STABILITY ANALYSIS OF DIRECTIONAL TUNNEL IN SANDY SOIL

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Abstract
In recent times, water storage is becoming a confronting task because of the depletion of water resources worldwide. Domestic rainwater harvesting and human-made structures for water procurement achieved significance because of the increase in intermittent water accessibility. In turn, functional water infrastructures fetch prominence in the wake of constructive coordination among the communities in a locality. Low water security and losses through evaporation observed by practising different rainwater harvesting methods create a research gap to construct water infrastructure in rural areas to procure water productively. The current research work represents the model of a water storage structure, named directional tunnel (DT), which is placed below the ground level in a declination, as it reduces evaporation and temperature, thus storing rainwater for longer days. DT stores runoff and rainwater collected from the rooftop of multiple houses in a selected locality. The detailed working of the DT is discussed using Building Information Modelling (BIM) concept. Combined with the engineering geological characteristics, the DT's stability during water storage comes into the picture as the whole structure interacts with the soil. The current study also focuses on the behaviour of DT with respect to sandy soil using PLAXIS 3D software, and the results are interpreted for practical viability.

Keywords: Building Information Modelling; Directional tunnel; Rainwater harvesting; Stability analysis

1. Introduction
The groundwater level is declining throughout many parts of the world. Earth may end up in groundwater unavailability in the coming years if necessary actions are not accommodated. Therefore recharging the groundwater or creating water resources for future use is very much obligatory. Rainwater harvesting and water storage are two of the essential methods to curb water inadequacy. The increase in water demand must be satisfied by maintaining sufficient per capita water [1]. By the end of 2020, around 784 million population globally do not have access to better quality water [2]. 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 [3]. Therefore, water for the future can be reserved in water storage structures by constructing sufficient water infrastructures. Especially in rural areas, they have to effectively serve the future purpose of water requirement without significant disadvantages. Infrastructure in a rural domain can meet the growing population's demand by incorporating engineered solutions and natural sources [4].
Rainwater harvesting has been a common practice followed in India. However, rainwater harvesting advancements are essential since storage of rainwater harvesting for longer durations experiences a few disadvantages. Primarily, the harvesting techniques entail collection and runoff storage from all potential sources. The rainwater harvesting in a region can reach a successful point, dependent on the quantifiable harvested water owing to climatic conditions [5]. In the 1970s and '80s, runoff collection was held in two ways, a) Micro – catchment water harvesting and b) Runoff farming water harvesting. Planned water supply assists in the management of reducing the current and future water deficiencies.

1.1 Status of rural water infrastructure in India
In coordination with the different state governments, the Government of India work progressively towards the accomplishment of 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 [6]. Despite several government and water bodies’ policies, schemes, and efforts in communities, India's water supply is insufficient, and those do not reach people in time. Updating water sources with new technology and methods would benefit the people as per the circumstances [7]. In a step towards active participation among rural people in India, under Mahatma Gandhi National Rural Employment Guarantee Act (NREGA), the members were made to devote an ample amount of their time to maintaining water infrastructure. After implementing the system, old and educated men showed interest in interactions, decision making rather than young, uneducated men and women [8]. Close to 1.4 billion (Population, 2021), India's population bears an expected water demand of 910 billion cubic meters by 2025 and 1072 billion cubic meters by 2050 [9]. Improper water management made 97 per cent of the overall population suffer water scarcity for at least one month [10]. With the introduction of Jal Jeevan Mission - rural, 2019, only 34 per cent of households were incorporated with the infrastructure [11].

The current study focuses on rainwater harvesting because of its affordability in India's rural areas and turns out to be an adjunct source for other prevailing water supply plans. Rainwater can be harvested in two types; primarily, the collected rainwater from the roof gets stored in an underground tank and secondly, for groundwater recharge [12]. In practice, rainwater harvesting performs as a reliable alternative for domestic use over the constrained public water supply in rural areas [13]. Rainwater storage structures are vital to evade evaporation loss, flooding, stormwater runoff, and surface water contamination in a village's community.

Previous research works reveal multiple attempts for storing rainwater by constructing above the ground and underground structures as community tanks in a village. Some of the research works were a vertical underground tank with one surface open to the atmosphere, or with an inlet through a pipe, a vertical tank with a manhole [14], a ground tank, etc. However, the main disadvantage linked to open vertical tanks was that the water gets evaporated at surface level after getting exposed to the atmosphere and the next layer, so on; as a result, the rate of evaporation remains the same. Moreover, a large-sized community tank occupies a vast area in a village, which becomes a constraint. The current research identifies a research gap that lies in implementing innovative rural water structures in India. In order to overcome limitations and drawbacks, current research work proposes an innovative method called a directional tunnel for underground rainwater storage.

1.2 Building Information Modelling for infrastructures
BIM is one of the significant mechanisms applied in Civil Engineering because of the multiple deliverable benefits during the plan, design, build, and operation phases. The advantages primarily
include time as well as cost reduction of the construction project. During the functional stage of any project, BIM implementation provides a broad scope concerning communication and coordination among all the teams and stakeholders involved [15]. BIM implementation does not have any comprehensive accepted master plan for any project. However, any adopted BIM implementation strategy in a particular field helps set or create an approach for the intended action method.

Over the years, BIM evolved into multiple dimensions. Through BIM, various approaches widen construction and management across disciplines, domains, and knowledge base [16]. For instance, any change in the structural plan can be updated using the BIM platform; subsequently, other engineers involved in planning the Mechanical-Electrical-Plumbing (MEP) works can act according to the reflected changes effectively. Graphical simulations developed by using BIM permits to visualize the project in a real-life scenario. Architectural visualizations give the perspective of the entire design before the initiation of construction. In another situation, BIM can be utilized to identify clash detection in a building among structural members and pipelines or ducts. Henceforth, clashes get avoided, and timely project completion, as well as cost-efficiency, can be achieved [17]. BIM enhanced numerous dimensions concerning quality management, safety management, and energy analysis with productive frameworks [18]. In Malaysia, even safety management among the construction works also started to emerge through BIM with the intervention of operational and organizational frameworks in the new concept called Prevention through Design (PtD) [19]. Hence, the current study intended to use BIM tools for the visualization of the innovative structure.

1.3 Stability analysis for underground structures
Soil as an engineering material is non-coherent in nature. An underground space can provide us with the site for infrastructures needed in rural areas. Underground construction works have always been very challenging from the civil engineering point of view. The current research explores the ground's downward direction in the storage of rainwater harvesting, hence the study of DT, which is installed underground, stability analysis comes into the picture for the prior identification of stresses and deformations. Dependent factors in the underground stability are the type of tunnel section, crack inclination angle on tunnel stability, the effect of overlying strata, stratification of soil, and soil-structure interaction [20].

2. Methodology
The creative method of underground rainwater harvesting proposed in the current research work is the directional tunnelling method for a rural community. Initially, the process of rainwater harvesting is practiced in multiple houses of a selected group. Then, each rainwater harvesting tank (RHT) would be again facilitated with a pipe at the upper portion, and water surpassing the storage cap would be transmitted to the DT (Figure 1). The DT method involves storing both the surplus rainwater from the RHT and runoff water near DT. Filters would be placed at the inlet pipe as well as the outlet pipe used for gathering dirt-free water. DT is placed at an angular position below the ground level and thus gets the name of the directional tunnel [21].

![Figure 1. Directional tunnel as underground water storage](image-url)
1 – Water storing directional tunnel, 2 – Inlet pipe from runoff, 3 – Water filter at runoff inlet, 4 – Multiple inlets from RHTs, 5 – Outlet pipe. L – Length of the directional tunnel, d – diameter of the directional tunnel.

3. Materials and Methodology

DT method functions as a solution for shortage among community water sources. The concept of DT assures ample rainwater storage with minimum area occupancy. The objectives of the DT for rainwater harvesting are: to reduce the rate and amount of water evaporation in the storage structure and to collect a large volume of water using less ground space without hindering adjacent structures.

Before construction, the DT is modelled by BIM tools for comprehensive understanding and execution. The current study utilized AutoCAD and Autodesk Infraworks, conceptual design software [22], to visualize the infrastructure’s working in a real and natural environment. DT was planned to accommodate a water capacity of 150m³ (Figure 2). Autodesk Infraworks software helped to design multiple RHTs in the selected community. All the RHTs were interlinked at the top portion, which subsequently connects to the DT for gathering excess water flow (Figure 3).

![Figure 2. Details of directional tunnel](image)

(All measurements are in meters)

Stability analysis for the underground structures is essential since the earth pressure directly impacts the structure’s condition. Numerical modelling is one of the techniques to check the practical viability of a structure before its execution. Therefore, civil engineers' responsibility is to design and test whether the rainwater storage device, i.e., DT, can withstand without any failure. In the current study, the DT is placed below the ground level. Geotechnical tools in recent times made us forgo the soil deeper and deeper. With the help of Plaxis 3D, a fast and reliable Finite Element Method based software, the behavior can be interpreted. Powerful Plaxis analytics and versatile reporting functionalities ensure data-driven decision making and high-quality deliverables. It helps to describe soil behaviour and structure in addition to their interaction [23].
Plaxis 3D contributes to the scope of BIM as well as other engineering software. Hence keeps the infrastructures safe in real-time execution. The current study follows a numerical modelling approach to understand the installation of DT since numerical modelling is a vital tool for facing geological related complexities.

4. Results & discussion

The DT method for rainwater harvesting was a unique technique; visual modelling was performed for the villagers and all the stakeholders' involvement in the execution. After creating virtual models of the whole rainwater harvesting system of the community, a fly through video was rendered. The video was used as an interaction tool among all participants regarding rainwater harvesting, highlighting all RHT and DT connections. Furthermore, the complete rainwater harvesting system illustration made the villagers in the community perceive the working system. As a result, all the individuals living in the community approved the installation of DT.

Since the DT was placed in a declination below the ground level, the DT’s angle was checked for five cases and analyzed for stability. The five angles of orientation were 10°, 20°, 30°, 45°, and 60°. The angles were selected based on the practical feasibility of the installation. Model creation of DT in Plaxis 3D was based entirely on the site conditions in the desired community of the village Ramnathpura in Rajasthan, India. Its coordinates are 28°18’ 38.628”N, and 75°39’ 43.38”E.
A borehole was set for a depth of 20m. The soil model with two layers, i.e., loose sand and dense sand, was created concerning the location. All the soil properties were assigned. Then, the tunnel with a trajectory of the required dimensions was set with a diameter of 3.05m, a thickness of 0.005m (Figure 4), and a length of 21.34m.

Medium mesh for the DT was opted before the calculation. Two stages, i.e. i) Initial phase and ii) Load Phase, were analyzed for stability in the whole soil medium, including DT. The core segment of the tunnel was made up of a glass fire composite plate with a thickness of 0.005m. The material properties and fixed boundary condition of the DT were the same throughout all five cases. Static load condition was created for the whole model. Out of the multiple results, three parameters of total displacement, total principal stress and total principal strain were taken into consideration for studying the response of the DT.

Stability analysis of all the five cases is as follows:

**Case 1: Declination angle - 10°**
The model with a declined trajectory of 10° was simulated for analysis, and the three results were obtained (Figure 5.a, Figure 5.b, Figure 5.c).

![Figure 5.a) Total displacement after simulation of phase 2](image-url)
Case 2 – Declination angle $20^\circ$

The model with a declined trajectory of $20^\circ$ was simulated for analysis, and the three results were obtained (Figure 6.a, Figure 6.b, Figure 6.c).
Figure 6.a) Total displacement after simulation of phase 2

Figure 6.b) Total principal stress after simulation of phase 2
Case 3 – Declination angle 30°
The model with a declined trajectory of 30° was simulated for analysis, and the three results were obtained (Figure 7.a, Figure 7.b, Figure 7.c).

Figure 6.c) Total principal strain after simulation of phase 2

Figure 7.a) Total displacement after simulation of phase 2
Case 4 – Declination 45°
The model with a declined trajectory of 45° was simulated for analysis, and the three results were obtained (Figure 8.a, Figure 8.b, Figure 8.c).
Figure 8.a) Total displacement after simulation of phase 2

Figure 8.b) Total principal stress after simulation of phase 2
Case 5: Declination angle 60°
The model with a declined trajectory of 60° was simulated for analysis, and the three results were obtained (Figure 9.a, Figure 9.b, Figure 9.c).

Figure 8.c) Total principal strain after simulation of phase 2

Figure 9.a) Total displacement after simulation of phase 2
Figure 9.b) Total principal stress after simulation of phase 2

Figure 9.c) Total principal strain after simulation of phase 2

All three parameters for five cases of declination angles were obtained (Table 1).

| S. No | Declination angle | Total displacement (m) | Total principal stress (KN/m²) | Total principal strain |
|-------|------------------|------------------------|-------------------------------|-----------------------|

Table 1. Obtained results for five cases of declinations in the directional tunnel.
1. 10° 0.01888x10^{-3} 2.677 0.02884x10^{-3}
2. 20° 0.01474x10^{-3} 2.502 0.02405x10^{-3}
3. 30° 0.02060x10^{-3} 2.306 0.02310x10^{-3}
4. 45° 0.03395x10^{-3} 2.179 0.03211x10^{-3}
5. 60° 0.03952x10^{-3} 2.973 0.04755x10^{-3}

The declination angle of 30° yields moderate total displacement in the selected soil medium with the least total principal stress and strain. Even though displacement at 10° and 20° experience lesser total displacement than 30°, the stress and strain caused in the soil medium was comparatively higher. Other angles of 45° and 60° result in slightly higher total displacement, total principal stress and total principal strain; therefore, they were out of workable consideration. Thus, the current study recommends the DT at a declined angle of 30° is suitable for practical implementation in sandy soils.

5. Conclusion
Rainwater harvesting in rural areas seeks improvisation from the traditional technique because of the disadvantages faced through evaporation, surface storage and runoff. The current research proposes the innovative idea of directional tunnelling. Modern structures require more straightforward methodologies for comprehensive understanding and implementation. Usage of BIM tools for the visual demonstration to the workmen in the rural areas resulted in smooth onsite construction. AutoCAD and Autodesk Infraworks software were employed as BIM tools to create the community's entire rainwater harvesting set-up. Simultaneously, the DT was checked for stability. The location selected for construction was examined for soil type, and the tunnel’s stability was studied for various declinations of 10°, 20°, 30°, 45°, 60°. The analysis made by PLaxis 3D and from the acquired results, the study reveals that directional tunnelling at 30° was more feasible in sandy soil for effective operation. Simultaneously, the current research limits the practice of DT in rural areas with static load conditions where future scope can be extended towards urban areas with dynamic loading and its practicality.

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