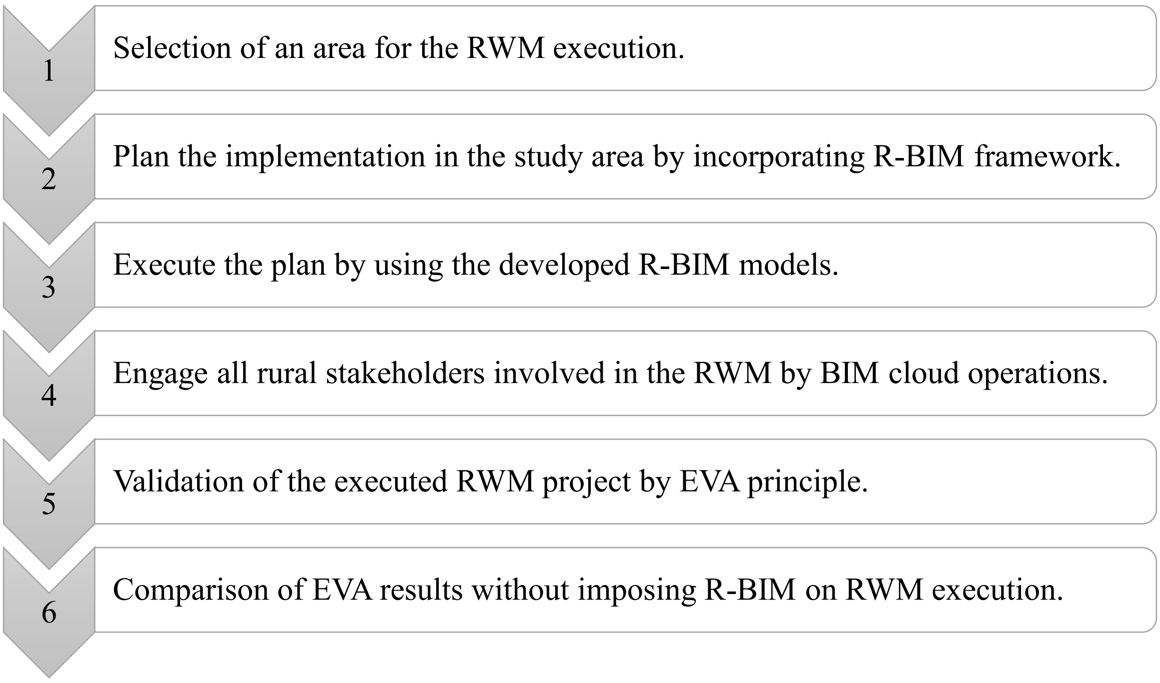


Figure 5. 2 Flowchart of the adopted methodology in the study

5.4.1 Initiation of RWM study

The study commenced with a feasibility survey including regional NGO personnel for analysing the community's situation in the selected area. It involved data collection concerning population enquiry, water requirements, and the availability of alternate water sources. As a result, it helped in the plan and follow up of RWM on the targeted community. The complete set-up of RWM was communicated to the community's residents, as depicted in Figure 5.3. According to this method, initially constructed household tanks store rainwater from the rooftop RWH system. Gutters and downspouts would be connected from the roof of a house, and the corresponding connections make the rainwater flow and reach the household tank. The upper portion of a household tank would be connected with a pipe; therefore, water exceeding the storage limit would be conveyed to the community tank, an innovative construction called a directional tunnel, discussed in section 4.3.

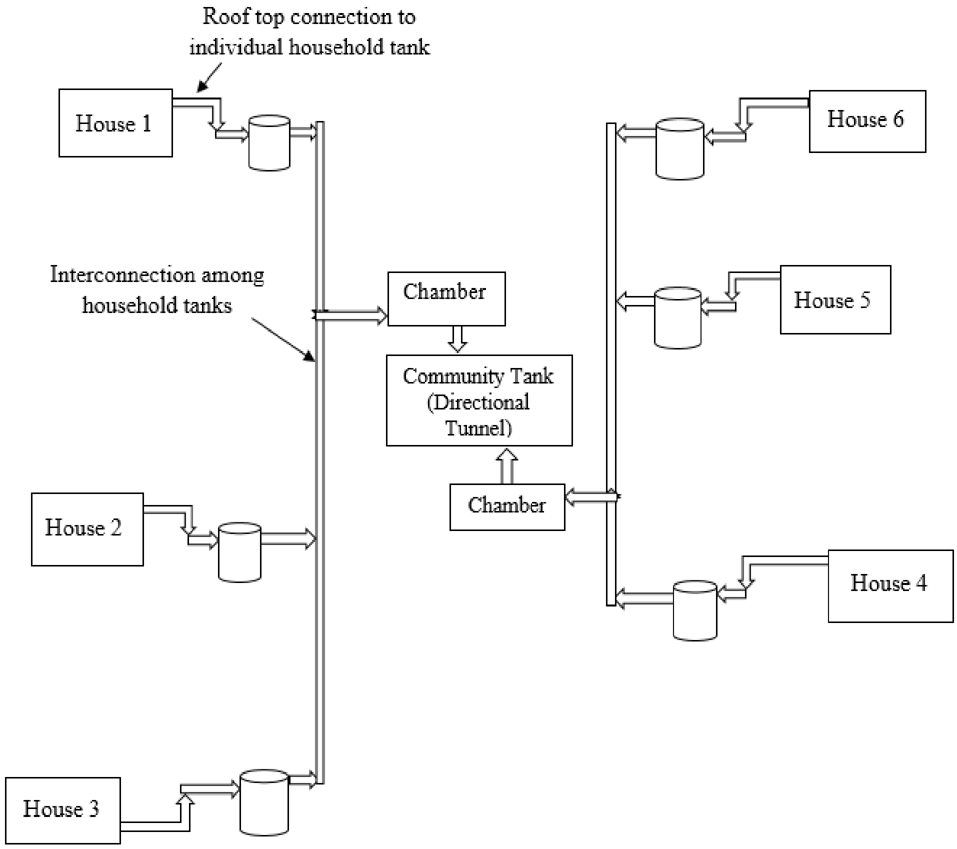


Figure 5. 3 Set-up for RWM at the community

In line with this process, twenty-five residents have been selected and involved in harvesting rainwater at the household level. Subsequently, all household tanks at each house collected the rainwater. Later, the directional tunnel amassed the surplus rainwater from all household tanks through a channelled pipe network. GRP was the material type utilised for household tanks and directional tunnel. The complete RWM study has been put into effect by the developed R-BIM framework, which endured for two phases, as discussed earlier.

5.4.2 Planned phase

5.4.2.1 R-BIM: 2D - Planning

The application of the R-BIM framework started with the inception of participatory management in the 2D - planning stage of construction. The participatory management concept believes in empowering a group of people to be involved in functional decision-making. It also prioritises community-specific action's success or failure in conservation by accepting local people's inputs and participation (Caro-Borrero et al., 2020). Especially it is an approach applied by various NGOs and institutions in the developmental stages. Incorporation of the participatory management principle has been done by selecting the best alternative among conventional pipe networks, and directional tunnel location based on residents' feedback. It involved the inputs regarding accessible proximity, geographical feasibility, and runoff accumulation in the community.

The planned phase activities have been framed as shown in Table 5.2, from the identification of the village (P1) to finishing works (P31). Dimensions for each activity, as per R-BIM have also been presented. The aspect of dimensions' mapping to activities makes planners define their objectives vividly in R-BIM application. In activity code, P refers to denotation regarding activities with respect to effect of R-BIM.

Table 5. 2 Activities at the planning phase of RWM

Activity Code	Description	Assigned dimensions as per R-BIM
P1	Identification of village	2D
P2	Feasibility survey	2D
P3	Creation of visualisations for water management in a community	3D
P4	Community meetings and collection of inputs from residents	2D, 3D
P5	Identification of residents	2D, 3D
P6	Selection of residents	2D, 3D
P7	Household survey	2D
P8	Selecting feasible location of household tanks	2D,3D
P9	Schedule estimation for onsite execution	4D

P10	Resources and cost estimation	5D
P11	Skill development for workers	6D
P12	Risk identification and determining safety guidelines	7D
P13	Procurement of materials for dye frame & GRP panels	4D,5D
P14	Preparation of dye frame	3D, 4D, 5D, 6D, 7D
P15	Manufacturing GRP panels for household tanks	3D, 4D, 5D, 6D, 7D
P16	Transportation of GRP panels of household tanks	4D, 5D, 6D, 7D
P17	Fabrication of household tanks at the site	4D, 5D, 6D, 7D
P18	Excavation for household tanks	3D, 4D, 5D, 6D, 7D
P19	Placing of household tanks	4D, 5D, 6D, 7D
P20	Backfilling for household tanks	4D, 5D, 6D, 7D
P21	Connection of roof top rainwater harvesting system & Solar water pump	4D, 5D, 7D
P22	Directional tunnel area selection	2D, 3D, 4D, 5D
P23	Site approval for directional tunnel	2D
P24	Cleaning and excavation for directional tunnel	3D, 6D, 7D
P25	Manufacturing GRP panels for directional tunnel	3D, 4D, 5D, 6D, 7D
P26	Transportation of GRP panels for directional tunnel	4D, 5D, 6D, 7D
P27	Fabrication of GRP panels for directional tunnel at the site	4D, 5D, 6D, 7D
P28	Excavation for interconnection among all household tanks and directional tunnel	3D, 4D, 5D, 6D, 7D
P29	Laying of pipelines	3D, 4D, 5D, 6D, 7D
P30	Backfilling of pipeline and directional tunnel	3D, 4D, 5D, 6D, 7D
P31	Finishing works	4D, 5D, 6D, 7D

The household tank and directional tunnel size determination have been the subsequent steps in planning. According to Central Ground Water Board 2020 report of Rajasthan, the groundwater water level has fallen greater than 4m from the existing level in Jhunjhunu district (CGWB Western Region 2020). Jung et al. (2014) stated that a tank must serve for regular water supply so that the structure behaves like a resource across seasons. Rainwater tanks in individual houses are dependent on the efficiency of collection, type of catchment, connected devices, and amount of rainfall (Mukheibir et al., 2014). The capacity of the household tank has been determined based on these dependent factors and the RWH guidelines of India. The equation (5.1) (India Water Portal, 2006) helped in determining the volume of the tank (V).

$$V = Roof\ area\ \ x\ total\ annual\ rainfall\ \ x\ Runoff\ coefficient \tag{5.1}$$

Considered data: As per the selected twenty-five houses in the community, the dimensions of all their roofs have been calculated. The average roof area has been 54m^2. The nearest rainfall data station – Surajgarh, was taken into effect for total annual rainfall as 0.452m (Water Resources Department - Rajasthan, 2019). Runoff coefficient as 0.8 for roof type of tile/corrugated metal (Central Pollution Control Board - ENVIS, 2016). The volume calculation for a household tank has been presented in Table 5.3.

Table 5. 3 Volume of household tank

Roof area (m^2)	54
Total annual rainfall (m)	0.452
Runoff coefficient	0.8
Volume of an individual household tank (V) (m^3)	19.526

The equation (5.2) (Central Pollution Control Board - ENVIS, 2016) has been used in enumerating the volume of the directional tunnel (V_1).

$$V_1 = Dry\ season\ x\ No.of\ people\ using\ tank\ x\ Per\ capita\ per\ day\ consumption \tag{5.2}$$

Considered data: A minimum number of the dry season or water-scarce days for the people in the community has been taken as 30. The other variables, such as a total of 100 people for using the directional tunnel as the water source and minimum per capita water consumption (for drinking, cooking and limited activities) of 0.05m^3, have been considered. The volume calculation of the directional tunnel has been represented in Table 5.4.

Table 5. 4 Volume of directional tunnel

Dry season (Number of days)	30
No. of people using the tank	100
Per capita per day consumption (m^3)	0.05
Volume of Directional tunnel (V_1) (m^3)	150

5.4.2.2 Decision-making in the pipe network for the RWM set-up

The planned household tanks and directional tunnel necessitated an efficient pipe network for the collection of harvested rainwater in the community. Decision-making in water infrastructures' related activities requires a wise approach. The Analytic Hierarchy Process (AHP) has been one of the most commonly applied decision-making methods in water infrastructures (Al-Barqawi and Zayed 2008; Tanyimboh and Kalungi 2009; El Chanati et al., 2016; Zyoud et al., 2016, Aşchilean et al., 2017; Wei and Chen 2017; Jan et al., 2020; Pagano et al., 2021). AHP enables modelling a complex problem in a hierarchical structure, giving a general overview of the problem for a decision-maker. The hierarchical system of criteria follows the structure of several well-known analogies and weights by pairwise comparisons. Therefore, a principal advantage of using AHP allows the end-users or decision-makers to avoid mathematical details of the calculations, thereby increasing participation.

The significance of decision-making for the pipe network had been set as the objective in the R-BIM 2D: planning phase. The study adopted AHP as the prioritization tool, which models the decision problem in a hierarchical structure consisting of goals, criteria, and alternatives (Wei and Chen 2017). The first level consists of the goal that needs to be achieved. The selection of a pipe network according to pre-determined criteria was the goal for this segment. The second and third levels were criteria and sub-criteria by which the alternatives were evaluated. The criteria used were economy, hydraulics, social criteria, and technology. Each criterion was divided into sub-criteria, such as economy: material, machinery, and labour; operation and maintenance; excavation; and life cycle cost. Whereas in hydraulics, the sub-criteria were head pressure, water tightness to prevent losses and contamination, number of bends/connections, slope/gradient, and pipe dimensions as length and diameter. Social criteria had the sub-criteria as improved social status of girls and women, easy access to clean water, and reduced health risk. Finally, the sub-criteria of technology: consumption of low energy for water extraction; and organized central database of user activity/feedback. The lowest level, i.e., the fourth level, consisted of four pipe network alternatives: grid-iron, ring, radial, and dead-end/tree system, as shown in Figure 5.4 – Figure 5.7, respectively.

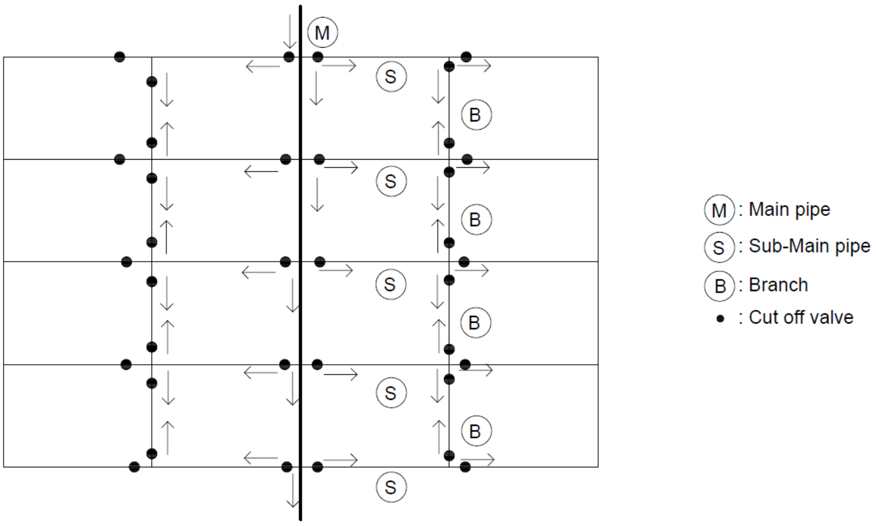


Figure 5. 4 Grid iron system

(Stauffer 2020)

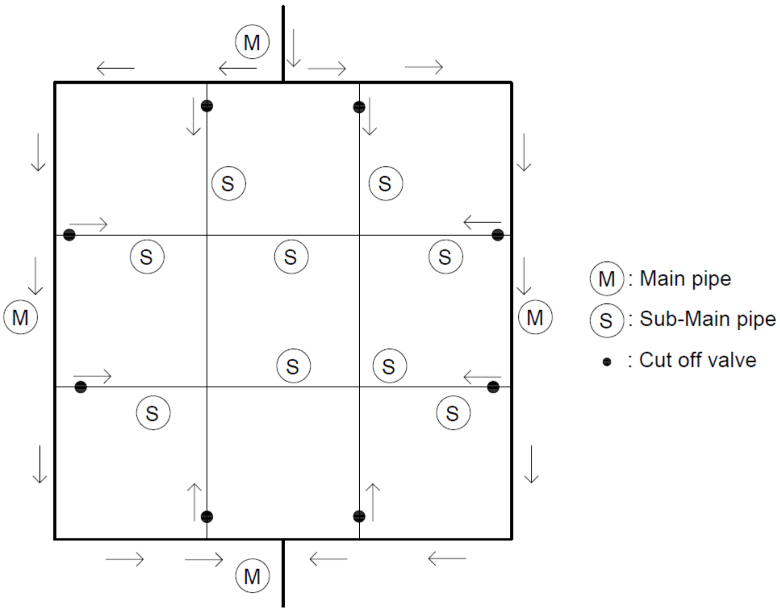


Figure 5. 5 Ring system

(Stauffer 2020)

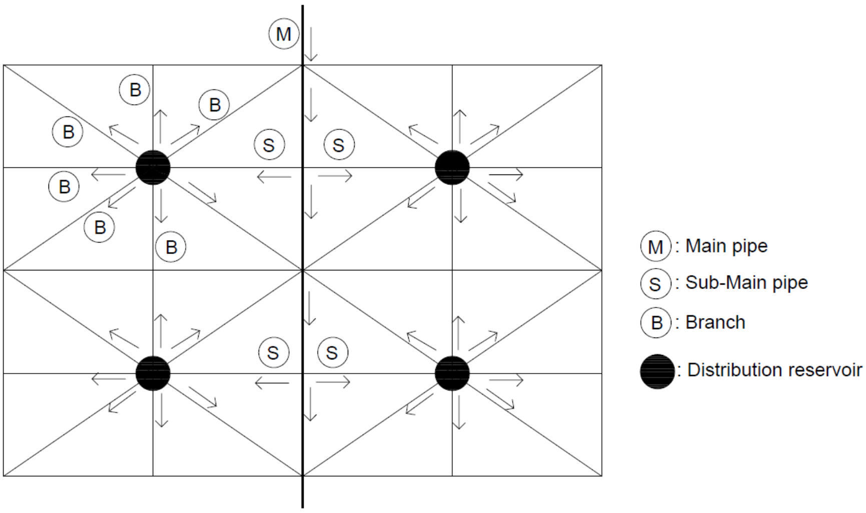


Figure 5. 6 Radial system

(Stauffer 2020)

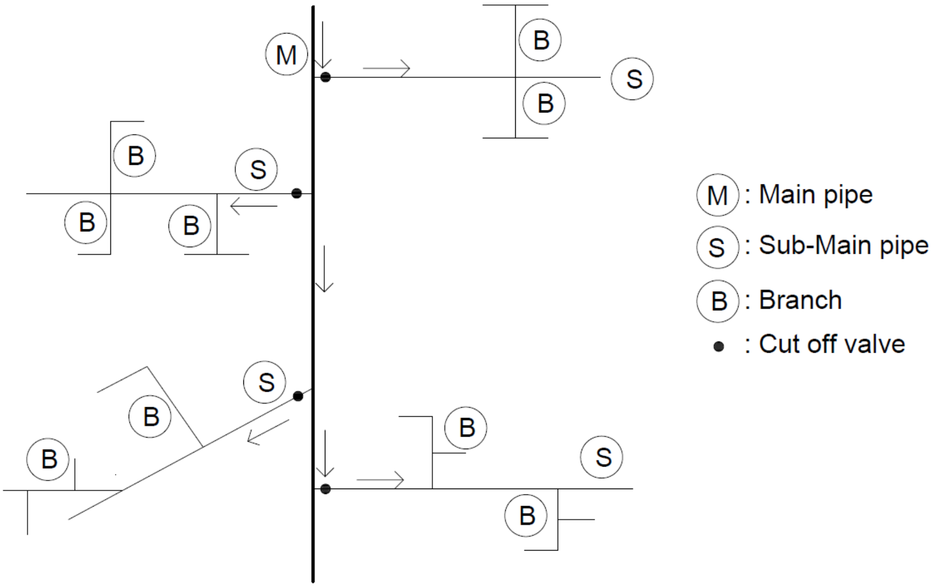


Figure 5. 7 Dead-end/Tree system

(Stauffer 2020)

All the criteria, sub-criteria and alternatives were selected based on the issued pipe network guidelines in the Indian scenario (Central Water Commission 2017). The complete AHP hierarchical structure for the desired objective of pipe network selection has been depicted in Figure 5.8.

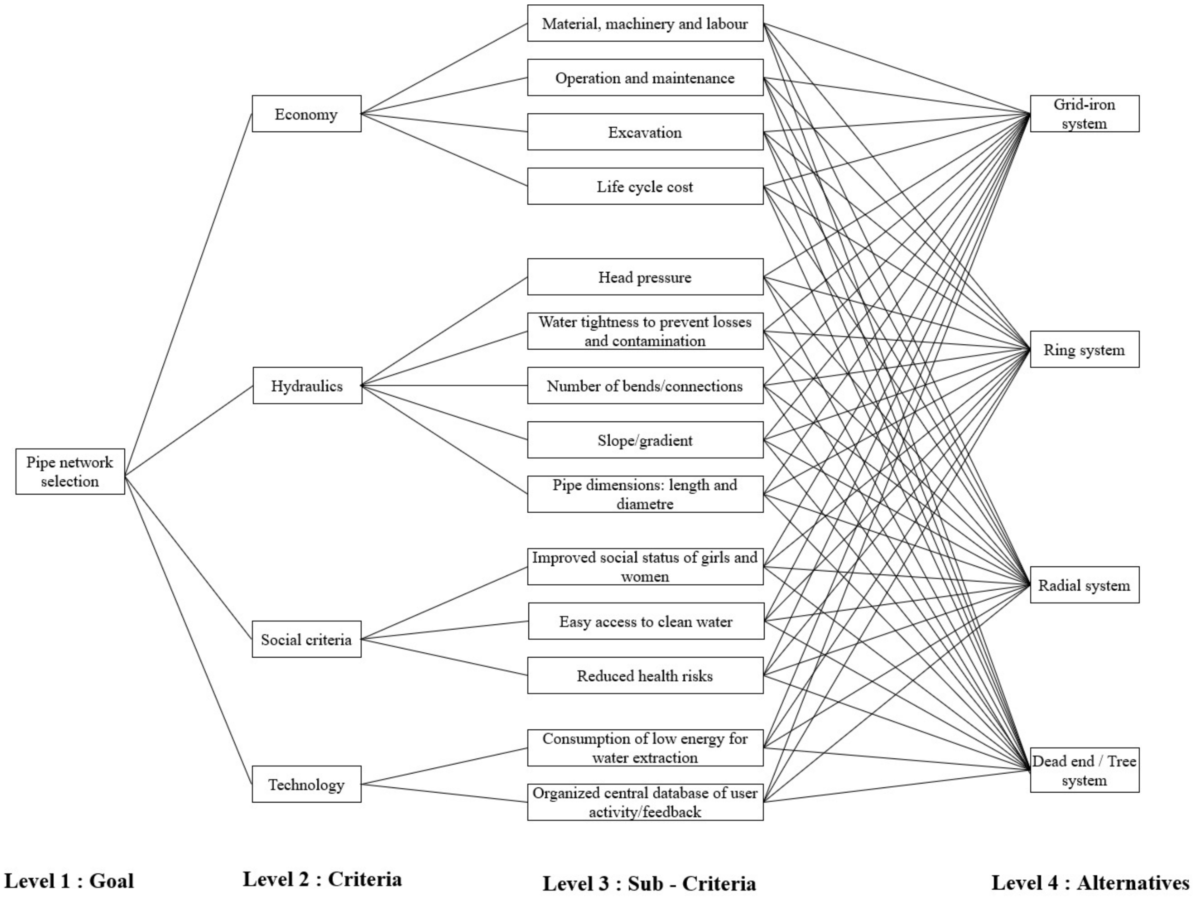


Figure 5. 8 AHP hierarchy structure for pipe network selection

Subsequently, the pairwise table compared the relationship between attributes and alternatives using Saaty's scale, as represented in Table 5.5. This table was constructed by integrating ratio scale values of levels 1 to 9 and their reciprocals according to the decision makers' tendencies, beliefs, and experiences.

Table 5. 5 Saaty's Scale (Saaty 1994)

Numerical rating	Verbal judgments of preferences
9	Extremely preferred
8	Very strongly to extremely
7	Very strongly preferred
6	Strongly to very strongly
5	Strongly preferred
4	Moderately to strongly
3	Moderately preferred

2	Equally to moderately
1	Equally preferred

All the rural stakeholders were involved in the decision-making. The 4 criteria, 14 sub-criteria, and 4 alternatives. Geometric mean of different decision-makers' scores helped in framing comparison tables, a) pipe network selection with criteria, represented in Table 5.6, b) sub-criteria under criterion of economy, shown in Table 5.7, and c) alternatives under the sub-criterion of operation and maintenance, presented in Table 5.8. Similar process has been executed for all the pairwise comparisons in criteria, sub-criteria and alternatives.

Table 5. 6 Pairwise comparison of pipe network selection

Criterion (→) (↓)	**Economy**	**Hydraulics**	**Social criteria**	**Technology**
Economy	1.00	1.87	0.49	1.29
Hydraulics	0.51	1.00	2.00	1.19
Social criteria	1.77	0.50	1.00	1.00
Technology	0.70	0.80	1.00	1.00

Table 5. 7 Comparison of sub-criteria under the criterion of economy

Overall economics of the network (→) (↓)	**Material, machinery, and labor**	**Operation and maintenance**	**Excavation**	**Life cycle cost**
Material, machinery, and labor	1.00	1.74	1.06	1.43
Operation and maintenance	0.57	1.00	1.23	1.86
Excavation	0.94	0.81	1.00	1.51
Life cycle cost	0.70	0.54	0.66	1.00

Table 5. 8 Comparison of alternatives under the sub-criterion of operation and maintenance

Costs incurred under operation and maintenance (→) (↓)	Grid-iron system	Ring system	Radial system	Dead end system
Grid iron system	1.00	1.72	1.18	1.30
Ring system	0.58	1.00	1.04	1.55
Radial system	0.85	0.96	1.00	1.52
Dead end system	0.77	0.64	0.66	1.00

Implementation of statistical ranking methods to the weight tables yield priorities for the attributes and options. The comparison table was transformed into a weight matrix, and the consistency of the decision-makers was checked. Table 5.9 determines the performance of the four alternatives in connection with the four decision criteria, where results have been obtained by combining the criteria, sub-criteria, and alternatives for producing final scores. The overall ranking enabled the final decision, as represented in Table 5.10. The responses of decision makers/experts from Rural Water Supply and Sanitation Department and rural contractors, as well as calculation of consistency index by AHP have been provided elaboratively in Appendix – A.

Table 5. 9 Normalization for decision-making among criteria and alternatives

Final score:	Economical	Hydraulics	Social	Technological	Total
Grid iron system	0.0739	0.0748	0.0654	0.0601	0.274
Ring system	0.0705	0.0540	0.0485	0.0478	0.220
Radial system	0.0703	0.0522	0.0534	0.0425	0.218
Dead end/ Tree system	0.0606	0.0811	0.0814	0.0529	0.276

Table 5. 10 Overall ranking of alternatives

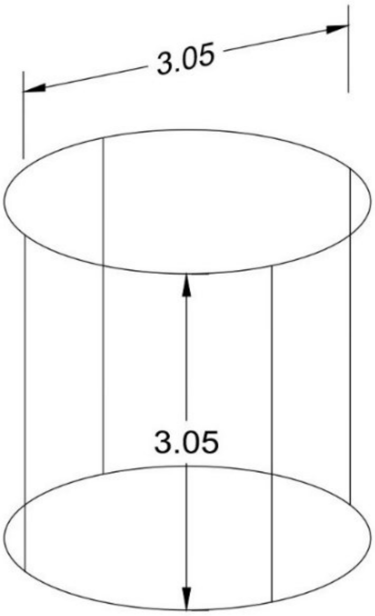
Type of system	Score	Rank
Dead end	0.276	1
Grid-iron	0.274	2

Ring	0.220	3
Radial	0.218	4

The preferred alternative of the dead-end system received a score of 0.276, followed by grid-iron and ring systems with values of 0.274 and 0.220, respectively. The radial system was the least preferable alternative, with a score of 0.218. The result of the dead-end system pipe network for the community has directed towards creating visualization for the RWH set-up in the community.

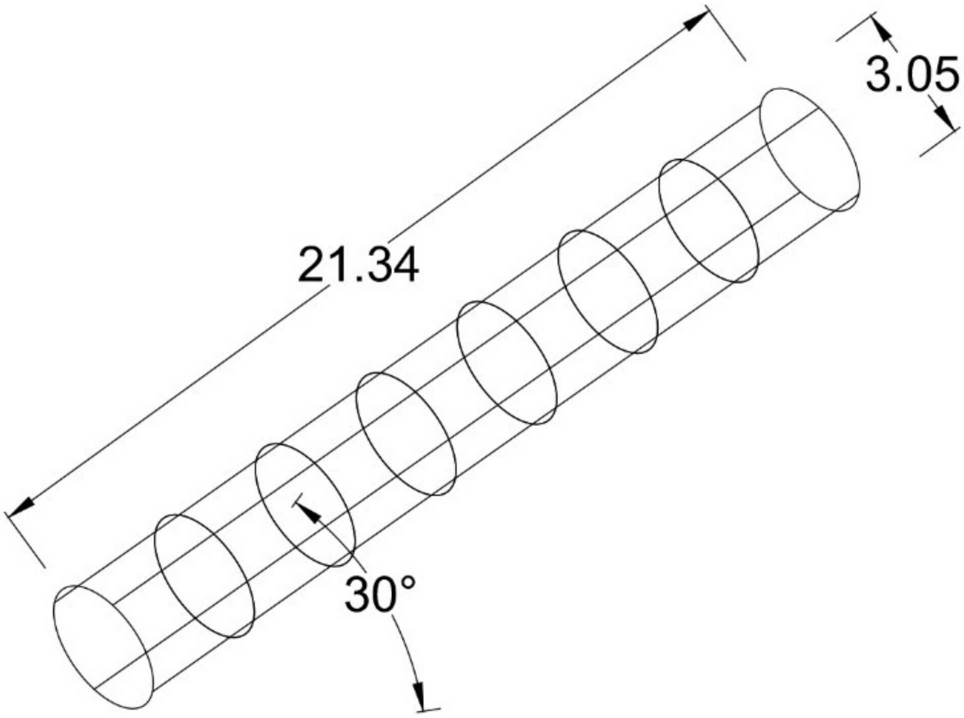
5.4.2.3 R-BIM: 3D – Visualisation

As per R-BIM: 3D, RWH structures' visualisations make the interpretations of the on-site construction efficient. The finalised volume of the household tank for preserving rainwater was 20m^3. The tank's shape has been fixed as cylindrical with a diameter of 3.05m and a height of 3.05m, as illustrated in Figure 5.9. The planned directional tunnel holding a volume of 150m^3 bears the dimensions of 3.05m diameter, 21.34m length, and an angular value of 30° (based on the stability analysis discussed in section 4.4.1) has been depicted in Figure 5.10. Both 3D models of the structures have been created in AutoCAD modelling.



(All dimensions are in metres)

Figure 5. 9 Household tank



(All dimensions are in metres)

Figure 5. 10 Directional tunnel

Adopting compatible software for modelling a rural environment is crucial in any case study. Autodesk Infraworks, a BIM tool supported by Autodesk, has been undertaken to visualize infrastructure, site location, and roads to create the Worcester Polytechnic Institute 3D campus (Guillermo et al., 2016). A few research studies (Eliseev et al. 2017, Shahid et al. 2019, Maqsoom et al. 2020) reported the usage of this BIM tool. However, this thesis portrays the BIM tools' application for the RWI, which has been unexplored earlier. Autodesk Infraworks has been undertaken for establishing the virtual system by taking the real-world atmosphere inputs of the community in the present study. Figure 5.11 presents the overall flow of 3D modelling performed in R-BIM. The models developed in AutoCAD modelling have been converted to .dxf format and used as inputs to form a virtual RWH system in Autodesk Infraworks. The model builder function integrates the features like roads, vegetation, and boundary limits of all structures within the determined geographic coordinates. Later, all the RWH connections among household tanks and the directional tunnel were incorporated for the outcome of visual design.

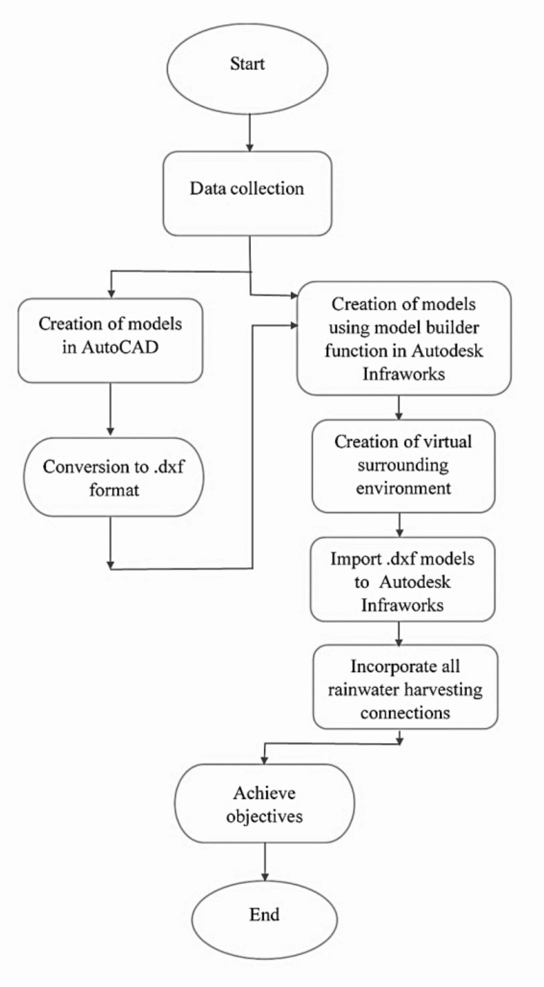


Figure 5. 11 Flow of 3D modelling in R-BIM

5.4.2.4 R-BIM: 4D – Schedule management

4D of R-BIM deals with schedule management of RWM, which involved the Program Evaluation and Review Technique (PERT) method, considering optimistic time (t_o), pessimistic time (t_p) and most likely time (t_m). Determination of each activity's expected duration (t_e) depended on equation (5.3) (Punmia and Khandelwal, 2006). All the defined activities as per Table 5.2, have been considered for the schedule preparation and presented in Table 5.11. Eventually, the estimated schedule to finish the execution of RWM at the study area had a deadline of 135.5 days. A network diagram has been formed, as depicted in Figure 5.12. The other aspect of transportation of materials has been discussed in Chapter 6 under the actual phase category.

$$t_e = \frac{t_o + 4t_m + t_p}{6} \tag{5.3}$$

Table 5. 11 Scheduling of RWM execution

Activity Code	**Description**	**Predecessor**	**Optimistic time (t_o) (days)**	**Most likely time (t_m) (days)**	**Pessimistic time (t_p) (days)**	**Expected duration (t_e) (days)**
P1	Identification of village	-	1	2	4	2
P2	Feasibility survey	P1	4	2	5	3
P3	Creation of visualisations for water management in a community	P2	1	2	3	2
P4	Community meetings and collection of inputs from residents	P3	1	2	4	2
P5	Identification of residents	P4	4	6	8	6
P6	Selection of residents	P4	1	2	3	2
P7	Household survey	P6, P5	1	2	4	2
P8	Selecting feasible location of household tanks	P7	1	2	4	2

Activity Code	**Description**	**Predecessor**	**Optimistic time (t_o) (days)**	**Most likely time (t_m) (days)**	**Pessimistic time (t_p) (days)**	**Expected duration (t_e) (days)**
P9	Schedule estimation for onsite execution	P7	1	2	3	2
P10	Resources and cost estimation	P7	1	2	3	2
P11	Skill development for workers	P9	3	4	5	4
P12	Risk identification and determining safety guidelines	P9	1	1	1	1
P13	Procurement of materials for dye frame & GRP panels	P10, P12	5	6	13	7
P14	Preparation of dye frame	P11, P13	4	5	8	5.5
P15	Manufacturing GRP panels for household tanks	P14	30	35	45	36
P16	Transportation of GRP panels of household tanks	P15	3	4	8	4.5

Activity Code	**Description**	**Predecessor**	**Optimistic time (t_o) (days)**	**Most likely time (t_m) (days)**	**Pessimistic time (t_p) (days)**	**Expected duration (t_e) (days)**
P17	Fabrication of household tanks at the site	P16	10	14	24	15
P18	Excavation for household tanks	P8, P17	4	7	10	7
P19	Placing of household tanks	P18	1	2	6	2.5
P20	Backfilling for household tanks	P19	4	5	6	5
P21	Connection of roof top rainwater harvesting system & Solar water pump	P20	10	14	24	15
P22	Directional tunnel area selection	P7	1	1	1	1
P23	Site approval for directional tunnel	P22	1	1	1	1
P24	Cleaning and excavation for directional tunnel	P23	2	2	3	2

Activity Code	Description	Predecessor	Optimistic time (t_o) (days)	Most likely time (t_m) (days)	Pessimistic time (t_p) (days)	Expected duration (t_e) (days)
P25	Manufacturing GRP panels for directional tunnel	P14	6	11	22	12
P26	Transportation of GRP panels for directional tunnel	P21, P24, P25	1	2	3	2
P27	Fabrication of GRP panels for directional tunnel at the site	P26	4	7	10	7
P28	Excavation for interconnection among all household tanks and directional tunnel	P27	2	3	4	3
P29	Laying of pipelines	P28	1	2	3	2
P30	Backfilling of pipeline and directional tunnel	P29	2	3	4	3
P31	Finishing works	P28, P30	1	2	3	2

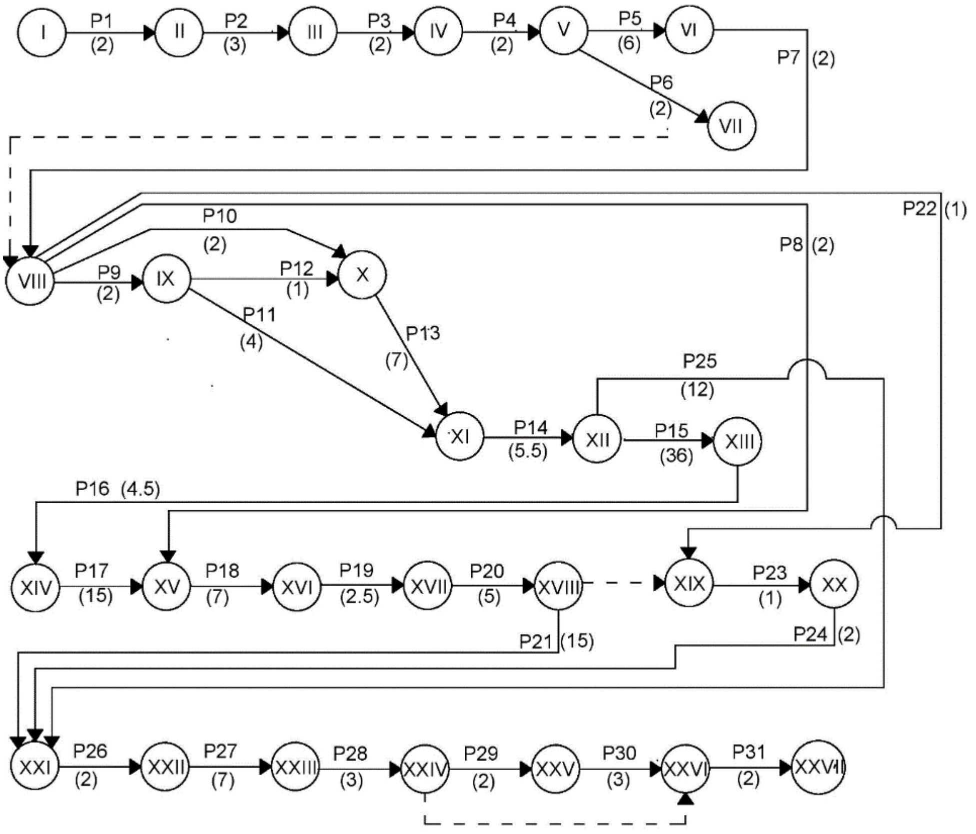


Figure 5. 12 Network diagram of RWM

5.4.2.5 R-BIM: 5D – Cost management

5D in R-BIM corresponds to resource allocation and cost estimation of the related activities in the planned phase. The workers/labour considered were carpenters, helpers, plumbers, drivers, cranes operators, and hydraulic excavator operators. Since the initially planned duration was 135.5 days, the different types of aforementioned labour were allocated for RWM. Assigned workers on a day against the entire timeline of the planned work have been depicted in Figure 5.13. Cost estimation accounted for the rates of items, materials, and vendor prices of different raw materials and earthwork excavation based on guidelines - schedule of rates (Integrated Schedule of Rates, 2017). Workforce costs were carpenter: Rs.500/day, helper: Rs. 350/day, and plumber: Rs.400/day, whereas operator costs were inclusive in machinery operation. The raw materials for household tanks and directional tunnel were epoxy resin, hardener, and bi-directional glass fibre mats, whereas machinery consisted of a crane, truck, and hydraulic excavator. Based on these factors, the estimated budget for completion has been Rs.40,55,005, presented in Table 5.12. The entire cost estimation details have been incorporated in Appendix – B.

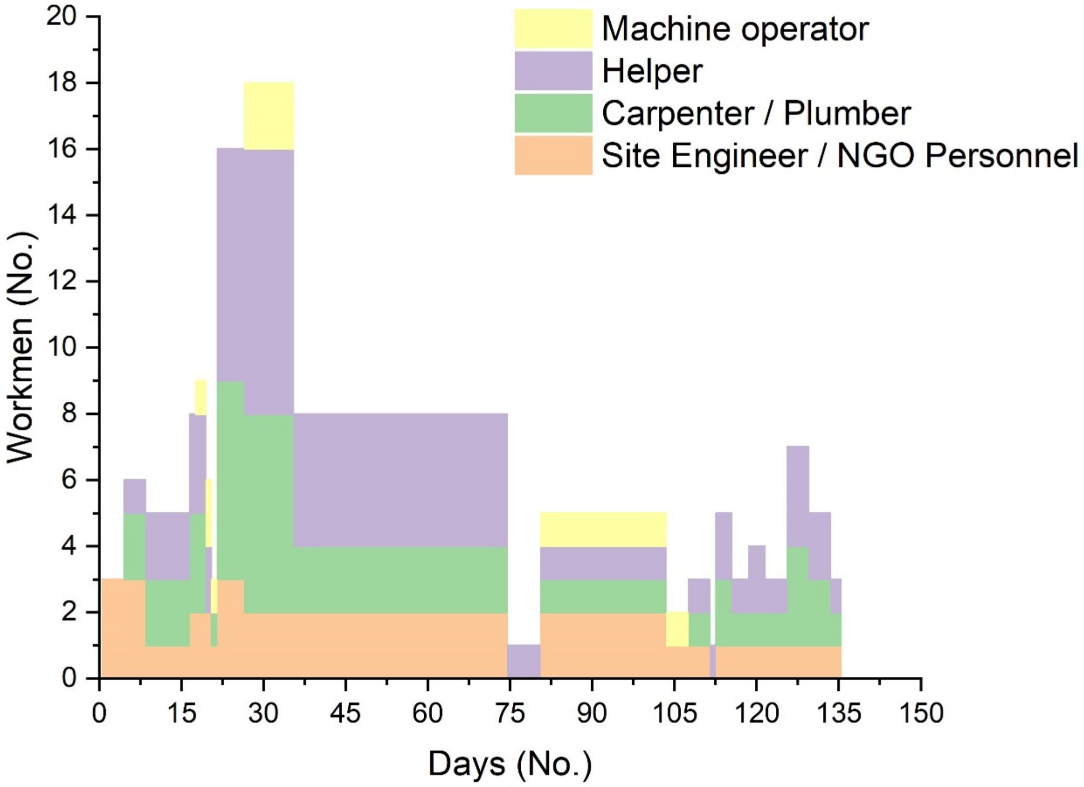


Figure 5. 13 Resource allocation for the RWM execution

Table 5. 12 Estimated budget for completion

Activity Code	**Description**	**No.s / Quantity (cu.m)**	**Rate (Rs.)**	**Cost (Rs.)**
P13	Procurement of materials for dye frame & GRP panels	1	34,685	34,685
P14	Preparation of dye frame	1	1,26,270	1,26,270
P15	Manufacturing GRP panels for household tanks	25	96,600	24,15,000
P16	Transportation of GRP panels of household tanks	4	800	3200
P17	Fabrication of household tanks at the site	25	1159	28,975
P18	Excavation for household tanks	499.25	56.085	28,000.44
P19	Placing of household tanks	25	1156	28,900
P20	Backfilling for household tanks	499.25	56.085	28,000.44

P21	Connection of roof top rainwater harvesting system & Solar water pump	25	10,411.5	26,0287.5
P24	Cleaning and excavation for directional tunnel	312.5	78.75	24,609.38
P25	Manufacturing GRP panels for directional tunnel	1	7,28,650	7,28,650
P26	Transportation of GRP panels for directional tunnel	1	800	800
P27	Fabrication of GRP panels for directional tunnel at the site	7	1156	8092
P28	Excavation for interconnection among all household tanks and directional tunnel	480	82	39,360
P29	Laying of pipelines	1919.3	122.54	2,35,190
P30	Backfilling of pipeline and directional tunnel	792.5	82	64,985
	Final Estimate			**40,55,005**

(Note: The identified activities are given in Table 5.2)

5.4.2.6 R-BIM: 6D – Capacity management

The next dimension in R-BIM is capacity management. It incorporates the concept of skill development of workers in rural areas. RWM in the study area followed the process of prefabrication. This concept of capacity management has been employed in developing the fabrication skill of unskilled workers. This aspect has been discussed elaboratively in Chapter 6.

5.4.2.7 R-BIM: 7D – Safety management

Another salient feature identified and integrated into the study is safety management. Stakeholders overlook safety guidelines during construction in rural areas; consequently, it impends to an increase in fatality rates. Assessing the risk factor involved in the construction activities produces safety for on-site workers. Risk assessment, postulation of safety guidelines for the project activities, and monitoring at the sites using BIM technology facilitate the workers with ensured safety. Choudhry et al. (2008) pointed out the establishment of safety principles in developing countries by simultaneously considering the international and national/regional practices in effect. Hence, this thesis followed a set of regulations in safety management from a developed country (China) by focusing on the regional construction traditions. Risk degree (*r*) has been determined by equation (5.4) (Ding et al., 2014) in representing the level of risk associated with each activity. P_f denotes risk probability whereas

C_f represents the severity of consequences. The values of P_f and C_f have been obtained based on the standards in Table 5.13 and Table 5.14. The attained value of risk leads to determining the risk levels ranging from 0-1 among the five categories as represented in Table 5.15.

$$r = P_f + C_f - P_f C_f \tag{5.4}$$

Table 5. 13 Value of risk probability(P_f)

Level	**Estimate value**	**Description**
First	0.0 – 0.2	Risk severity is small
Second	0.2 – 0.4	Risk severity is mild
Third	0.4 – 0.6	Risk severity is medium
Fourth	0.6 – 0.8	Risk severity is high
Fifth	0.8 – 1.0	Risk severity is extremely high

Table 5. 14 Value of severity of consequences(C_f)

Level	**Estimate value**	**Description**
First	0.0 – 0.2	Risk severity is small
Second	0.2 – 0.4	Risk severity is mild
Third	0.4 – 0.6	Risk severity is medium
Fourth	0.6 – 0.8	Risk severity is high
Fifth	0.8 – 1.0	Risk severity is extremely high

Table 5. 15 Value of risk level (r)

Level	Estimated value	Colour code	Description
First	0 – 0.2	🟩	Risk can be ignored
Second	0.2 – 0.25	🟦	Risk level is low, but needs attention
Third	0.25 – 0.3	🟨	Risk level is acceptable, but needs supervision
Fourth	0.3 – 0.35	🟧	Risk level is not acceptable, and accident preventive actions should be taken
Fifth	0.35 – 0.1	🟥	Risk level is not acceptable, and construction work should be suspended and carried with safety guidelines.

As per Table 5.2, the list of activities regarding manufacturing, transportation, fabrication, on-site construction, and underground excavation (P14 to P31) has been assessed and classified for risk level and presented in Table 5.16. The above-mentioned activities have been shared with the safety management personnel and rural stakeholders, and based on their responses, the risk assessment feature has been carried. The details of the expert responses have been included in Appendix – C.

Table 5. 16 Risk identification and classification concerning project activities

Activity Code	Description	Risk Value	Category	Colour Classification
P14	Preparation of dye frame	0.15	First	🟩
P15	Manufacturing GRP panels for household tanks	0.22	Second	🟦
P16	Transportation of GRP panels of household tanks	0.19	First	🟩
P17	Fabrication of household tanks at the site	0.28	Third	🟨
P18	Excavation for household tanks	0.29	Third	🟨
P19	Placing of household tanks	0.33	Fourth	🟧
P20	Backfilling for household tanks	0.32	Fourth	🟧
P21	Connection of rooftop rainwater harvesting system & Solar water pump	0.17	Second	🟦
P24	Cleaning and excavation for directional tunnel	0.37	Fifth	🟥
P25	Manufacturing GRP panels for directional tunnel	0.22	Second	🟦

P26	Transportation of GRP panels of directional tunnel	0.19	First	🟩
P27	Fabrication of GRP panels for directional tunnel at the site	0.38	Fifth	🟥
P28	Excavation for interconnection among all water tanks and directional tunnel	0.41	Fifth	🟥
P29	Laying of pipelines	0.24	Second	🟦
P30	Backfilling of pipeline and directional tunnel	0.42	Fifth	🟥
P31	Finishing works	0.21	Second	🟦

Risk analysis helped in assisting the workers regarding upcoming risks, safety measures, and real-time threats. Safety dashboards were communicated and monitored via the BIM cloud platform. Moreover, the Occupational Safety and Health Administration (OSHA) standards have also been considered for the risk assessment by a 5x5 matrix method. Out of the three matrix sizes, i.e., 3x3, 4x4, and 5x5, the selected format allowed for conducting risk assessment in a detailed manner (Central Bedfordshire n.d.). Risk has been computed by equation 5.5 (International Labour Organization 2019), where each activity's likelihood and consequence levels were checked.

$$\text{Risk} = \text{Likelihood} \times \text{Consequence} \qquad (5.5)$$

The 5x5 matrix system involves likelihood and consequence scores ranging from 1-5 for different scenarios, as represented in Table 5.17 and Table 5.18. The product of the acquired scores leads to colour classification in a 5x5 matrix comprising four colours, as depicted in Figure 5.14. The final risk assessment of the activity depends on the four classifications such as acceptable, adequate, tolerable and unacceptable, as illustrated in Table 5.19.

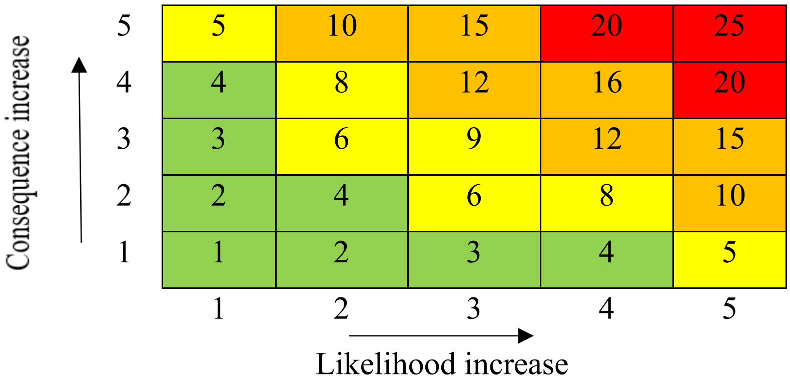
Table 5. 17 Standards in scoring for the likelihood

Likelihood	**Description**	**Score**
Catastrophic	Chance of death	5
Major	Worker would be unavailable for more than 3 days	4
Moderate	Worker would be unavailable for 1-3 days	3

Unlikely	Chance of happening is 1 in 100,000	2
Very unlikely	Chance of happening is 1 in a million	1

Table 5. 18 Standards in scoring for the consequence

Consequence	**Description**	**Score**
Insignificant	No injury	1
Minor	Minor injuries and needs first aid	2
Fairly Likely	Chance of happening is 1 in 10,000	3
Likely	Chance of happening is 1 in 1,000	4
Very Likely	Chance of happening is 1 in 100	5



5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
	1	2	3	4	5

Figure 5. 14 Colour classification by risk matrix

Table 5. 19 Risk assessment based on colour code

Range	**Colour**	**Classification**	**Description**
1-4	🟩	Acceptable	Further action not required, however ensure control measures.
5-9	🟨	Adequate	Safety measures seek improvement at the next review
10-16	🟧	Tolerable	Require improvement in safety measures within specific timeline.

17-25	🟥	Unacceptable	Suspend the activity and make instant corrections

The earlier mentioned activities, P14 to P31 (as per Table 5.2) have been communicated to the safety management personnel and rural stakeholders and the pertaining risk level has been assessed. The collected responses helped in determining risk value and category for all activities, presented in Table 5.20. The details of the expert responses have been included in Appendix – D.

Table 5. 20 Risk assessment for the planned activities

Activity No.	Description	Risk Value	Category	Colour Classification
P14	Preparation of dye frame	1	Acceptable	🟩
P15	Manufacturing GRP panels for household tanks	2	Acceptable	🟩
P16	Transportation of GRP panels of household tanks	3	Acceptable	🟩
P17	Fabrication of household tanks at the site	5	Adequate	🟨
P18	Excavation for household tanks	7	Adequate	🟨
P19	Placing of household tanks	12	Tolerable	🟧
P20	Backfilling for household tanks	10	Tolerable	🟧
P21	Connection of rooftop rainwater harvesting system & Solar water pump	2	Acceptable	🟩
P24	Cleaning and excavation for directional tunnel	20	Unacceptable	🟥
P25	Manufacturing GRP panels for directional tunnel	2	Acceptable	🟩
P26	Transportation of GRP panels of directional tunnel	3	Acceptable	🟩
P27	Fabrication of GRP panels for directional tunnel at the site	20	Unacceptable	🟥
P28	Excavation for interconnection among all water tanks and directional tunnel	20	Unacceptable	🟥
P29	Laying of pipelines	2	Acceptable	🟩
P30	Backfilling of pipeline and directional tunnel	16	Unacceptable	🟥

P31	Finishing works	3	Acceptable	🟩

The conducted risk analyses with respect to both standards produce close results in risk classification. Hence, the real-time safety management measures were performed in the actual phase for the on-site workers.

5.5 Summary of the chapter

R-BIM framework varying from 2D to 7D, focusing on the solution of RI problems, has been formed. This framework has been discussed through a case study on RWM strategy involving directional tunnel execution. The tasks in the planning: 2D involved determination of multiple activities, household tank and directional tunnel size, and selection of dead-end pipe network based on the decision-maker's results through AHP. Visualisation involved the development of 3D models in the RWM. Schedule management: 4D and cost management: 5D highlighted the scheduling information of 135.5 days through the PERT technique and cost estimation of Rs. 40,55,005 for the complete RWM execution. Simultaneously, two standard risk assessment procedures have emphasised risk classification for on-site workers, i.e., safety management: 7D. The execution phase of the RWM using the developed R-BIM models and the validations have been discussed in the next chapter.

References

Al-Barqawi, H. and Zayed, T., 2008. Infrastructure Management: Integrated AHP/ANN Model to Evaluate Municipal Water Mains' Performance. Journal of Infrastructure Systems, 14 (4), 305–318.

Aşchilean, I., Badea, G., Giurca, I., Naghiu, G.S., and Iloaie, F.G., 2017. Choosing the Optimal Technology to Rehabilitate the Pipes in Water Distribution Systems Using the AHP Method. Energy Procedia, 112, 19–26.

Caro-Borrero, A., Carmona-Jiménez, J., and Figueroa, F., 2020. Water resources conservation and rural livelihoods in protected areas of central Mexico. Journal of Rural Studies, 78, 12–24.

Central Bedfordshire, n.d. Risk Assessment Guidelines & Template [online]. Available from: https://www.centralbedfordshire.gov.uk/migrated_images/risk-assessment-theatre_tcm3-23223.pdf [Accessed 20 Oct 2021].

CGWB, 2020. Ground Water Year Book Rajasthan, Department of Water Resources, River Development & Ganga Rejuvenation. 24.

Central Pollution Control Board - ENVIS, 2016. Rainwater Harvesting in India – An appraisal [online]. Available from: http://cpcbenvis.nic.in/envis_newsletter/RWH in India - An Appraisal CPCBENVIS.pdf [Accessed 1 May 2019].

Choudhry, R.M., Fang, D., and Rowlinson, S., 2008. Challenging and Enforcing Safety Management in Developing Countries: A Strategy. International Journal of Construction Management, 8 (1), 87–101.

Central Water Commission, 2017. Guidelines for Planning and Design of Piped Irrigation Network, Ministry of Water Resources, Government Of India, New Delhi., 1-126.

Ding, L., Zhou, Y., and Akinci, B., 2014. Building Information Modeling (BIM) application framework: The process of expanding from 3D to computable nD. Automation in Construction, 46, 82–93.

El Chanati, H., El-Abbasy, M.S., Mosleh, F., Senouci, A., Abouhamad, M., Gkountis, I., Zayed, T., and Al-Derham, H., 2016. Multi-Criteria Decision Making Models for Water Pipelines. Journal of Performance of Constructed Facilities, 30 (4), 1-12.

Eliseev, M., Tomchinskaya, T., Lipenkov, A., and Blinov, A., 2017. Using 3D-modeling Technologies to Increase Road Safety. Transportation Research Procedia, 20, 171–179.

India Water Portal, 2006. Roof Top Rainwater Harvesting [online]. Available from: https://www.indiawaterportal.org/sites/indiawaterportal.org/files/Roof Top Rainwater

Harvesting_Presentation_2006.pdf [Accessed 12 Apr 2019].

Integrated Schedule of Rates, 2017. [online]. Available from: https://urban.rajasthan.gov.in/content/dam/raj/udh/organizations/ruidp/Downloads/BSR/RUIDP ISOR- 2017.pdf [Accessed 10 Sep 2019].

International Labour Organization, 2019. Improving OSH for Young Workers: A Self-Training Package [online]. Available from: https://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---lab_admin/documents/publication/wcms_724880.pdf [Accessed 22 Jan 2022].

Jan, S., Cohen, A., and Oron, G., 2020. Multi-objective optimization for solving water shortage issues in arid zones via the analytic hierarchy process (AHP): The Israeli case. Desalination and Water Treatment, 188, 10–19.

Jung, Y. and Joo, M., 2011. Building information modelling (BIM) framework for practical implementation. Automation in Construction, 20 (2), 126–133.

Jung, K., Lee, T., Choi, B.G., and Hong, S., 2014. Rainwater Harvesting System for Continuous Water Supply to the Regions with High Seasonal Rainfall Variations. Water Resources Management, 29 (3), 961–972.

Maqsoom, A., Rashid, H.B., Aslam, B., Ashraf, H., Abid, M., and Ejaz, A., 2020. Building information modeling application for groundwater recharge: Development of multiple structures. Environmental Engineering and Management Journal, 19 (7), 935–945.

McArthur, J.J., 2015. A Building Information Management (BIM) Framework and Supporting Case Study for Existing Building Operations, Maintenance and Sustainability. Procedia Engineering, 118, 1104–1111.

Mukheibir, P., Boyle, T., Moy, C., and White, S., 2014. Estimating the reliable residential water substitution from household rainwater tanks. Water Practice and Technology, 9 (3), 377–385.

Pagano, A., Giordano, R., and Vurro, M., 2021. A Decision Support System Based on AHP for Ranking Strategies to Manage Emergencies on Drinking Water Supply Systems. Water Resources Management, 35 (2), 613–628.

Punmia, B. C., and Khandelwal, K. K., 2006. Project Planning and Control with PERT & CPM. 4th edition, Lakshmi Publication, New Delhi, Firewall media.

Saaty, T. L. 1994. How to make a decision: the analytic hierarchy process. Interfaces, 24(6), 19-43.

Salazar, G.F., and Romero, S.A., 2016. Site-Building Integrated BIM Models: Lessons Learned in Education. Proceedings of the 10th BIM Academic Symposium, April 2016, 84-91.

Shahid, F., Ahmed, Z., Hussain Ali, T., Ali Moriyani, M., and Hussain Khahro, S., 2019. A Stepped Wise Approach and Barriers towards Implementation of BIM Toolkits of Infrastructure Project in Pakistan. 2nd International Conference on Sustainable Development in Civil Engineering, MUET, Pakistan, 53-57.

Stauffer, B., 2020. Network Design and Dimensioning [online]. Available from: https://sswm.info/sswm-university-course/module-2-centralised-and-decentralised-systems-water-and-sanitation-1/network-design-and-dimensioning [Accessed 22 Oct 2021].

Succar, B., Sher, W., Aranda-mena, G., and Williams, T., 2007. A Proposed Framework To Investigate Building Information Modelling Through Knowledge Elicitation and Visual Models. Conference Proceedings of the Australasian Universities Building Education Association (AUBEA), 1-18.

Tagliabue, L. C., and Ciribini, A. L. C., 2018. A BIM-Based IoT Approach to the Construction Site Management. New Frontiers of Construction Management Workshop, 9(13), 136-145.

Tanyimboh, T.T. and Kalungi, P., 2009. Multicriteria assessment of optimal design, rehabilitation and upgrading schemes for water distribution networks. Civil Engineering and Environmental Systems, 26 (2), 117–140.

Water Resources Department - Rajasthan, 2019. Annual Rainfall Data for year 2018 [online]. Available from: http://water.rajasthan.gov.in/content/dam/water/water-resources-department/Rainfall/Rainfall data/DAILY RAINFALL DATA FOR YEAR 2018.pdf [Accessed 15 Apr 2019].

Wei, T. and Chen, G., 2017. Optimal selection on water-supply pipe of building based on analytic hierarchy process. IOP Conference Series: Earth and Environmental Science, 61 (1), 1–7.

Zyoud, S.H., Fuchs-Hanusch, D., Shaheen, H., Samhan, S., Rabi, A., and Al-Wadi, F., 2016. Utilizing analytic hierarchy process (AHP) for decision making in water loss management of intermittent water supply systems. Journal of Water Sanitation and Hygiene for Development, 6 (4), 534–546.

CHAPTER 6: EXECUTION OF R-BIM AND ITS VALIDATION BY EARNED VALUE ANALYSIS

6.1 Chapter overview

This chapter considers the execution phase of the R-BIM framework applied to RWM. The complete application in achieving all the objectives has been focused on by the operation of BIM Cloud. The executed study was validated by adopting the EVA principle. The RWM study without the effect of R-BIM has been compared with that of the R-BIM application. The EVA results have been interpreted for perceiving the overall compatibility of the deployed R-BIM framework.

6.2 Actual phase

The actual phase of R-BIM began with the efficient utilisation of 3D models. Firstly, the visual modelling of the whole RWM system including the identified household tanks and directional tunnel at the community before expert ranked pipe network selection has been created, shown in Figure 6.1. The usage of BIM tools; AutoCAD and Autodesk Infraworks assisted in achieving the outcome. Secondly, after considering the attained result of dead-end system pipe network, discussed in section 5.4.2.2, the connection among the household tanks and directional tunnel was developed, as illustrated in Figure 6.2. Eventually, the intended objective of conveying the excess rainwater from each household tank into directional tunnel was demonstrated. The water overflow diversion to the directional tunnel acts as an alternate solution in the existing RWH systems at rural areas.

The created models have been communicated to all the stakeholders. A rendered video, known as a flythrough video, made the residents experience a more straightforward interpretation. As a result, it helped in convincing the residents to follow up and install the RWH method. In this conjuncture, the participatory management concept has been explored in three ways by involving stakeholders in the decision-making of the pipe network, residents' role in selecting the directional tunnel's location, and pursuance of RWH. Finally, the virtual models assisted the client and other stakeholders perceive the pipe network and directional tunnel installation distinctly.

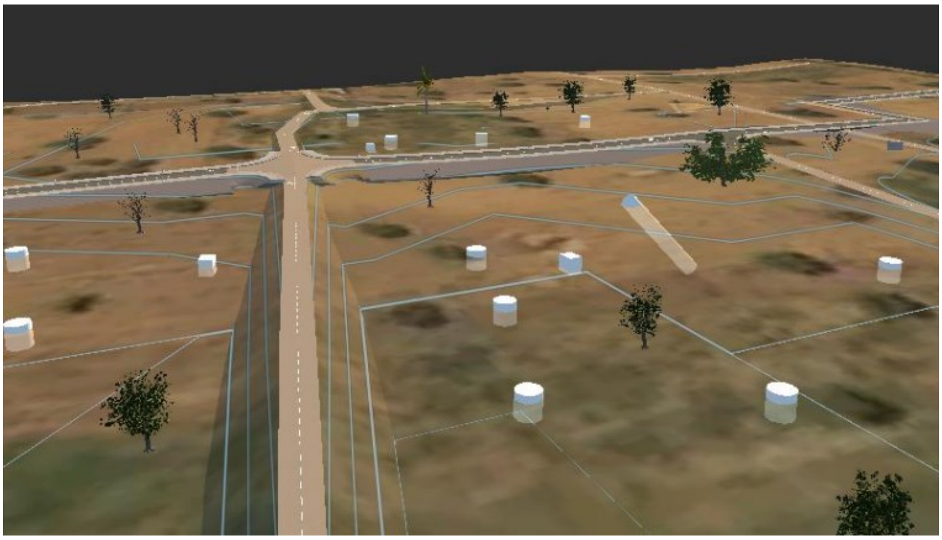


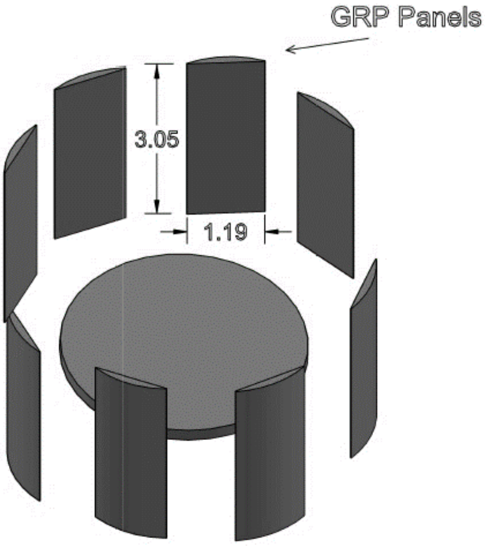
Figure 6. 1 Visual modelling of identified household tanks and directional tunnel at the community level before pipe network selection

Figure 6. 2 Visual modelling of entire RWM set-up with the dead-end system pipe network

The literature study inferred that managing equipment and materials at construction sites had been a significant obstacle in RI projects. The study area (Ramnathpura in Rajasthan) was at a remote location. Off-site prefabricated GRP panels of both water infrastructures were desired to reach the construction site without any deformation. Hence, the transport vehicles favouring the sub-contractors for organised haulage of the prefabricated materials to the on-site location have been modelled, as indicated in Figure 6.3.

Figure 6. 3 Modelling for haulage of prefabricated materials

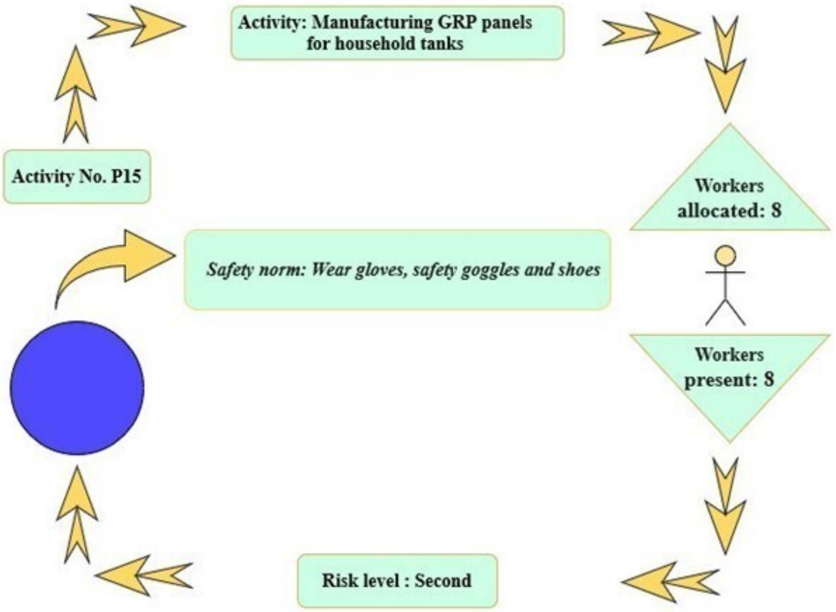
Many of the workers in the selected rural area were unskilled and unaware of the prefabrication and assembling process at the worksite. A skill development feature, i.e., capacity management for their skill enhancement, has been incorporated through R-BIM. According to this aspect, eight separate GRP panels have been manufactured to form a household tank, as illustrated in Figure 6.4. The engineers shared the fabrication process's virtual models through a BIM cloud platform; later, the contractor team head demonstrated the combining process to the on-site workers.



(All dimensions are in metres)

Figure 6. 4 Fabrication and assembling process for household tanks

The risk analysis, discussed in section 5.4.2.7, helped to postulate safety guidelines concerning each activity in the RWM execution timeline. The first risk assessment has been preferred between the two adopted standards since it correlates with the R-BIM study. Safety measures were categorised depending on the five risk levels. Each activity's associated rural stakeholders were communicated regarding the safety guidelines through dashboards in the BIM cloud platform. Later, those corresponding stakeholders notified and assured the implementation of those safety measures to the on-site workers, as illustrated in Figure 6.5 (instance of activity P15 has been displayed).



(P15: Manufacturing GRP panels for household tanks)

Figure 6. 5 Safety dashboard operated in BIM cloud for activity P15

6.2.1 Progress of RWM execution in the selected area

Reciprocation of the planned activities into the actual on-site execution was challenging. The actual duration of RWM completion led to 163 days. Duration of activities P4 & P5 increased since community meetings and identification of residents involved consent regarding the innovative method's implementation. The final activities assigned against the actual duration involved during the actual phase have been indicated in Table 6.1. During the actual phase, the manufacturing and fabrication of GRP panels for the household tanks have been more than the expected duration (activities P15 & P17 in Table 6.1) because of the time required in perceiving technology. In contrast, those activities for the directional tunnel (activities P25 & P27 in Table 6.1) have been faster than the planned duration.

Table 6. 1 Activities at the actual phase of RWM

Activity Code	Description	Actual duration (days)
P1	Identification of villages	2
P2	Feasibility survey	3
P3	Creation of visualisations for whole water management in the community	2
P4	Community meetings and collection of inputs from residents	4
P5	Identification of residents	8
P6	Selection of residents	2
P7	Household survey	2
P8	Selecting feasible location of household tanks	4
P9	Schedule estimation for onsite execution	1
P10	Resources and cost estimation	1
P11	Skill development for workers	4
P12	Risk identification and determining safety guidelines	1
P13	Procurement of materials for dye frame & GRP panels	13
P14	Preparation of dye frame	5.5
P15	Manufacturing GRP panels for household tanks	46
P16	Transportation of GRP panels of household tanks	5.5
P17	Fabrication of household tanks at the site	23
P18	Excavation for household tanks	7
P19	Placing of household tanks	2.5
P20	Backfilling for household tanks	5
P21	Connection of roof top rainwater harvesting system & Solar water pump	15
P22	Directional tunnel area selection	1.5
P23	Site approval for directional tunnel	1.5
P24	Cleaning and excavation for directional tunnel	2.5
P25	Manufacturing GRP panels for directional tunnel	10.5
P26	Transportation of GRP panels of directional tunnel	2
P27	Fabrication of GRP panels for directional tunnel at the site	5.5
P28	Excavation for interconnection among all household tanks and directional tunnel	3
P29	Laying of pipelines	2

P30	Backfilling of pipeline and directional tunnel	3
P31	Finishing works	3

The manufactured GRP panels have been transported and assembled at the site area, as shown in Figure 6.6. The final GRP household tank has been erected, as depicted in Figure 6.7. Once the household tank was identified in perfect condition, its installation 2.45m below the ground level has been performed, as depicted in Figure 6.8. The upper portion of the tank connects the inlets and outlets from various other tanks in the community by forming a channelled pipe network.

Figure 6. 6 Assembling GRP panels

Figure 6. 7 Final GRP household tank

Figure 6. 8 Installed household tank

Gutters and downspouts have been utilised for the rooftop connection, and these fittings allowed a free flow of rainwater to the household tanks. The first flush connection has been integrated into the household tanks since it has the advantages of collecting settleable solids, debris and improving the water quality through rooftop rainwater connections (Stump et al., 2012). After the construction and installation of twenty-five GRP household tanks, the installation of the directional tunnel has been carried out. The materials and method adopted for the directional tunnel have been similar to household tanks. Therefore, all the GRP panels of the directional tunnel have been manufactured, transported, and assembled at the worksite. A total of seven GRP household tanks were connected in a series, forming the directional tunnel with a volume of 150m^3 for the harvested rainwater, as portrayed in Figure 6.9. The joints between the longitudinally connecting GRP panels have been covered with the selected glass fibre mats. The failure analysis discussed in chapter 4, has indicated failure points at the cover and base areas of the directional tunnel. Hence, this failure scenario has been compensated and structurally strengthened with the providence of diagonally placed wooden logs at both locations of the structure, as represented in Figure 6.10. Initially, the joints of the directional tunnel were covered with the bi-directional glass fibre mats and coated with epoxy-resin hardener mixture. The joints were hand pressed by pressure and set to cure. Wooden planks were fixed to the exact internal diameter at the base and cover areas of the directional tunnel as per the highlighted spots in failure analysis of PLAXIS 3D simulations. Later, the sandy soil was compacted layer by layer and backfilled around the external surface area of directional tunnel. Consequently, the overall installation has been done and failure of soil layers surrounding the directional tunnel has been overcome during on-site execution. The final directional tunnel has been represented in Figure 6.11. Subsequently, the interconnection of pipes through the dead-end pipe system among the GRP household tanks and directional tunnel has resulted in a channelled pipe network. All the pipe connections have been joined to three masonry chambers for maintaining water head balance. Three inlets have been connected to the directional tunnel for conveying the exceeded rainwater from twenty-five GRP household tanks. Solar water pumps have been installed for retrieving water from these rainwater storage structures in an energy-efficient manner, as shown in Figure 6.12.

Figure 6. 9 Assembling GRP panels of directional tunnel

Figure 6. 10 Strengthening of directional tunnel at analysed failure points during execution

Figure 6. 11 Final directional tunnel

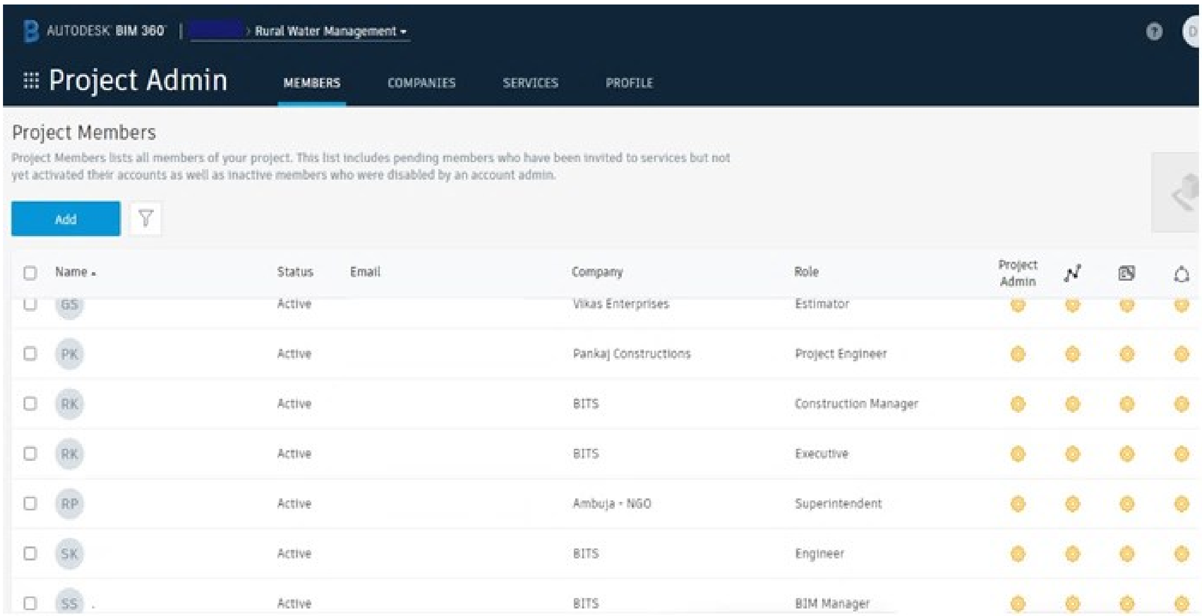
Figure 6. 12 Installation of solar water pump at a household GRP water tank

6.3 Operation of R-BIM by concerned rural stakeholders

The field of BIM cloud operations is growing faster in the modern world. The different stakeholders' cloud operations yield the advantage of precise and effective evaluation. Du et al. (2014) have developed a Building Information Modelling Cloud Score (BIMCS) application for assessing and scoring a broad range of BIM users across a nation. Eventually, the complete operations of R-BIM have been managed in a BIM cloud application. Autodesk BIM 360, a common shared platform for obtaining successful outcomes and engaging all project teams using real-time construction data (Construction management software, 2019), has been adopted for rural stakeholders' participation and synchronised coordination in R-BIM's planned and actual phases. It consists of two main features, a) Document management and b) Design collaboration. Different electronic devices such as computers, mobiles, and tablets have been used for daily tracking. The design collaboration feature in the BIM cloud; helped in communicating flythrough videos of the RWM set-up. The cloud platform has included capacity management concerning the prefabrication method's demonstration for unskilled workers and haulage vehicle modelling. Moreover, it also supported the manufacturing and fabrication of directional tunnel related activities, which led to faster completion than the estimated time. In comparison, document management dealt with codes, specifications, schedules, drawings, and plans of household tanks, directional tunnel, and EVA reports of the complete RWM execution.

Team heads may vary concerning different projects in an urban scenario, but the most prominently recognised have been client/owner, architect/designer, consultant/engineer, and contractor (Tang et al., 2019). Distinguished primary team heads do not exist in R-BIM; hence this thesis defines potential roles. The client provided funds for constructing the whole RWM. Engineers were involved in the construction and supervision. Unlike the urban set-up, residents participated directly in the RI project's decision-making. Finally, the different stakeholders identified in the R-BIM process were client, engineers, rural officials, contractors, rural coordinators, NGO personnel, and residents. The rural stakeholders' engagement throughout different dimensions of R-BIM process and their inclusion in the Autodesk BIM 360 platform have been depicted in Figure 6.13 and Figure 6.14, respectively. The rural stakeholders accessed tender documents, drawing plans, virtual models, flythrough videos, project schedules, cost estimation documents, and skill enhancement concepts on the common platform. A contractor raised an issue concerning the directional tunnel's plan within a stipulated deadline, and the engineer reviewed the case with a detailed update. Similarly, the cloud operation clarified multiple issues concerning rural stakeholders, such as schedule updates, technical details, and execution progress.

Figure 6. 13 Rural stakeholders and their engagement in R-BIM



Project Members

Project Members lists all members of your project. This list includes pending members who have been invited to services but not yet activated their accounts as well as inactive members who were disabled by an account admin.

☐	Name ▴	Status	Email	Company	Role	Project Admin			
☐	GS	Active		Vikas Enterprises	Estimator	●	●	●	●
☐	PK	Active		Pankaj Constructions	Project Engineer	●	●	●	●
☐	RK	Active		BITS	Construction Manager	●	●	●	●
☐	RK	Active		BITS	Executive	●	●	●	●
☐	RP	Active		Ambuja - NGO	Superintendent	●	●	●	●
☐	SK	Active		BITS	Engineer	●	●	●	●
☐	SS .	Active		BITS	BIM Manager	●	●	●	●

Figure 6. 14 Joining stakeholders in the BIM Cloud platform

6.4 Validation by Earned Value Analysis

The popular methods followed in evaluating and assessing projects have been a) Forecasting: utilises budgeted cost, total estimated cost, liable costs, present costs, and under or over-budgeted costs to estimate future costs, b) Variance analysis: entails determining whether the project is on budget by examining the variation between the budgeted and actual expenditures, c) Performance reviews: evaluates the status of a project by identifying the project's expenses, schedule, scope, quality, and teamwork, d) Earned Value Analysis: follows a set of formulae to measure the progress of a project against the planned work (Project Cost Management 2021). ss

Among all the methods, EVA is a widely sought-after concept for project managers and leaders since it has been a broad technique for analysing a team's performance throughout a project. Eventually, EVA has been considered for validating the case study. It supported in evaluating the present study’s performance of the work executed against the work planned. EVA acts as an accounting tool by accumulating the project's schedule, work scope, and cost components (Kenley and Harfield, 2015). Besides construction firms, multiple sectors acknowledged EVA in project management (Keng and Shahdan, 2015; Martynenko et al., 2017). The EVA reports depended on the activities, schedule, and expenses incurred in the study area. The main parameters used in EVA have been a) Planned Value (PV), b) Actual Cost (AC), and c) Earned Value (EV). Standards of EVA, as presented in Table 6.2, helped in the computation and analysis of different cost and schedule variables (Project Management Institute, 2005; BIS15883, 2013).

Table 6. 2 Standards of Earned Value Analysis

Performance Indicator	**Formula**	**Analysis**		
Schedule Variance (SV)	EV – PV	< 0; Delay in plan	= 0; On plan	> 0; Ahead of plan
Cost Variance (CV)	EV – AC	< 0; Over budget	= 0; On budget	> 0; Within budget
Schedule Performance Index (SPI)	EV / PV	< 1; Behind plan	= 1; On plan	>1; Within plan
Cost Performance Index (CPI)	EV/AC	< 1; Over budget	= 1; On budget	>1; Within budget

The collective efforts of all rural stakeholders led to 78% accomplishment of the overall planned work on the 135th day. Simultaneously, the planned value for project completion (budget at completion) was Rs.40,55,005. Engineers and client tracked the work progress. The computed earned value on an interval of 30th day was based on equation (6.1) (Lukas, 2012). Moreover, the planned value has been cumulative of the budgeted cost of activities at the same interval in the complete planned duration. The schedule and cost performance index values on the 135th day were thus obtained and adhered to the standards of EVA, shown in Table 6.3.

$$Earned\ Value\ (EV) = Percentage\ of\ work\ completed\ x\ Budget\ at\ completion \quad (6.1)$$

Table 6. 3 Calculation of SPI and CPI as per EVA

S.No.	Days (nos.)	Planned Value (PV) (INR)	Actual Cost (AC) (INR)	Percentage of work completed (%)	Earned Value (EV) (INR)	Schedule Variance (SV) (INR)	Cost Variance (CV) (INR)	Schedule Performance Index (SPI)	Cost Performance Index (CPI)
1.	30	1322340	1298538	30	1216502	-105839	-82037	0.92	0.94
2.	60	2022735	2022730	40	1622002	-400733	-400728	0.80	0.80
3.	90	3567890	3687906	55	2230253	-1337637	-1457653	0.63	0.60
4.	120	3845705	3966330	66	2676303	-1169402	-1290027	0.70	0.67
5.	135	4055005	4292909	78	3162904	-892101	-1130005	0.78	0.74

The final EVA of RWM has been plotted based on the obtained results, as shown in Figure 6.15. Besides, SPI and CPI have been outlined for the schedule and cost variation identified on the 135th day, shown in Figure 6.16. The negative sign (-ve) of SV and CV indicate delayed work and cost overrun. Values of SPI and CPI on the 30th day have been 0.92 and 0.94, respectively, which means time and budget have been near control. Both index values on 60th, 90th, 120th day reflect that the implementation has been behind the plan and over the budget. On the 135th day, SPI and CPI were recorded 0.78 and 0.74, respectively. Finally, the total accounted cost for the RWM implementation has been Rs.48,28,279 after its completion on the 163rd day. Even though the R-BIM framework method applied to the RWM study has been innovative with a modern application, the time for technology adoption resulted in delay and over budget.

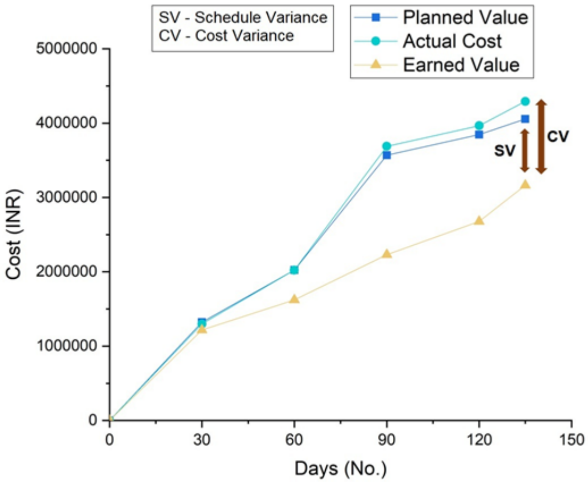


Figure 6. 15 Final Earned Value Analysis of RWM

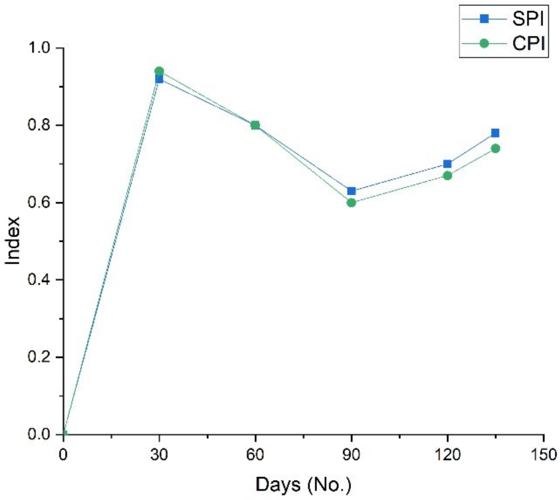


Figure 6. 16 Variability of SPI and CPI

6.4.1 Rural Water Management execution ignoring the R-BIM effect

On the contrary, the scenario of executing the entire RWM through the RWH method in the selected locality without imposing R-BIM has been considered for finding the permissibility of the R-BIM framework. This aspect's schedule and cost for completion have been projected based on the reflections of two components: a) local people and rural stakeholders' inputs regarding the earlier water management projects in the region, and b) estimated items' quantities and workforce required in the execution.

The complete activities involved in execution have been initially framed, indicated in Table 6.4. The schedule estimation as per PERT method, resulted in a deferred deadline of 195 days, accounting for Rs.56,68,560, as shown in Table 6.5. The primary impediments such as remote location, haulage of materials, fabrication process, increase in labour, local people disagreement, distorted pipe network and their lay-up could lead to extended delay and over budget. In activity code, R refers to denotation regarding activities without the effect of R-BIM.

Table 6. 4 Activities of RWM execution without R-BIM application

Activity Code	Description	Duration (days)	Predecessor
R1	Identification of villages	2	-
R2	Feasibility survey	7	R1
R3	Community meetings and collection of inputs from residents	8	R2
R4	Identification of residents	7	R3
R5	Selection of residents	3	R4
R6	Household survey	2	R4
R7	Selecting feasible location of household tanks	4	R5
R8	Procurement of materials for dye frame & GRP panels	15	R6, R7
R9	Preparation of dye frame	10	R8

R10	Manufacturing GRP panels for household tanks	50	R8
R11	Transportation of GRP panels of household tanks	8	R10
R12	Fabrication of household tanks at the site	30	R11
R13	Excavation for household tanks	7	R7, R12
R14	Placing of household tanks	2	R13
R15	Backfilling for household tanks	5	R14
R16	Connection of roof top rainwater harvesting system & Solar water pump	14	R15
R17	Directional tunnel area selection	3	R6
R18	Site approval for directional tunnel	4	R17
R19	Cleaning and excavation for directional tunnel	2	R18
R20	Manufacturing GRP panels for directional tunnel	14	R9
R21	Transportation of GRP panels of directional tunnel	4	R16, R19, R20
R22	Fabrication of GRP panels for directional tunnel at the site	10	R21
R23	Excavation for interconnection among all household tanks and directional tunnel	3	R22
R24	Laying of pipelines	5	R23
R25	Backfilling of pipeline and directional tunnel	6	R24
R26	Finishing works	5	R23, R25

Table 6. 5 Estimated budget for completion of RWM excluding R-BIM effect

Activity Code	**Description**	**No.s/Qty**	**Rate (Rs.)**	**Cost (Rs.)**
R8	Procurement of materials for dye frame & GRP panels	1	34,685	34,685

R9	Preparation of dye frame	1	1,78,865	1,78,865
R10	Manufacturing GRP panels for household tanks	25	1,45,838	3,64,5950
R11	Transportation of GRP panels of household tanks	8	900	7200
R12	Fabrication of household tanks at the site	25	2134	53,350
R13	Excavation for household tanks	499.25	56.085	28,000
R14	Placing of household tanks	25	1156	28,900
R15	Backfilling for household tanks	499.25	56.085	28,000
R16	Connection of roof top rainwater harvesting system & Solar water pump	25	10411.5	2,60,288
R19	Cleaning and excavation for directional tunnel	312.5	78.75	24,609
R20	Manufacturing GRP panels for directional tunnel	1	9,93,538	9,93,538
R21	Transportation of GRP panels of directional tunnel	2	900	1800
R22	Fabrication of GRP panels for directional tunnel at the site	7	2134	14,938
R23	Excavation for interconnection among all household tanks and directional tunnel	575	82	47,150
R24	Laying of pipelines	2028	122.54	2,48,511
R25	Backfilling of pipeline and directional tunnel	887.5	82	72,775
	Final Estimate			56,68,560

Apparently, considering the planned values from the prior EVA validation (Table 6.3) and the statistical data concerning the RWM cost estimation (Table 6.5), the subsequent variables such as earned value, percentage of completion, schedule variance, and cost variance have been determined in the assessment. Using the EVA principle, the derived computations assisted in finding schedule and cost performance indicators for this aspect up to the R-BIM study's scheduled duration of 135 days, as shown in Table 6.6.

Table 6. 6 Calculation of SPI and CPI as per EVA ignoring R-BIM for RWM execution

S.No.	Days (nos.)	Planned Value (PV) (INR)	Actual Cost (AC) (INR)	Percentage of work completed (%)	Earned Value (EV) (INR)	Schedule Variance (SV) (INR)	Cost Variance (CV) (INR)	Schedule Performance Index (SPI)	Cost Performance Index (CPI)
1.	30	1322340	1533078	28	1135401	-186939	-397677	0.86	0.74
2.	60	2022735	2357065	34	1378702	-644033	-978363	0.68	0.58
3.	90	3567890	3900510	47	1905852	-1662038	-1994658	0.53	0.49
4.	120	3845705	4281428	59	2392453	-1453252	-1888975	0.62	0.56
5.	135	4055005	4612688	68	2757403	-1297602	-1855285	0.68	0.60

The EVA fluctuation in this scenario has been plotted, as shown in Figure 6.17. SPI's and CPI's variation identified on the planned 135th day has been illustrated in Figure 6.18. Values of SPI and CPI on the 30th day have been 0.86 and 0.74, respectively, which means time and budget have been behind the R-BIM study's attained valuation. Both index values have been below the R-BIM study's index levels throughout the set intervals of 60th, 90th, 120th, and 135th day in the assessment.

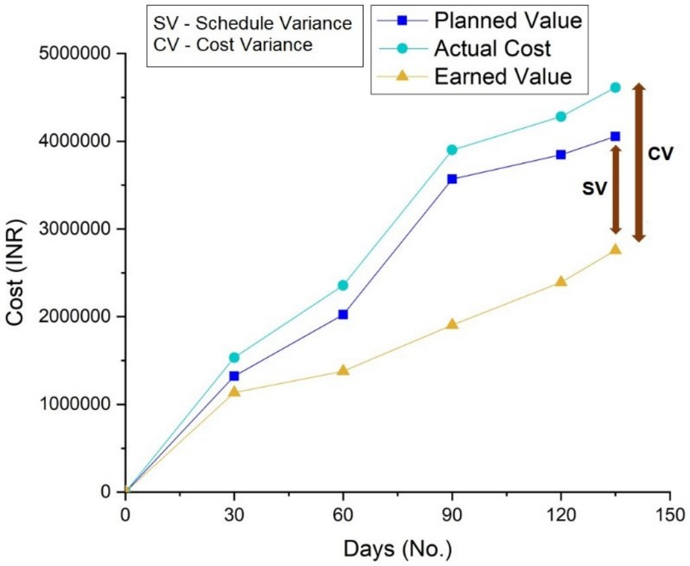


Figure 6. 17 Final Earned Value Analysis of RWM system ignoring R-BIM

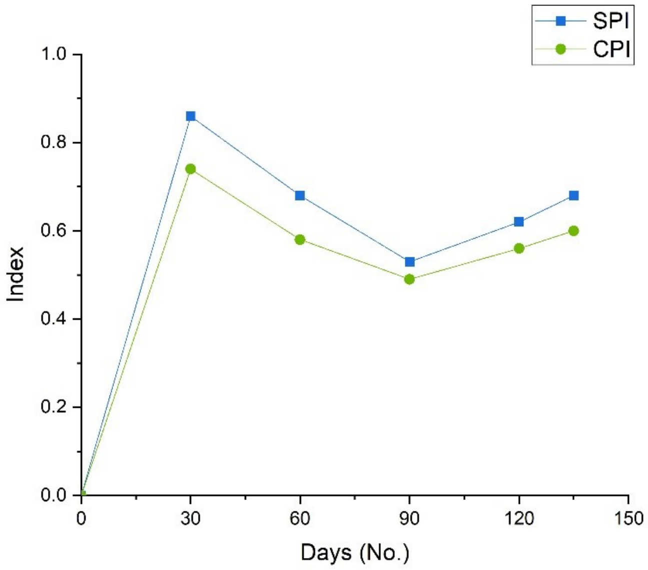


Figure 6. 18 Variation of SPI and CPI

Hence, the R-BIM framework application through RWM study upholds its acceptability; however, its enhancement is essential for attaining the optimum schedule and cost performance indicators' results closer to 1, so that the budget and schedule meet the planned phase estimation.

6.5 Summary of the chapter

The actual phase of the implemented RWM study using R-BIM framework at different stages has been portrayed in this chapter. The usage of the developed BIM models in 3D, 4D, 6D and 7D have been intensively discussed. The overall RWM execution lasted for 163 days and resulted in an expenditure of Rs. 48,28,279. An excess of 27.5 days and 19% more cost than the initial planned value has been observed. The role of rural stakeholders in the R-BIM's communication platform, i.e., Autodesk BIM 360 has been emphasized. The results of case study have been validated through the EVA principle. Moreover, the conducted analysis represents that the study needs enhancement for better outcomes in the terms of time and cost management. The scenario of implementing RWM execution excluding the effect of R-BIM has been compared in order to check the feasibility of the developed framework. The estimation produced an exceeding schedule of 59.5 days with 40% more cost than initial planned value. Finally, the acquired EVA results exhibited that the RWM system could experience over budget and delay compared with R-BIM framework's application.

References

BIS15883, 2013. Construction Project Management - Guidelines: Part 3 Cost Management, Draft IS 15883: Part 3, 30.

Construction management software. 2019. Connect your workflows, teams, and data, [online]. Available from: https://www.autodesk.com/bim-360/ [Accessed 17 Dec 2019].

Du, J., Liu, R., and Issa, R.R.A., 2014. BIM Cloud Score: Benchmarking BIM Performance. Journal of Construction Engineering and Management, 140 (11), 1-13.

Keng, T, C., and Shahdan, N., 2015. The application of Earned Value Management (EVM) in construction project management. Journal of Technology Management and Business, 2(2), 1-11.

Kenley, R. and Harfield, T., 2015. Construction Project Control Methodologies and Productivity Improvement: EVM, BIM, LBM, [online]. Available from: https://survey.unitec.ac.nz/bitstream/handle/10652/3400/Construction%20Project%20Control%20Methodologies%20and%20Productivity%20Improvement_EVM.pdf?sequence=3&isAllowed=y [Accessed 22 Oct 2020].

Lukas, J. A., 2012. How to make earned value work on your project. PMI Global Congress 2012 - Vancouver, British Columbia, Canada. Newtown Square, PA: Project Management Institute.

Martynenko, O., Husieva, Y., and Chumachenko, I., 2017. The method of earned requirements for project monitoring. Innovative technologies and scientific solutions for industries, 1(1), 58-63.

Project Cost Management, 2021. What is project cost management? Concepts [online]. Available from: https://www.workfront.com/project-management/knowledge-areas/cost-management [Accessed 28 Nov 2021].

Project Management Institute (PMI), 2011. Practice standard for earned value management. 2nd ed. Newtown Square, PA: Project Management Institute.

Stump, B., McBroom, M., and Darville, R., 2012. Demographics, practices and water quality from domestic potable rainwater harvesting systems. Journal of Water Supply: Research and Technology, 61 (5), 261–271.

Tang, Y., Wang, G., Li, H., Cao, D., and Li, X., 2019. Comparing Project-Based Collaborative Networks for BIM Implementation in Public and Private Sectors: A Longitudinal Study in Hong Kong. Advances in Civil Engineering, August, 1-15.

CHAPTER 7: CONCLUSIONS AND FUTURE SCOPE

7.1 Chapter overview

The final chapter provides all the statements of the work representing the established findings. Sections 7.2 portrays the surpassed challenges in RI projects highlighting water management, and section 7.3 derives the importance of directional tunnel as a rainwater storage structure. Section 7.4 elaborates on R-BIM framework and its results in the case study, and section 7.5 exhibits the conclusions of the research findings. Finally, sections 7.6 and 7.7 present the limitations and future scope, respectively.

7.2 Surpassing challenges in rural infrastructure projects

Rural development projects have a generic approach for rectifying practical issues, whereas RI projects lack a comprehensive problem-solving method since the nature and scenario have differed. The reviewed studies regarding the obstacles in RI projects in Chapter 2 accounted for developing the research method of R-BIM. The study concentrated on RWI; therefore, the features and evaluative techniques required for a better-planned water infrastructure system have been discussed. Literature study indicated that poor decision-making pertaining to RWIs has resulted in failures; therefore, the AHP technique has been endured in the pipe networking of RWH for functional water collection. The aspect of risk assessment has been practised in the planning stage of the RWM case study for workers' safety in remote locations. Hurdles in detailed construction, skill enhancement for labour, and communication platforms for RI project stakeholders have been solved through this study. A significant setback in the construction of RI projects lies in the level of projects' implementation since new technologies are not employed regularly. Hence, the combined effect of innovative water infrastructure and a modern technique has been explored through a directional tunnel and R-BIM concept validations.

7.3 Directional tunnel as a rainwater storage structure in rural community

Literature study denotes that the discussed RWH systems have challenges in the perspective of the individual's participation, water carriage and collection in a community. The innovative directional tunnel method for RWH has been proposed and executed, which has been under use at a village in Rajasthan, India.

The directional tunnel offers saved rainwater for multipurpose water-related activities besides potable uses, accumulating total storage of 150 m^3. Simultaneously, directional tunnel manufacturing using natural jute and glass fibre has been explored. Out of which, fabrication using jute fibre has the highlighted advantages of high mechanical strength and eco-friendliness. In comparison, glass fibre is lightweight and easy for haulage and fabrication. Moreover, the developed system's fabrication using GRP could be easily dismantled and moved from one location to another location. Manufacturing and fabrication of three-layered GRP panels have been useful for directional tunnel.

The installation of a directional tunnel demands a possible angle for execution; hence it has been checked for the stability in sandy soil concerning various declinations of 10°, 20°, 30°, 35°, and 40°. The stability analysis has been performed in PLAXIS 3D because of the software's high-quality deliverables and versatile reporting functionalities for data-driven decision-making. The simulated stability and failure analysis results recommend that the directional tunnel's position in the range of 30° - 34° is more practically viable in sandy soil for effective operation.

7.4 Emphasis on R-BIM framework

The concept of construction management for successful project delivery in rural areas has been highlighted in the thesis. Most of the existing efforts stress that role of BIM in infrastructure projects is crucial for comprehensive completion. On the other side, research concerning BIM's enforcement in RI projects is limited. The literature study inferred that RI difficulties and I-BIM application are distinctively noteworthy; however, these RI issues have not been explored by applying a BIM framework. The application of the BIM framework in a rural scenario, i.e., R-BIM framework has been emphasised through a RWM project. Besides, the carried-out work has been the first of its kind to implement digital models in India's RI sector.

Incorporating participatory management into R-BIM has been a defying task to overcome the RI problems. Moreover, the scope of organised planning, modelling, and coordination has been endeavoured. Decision-making in rural areas has been enforced into BIM adoption in the case study. R-BIM has been highlighted as the pre-visualisation tool before on-site execution. The literature study inferred that the migration of skilled workers is uncontrollable in developing countries, and they travel to developed nations for better emoluments. As a result, the enrichment of skills for existing workers has turned out essential. In this connection, the thesis has strengthened the skill enhancement of workers and recommends it as an integral part of RI projects. This objective has been incorporated as a new dimension in R-BIM, named capacity management. The study presented risk assessment linked with various activities in the field execution at the rural level through two standards. As a result, the risk intensity associated with each underground activity and on-site construction have been evaluated beforehand, and the whole construction had no injury or fatality. Although the conventional process of BIM recognised 6D and 7D as sustainability and facility management in urban projects, the thesis highlighted skill enhancement and risk assessment for workers in the R-BIM's execution because of their immense value. This developed method and adopted methodology through case study would benefit the execution of RI projects in developing countries. The overall outcomes of the fostered R-BIM framework have been listed in Table 7.1.

Table 7. 1 Outcomes of the developed R-BIM framework through the performed RWM study

S.No.	Dimension / aspect	Outcomes
1.	2D	Planning the RWH set-up and decision-making for water tank size requirements and pipe network connection by grasping users' inputs.
2	3D	Creating virtual models of the RWH structures in a simulated environment. Extracting rendered videos for the broad understanding and convenience of rural stakeholders.
3.	4D	Creating a schedule of the entire planned work, including hauling materials and equipment to a remote location.
4.	5D	Estimating the complete expenditure of the project.
5.	6D	Enhancing skills of existing workers for the prefabricated related constructions adopted in the RWM study.
6.	7D	Ensuring safety norms for the on-site workers based on the activity type and determined risk level.
7.	BIM Cloud	Managing and communicating with the rural stakeholders for flexible and synchronised coordination from different locations.

7.5 Conclusions on research findings

The installed RWH system through the directional tunnelling method reduced the physical struggle of the water carriers in the selected community of the rural area. Investigation of feasible material for the directional tunnel contributed towards identifying a lightweight and tough material for better construction. Moreover, this structure acted as the additional source for excess rainwater storage among the households. The declination of directional tunnel at 30° (considered angle for implementation) has a depth of 9.145m. In the case of vertical installation, the depth could have been the complete length of directional tunnel, i.e., 21.34m. Hence the depth variation is 57.14%, which leads to less energy requirement.

Uncertainties in RI projects such as inadequate resources, hauling equipment, and the unskilled labour might impede the advanced technology implementation. The novel R-BIM concept in the purview of RIs obtained benefits in comprehensive execution, skill enhancement of workers, and economical model in rural areas. With the help of R-BIM, planning the technological parameters for RI projects have been formulated. Getting accustomed to the BIM platform has been a broad experience for various stakeholders involved in the study. Usage of BIM tools in the study, directed towards virtual demonstration of the community's entire RWM set-up. Mapping the planning phase activities to different dimensions of R-BIM delivered defined roles for the entitled rural stakeholders. Because of their absence in previous studies, these rural stakeholders have been defined with their potential roles in R-BIM process.

The usage of BIM in the rural aspect was a defying task with a lively environment of participatory management which involved decision-making of multiple residents and rural stakeholders. Introduction of BIM cloud platform tool in the rural area assisted in raising time-to-time issues related to planning, implementation, and review for better completion. It has regulated the rural stakeholders for flexible and synchronised coordination from different locations. The EVA results suggest that the R-BIM framework in the case study experienced over budget and time delay. The total number of working days increased by 27.5 days, due to proficiency development for unskilled workers in RWM. However, the case of RWM study without the R-BIM effect and its EVA validation helped conclude the acceptable permissibility of the R-BIM framework. The comparison of RWM system with and without the application R-BIM clearly indicates reduction in cost by14.82% and schedule by 32 days.

The development of directional tunnel performed in the present study would have an impact on the RWI sector, especially in RWH applications. The established technique will provide the basis for future infrastructure projects in rural scenario.

7.6 Limitations of the study

The thesis has discussed the enforcement of directional tunnel as a RWH structure only to rural areas. The stability analysis performed on the directional tunnel has been constrained to linear static analysis conditions in sandy soil. The application could be extended to different load conditions and dynamic analysis on various soil types. Hence, a more comprehensive study regarding declination angle in different soil types could be explored for the cause of practical execution. Construction in remote sites of rural areas remains a challenge for hauling materials. As a result, chances for rescheduling and postponement are natural. These consequences hampered the final schedule and completion, in the R-BIM's case study. This skill demonstration has been inhibited to manual instructions; eventually, usage of virtual reality (VR) devices could be duly manoeuvred in future. This targeted method has the potential of resolving schedule-related issues.

7.7 Future scope

Future research could be concentrated on the different types of RWH structures resulting in rural community water management from the current research findings. Simultaneously, the current thesis focused on the practice of directional tunnel in rural areas; therefore, the study can be further extended to urban areas. Moreover, cities are prone to severe air pollution and may further cause water pollution. Besides, the directional tunnel could come in contact with the foundations of adjacent existing buildings in the location. Reflecting these valid constraints, the process of directional tunnelling could be adopted in urban communities. Future studies could explore this method's manufacturing using other natural and eco-friendly materials. Moreover, this possesses less land occupancy, therefore its capacity with a massive volume at deep excavation could be investigated.

Simultaneously, the R-BIM framework has been explored in RWI perspective; therefore, its deployment could be extended to other large-scale RI projects to assess the performance. Enhancement of safety management in remote construction sites by incorporating IoT services and capturing real-time data could be additionally explored. Modern constructions are moving towards a prefabricated/modular set-up; therefore, a fast-track frame enforcing capacity management during the early stages of planning in R-BIM would reduce time. Dimension linked to sustainability can be considered further. The incorporation of rural stakeholders' inputs in R-BIM scenario has been a novel approach highlighted in the thesis. This practice could be adopted for monitoring and supervising future RI projects. Finally, the current thesis collates the knowledge of infrastructure development in rural areas by enforcing BIM with a potential opportunity for increased efficiency and productivity.

APPENDIX – A: Reponses and Calculation of Consistency Index by AHP

Decision maker 1 – Responses

Table A.1 Criteria

	Economical	Hydraulics	Social criteria	Technological
Economical	1	2	1/6.	1/4.
Hydraulics	1/2.	1	2	3
Social criteria	6	1/2.	1	4
Technological	4	1/3.	1/4.	1

Table A.2 Sub-criteria: Economical

	Material, machinery, and labour	Operation and maintenance	Excavation	Life cycle cost
Material, machinery, and labour	1	2	2	1
Operation and maintenance	1/2.	1	1	3
Excavation	1/2.	1	1	1/4.
Life cycle cost	1	1/3.	4	1

Table A.3 Sub-criteria: Hydraulics

	Head Pressure	Watertightness to prevent losses and contamination	Number of bends/ connections	Slope/ gradient	Pipe dimensions: length and diameter
Head Pressure	1	1/4.	1/5.	1/2.	1/3.
Watertightness to prevent losses and contamination	4	1	4	4	3
Number of bends/ connections	5	1/4.	1	2	1/2.
Slope/ gradient	2	1/4.	1/2.	1	1/2.
Pipe dimensions: length and diameter	3	1/3.	2	2	1

Table A.4 Sub-criteria: Social criteria

	Improved social status of girls and women	Easy access to clean water	Reduced health risks
Improved social status of girls and women	1	1/2.	2
Easy access to clean water	2	1	3
Reduced health risks	1/2.	1/3.	1

Table A.5 Sub-criteria: Technological

	Consumption of low energy for water extraction	Organized central database of user activity/ feedback
Consumption of low energy for water extraction	1	4
Organized central database of user activity/ feedback	1/4.	1

Table A.6 Alternatives in line with sub-criteria: Material, machinery, and labour

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1	1/3.	3
Ring system	1	1	2	2
Radial system	3	1/2.	1	2
Dead end (tree) system	1/3.	1/2.	1/2.	1

Table A.7 Alternatives in line with sub-criteria: Operation and maintenance

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1	1/2.	1/4.
Ring system	1	1	3	5
Radial system	2	1/3.	1	4
Dead end (tree) system	4	1/5.	1/4.	1

Table A.8 Alternatives in line with sub-criteria: Excavation

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1	1/2.	1/5.
Ring system	1	1	2	3
Radial system	2	1/2.	1	3
Dead end (tree) system	5	1/3.	1/3.	1

Table A.9 Alternatives in line with sub-criteria: Life-cycle cost

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1	2	5
Ring system	1	1	2	4
Radial system	1/2.	1/2.	1	3

Dead end (tree) system	1/5.	1/4.	1/3.	1

Table A.10 Alternatives in line with sub-criteria: Head pressure

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	1/2.	4
Ring system	1/2.	1	1/2.	4
Radial system	2	2	1	4
Dead end (tree) system	1/4.	1/4.	1/4.	1

Table A.11 Alternatives in line with sub-criteria: Water-tightness to prevent losses and contamination

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1	2	1/4.
Ring system	1	1	1/3.	1/5.
Radial system	1/2.	3	1	1/3.
Dead end (tree) system	4	5	3	1

Table A.12 Alternatives in line with sub-criteria: Number of bends/ connections

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/2.	1	1/4.
Ring system	2	1	1/2.	1/5.
Radial system	1	2	1	1/4.
Dead end (tree) system	4	5	4	1

Table A.13 Alternatives in line with sub-criteria: Slope gradient

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/2.	3	1/3.
Ring system	2	1	3.00	1/4.
Radial system	1/3.	1/3.	1	1/3.
Dead end (tree) system	3	4	3	1

Table A.14 Alternatives in line with sub-criteria: Pipe dimensions - length and diameter

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/2.	1	1/4.
Ring system	2	1	2.00	1/5.
Radial system	1	1/2.	1	1/4.
Dead end (tree) system	4	5	4	1

Table A.15 Alternatives in line with sub-criteria: Improved social status of girls and women

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2.00	2	1/3.
Ring system	1/2.	1	1/2.	1/3.
Radial system	1/2.	2	1	1/2.
Dead end (tree) system	3	3	2	1

Table A.16 Alternatives in line with sub-criteria: Easy access to clean water

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	1	1/2.
Ring system	1/2.	1	1/3.	1/3.
Radial system	1	3	1	1/2.
Dead end (tree) system	2	3	2	1

Table A.17 Alternatives in line with sub-criteria: Reduced health risks

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	1/3.	1/4.
Ring system	1/2.	1	1/2.	1/4.
Radial system	3	2	1	1/2.
Dead end (tree) system	4	4	2	1

Table A.18 Alternatives in line with sub-criteria: Consumption of low energy for water extraction

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/2.	2	4
Ring system	2	1	2	5
Radial system	1/2.	1/2.	1	4
Dead end (tree) system	1/4.	1/5.	1/4.	1

Table A.19 Alternatives in line with sub-criteria: Organized central database of user activity/ feedback

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	2	3
Ring system	1/2.	1	1/2.	2
Radial system	1/2.	2	1	1
Dead end (tree) system	1/3.	1/2.	1	1

Decision maker 2 – Responses

Table A.20 Criteria

	Economical	Hydraulics	Social criteria	Technological
Economical	1	2	1	4
Hydraulics	1/2.	1	8	5
Social criteria	1	1/8.	1	3
Technological	1/4.	1/5.	1/3.	1

Table A.21 Sub-criteria: Economical

	Material, machinery, and labour	Operation and maintenance	Excavation	Life cycle cost
Material, machinery, and labour	1	8	1	9
Operation and maintenance	1/8.	1	4	5
Excavation	1	1/4.	1	3
Life cycle cost	1/9.	1/5.	1/3.	1

Table A.22 Sub-criteria: Hydraulics

	Head Pressure	Watertightness to prevent losses and contamination	Number of bends/ connections	Slope/ gradient	Pipe dimensions: length and diameter
Head Pressure	1	3	5	1	2
Watertightness to prevent losses and contamination	1/3.	1	4	4	6
Number of bends/ connections	1/5.	1/4.	1	2	5
Slope/ gradient	1	1/4.	1/2.	1	4
Pipe dimensions: length and diameter	1/2.	1/6.	1/5.	1/4.	1

Table A.23 Sub-criteria: Social criteria

	Improved social status of girls and women	Easy access to clean water	Reduced health risks
Improved social status of girls and women	1	1	2
Easy access to clean water	1	1	3
Reduced health risks	1/2.	1/3.	1

Table A.24 Sub-criteria: Technological

	Consumption of low energy for water extraction	Organized central database of user activity/ feedback
Consumption of low energy for water extraction	1	5
Organized central database of user activity/ feedback	1/5.	1

Table A.25 Alternatives in line with sub-criteria: Material, machinery, and labour

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	4	2
Ring system	1/5.	1	2	6
Radial system	1/4.	1/2.	1	3
Dead end (tree) system	1/2.	1/6.	1/3.	1

Table A.26 Alternatives in line with sub-criteria: Operation and maintenance

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	3	2	5
Ring system	1/3.	1	6	3
Radial system	1/2.	1/6.	1	4
Dead end (tree) system	1/5.	1/3.	1/4.	1

Table A.27 Alternatives in line with sub-criteria: Excavation

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	2	6
Ring system	1/5.	1	3	4
Radial system	1/2.	1/3.	1	7
Dead end (tree) system	1/6.	1/4.	1/7.	1

Table A.28 Alternatives in line with sub-criteria: Life-cycle cost

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	4	2
Ring system	1/5.	1	2	6
Radial system	1/4.	1/2.	1	3
Dead end (tree) system	1/2.	1/6.	1/3.	1

Table A.29 Alternatives in line with sub-criteria: Head pressure

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	7	5	3
Ring system	1/7.	1	3	4
Radial system	1/5.	1/3.	1	5
Dead end (tree) system	1/3.	1/4.	1/5.	1

Table A.30 Alternatives in line with sub-criteria: Water-tightness to prevent losses and contamination

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	2	6
Ring system	1/5.	1	3	4

Radial system	1/2.	1/3.	1	7
Dead end (tree) system	1/6.	1/4.	1/7.	1

Table A.31 Alternatives in line with sub-criteria: Number of bends/ connections

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	4	6
Ring system	1/2.	1	3	2
Radial system	1/4.	1/3.	1	5
Dead end (tree) system	1/6.	1/2.	1/5.	1

Table A.32 Alternatives in line with sub-criteria: Slope gradient

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	3	5	6
Ring system	1/3.	1	4	3
Radial system	1/5.	1/4.	1	2
Dead end (tree) system	1/6.	1/3.	1/2.	1

Table A.33 Alternatives in line with sub-criteria: Pipe dimensions - length and diameter

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	2	6
Ring system	1/5.	1	3	4
Radial system	1/2.	1/3.	1	7
Dead end (tree) system	1/6.	1/4.	1/7.	1

Table A.34 Alternatives in line with sub-criteria: Improved social status of girls and women

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	5	1
Ring system	1/2.	1	3	2
Radial system	1/5.	1/3.	1	5
Dead end (tree) system	1	1/2.	1/5.	1

Table A.35 Alternatives in line with sub-criteria: Easy access to clean water

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	6	7
Ring system	1/2.	1	3	5
Radial system	1/6.	1/3.	1	4
Dead end (tree) system	1/7.	1/5.	1/4.	1

Table A.36 Alternatives in line with sub-criteria: Reduced health risks

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	2	6
Ring system	1/5.	1	3	4
Radial system	1/2.	1/3.	1	7
Dead end (tree) system	1/6.	1/4.	1/7.	1

Table A.37 Alternatives in line with sub-criteria: Consumption of low energy for water extraction

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	7	5	3
Ring system	1/7.	1	3	4
Radial system	1/5.	1/3.	1	5
Dead end (tree) system	1/3.	1/4.	1/5.	1

Table A.38 Alternatives in line with sub-criteria: Organized central database of user activity/ feedback

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	3	2
Ring system	1/2.	1	4	5
Radial system	1/3.	1/4.	1	3
Dead end (tree) system	1/2.	1/5.	1/3.	1

Decision maker 3 – Responses

Table A.39 Criteria

	Economical	Hydraulics	Social criteria	Technological
Economical	1	9	9	5
Hydraulics	1/9.	1	5	1
Social criteria	1/9.	1/5.	1	4
Technological	1/5.	1	1/4.	1

Table A.40 Sub-criteria: Economical

	Material, machinery, and labour	Operation and maintenance	Excavation	Life cycle cost
Material, machinery, and labour	1	4	2	3
Operation and maintenance	1/4.	1	1	3
Excavation	1/2.	1	1	9
Life cycle cost	1/3.	1/3.	1/9.	1

Table A.41 Sub-criteria: Hydraulics

	Head Pressure	Watertightness to prevent losses and contamination	Number of bends/ connections	Slope/ gradient	Pipe dimensions: length and diameter
Head Pressure	1	9	5	5	5
Watertightness to prevent losses and contamination	1/9.	1	1	5	7
Number of bends/ connections	1/5.	1	1	9	5
Slope/ gradient	1/5.	1/5.	1/9.	1	5
Pipe dimensions: length and diameter	1/5.	1/7.	1/5.	1/5.	1

Table A.42 Sub-criteria: Social criteria

	Improved social status of girls and women	Easy access to clean water	Reduced health risks
Improved social status of girls and women	1	9	9
Easy access to clean water	1/9.	1	9
Reduced health risks	1/9.	1/9.	1

Table A.43 Sub-criteria: Technological

	Consumption of low energy for water extraction	Organized central database of user activity/ feedback
Consumption of low energy for water extraction	1	3
Organized central database of user activity/ feedback	1/3.	1

Table A.44 Alternatives in line with sub-criteria: Material, machinery, and labour

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	3	1
Ring system	1/5.	1	1/5.	1/2.
Radial system	1/3.	5	1	1/2.
Dead end (tree) system	1	2	2	1

Table A.45 Alternatives in line with sub-criteria: Operation and maintenance

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	3	1
Ring system	1/5.	1	1/5.	1/2.
Radial system	1/3.	5	1	1/2.
Dead end (tree) system	1	2	2	1

Table A.46 Alternatives in line with sub-criteria: Excavation

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/4.	1/4.	1
Ring system	4	1	1	1/4.
Radial system	4	1	1	1/4.
Dead end (tree) system	1	4	4	1

Table A.47 Alternatives in line with sub-criteria: Life-cycle cost

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/9.	1/9.	1
Ring system	9	1	1	9
Radial system	9	1	1	9

Dead end (tree) system	1	1/9.	1/9.	1

Table A.48 Alternatives in line with sub-criteria: Head pressure

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/9.	1/9.	1
Ring system	9	1	1	9
Radial system	9	1	1	9
Dead end (tree) system	1	1/9.	1/9.	1

Table A.49 Alternatives in line with sub-criteria: Water-tightness to prevent losses and contamination

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	9	9	1
Ring system	1/9.	1	1	9
Radial system	1/9.	1	1	9
Dead end (tree) system	1	1/9.	1/9.	1

Table A.50 Alternatives in line with sub-criteria: Number of bends/ connections

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/9.	1/9.	1
Ring system	9	1	1	1/9.
Radial system	9	1	1	1/9.
Dead end (tree) system	1	9	9	1

Table A.51 Alternatives in line with sub-criteria: Slope gradient

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1	1	1
Ring system	1	1	1	1
Radial system	1	1	1	1
Dead end (tree) system	1	1	1	1

Table A.52 Alternatives in line with sub-criteria: Pipe dimensions - length and diameter

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	7	6	1
Ring system	1/7.	1	5	1/9.
Radial system	1/6.	1/5.	1	1/7.
Dead end (tree) system	1	9	7	1

Table A.53 Alternatives in line with sub-criteria: Improved social status of girls and women

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1	1	1
Ring system	1	1	1	1
Radial system	1	1	1	1
Dead end (tree) system	1	1	1	1

Table A.54 Alternatives in line with sub-criteria: Easy access to clean water

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1	1	1
Ring system	1	1	1	1
Radial system	1	1	1	1
Dead end (tree) system	1	1	1	1

Table A.55 Alternatives in line with sub-criteria: Reduced health risks

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1	1	1
Ring system	1	1	1	1
Radial system	1	1	1	1
Dead end (tree) system	1	1	1	1

Table A.56 Alternatives in line with sub-criteria: Consumption of low energy for water extraction

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	5	1
Ring system	1/5.	1	1/2.	1/9.
Radial system	1/5.	2	1	1/8.
Dead end (tree) system	1	9	8	1

Table A.57 Alternatives in line with sub-criteria: Organized central database of user activity/ feedback

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/9.	1/7.	1
Ring system	9	1	1	9
Radial system	7	1	1	9
Dead end (tree) system	1	1/9.	1/9.	1

Decision maker 4 – Responses

Table A.58 Criteria

	Economical	Hydraulics	Social criteria	Technological
Economical	1	5	1/5.	6
Hydraulics	1/5.	1	2	1
Social criteria	5	1/2.	1	1/8.
Technological	1/6.	1	8	1

Table A.59 Sub-criteria: Economical

	Material, machinery, and labour	Operation and maintenance	Excavation	Life cycle cost
Material, machinery, and labour	1	2	2	2
Operation and maintenance	1/2.	1	5	4
Excavation	1/2.	1/5.	1	7
Life cycle cost	1/2.	1/4.	1/7.	1

Table A.60 Sub-criteria: Hydraulics

	Head Pressure	Watertightness to prevent losses and contamination	Number of bends/ connections	Slope/ gradient	Pipe dimensions: length and diameter
Head Pressure	1	2	3	2	5
Watertightness to prevent losses and contamination	1/2.	1	2	6	3
Number of bends/ connections	1/3.	1/2.	1	7	3
Slope/ gradient	1/2.	1/6.	1/7.	1	2
Pipe dimensions: length and diameter	1/5.	1/3.	1/3.	1/2.	1

Table A.61 Sub-criteria: Social criteria

	Improved social status of girls and women	Easy access to clean water	Reduced health risks
Improved social status of girls and women	1	1/8.	1/6.
Easy access to clean water	8	1	2
Reduced health risks	6	1/2.	1

Table A.62 Sub-criteria: Technological

	Consumption of low energy for water extraction	Organized central database of user activity/ feedback
Consumption of low energy for water extraction	1	4
Organized central database of user activity/ feedback	1/4.	1

Table A.63 Alternatives in line with sub-criteria: Material, machinery, and labour

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	4	2	1/6.
Ring system	1/4.	1	2	1/7.
Radial system	1/2.	1/2.	1	1/7.
Dead end (tree) system	6	7	7	1

Table A.64 Alternatives in line with sub-criteria: Operation and maintenance

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	3	3	6
Ring system	1/3.	1	2	6
Radial system	1/3.	1/2.	1	7
Dead end (tree) system	1/6.	1/6.	1/7.	1

Table A.65 Alternatives in line with sub-criteria: Excavation

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	3	5
Ring system	1/2.	1	2	4
Radial system	1/3.	1/2.	1	5
Dead end (tree) system	1/5.	1/4.	1/5.	1

Table A.66 Alternatives in line with sub-criteria: Life-cycle cost

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	3	7
Ring system	1/2.	1	3	6
Radial system	1/3.	1/3.	1	6
Dead end (tree) system	1/7.	1/6.	1/6.	1

Table A.67 Alternatives in line with sub-criteria: Head pressure

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	7	8
Ring system	1/2.	1	4	1/6.
Radial system	1/7.	1/4.	1	1/5.
Dead end (tree) system	1/8.	6	5	1

Table A.68 Alternatives in line with sub-criteria: Water-tightness to prevent losses and contamination

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	6	7	3
Ring system	1/6.	1	4	1/6.

Radial system	1/7.	1/4.	1	1/5.
Dead end (tree) system	1/3.	6	5	1

Table A.69 Alternatives in line with sub-criteria: Number of bends/ connections

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	6	2
Ring system	1/5.	1	5	1/7.
Radial system	1/6.	1/5.	1	1/7.
Dead end (tree) system	1/2.	7	7	1

Table A.70 Alternatives in line with sub-criteria: Slope gradient

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	7	7	2
Ring system	1/7.	1	2	1/7.
Radial system	1/7.	1/2.	1	1/6.
Dead end (tree) system	1/2.	7	6	1

Table A.71 Alternatives in line with sub-criteria: Pipe dimensions - length and diameter

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	4	6
Ring system	1/5.	1	5	1/5.
Radial system	1/4.	1/5.	1	1/6.
Dead end (tree) system	1/6.	5	6	1

Table A.72 Alternatives in line with sub-criteria: Improved social status of girls and women

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	2	6
Ring system	1/2.	1	3	1/5.
Radial system	1/2.	1/3.	1	1/6.
Dead end (tree) system	1/6.	5	6	1

Table A.73 Alternatives in line with sub-criteria: Easy access to clean water

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	4	6
Ring system	1/5.	1	3	1/3.
Radial system	1/4.	1/3.	1	1/4.
Dead end (tree) system	1/6.	3	4	1

Table A.74 Alternatives in line with sub-criteria: Reduced health risks

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	5	6	2
Ring system	1/5.	1	3	1/4.
Radial system	1/6.	1/3.	1	1/5.
Dead end (tree) system	1/2.	4	5	1

Table A.75 Alternatives in line with sub-criteria: Consumption of low energy for water extraction

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/2.	1/3.	5
Ring system	2	1	2	1/5.
Radial system	3	1/2.	1	1/4.
Dead end (tree) system	1/5.	5	4	1

Table A.76 Alternatives in line with sub-criteria: Organized central database of user activity/ feedback

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2	2	4
Ring system	1/2.	1	2	1/3.
Radial system	1/2.	1/2.	1	1/3.
Dead end (tree) system	1/4.	3	3	1

Decision maker 5 – Responses

Table A.77 Criteria

	Economical	Hydraulics	Social criteria	Technological
Economical	1	1/6.	1/8.	1/7.
Hydraulics	6	1	1/5.	1/6.
Social criteria	8	5	1	1/6.
Technological	7.00	6.00	6.00	1.00

Table A.78 Sub-criteria: Economical

	Material, machinery, and labour	Operation and maintenance	Excavation	Life cycle cost
Material, machinery, and labour	1	1/8.	1/6.	1/9.
Operation and maintenance	8	1	1/7.	1/8.
Excavation	6	7	1	1/6.
Life cycle cost	9	8	6	1

Table A.79 Sub-criteria: Hydraulics

	Head Pressure	Watertightness to prevent losses and contamination	Number of bends/ connections	Slope/ gradient	Pipe dimensions: length and diameter
Head Pressure	1	1/8.	1/6.	1/6.	1/5.
Watertightness to prevent losses and contamination	8	1	1/5.	1/3.	1/6.
Number of bends/ connections	6	5	1	1/2.	1/3.
Slope/ gradient	6	3	2	1	1/5.
Pipe dimensions: length and diameter	5	6	3	5	1

Table A.80 Sub-criteria: Social criteria

	Improved social status of girls and women	Easy access to clean water	Reduced health risks
Improved social status of girls and women	1	1	1
Easy access to clean water	1	1	1
Reduced health risks	1	1	1

Table A.81 Sub-criteria: Technological

	Consumption of low energy for water extraction	Organized central database of user activity/ feedback
Consumption of low energy for water extraction	1	2
Organized central database of user activity/ feedback	1/2.	1

Table A.82 Alternatives in line with sub-criteria: Material, machinery, and labour

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/3.	1/4.	1/3.
Ring system	3	1	1/2.	1/5.
Radial system	4	2	1	1/6.
Dead end (tree) system	3	5	6	1

Table A.83 Alternatives in line with sub-criteria: Operation and maintenance

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/3.	1/4.	1/2.
Ring system	3	1	1/6.	1/5.
Radial system	4	6	1	1/7.
Dead end (tree) system	2	5	7	1

Table A.84 Alternatives in line with sub-criteria: Excavation

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/6.	1/5.	1/4.
Ring system	6	1	1/5.	1/3.
Radial system	5	5	1	1/2.
Dead end (tree) system	4	3	2	1

Table A.85 Alternatives in line with sub-criteria: Life-cycle cost

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/5.	1/4.	1/6.
Ring system	5	1	1/5.	1/3.
Radial system	4	5	1	1/7.
Dead end (tree) system	6	3	7	1

Table A.86 Alternatives in line with sub-criteria: Head pressure

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/7.	1/6.	1/5.
Ring system	7	1	1/7.	1/8.
Radial system	6	7	1	1/6.
Dead end (tree) system	5	8	6	1

Table A.87 Alternatives in line with sub-criteria: Water-tightness to prevent losses and contamination

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/6.	1/4.	1/3.
Ring system	6	1	1/7.	1/8.
Radial system	4	7	1	1/9.
Dead end (tree) system	3	8	9	1

Table A.88 Alternatives in line with sub-criteria: Number of bends/ connections

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/4.	1/6.	1/5.
Ring system	4	1	1/8.	1/6.
Radial system	6	8	1	1/3.
Dead end (tree) system	5	6	3	1

Table A.89 Alternatives in line with sub-criteria: Slope gradient

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/8.	1/6.	1/4.
Ring system	8	1	1/7.	1/6.
Radial system	6	7	1	1/5.
Dead end (tree) system	4	6	5	1

Table A.90 Alternatives in line with sub-criteria: Pipe dimensions - length and diameter

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/7.	1/6.	1/8.
Ring system	7	1	1/5.	1/7.
Radial system	6	5	1	1/5.
Dead end (tree) system	8	7	5	1

Table A.91 Alternatives in line with sub-criteria: Improved social status of girls and women

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/5.	1/6.	1/4.
Ring system	5	1	1/7.	1/5.
Radial system	6	7	1	1/6.
Dead end (tree) system	4	5	6	1

Table A.92 Alternatives in line with sub-criteria: Easy access to clean water

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/5.	1/6.	1/7.
Ring system	5	1	1/7.	1/8.
Radial system	6	7	1	1/9.
Dead end (tree) system	7	8	9	1

Table A.93 Alternatives in line with sub-criteria: Reduced health risks

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/6.	1/7.	1/8.
Ring system	6	1	1/8.	1/4.
Radial system	7	8	1	1/3.
Dead end (tree) system	8	4	3	1

Table A.94 Alternatives in line with sub-criteria: Consumption of low energy for water extraction

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/5.	1/4.	1/3.
Ring system	5	1	1/3.	1/7.
Radial system	4	3	1	1/8.
Dead end (tree) system	3	7	8	1

Table A.95 Alternatives in line with sub-criteria: Organized central database of user activity/ feedback

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1/7.	1/6.	1/5.
Ring system	7	1	1/4.	1/3.
Radial system	6	4	1	1/5.
Dead end (tree) system	5	3	5	1

Geometric Mean of Decision makers' scores

A1

Table A.96 Criteria

	Economical	Hydraulics	Social criteria	Technological
Economical	1.00	1.87	0.49	1.29
Hydraulics	0.51	1.00	1.94	1.19
Social criteria	1.77	0.49	1.00	1.00
Technological	0.70	0.78	1.00	1.00
Sum	**3.980**	**4.140**	**4.430**	**4.470**

A1

Table A.97 Sub-criteria: Economical

	Material, machinery, and labour	Operation and maintenance	Excavation	Life cycle cost
Material, machinery, and labour	1.000	1.741	1.059	1.431
Operation and maintenance	0.574	1.000	1.234	1.864
Excavation	0.944	0.811	1.000	1.511
Life cycle cost	0.699	0.536	0.662	1.000
Sum	3.217	4.088	3.955	5.806

A1

Table A.98 Sub-criteria: Hydraulics

	Head Pressure	Watertightness to prevent losses and contamination	Number of bends/ connections	Slope/ gradient	Pipe dimensions: length and diameter
Head Pressure	1.000	1.110	1.201	0.964	1.272
Watertightness to prevent losses and contamination	0.901	1.000	1.450	2.759	2.290
Number of bends/ connections	0.833	0.690	1.000	2.631	1.657
Slope/ gradient	1.037	0.362	0.380	1.000	1.320
Pipe dimensions: length and diameter	0.786	0.437	0.603	0.758	1.000
Sum	4.556	3.599	4.634	8.112	7.539

A1

Table A.99 Sub-criteria: Social criteria

	Improved social status of girls and women	Easy access to clean water	Reduced health risks
Improved social status of girls and women	1.000	0.891	1.431
Easy access to clean water	1.122	1.000	2.766
Reduced health risks	0.699	0.361	1.000
Sum	2.821	2.253	5.197

A1

Table A.100 Sub-criteria: Technological

	Consumption of low energy for water extraction	Organized central database of user activity/ feedback
Consumption of low energy for water extraction	1.000	3.438
Organized central database of user activity/ feedback	0.291	1.000
Sum	1.291	4.438

A1

Table A.101 Alternatives in line with sub-criteria: Material, machinery, and labour

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1.000	2.016	1.149	0.803
Ring system	0.496	1.000	0.956	0.703
Radial system	0.871	1.046	1.000	0.590
Dead end (tree) system	1.246	1.423	1.695	1.000
Sum	3.612	5.485	4.800	3.095

A1

Table A.102 Alternatives in line with sub-criteria: Operation and maintenance

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1.7187	1.1760	1.3025
Ring system	0.5818	1	1.0371	1.5518
Radial system	0.8502	0.9641	1	1.5157
Dead end (tree) system	0.7677	0.6443	0.6597	1
Sum	3.200	4.327	3.873	5.370

A1

Table A.103 Alternatives in line with sub-criteria: Excavation

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	0.8393	0.6842	1.08447
Ring system	1.1913	1	1.1913	1.31950
Radial system	1.4614	0.8393	1	1.67347

Dead end (tree) system	0.922107911	0.757858283	0.5975581	1
Sum	4.575	3.437	3.473	5.077

A1

Table A.104 Alternatives in line with sub-criteria: Life-cycle cost

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	0.7402	0.9221	1.6345
Ring system	1.3509	1	1.1913	3.3658
Radial system	1.0844	0.8393	1	2.3351
Dead end (tree) system	0.6118	0.2971	0.4282	1
Sum	4.047	2.877	3.542	8.335

A1

Table A.105 Alternatives in line with sub-criteria: Head pressure

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	0.8502	0.7982	1.8057
Ring system	1.1760	1	0.9696	1.2457
Radial system	1.2527	1.0313	1	1.4309
Dead end (tree) system	0.5537	0.8027	0.6988	1
Sum	3.983	3.684	3.467	5.482

A1

Table A.106 Alternatives in line with sub-criteria: Water-tightness to prevent losses and contamination

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	2.1411	2.2901	1.0844
Ring system	0.4670	1	1.1442	0.6842
Radial system	0.4366	1.1184	1	0.8586
Dead end (tree) system	0.9221	1.4614	1.16466	1
Sum	2.826	5.721	5.599	3.627

A1

Table A.107 Alternatives in line with sub-criteria: Number of bends/ connections

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	0.6738	0.8502	0.9028
Ring system	1.4841	1	0.9871	0.2540
Radial system	1.1760	1.0129	1	0.3665
Dead end (tree) system	1.1075	3.9362	2.7284	1
Sum	4.768	6.623	5.566	2.523

A1

Table A.108 Alternatives in line with sub-criteria: Slope gradient

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1.055892882	1.772587203	1
Ring system	0.947065765	1	1.279448002	0.44705648
Radial system	0.564147139	0.781587058	1	0.467043677
Dead end (tree) system	1	2.236853829	2.141127368	1
Sum	3.511	5.074	6.193	2.914

A1

Table A.109 Alternatives in line with sub-criteria: Pipe dimensions - length and diameter

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1.657227009	1.515716567	1.023836256
Ring system	0.603417634	1	1.974350486	0.302660599
Radial system	0.659753955	0.506495684	1	0.38385195
Dead end (tree) system	0.976718684	3.304030999	2.605171085	1
Sum	3.240	6.468	7.095	2.710

A1

Table A.110 Alternatives in line with sub-criteria: Improved social status of girls and women

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1.0985	1.2722	0.8705
Ring system	0.9102	1	0.9154	0.4843
Radial system	0.7860	1.0923	1	0.5865
Dead end (tree) system	1.1486	2.0644	1.7047	1
Sum	3.845	5.255	4.892	2.942

A1

Table A.111 Alternatives in line with sub-criteria: Easy access to clean water

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1.3195	1.3195	1.2457
Ring system	0.7578	1	0.8441	0.5865
Radial system	0.7578	1.1846	1	0.5609
Dead end (tree) system	0.8027	1.7047	1.7826	1
Sum	3.318	5.209	4.946	3.393

A1

Table A.112 Alternatives in line with sub-criteria: Reduced health risks

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1.5281	0.8941	0.8218
Ring system	0.6543	1	0.8913	0.5743
Radial system	1.1184	1.1219	1	0.7474
Dead end (tree) system	1.2167	1.7411	1.3378	1
Sum	3.990	5.391	4.123	3.144

A1

Table A.113 Alternatives in line with sub-criteria: Consumption of low energy for water extraction

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	1.1184	1.3303	1.8205
Ring system	0.8941	1	1.1486	0.5761
Radial system	0.7516	0.8705	1	0.6005
Dead end (tree) system	0.5492	1.7356	1.6651	1
Sum	3.195	4.725	5.144	3.997

A1

Table A.114 Alternatives in line with sub-criteria: Organized central database of user activity/ feedback

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	1	0.6618	0.7783	1.3685
Ring system	1.5109	1	1	1.5848
Radial system	1.2847	1	1	1.1247
Dead end (tree) system	0.7307	0.6309	0.8890	1
Sum	4.526	3.293	3.667	5.078

A2 (normalized relative weight)

Table A.115 Criteria

	Economical	Hydraulics	Social criteria	Technological
Economical	0.251	0.452	0.111	0.287
Hydraulics	0.128	0.242	0.438	0.265
Social criteria	0.445	0.118	0.226	0.224
Technological	0.176	0.188	0.226	0.224

A2 (normalized relative weight)

Table A.116 Sub-criteria: Economical

	Material, machinery, and labour	Operation and maintenance	Excavation	Life cycle cost
Material, machinery, and labour	0.311	0.426	0.268	0.246

Operation and maintenance	0.179	0.245	0.312	0.321
Excavation	0.293	0.198	0.253	0.260
Life cycle cost	0.217	0.131	0.167	0.172

A2 (normalized relative weight)

Table A.117 Sub-criteria: Hydraulics

	Head Pressure	Watertightness to prevent losses and contamination	Number of bends/ connections	Slope/ gradient	Pipe dimensions: length and diameter
Head Pressure	0.219	0.308	0.259	0.119	0.169
Watertightness to prevent losses and contamination	0.198	0.278	0.313	0.340	0.304
Number of bends/ connections	0.183	0.192	0.216	0.324	0.220
Slope/ gradient	0.228	0.101	0.082	0.123	0.175
Pipe dimensions: length and diameter	0.173	0.121	0.130	0.093	0.133

A2 (normalized relative weight)

Table A.118 Sub-criteria: Social criteria

	Improved social status of girls and women	Easy access to clean water	Reduced health risks
Improved social status of girls and women	0.355	0.396	0.275
Easy access to clean water	0.398	0.444	0.532
Reduced health risks	0.248	0.160	0.192

A2 (normalized relative weight)

Table A.119 Sub-criteria: Technological

	Consumption of low energy for water extraction	Organized central database of user activity/ feedback
Consumption of low energy for water extraction	0.775	0.775
Organized central database of user activity/ feedback	0.225	0.225

A2 (normalized relative weight)

Table A.120 Alternatives in line with sub-criteria: Material, machinery, and labour

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.277	0.368	0.239	0.259
Ring system	0.137	0.182	0.199	0.227
Radial system	0.241	0.191	0.208	0.191
Dead end (tree) system	0.345	0.259	0.353	0.323

A2 (normalized relative weight)

Table A.121 Alternatives in line with sub-criteria: Operation and maintenance

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.313	0.397	0.304	0.243
Ring system	0.182	0.231	0.268	0.289
Radial system	0.266	0.223	0.258	0.282
Dead end (tree) system	0.240	0.149	0.170	0.186

A2 (normalized relative weight)

Table A.122 Alternatives in line with sub-criteria: Excavation

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.219	0.244	0.197	0.214
Ring system	0.260	0.291	0.343	0.260
Radial system	0.319	0.244	0.288	0.330
Dead end (tree) system	0.202	0.221	0.172	0.197

A2 (normalized relative weight)

Table A.123 Alternatives in line with sub-criteria: Life-cycle cost

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.247	0.257	0.260	0.196
Ring system	0.334	0.348	0.336	0.404
Radial system	0.268	0.292	0.282	0.280
Dead end (tree) system	0.151	0.103	0.121	0.120

A2 (normalized relative weight)

Table A.124 Alternatives in line with sub-criteria: Head pressure

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.251	0.231	0.230	0.329
Ring system	0.295	0.271	0.280	0.227
Radial system	0.315	0.280	0.288	0.261
Dead end (tree) system	0.139	0.218	0.202	0.182

A2 (normalized relative weight)

Table A.125 Alternatives in line with sub-criteria: Water-tightness to prevent losses and contamination

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.354	0.374	0.409	0.299
Ring system	0.165	0.175	0.204	0.189
Radial system	0.155	0.195	0.179	0.237
Dead end (tree) system	0.326	0.255	0.208	0.276

A2 (normalized relative weight)

Table A.126 Alternatives in line with sub-criteria: Number of bends/ connections

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.210	0.102	0.153	0.358
Ring system	0.311	0.151	0.177	0.101
Radial system	0.247	0.153	0.180	0.145
Dead end (tree) system	0.232	0.594	0.490	0.396

A2 (normalized relative weight)

Table A.127 Alternatives in line with sub-criteria: Slope gradient

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.285	0.208	0.286	0.343
Ring system	0.270	0.197	0.207	0.153
Radial system	0.161	0.154	0.161	0.160
Dead end (tree) system	0.285	0.441	0.346	0.343

A2 (normalized relative weight)

Table A.128 Alternatives in line with sub-criteria: Pipe dimensions - length and diameter

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.309	0.256	0.214	0.378
Ring system	0.186	0.155	0.278	0.112
Radial system	0.204	0.078	0.141	0.142
Dead end (tree) system	0.301	0.511	0.367	0.369

A2 (normalized relative weight)

Table A.129 Alternatives in line with sub-criteria: Improved social status of girls and women

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.260	0.209	0.260	0.296
Ring system	0.237	0.190	0.187	0.165
Radial system	0.204	0.208	0.204	0.199
Dead end (tree) system	0.299	0.393	0.348	0.340

A2 (normalized relative weight)

Table A.130 Alternatives in line with sub-criteria: Easy access to clean water

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.301	0.253	0.267	0.367
Ring system	0.228	0.192	0.171	0.173
Radial system	0.228	0.227	0.202	0.165
Dead end (tree) system	0.242	0.327	0.360	0.295

A2 (normalized relative weight)

Table A.131 Alternatives in line with sub-criteria: Reduced health risks

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.251	0.283	0.217	0.261
Ring system	0.164	0.185	0.216	0.183
Radial system	0.280	0.208	0.243	0.238
Dead end (tree) system	0.305	0.323	0.324	0.318

A2 (normalized relative weight)

Table A.132 Alternatives in line with sub-criteria: Consumption of low energy for water extraction

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.313	0.237	0.259	0.455
Ring system	0.280	0.212	0.223	0.144
Radial system	0.235	0.184	0.194	0.150
Dead end (tree) system	0.172	0.367	0.324	0.250

A2 (normalized relative weight)

Table A.133 Alternatives in line with sub-criteria: Organized central database of user activity/ feedback

	Grid iron system	Ring system	Radial system	Dead end (tree) system
Grid iron system	0.221	0.201	0.212	0.269
Ring system	0.334	0.304	0.273	0.312
Radial system	0.284	0.304	0.273	0.221
Dead end (tree) system	0.161	0.192	0.242	0.197

Calculation of consistency index and consistency ratio

Table A.134 Criteria

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.275	1.162	4.222	4.236	0.0785	0.0873
	0.268	1.141	4.254			
	0.253	1.075	4.247			
	0.203	0.858	4.220			
Sum	1					

Table A.135 Sub-criteria: Economical

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.313	1.285	4.108	4.075	0.0248	0.0276
	0.264	1.074	4.068			
	0.251	1.020	4.062			
	0.172	0.698	4.061			
Sum	1					

Table A.136 Sub-criteria: Hydraulics

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.215	1.108	5.153	5.180	0.044	0.040
	0.286	1.498	5.229			
	0.227	1.192	5.253			
	0.142	0.726	5.124			
	0.130	0.668	5.140			
Sum	1					

Table A.137 Sub-criteria: Social criteria

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.342	1.037	3.032	3.033	0.016	0.028
	0.458	1.395	3.047			
	0.200	0.605	3.020			
Sum	1					

Table A.138 Sub-criteria: Technological

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.775	1.549	2.000	2.000	0	0
	0.225	0.451	2.000			
Sum	1					

Table A.139 Alternatives in line with sub-criteria: Material, machinery, and labour

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.286	1.157	4.050	4.042	0.014	0.015
	0.186	0.752	4.031			
	0.208	0.840	4.047			
	0.320	1.293	4.040			
Sum	1					

Table A.140 Alternatives in line with sub-criteria: Operation and maintenance

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.314	1.276	4.064	4.049	0.016	0.018
	0.242	0.981	4.047			
	0.257	1.040	4.044			
	0.186	0.753	4.043			
Sum	1					

Table A.141 Alternatives in line with sub-criteria: Excavation

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.218	0.877	4.017	4.020	0.006	0.007
	0.289	1.161	4.025			
	0.295	1.188	4.022			
	0.198	0.794	4.016			
Sum	1					

Table A.142 Alternatives in line with sub-criteria: Life-cycle cost

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.240	0.964	4.015	4.018	0.0061	0.0067
	0.355	1.431	4.026			
	0.281	1.129	4.022			
	0.124	0.497	4.010			
Sum	1					

Table A.143 Alternatives in line with sub-criteria: Head pressure

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.260	1.051	4.038	4.032	0.0106	0.012
	0.268	1.083	4.034			
	0.286	1.154	4.035			
	0.185	0.745	4.021			
Sum	1					

Table A.144 Alternatives in line with sub-criteria: Water-tightness to prevent losses and contamination

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.359	1.478	4.118	4.098	0.0327	0.0363
	0.183	0.752	4.104			
	0.191	0.782	4.086			
	0.266	1.088	4.085			
Sum	1					

Table A.145 Alternatives in line with sub-criteria: Number of bends/ connections

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.206	0.871	4.238	4.266	0.0885	0.0983
	0.185	0.778	4.202			
	0.181	0.767	4.236			
	0.428	1.879	4.386			
Sum	1					

Table A.146 Alternatives in line with sub-criteria: Slope gradient

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.281	1.134	4.044	4.048	0.0159	0.0177
	0.207	0.834	4.035			
	0.159	0.644	4.048			
	0.354	1.437	4.064			
Sum	1					

Table A.147 Alternatives in line with sub-criteria: Pipe dimensions - length and diameter

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.289	1.202	4.159	4.145	0.0481	0.0535
	0.183	0.753	4.121			
	0.141	0.573	4.060			
	0.387	1.641	4.238			
Sum	1					

Table A.148 Alternatives in line with sub-criteria: Improved social status of girls and women

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.256	1.030	4.019	4.021	0.007	0.007
	0.195	0.782	4.016			
	0.204	0.821	4.022			
	0.345	1.389	4.027			
Sum	1					

Table A.149 Alternatives in line with sub-criteria: Easy access to clean water

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.297	1.202	4.045	4.036	0.01196	0.013289
	0.191	0.769	4.029			
	0.206	0.829	4.027			
	0.306	1.237	4.042			
Sum	1					

Table A.150 Alternatives in line with sub-criteria: Reduced health risks

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.253	1.017	4.017	4.015	0.0051	0.0057
	0.187	0.751	4.014			
	0.242	0.973	4.016			
	0.318	1.275	4.015			
Sum	1					

Table A.151 Alternatives in line with sub-criteria: Consumption of low energy for water extraction

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.316	1.317	4.168	4.114	0.0378	0.0421
	0.215	0.877	4.084			
	0.191	0.783	4.096			
	0.278	1.143	4.106			
Sum	1					

Table A.152 Alternatives in line with sub-criteria: Organized central database of user activity/ feedback

	A3 normalized principal eigen vector (row average)	A4= A3*A1	A5=A4/A3	λ_{max}	CI	CR
	0.226	0.910	4.027	4.026	0.0086	0.0096
	0.306	1.231	4.030			
	0.270	1.089	4.027			
	0.198	0.796	4.020			
Sum	1					

APPENDIX – B: Details of cost estimation

Item No.	Description	Cost (Rs.)	Total (Rs.)
1	Procurement of material		34,685
	Material shipping from vendor 1	2,080	
	Material shipping from vendor 2	5,200	
	Material shipping from vendor 3	2,125	
	Material shipping from vendor 4	2,000	
	Material shipping from vendor 4	2,690	
	Material shipping from vendor 5	11,590	
2	Preparation of dye frame		1,26,270
	Plyboard		
	6x12 - 4	25,200	
	4x8 - 6	25,200	
	6x6 - 4	16,000	
	Nuts	940	
	Bolts	940	
	Washers	470	
	Making charges	57,520	
3	Manufacturing GRP panels for household tanks		96,600
	Fibre Sheet Rolls 2.5 rolls	11,000	
	Epoxy resin 7 containers	46,200	
	Hardener 1.5 container	13,950	
	Fren Chalk powder 10kg	315	
	Making Charges	24,000	
	Nuts 5.2 kg	520	
	Bolts 5.2 kg	520	
	Washers 2.6 kg	260	
4	Manufacturing GRP panels for directional tunnel		7,28,650
	Fibre Sheet Rolls 17.5 rolls	84,000	
	Epoxy resin 49 containers	3,67,500	
	Hardener 10.5 container	97,650	
	Fren Chalk powder 70kg	2205	
	Making Charges	1,68,000	
	Nuts 36.4 kg	3640	
	Bolts 36.4 kg	3640	
	Washers 18.2 kg	1820	
5	Pipe laying and excavation		
	Volume 744.24 cu.m	164	1,22,055.36

6	Pipe – 75mm		
	Length 3101m	122.54	3,79,996.54
7	Directional Tunnel Excavation		
	Volume 312.5cu.m	157.5	49,218.75
8	Solar Pump Installation & Commissioning		
	Water Pump with controller 0.5HP 12V Solar Panel Solar UPS with 20Ah battery DC Wires Pipe Connection and Misc	14,735	14,735

APPENDIX – C: Expert responses and Risk assessment as per R-BIM

Table C.1: Responses of Expert – 1

Activity Code	**Description**	**Risk probability** (P_f)	**Severity of consequences** (C_f)
P14	Preparation of dye frame	0.07	0.1
P15	Manufacturing GRP panels for household tanks	0.1	0.15
P16	Transportation of GRP panels of household tanks	0.1	0.15
P17	Fabrication of household tanks at the site	0.1	0.2
P18	Excavation for household tanks	0.14	0.15
P19	Placing of household tanks	0.2	0.2
P20	Backfilling for household tanks	0.3	0.4
P21	Connection of rooftop rainwater harvesting system & Solar water pump	0.2	0.12
P24	Cleaning and excavation for directional tunnel	0.16	0.25
P25	Manufacturing GRP panels for directional tunnel	0.2	0.1
P26	Transportation of GRP panels of directional tunnel	0.1	0.15
P27	Fabrication of GRP panels for directional tunnel at the site	0.3	0.25
P28	Excavation for interconnection among all water tanks and directional tunnel	0.4	0.3
P29	Laying of pipelines	0.1	0.1
P30	Backfilling of pipeline and directional tunnel	0.4	0.25
P31	Finishing works	0.14	0.1

Table C.2: Responses of Expert – 2

Activity Code	Description	Risk probability (P_f)	Severity of consequences (C_f)
P14	Preparation of dye frame	0.1	0.1
P15	Manufacturing GRP panels for household tanks	0.1	0.1
P16	Transportation of GRP panels of household tanks	0.02	0.1
P17	Fabrication of household tanks at the site	0.1	0.2
P18	Excavation for household tanks	0.12	0.15
P19	Placing of household tanks	0.25	0.1
P20	Backfilling for household tanks	0.1	0.15
P21	Connection of rooftop rainwater harvesting system & Solar water pump	0.05	0.1
P24	Cleaning and excavation for directional tunnel	0.1	0.25
P25	Manufacturing GRP panels for directional tunnel	0.1	0.1
P26	Transportation of GRP panels of directional tunnel	0.02	0.1
P27	Fabrication of GRP panels for directional tunnel at the site	0.1	0.25
P28	Excavation for interconnection among all water tanks and directional tunnel	0.1	0.2
P29	Laying of pipelines	0.2	0.2
P30	Backfilling of pipeline and directional tunnel	0.1	0.25
P31	Finishing works	0.12	0.12

Table C.3: Responses of Expert – 3

Activity Code	Description	Risk probability (P_f)	Severity of consequences (C_f)
P14	Preparation of dye frame	0.08	0.1
P15	Manufacturing GRP panels for household tanks	0.1	0.12
P16	Transportation of GRP panels of household tanks	0.07	0.13
P17	Fabrication of household tanks at the site	0.1	0.2
P18	Excavation for household tanks	0.15	0.2
P19	Placing of household tanks	0.15	0.2
P20	Backfilling for household tanks	0.1	0.2
P21	Connection of rooftop rainwater harvesting system & Solar water pump	0.1	0.15
P24	Cleaning and excavation for directional tunnel	0.2	0.25
P25	Manufacturing GRP panels for directional tunnel	0.13	0.1
P26	Transportation of GRP panels of directional tunnel	0.07	0.13
P27	Fabrication of GRP panels for directional tunnel at the site	0.15	0.25
P28	Excavation for interconnection among all water tanks and directional tunnel	0.2	0.2
P29	Laying of pipelines	0.05	0.05
P30	Backfilling of pipeline and directional tunnel	0.15	0.25
P31	Finishing works	0.15	0.15

Table C.4: Responses of Expert – 4

Activity Code	**Description**	**Risk probability (P_f)**	**Severity of consequences (C_f)**
P14	Preparation of dye frame	0.04	0.1
P15	Manufacturing GRP panels for household tanks	0.1	0.08
P16	Transportation of GRP panels of household tanks	0.12	0.1
P17	Fabrication of household tanks at the site	0.1	0.2
P18	Excavation for household tanks	0.1	0.15
P19	Placing of household tanks	0.06	0.2
P20	Backfilling for household tanks	0.05	0.15
P21	Connection of rooftop rainwater harvesting system & Solar water pump	0.002	0.1
P24	Cleaning and excavation for directional tunnel	0.16	0.2
P25	Manufacturing GRP panels for directional tunnel	0.13	0.1
P26	Transportation of GRP panels of directional tunnel	0.12	0.1
P27	Fabrication of GRP panels for directional tunnel at the site	0.1	0.2
P28	Excavation for interconnection among all water tanks and directional tunnel	0.2	0.3
P29	Laying of pipelines	0.2	0.2
P30	Backfilling of pipeline and directional tunnel	0.2	0.2
P31	Finishing works	0.1	0.1

Table C.5: Responses of Expert – 5

Activity Code	Description	Risk probability (P_f)	Severity of consequences (C_f)
P14	Preparation of dye frame	0.02	0.1
P15	Manufacturing GRP panels for household tanks	0.1	0.2
P16	Transportation of GRP panels of household tanks	0.05	0.18
P17	Fabrication of household tanks at the site	0.1	0.2
P18	Excavation for household tanks	0.08	0.3
P19	Placing of household tanks	0.05	0.4
P20	Backfilling for household tanks	0.01	0.3
P21	Connection of rooftop rainwater harvesting system & Solar water pump	0.01	0.1
P24	Cleaning and excavation for directional tunnel	0.16	0.3
P25	Manufacturing GRP panels for directional tunnel	0.2	0.1
P26	Transportation of GRP panels of directional tunnel	0.05	0.18
P27	Fabrication of GRP panels for directional tunnel at the site	0.2	0.3
P28	Excavation for interconnection among all water tanks and directional tunnel	0.3	0.1
P29	Laying of pipelines	0.1	0.1
P30	Backfilling of pipeline and directional tunnel	0.3	0.3
P31	Finishing works	0.08	0.08

Table C.6: Computation of risk value

Activity Code	**Description**	**Risk probability (P_f) (Mean)**	**Severity of consequences (C_f) (Mean)**	$P_f\ C_f$	**Risk**
P14	Preparation of dye frame	0.06	0.1	0.006	0.15
P15	Manufacturing GRP panels for household tanks	0.1	0.13	0.013	0.22
P16	Transportation of GRP panels of household tanks	0.07	0.13	0.0091	0.19
P17	Fabrication of household tanks at the site	0.1	0.2	0.02	0.28
P18	Excavation for household tanks	0.12	0.19	0.0228	0.29
P19	Placing of household tanks	0.14	0.22	0.0308	0.33
P20	Backfilling for household tanks	0.1	0.24	0.024	0.32
P21	Connection of rooftop rainwater harvesting system & Solar water pump	0.07	0.11	0.0077	0.17
P24	Cleaning and excavation for directional tunnel	0.16	0.25	0.04	0.37
P25	Manufacturing GRP panels for directional tunnel	0.13	0.1	0.013	0.22
P26	Transportation of GRP panels of directional tunnel	0.07	0.13	0.0091	0.19
P27	Fabrication of GRP panels for directional tunnel at the site	0.17	0.25	0.0425	0.38
P28	Excavation for interconnection among all water tanks and directional tunnel	0.24	0.22	0.0528	0.41
P29	Laying of pipelines	0.13	0.13	0.0169	0.24
P30	Backfilling of pipeline and directional tunnel	0.23	0.25	0.0575	0.42
P31	Finishing works	0.12	0.1	0.012	0.21

APPENDIX – D: Risk assessment as per likelihood matrix

Table D.1: Responses of Expert – 1

Activity Code	Description	Likelihood	Consequence	Risk value
P14	Preparation of dye frame	1	1	1
P15	Manufacturing GRP panels for household tanks	1	2	2
P16	Transportation of GRP panels of household tanks	1	2	2
P17	Fabrication of household tanks at the site	2	3	6
P18	Excavation for household tanks	3	2	6
P19	Placing of household tanks	3	3	9
P20	Backfilling for household tanks	3	3	9
P21	Connection of rooftop rainwater harvesting system & Solar water pump	2	1	2
P24	Cleaning and excavation for directional tunnel	4	5	20
P25	Manufacturing GRP panels for directional tunnel	2	1	2
P26	Transportation of GRP panels of directional tunnel	2	3	6
P27	Fabrication of GRP panels for directional tunnel at the site	5	4	20
P28	Excavation for interconnection among all water tanks and directional tunnel	4	5	20
P29	Laying of pipelines	2	1	2
P30	Backfilling of pipeline and directional tunnel	4	4	16
P31	Finishing works	3	2	6

Table D.2: Responses of Expert – 2

Activity Code	Description	Likelihood	Consequence	Risk value
P14	Preparation of dye frame	1	1	1
P15	Manufacturing GRP panels for household tanks	2	1	2
P16	Transportation of GRP panels of household tanks	1	2	2
P17	Fabrication of household tanks at the site	2	2	4
P18	Excavation for household tanks	3	2	6
P19	Placing of household tanks	3	4	12
P20	Backfilling for household tanks	3	3	9
P21	Connection of rooftop rainwater harvesting system & Solar water pump	1	2	2
P24	Cleaning and excavation for directional tunnel	5	4	20
P25	Manufacturing GRP panels for directional tunnel	1	2	2
P26	Transportation of GRP panels of directional tunnel	1	2	2
P27	Fabrication of GRP panels for directional tunnel at the site	4	5	20
P28	Excavation for interconnection among all water tanks and directional tunnel	5	4	20
P29	Laying of pipelines	1	2	2
P30	Backfilling of pipeline and directional tunnel	4	4	16
P31	Finishing works	2	2	4

Table D.3: Responses of Expert – 3

Activity Code	Description	Likelihood	Consequence	Risk value
P14	Preparation of dye frame	1	1	1
P15	Manufacturing GRP panels for household tanks	1	2	2
P16	Transportation of GRP panels of household tanks	2	3	6
P17	Fabrication of household tanks at the site	2	3	6
P18	Excavation for household tanks	3	3	9
P19	Placing of household tanks	4	4	16
P20	Backfilling for household tanks	3	4	12
P21	Connection of rooftop rainwater harvesting system & Solar water pump	1	2	2
P24	Cleaning and excavation for directional tunnel	4	5	20
P25	Manufacturing GRP panels for directional tunnel	1	2	2
P26	Transportation of GRP panels of directional tunnel	1	2	2
P27	Fabrication of GRP panels for directional tunnel at the site	5	4	20
P28	Excavation for interconnection among all water tanks and directional tunnel	4	5	20
P29	Laying of pipelines	1	2	2
P30	Backfilling of pipeline and directional tunnel	4	4	16
P31	Finishing works	1	1	1

Table D.4: Determination of risk value

Activity Code	Description	Risk value (Geometric mean)	Category
P14	Preparation of dye frame	1	Acceptable
P15	Manufacturing GRP panels for household tanks	2	Acceptable
P16	Transportation of GRP panels of household tanks	3	Acceptable
P17	Fabrication of household tanks at the site	5	Adequate
P18	Excavation for household tanks	7	Adequate
P19	Placing of household tanks	12	Tolerable
P20	Backfilling for household tanks	10	Tolerable
P21	Connection of rooftop rainwater harvesting system & Solar water pump	2	Acceptable
P24	Cleaning and excavation for directional tunnel	20	Unacceptable
P25	Manufacturing GRP panels for directional tunnel	2	Acceptable
P26	Transportation of GRP panels of directional tunnel	3	Acceptable
P27	Fabrication of GRP panels for directional tunnel at the site	20	Unacceptable
P28	Excavation for interconnection among all water tanks and directional tunnel	20	Unacceptable
P29	Laying of pipelines	2	Acceptable
P30	Backfilling of pipeline and directional tunnel	16	Unacceptable
P31	Finishing works	3	Acceptable

LIST OF PUBLICATIONS

Patent

1. Jute Fiber Water Tank: An Eco-Friendly Water Storage Method, India Provisional Patent Application No.: 201911045423 Inventors: Soumya Kar, Raya Raghavendra Kumar, Rajiv Gupta, Dated: November 4, 2019

Research papers

1. Raya, R.K. and Gupta, R., 2022. Mechanical Behaviour and Failure Analysis of Glass Fibre-Reinforced Plastic Panels for a Directional Tunnel: An Underground Water Storage Device, Arabian Journal for Science and Engineering, https://doi.org/10.1007/s13369-022-07190-w
2. Raya, R.K. and Gupta, R., 2022. Application of BIM framework on rural infrastructure. Asian Journal of Civil Engineering, 23(2), 249-268. https://doi.org/10.1007/s42107-022-00421-3
3. Raya, R.K. and Gupta, R., 2020. Rural community water management through directional tunnelling: visual modelling of rainwater harvesting system. Water Practice & Technology, 15(3), 734-747. https://doi.org/10.2166/wpt.2020.060
4. Raya, R.K., and Gupta, R, Review on rural water infrastructure development: A focus on Indian scenario (Communicated)

International conferences

1. Raya, R. K., Kar, S., Kumar, D., and Gupta, R. 2022. A Sustainable Integrated Rural Water Management with emphasis on Network Prioritization, Household Water Treatment and Real-Time Feedback. In 2022 IEEE Conference on Technologies for Sustainability (SusTech) 144-149. IEEE.
2. Raya, R.K., and Gupta, R., 2021. Stability Analysis of Directional Tunnel in Sandy Soil. In IOP Conference Series: Materials Science and Engineering 1197 (1), 1-15.

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Mr. Raya Raghavendra Kumar is a Research Scholar in the Civil Engineering Department, Birla Institute of Technology and Science, Pilani, Rajasthan, India. He received his B.E. degree in Civil Engineering from Rajalakshmi Engineering College, Anna University, Chennai, India, in 2013 and M. Tech. degree in Construction Engineering and Project Management from B. S. Abdur Rahman University, Chennai, India, in 2015. Before joining PhD in 2017, he had a teaching experience of 1.5 years in the Department of Civil Engineering at Madanapalle Institute of Technology and Science, Madanapalle, Andhra Pradesh, India. He was actively involved as a Project Assistant in the Department of Science and Technology (DST), India funded project titled "Conjunctive use of Rainwater and Groundwater to provide safe drinking water with the intervention of Advanced Technology" during his PhD tenure in BITS Pilani.

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Prof. Rajiv Gupta is currently a Senior Professor in the Civil Engineering Department, Birla Institute of Technology and Science, Pilani, Rajasthan, India, with more than 35 years of teaching experience. He has been involved in active research for the last 30 years and published around 70 papers in refereed journals, 120 conference papers and reviewed around 160 papers for reputed journals. He executed/executing sponsored projects worth more than Rs. 1000 lacs and guided/guiding 12 Doctoral candidates, 30 dissertations/M.E. projects, and 150 undergraduate students. He has authored and co-authored 3 books and other lecture materials. He won the grant funding of $1,96,000 at the Global Development Market place organized by World Bank in Washington in 2006. He has been actively involved in Water management systems in rural areas for the last 10 years, appreciated by all, mainly villagers and Rajasthan Government. He has more than 15 years of experience in institutional development and decision making. He worked as Deans (ESD, EHD), Assistant Unit Chief (Maintenance), Group Leader of various groups in BITS Pilani. He was involved in construction work for more than 250 crores, implemented rainwater harvesting and green architecture, and campus development of BITS Pilani.