PHYSICAL MODELLING OF TUNNELS UNDER STATIC LOADING

A DISSERTATION

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IN

GEOTECHNICAL ENGINEERING

Submitted By

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I, Akshay Kumar, Roll No. 2K16/GTE/02 of M.Tech. Geotechnical Engineering, hereby declare that the project Dissertation titled **"Physical Modelling of Tunnels under Static Loading"** which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of technology, is original and not copied from any source without proper citation. This work has not been used for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled **"Physical Modelling of Tunnels under Static Loading"** by **Akshay Kumar**, Roll No. **2K16/GTE/02**, Department of Civil Engineering, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in parts or full for any Degree or Diploma to this University or elsewhere.

Place, Delhi, India

Date:

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ABSTRACT

The study of stresses around the tunnels is an important step for any type of tunnel construction. The surrounding may be either rock or soil depending on the site and topography of the area. In the Himalayan ranges, the geology of the ground is rocky strata which are initially stressed due to the heavy overburden of more than 1000 meters. The rocks are also stressed due to the excavation process of the tunnel construction which induce secondary stresses in the surrounding rocks. The study of these stresses is done by geologists using various physical and numerical modeling techniques. The hazards in the tunnel construction can be mitigated with better measures of safety such as lining and support system. This requires an expert knowledge of rock mechanics as well as material technology. These stresses are highly affected due to the cover depth of the tunnels below the ground as well as lining material. In this report, we have made an attempt to study the effect of a change in the cover depth and lining of the tunnel by physical modeling technique.

In Jammu & Kashmir, Chenani-Nashri tunnel has been recently constructed which is broadly affected by the action of stresses due to the mountains above it causing it critical for deformation. The tunnel has become an important link between the two districts Udhampur and Ramban and the stability of this tunnel has become an important issue for safe transportation. So, this tunnel is selected as a case study for this thesis to check the stability of the tunnel using physical modelling technique. To determine the existing properties of the surrounding

rocks, tests have been performed in the laboratory to determine the properties which affect the stability of the tunnel.

Physical models are prepared by the theory of stresses which include the ratio of diameter of tunnel and distance from the center of the tunnel for the dimensioning of the model and test is performed to examine the failure mechanism of the tunnels and which is based on the study area. The models are also analyzed for the critical region of deformation.

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Abbreviation

TBM= Tunnel Boring Machine

CTM=Compression Testing Machine

POP= Plaster of Paris

PVC= Polyvinyl Chloride

UCS= Unconfined Compressive Strength

SEM= Sequential Excavation Method

W/c= Water Content

KN= Kilo Newton

J&K= Jammu and Kashmir

NCR= National Capital Region

2D= Two Dimensional

3D= Three Dimensional

s^{-1}= Per Second

D&B= Drilling and Blasting

ITS= Indirect Tensile Strength

GPS= Global Positioning System

μ= Poisson's Ratio

E= Modulus of Elasticity

CHAPTER1

INTRODUCTION

1.1 BACKGROUND

The study of stresses in the construction field in the hilly areas is the first and foremost step in the designing of a structure. With the increasing demands, vast population and heavy traffic, the need of rapid and accessible transportation system is required. Therefore, the tunnel construction in the Himalayan region has increased to a rapid rate for the past years and it has become an important aspect of transportation system in the Himalayas. The process of construction of a tunnel is a complex and challenging task in such hilly areas which is made simpler by various techniques suggested by scientists and geologists among which physical modelling plays a very important role. The study of stresses in the rocks where the tunnels are to be excavated are studied by geologists before any excavation and simulated in the laboratories using physical modelling techniques for obtaining a cost-effective and safe design. The study of stresses around tunnels gives an insight of the basic mechanisms like displacements and the stress zones and helps to provide suitable support for the underground opening. These tunnels are constructed in hard rock, weak rock, stiff soil, soft soil or mixed ground. The major challenges to an opening can be classified as in-situ stresses which are due to the overburden rock, induced stresses due to the excavation and traffic loads, not significant in the case of deep tunnels. The design of a tunnel in rocks differs from other types of designs in soils or under the ground in terms of the nature of loads acting on the system. In hilly areas, rocks are initially stressed and any opening created cause changes in the initial stress. The post-excavation stress in the tunnel is the resultant of initial state of stresses and stresses induced by excavation. Hence the determination of the initial state of stress of rocks is necessary for any design analysis. Cutting or the excavation technique plays a great role in how much stress is induced due to the excavation. These excavations can be done by any of the following method

- Drilling and blasting

- Using tunnel boring machines (TBM)

• Road headers

• Sequential excavation with small mechanical equipment

Groundwater also influences the state of stresses in the tunnels whose study is crucial and need to be considered during the design. After the estimation of initial stresses due to the overburden in the tunnels and the secondary stresses due to the excavations, the Tunnels are analyzed for a better design and support system which also requires a study of the lining material inside the tunnel. For a better support system to protect the tunnel, one needs the knowledge of rock mechanics and material technology. This report provides a study of the effect of both cover depth and lining material on the stresses of a tunnel and provides conclusions for a better design and risk mitigation. Also, the study of stress zones in the tunnels and physical modeling technique is discussed in this report.

1.2 CHALLENGES IN TUNNEL CONSTRUCTION

1.2.1 Ground Behaviour

Ground behavior refers to how the material of the ground will behave when construction has started. The “ground”—the rock or soil—behaving differently than expected is the most significant problem involved in tunnel construction. The nature and composition of the ground have implications for how construction should be approached: with hand-mining, drill-and-blast, with a shield or with tunnel-boring machines. Additionally, the presence of water can affect ground behavior. One major problem related to ground behaviour is stand-up time. A stand-up time problem arises when the ground cannot support itself for the time during which the tunnel is being constructed. This issue affects the type of ground support used, the manpower requirements of construction, production and schedule, equipment selection, and cost. Another major problem related to ground behaviour is in-situ stress, which refers to how some rock at certain depths is loaded with stress from other rock strata and from locked-in tectonic stress resulting from geologic development. When tunnels are excavated in the stressed rock, local stress fields are disrupted and new sets of stresses are induced in surrounding rock, which can have disastrous effects. Avoiding accidents related to unpredicted ground behaviour is not a simple matter, and an approach of probability-based risk assessment should be taken in order to minimize the chances of an accident.

1.2.2 Existing Conditions

The existing conditions of the construction site are often sensitive to the construction process. Engineers should take care to know as much as possible about surface and underground structures, as well as possible hazardous materials stored in the ground. Sometimes construction can expose gases previously trapped underground. These gases can be toxic and can cause significant construction problems. If and when gas is encountered, the gas's properties must be evaluated and studied for its potential effect on personnel. The worst industrial accident in American history occurred because of hazardous existing conditions during the construction of the Hawks Nest Tunnel. The tunnel was being built by Union Carbide through the Gauley Mountain in Fayette County, West Virginia. The tunnel was meant to redirect water from the New River to drop it down almost 200 feet to power turbines and create electricity. However, during construction, workers encountered 99.4 percent pure silica that they were instructed to drill without protection. As a result, more than 750 workers died.

1.2.3 Rock Face Fall-out

Rock face fall-out refers to when rocks fall from the construction face as a result of weakening ground and support conditions. According to studies, most accidents because of rock fall happen when workers approach a tunnel, cutting face in order to mount a steel arch support. In order to prevent rock face fall-out, the technique of "shotcreting" is used. Shot crating refers to spraying a newly excavated surface with a coat of concrete in order to give temporary support to the newly exposed rock face. It also helps stop ground surface deterioration and secures loose materials. If done remotely, this greatly minimizes the dangers of rock face fall-out.

1.2.4 Compressed Air

Compressed-air techniques of tunnel construction are used mainly on driving earth tunnels through water-bearing soils or adjacent to bodies of water. The technique is the most reliable technique of tunnel construction when the tunnel is being built below the water table, especially when face instability and water flow are predicted to be acute. Compressed-air techniques can pose risks to construction and personnel, and they are expensive. Personnel must be specially certified to work in the unique environment posed by compressed-air construction techniques. This raises both personnel and equipment costs since items needed such as airlocks and compressors are expensive. Decompression, flooding, and fire are among the possible risks of compressed-air construction. Therefore, other kinds of techniques should be evaluated for their possible effectiveness before engineers decide to use compressed air.

1.2.5 Groundwater and Water Flow

The presence and movement of water can influence ground behavior, which poses risks to tunnel construction. Flowing water might carry materials into newly excavated openings, causing general instability in the mass of rock. Additionally, water can change the ground's physical properties and behavior, making it unpredictable. Moreover, the presence of water makes handling of material difficult and may necessitate a centralized pumping system, which takes time and money to install, raising general costs and disrupting the construction schedule. Though necessary, underground construction is a dangerous and difficult process that requires preparation and many safety precautions.

1.3 STRESSES IN TUNNELS

The knowledge of stresses in the tunnels is prerequisite before any tunnel construction in the mountains. This study has been done in various researches by scientists and geologists which have assumed a 3D model of a tunnel of geometrical and characteristic similarity with the tunnel and studied the effect of surrounding stress due to the rocks using physical and numerical modeling techniques. Figure 1.1 shows a model of a tunnel which was assumed to study the stresses in a circular tunnel.

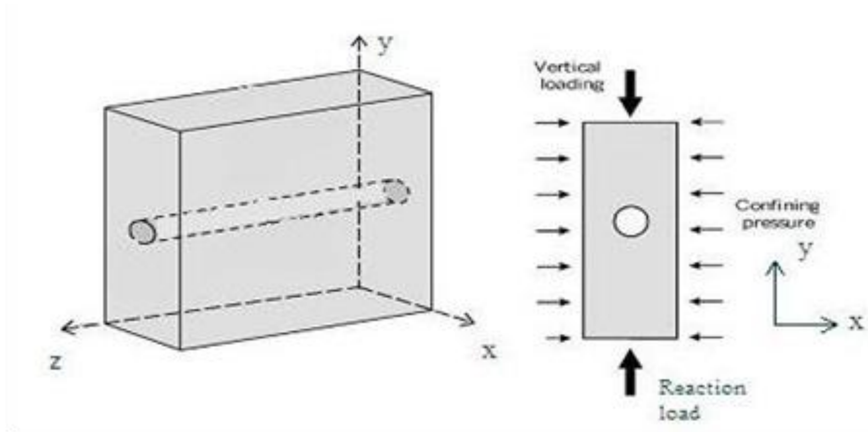

Figure 1.1 Sectional view of a long tunnel (Source: Duvall & Obert, 1967)

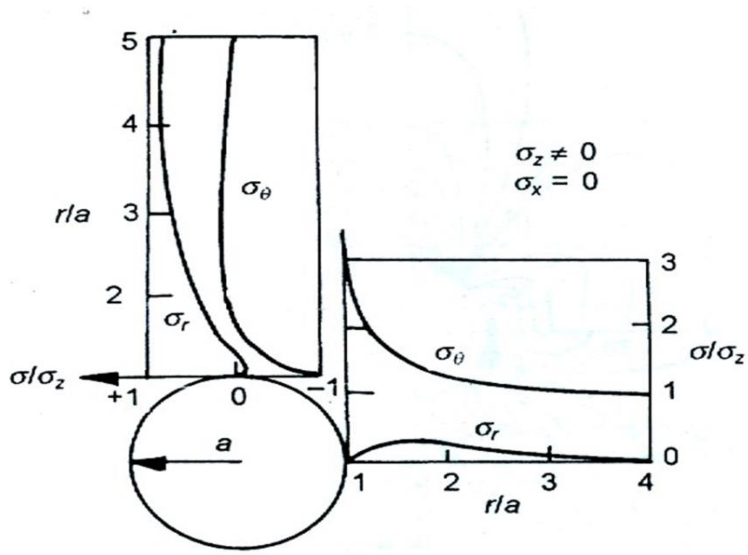

Figure 1.2 Stresses around circular openings (Source: Duvall & Obert, 1967)

1.4 TANGENTIAL AND RADIAL STRESSES AROUND TUNNELS

When the tangential stress around an opening is greater than about one- half of the unconfined compressive strength, cracks begin to form. At-large depth, such rock failure can cause violent bursts. Weak rocks like shale reach the condition for rock cracking at small depths. In such rocks, new cracking may initiate further loosening as water and air cause accelerated weathering. The zone of broken rock is driven deeper into the walls by the gradual destruction of rock strength. As a result, the load on the tunnel support system will increase and the supports experience a gradual build-up in pressure known as squeezing.

To gain a better understanding of the mechanics of a squeezing tunnel and to provide an analytical framework to provide appropriate support systems, the theoretical model proposed by Bray (1967) can be considered.

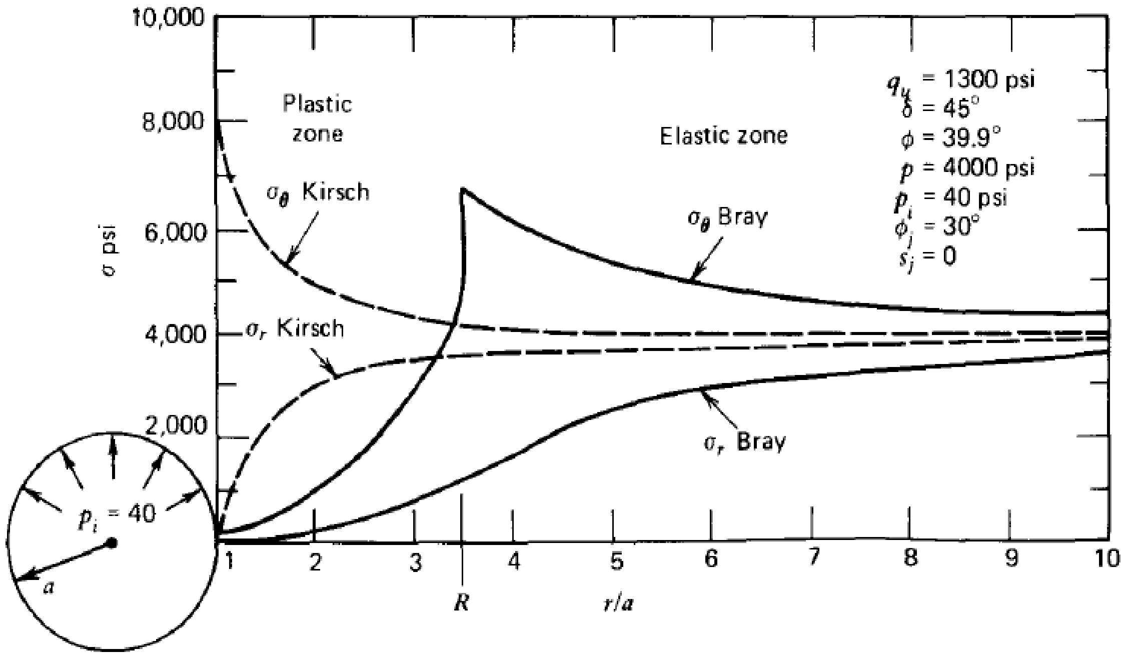

Figure 1.3 Stresses around the yielding tunnel (After Bray, 1967) (Source: Duvall & Obert, 1967)

The plastic behavior of the region near the tunnel has the effect of extending the influence of the tunnel considerably farther into the surrounding rock. In the wholly elastic case, the tangential stresses would have fallen to only 10% above the initial stresses at a radius of 3.5 times the tunnel radius but in the elastic-plastic case, the elastic zone stresses are 70% higher than the initial stresses at this distance and 10 radii are required before the stress falls down to 10% of initial stress. Thus, two tunnels that do not interact with one another in the elastic ground might interact in the plastic ground.

1.5 ZONE OF INFLUENCE AROUND CIRCULAR TUNNELS

Zone of the influence of an excavation is very important for underground tunneling and mining applications where multiple excavation/ tunnels are excavated. With the considerable simplification of a design problem, idea is to get the domain of significant disturbance of the excavation stress and get the stresses near field and far field of a tunnel. Stress distribution around a circular hole in the hydrostatic medium.

At r = 3a, the state of stress is not significantly different (within 5%) from the field stress.

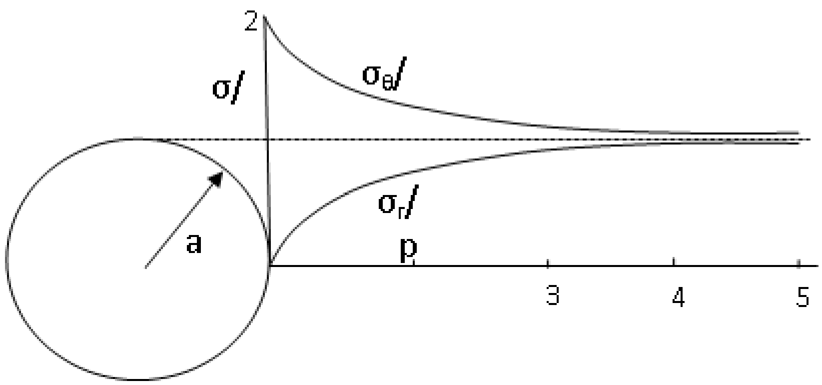

Figure 1.4 Radial and tangential stresses corresponding to the different radial distance (Source: Duvall & Obert, 1967)

Table 1.1 Tangential and radial stresses corresponding to the different radial distance (Source: Duvall & Obert, 1967)

Distance from center	Tangential stress	Radial stress
a	2P	0
2a	1.25P	0.75P
3a	1.06P	0.94P
4a	1.04P	0.96P

5a	1.01P	0.99P

1.6 SCOPE

As deformation of tunnels may lead to dangerous accidents which has the chances to occur anytime in the tunnel which causes tremendous loss of life and economy and also affects the social and economic features and the J&K region is an important area with urbanization taking place due to construction of modern tunnels, it is necessary to analyze the causes and mechanism of failure of the tunnels so that the strengthening of the tunnels can be done to prevent failures. The study also leads to appropriate lining material which helps in minimizing the risk of failure.

So this study will help in deciding the cover depth of the tunnel and practical solutions for the tunnel, maintenance, safety and control of deformations caused due to stresses triggered by overburden pressure.

1.7 OBJECTIVE OF THE WORK

- To study the existing geological parameters of the Chenani-Nashri tunnel J&K by physical modeling.
- To design a model similar to the existing rock at the site with similar geomechanical parameters.
- To test various tunnel models under static loading and study the effect of a change in the cover depth and lining material.
- To compare and analyze the stability of the model with standard results.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Deformation behavior of tunnels in rocks and soils at different strain rates has continued to attract research interest in order to understand their deformation and failure mechanisms at rapid rates of loading. From a practical point of view, when designing underground excavations in rocks, the goal is to minimize stress concentration problems, create a stress field as uniformly distributed as possible in the excavation of tunnels so that the optimum support systems is provided without compromising the safety of the structure. There has been a wide quantum of research on the load-deformation behavior of tunnels under static and dynamic loading.

Mauriya et al. (2010) illustrate the challenges and strategies for Tunnelling in the Himalayan Region. The study shows various tunneling technology, development of tunneling in India, challenges in tunneling, geological problems, engineering challenges and strategies for handling the challenges of fast-track tunneling.

Sudhir et al. (1964) studied the behavior of Plaster of Paris by performing various tests to estimate the engineering properties of POP and the relationship between water content and strength of the POP.

Russo et al. (2012) carried out an investigation to assess the engineering properties and geomechanical properties of the rocks surrounding the Chenani-Nashri tunnel located in J&K. They concluded that the rocks surrounding the tunnel are composed of Lower Murree formation which consists of sandstone, claystone, and siltstone.

Mustafa et al. (2017) performed a study to estimate various geomechanical properties of the Lower Murree formation that is found in the composition of the rocks of Himalayas in J&K. The prime focus of this study was to estimate the properties of sandstone which is the major constituent in the Lower Murree formation.

Singh et al. (2015) studied the engineering properties of the Himalayan rocks using the ANFIS technique. In this study, four key geomechanical properties of Himalayan rocks viz. UCS and cohesion were measured and correlated with the P-wave velocity. The correlation had been done using linear regression analysis technique as well as through ANFIS approach. The geomechanical parameters were initially correlated individually for each rock type and then the combined data was analyzed using ANFIS.

Zhenyu et al. (1990) studied the behavior of rock under cyclic loading and proposed an endo chronic constitutive equation that had an ability to describe the stress-strain curve under static loading conditions. Test results showed that the failed models of jointed rock were extremely susceptible to static failure. They also concluded on the effect of a pre-existing joint on initiation and propagation of cracks during static compression-tension tests.

Xiao et al. (2010) carried out a series of laboratory tests to assess the effects of confining pressure on the mechanical properties and fatigue damage evolution of sandstone samples subjected to static loading test.

Chen et al. (1986) presented a nonlocal analysis of the dynamic damage accumulation processes in brittle solids. The results indicated that the model reproduced, qualitatively, the brittle behavior of rock under blasting conditions.

Li et al. (2001) studied the mechanical characteristics and proposed a fatigue damage model for jointed rock masses and dry, frozen, and saturated sandstone samples subjected to loading. Surrounding rock of tunnel in soft rock at shallow depths is highly sensitive to disturbance.

Wood et al. (1979) illustrate a method to estimate the tangential stresses around underground openings. The stresses developed in the ground surrounding an underground opening are mainly a result of the original, in situ (virgin) stresses, the impact from the excavation works, and the dimensions and shape of the opening. Their distribution may, however, be influenced by joints occurring around the opening.

Meguid et al. (2006) illustrate the techniques of physical modeling. It says that physical modeling of soft ground tunnels is an essential part of the analysis and design of tunnels. Physical models can provide data that can validate and calibrate numerical models. For several decades, numerous researchers around the world have developed and implemented a variety of techniques to simulate the tunnel excavation process. Reduced scale tests under 1g conditions provide full control over the excavation method. However, they do not accurately simulate the in situ stress conditions. Centrifuge testing makes a more realistic simulation of in situ stresses possible but the tunnel construction process has to be simplified. Different methods have been developed to simulate the process of tunnel construction in soft ground. Soil arching around excavated tunnels has been successfully simulated using the trap door method. Table 2.1 summarizes the advantages and disadvantages of the modeling techniques discussed above.

Table 2.1 Method comparaison table (Source: Meguid et al. 2006)

Method	Advantages and applications	Disadvantages
Trapdoor	Used to evaluate surface settlement and pressure on the trap door simulating tunneling induced movement and lining stresses	Does not simulate the actual tunneling process
	Both 2D and 3D ground movement resulting from tunnel excavation can be evaluated under 1g and centrifuge conditions	Only an approximate estimate of the surface settlement and lining stresses can be obtained
Rigid tube with flexible face	Used to study failure mechanisms, face stability of shallow tunnels	Does not provide information on the surface settlement behind the tunnel face
	Tests can be conducted under 1g and centrifuge conditions	
Pressurized airbag	2D and 3D tests that can be conducted under both 1g and centrifuge Conditions	Used mostly for unlined tunnels Does not simulate the tunnel face advance

Polystyrene foam and organic solvent	Can be conducted in a centrifuge	Results were less satisfactory
Soil augering	Simulates the tunnel advance process	Used mostly for cohesive soils
	Easy to operate	Insertion of a shield is usually required
		1g only, not easily mechanized for a centrifuge
Miniature TBM	Conducted in a centrifuge	Expensive
	Simulates the complete tunneling process	Limited gravitational acceleration (up to 25g) may be applied in a centrifuge
Mechanically adjustable tunnel Diameter	Simulates the 2D tunnel excavation process	Manually controlled
	Simple to operate	Limited to 2D models under the 1g condition

2.2 GAPS IN LITERATURE REVIEW

Although many types of researches have been conducted for the study of tunnels and their construction along with modelling and study of stresses, still it lacks to know about the exact positions of the strains and deformations of the stresses and the need of the study of the cover depth effect on the boundary of the tunnels needs to be analysed for a safe and reliable design of the tunnels. The major gaps in the literature review are as follows

- Not much work has been done for the study of the effect of a change in the cover depth of a tunnel

- Also, it lacks in the study effect of lining material and its properties for the construction of the tunnel
- Less work has been done to study the exact deformation and strains inside the tunnel for the safe designing.
- Any study has not been conducted for the physical modeling of a tunnel to the stress-strain relationship and interpreting its engineering properties.

2.3 SUMMARY

From the above studies, it is concluded that tunnels are important elements of Infrastructure projects, Hydro Power, Transportation, water supply & sewerage system etc. Its construction involves many complexities in terms of different shapes, soil/rock conditions, alignments etc. The study of stresses before the construction of the tunnels is very important. The strength of the tunnel depends on how much overburden pressure is acting above the tunnels as well as the support system used for the tunnels. The prediction of tunnel stability is possible through physical and numerical modeling technique. Hence, through these techniques, the determination of the support system for a tunnel can be carried out. Analysis of the differential stresses allows the prediction on potential failure regions. Regions of high differential stress may result in cracking initiation and propagation problem. Significant displacement in tunnel induced high stress on the tunnel structure and will lead to failure. In a nutshell, the potential behaviors of a tunnel under high rock stress can be predicted through the analysis of the critical zones of tunnels. Under the influence of disturbance, and continuous deformation, the mechanical properties of the surrounding rock are also deteriorated, the elastic modulus, UCS, and other engineering properties are significantly lower. Soft-ground tunnels are typically circular in shape because this shape has greater strength and ability to readjust to future load changes. The stresses around the tunnels also depends on the geology of the rocks, their engineering properties and geomechanical parameters.

CHAPTER 3

METHODLOGY

3.1 INTRODUCTION

In the chapter, the materials and methodologies are described which are used in this research to ensure the achievement of the objectives. Region near J&K area, Chenani-Nashri tunnel has been considered for physical modeling tested under a static loading. The geomechanical properties and engineering properties of the site have been taken from a research paper and then characterization of the material used is done by Unconfined Compression Test to meet the inherent properties of the existing rock at the site. Further various tests are done to determine the properties of the material required for the study.

3.2 STUDY AREA

3.2.1 Overview of the Chenani-Nashri tunnel

Chenani-Nashri Tunnel, also known as Patnitop Tunnel, is a road tunnel in the Indian state of Jammu and Kashmir former J&K (before renumbering of all national highways). It is India's longest road tunnel with a length of 9.28 km. The all-weather tunnel bypasses snowfall and avalanche prone areas in winter at places like Patnitop, Kud, and Batote that obstruct NH 44 every winter and cause long queues of vehicles, sometimes for days.

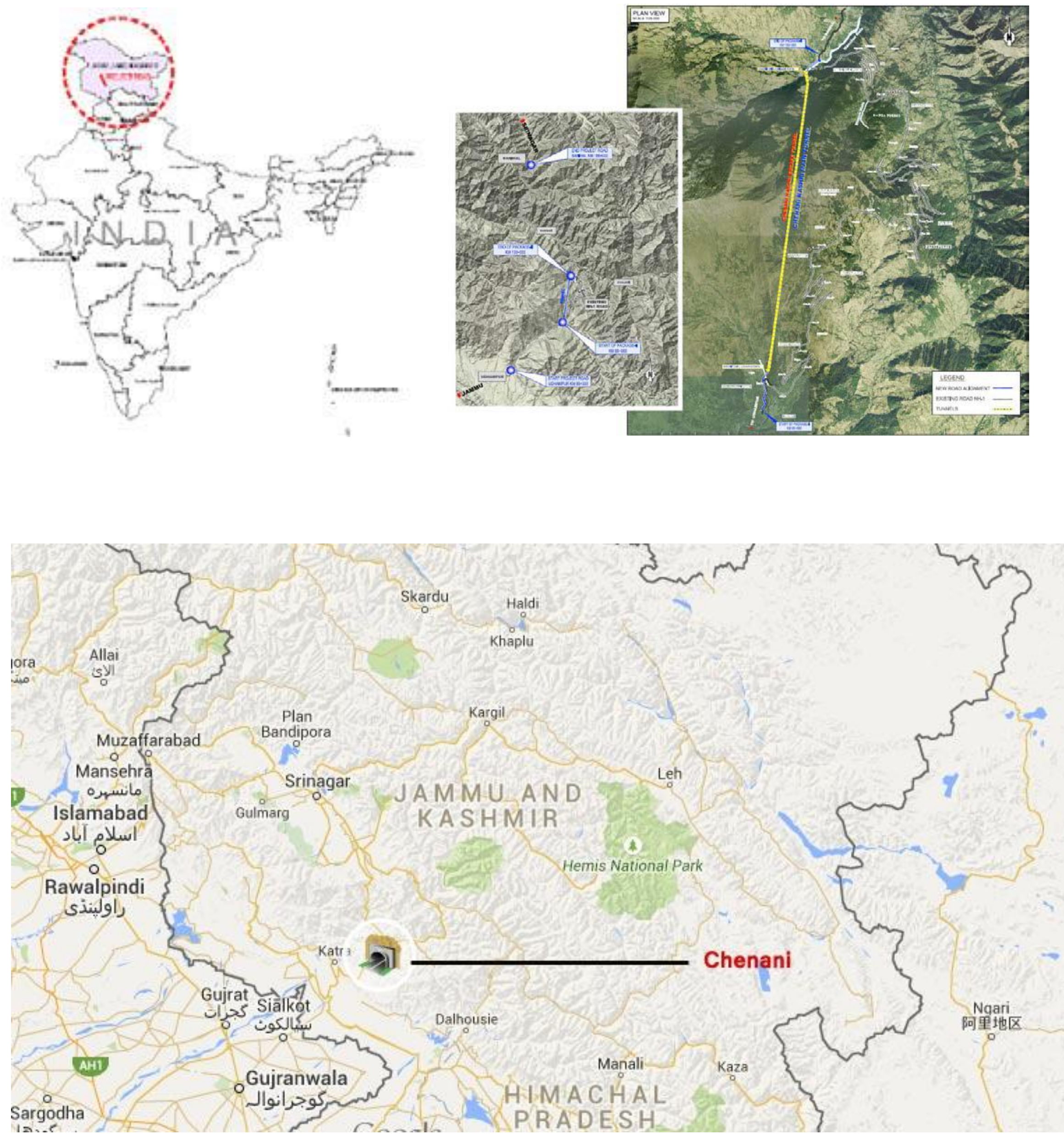

Figure 3.1.1 Sitemap of Chenani-Nashri tunnel (Source: www.nbmcw.com)

3.2.2 Description of the Tunnel

The Chenani-Nashri tunnel has an overall diameter of 10m which has been excavated using the Drilling and blasting technique. The overburden above the tunnel is the Himalayas of around 1050m. The main has a typical cross-section that is horizontal (H):9.35m x vertical (V):5.00m, plus 1.2m wide footpath each side (Facibeni et al., 2011).

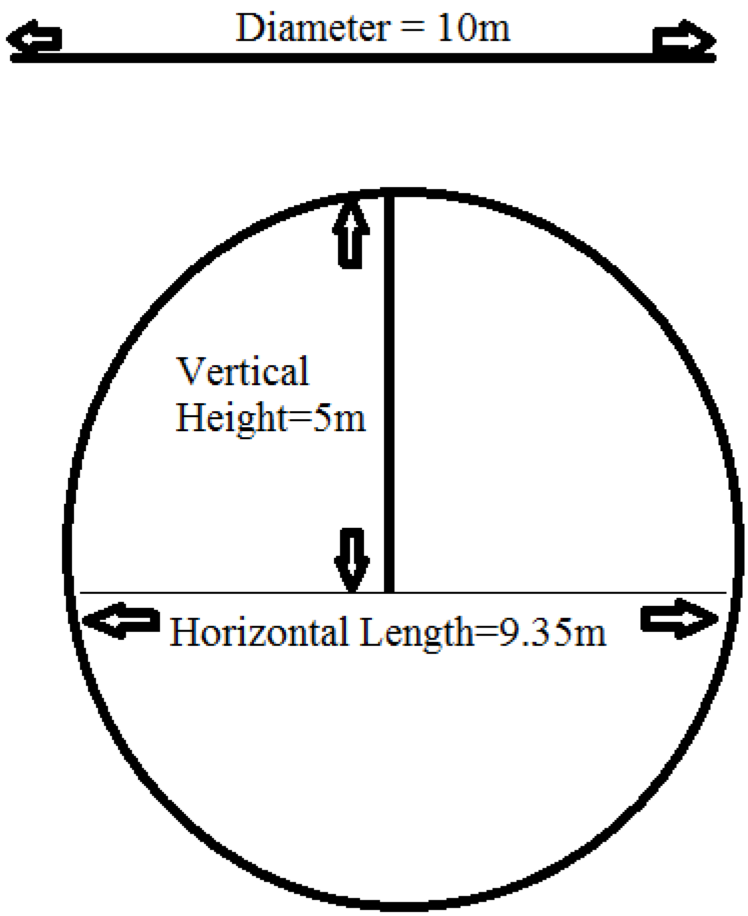

Figure 3.1.2 Cross-section of the Chenani-Nashri tunnel (Source: Facibeni et al. 2011)

The cross-section of the north face and south face of the tunnel are different. The dimensions of the tunnel are as follows (Facibeni et al. 2011)

- Horizontal length = 9.35m
- Vertical height = 5m
- Width of footpath = 1.2m
- Road elevation at north portal = 1209m
- Road elevation at south portal = 1230.5m

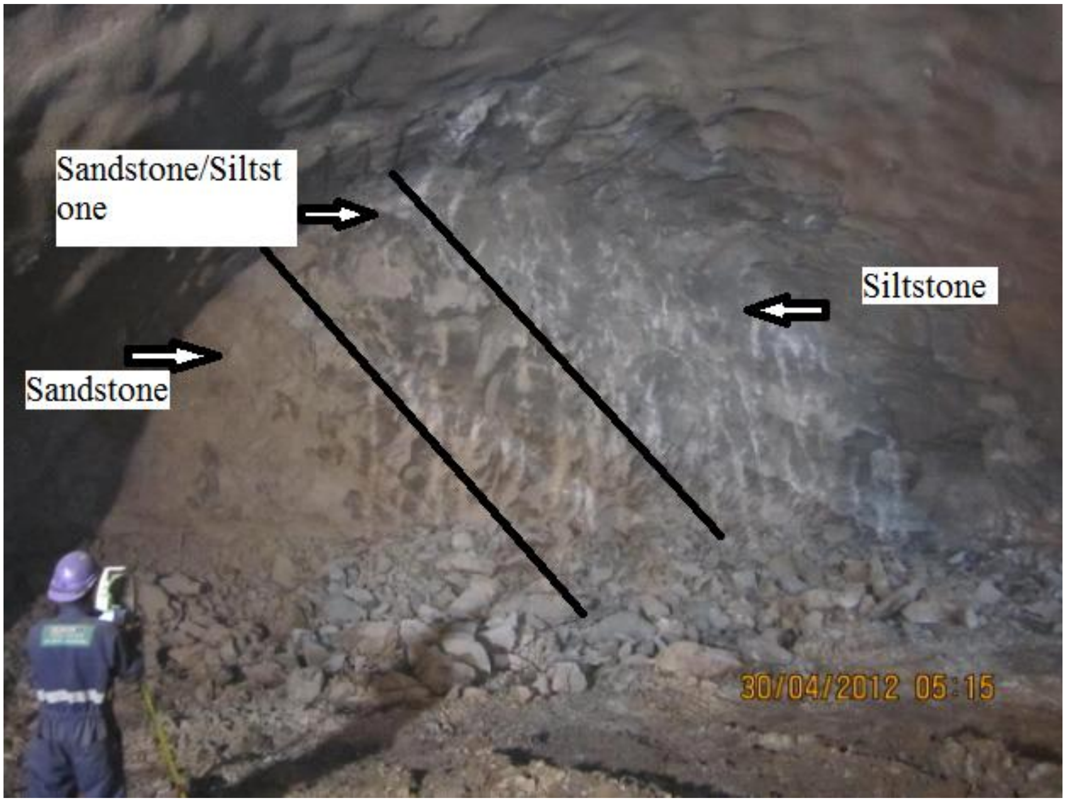

Figure 3.1.3 Murree formation of the South face (Source: Goel et al. 2012)

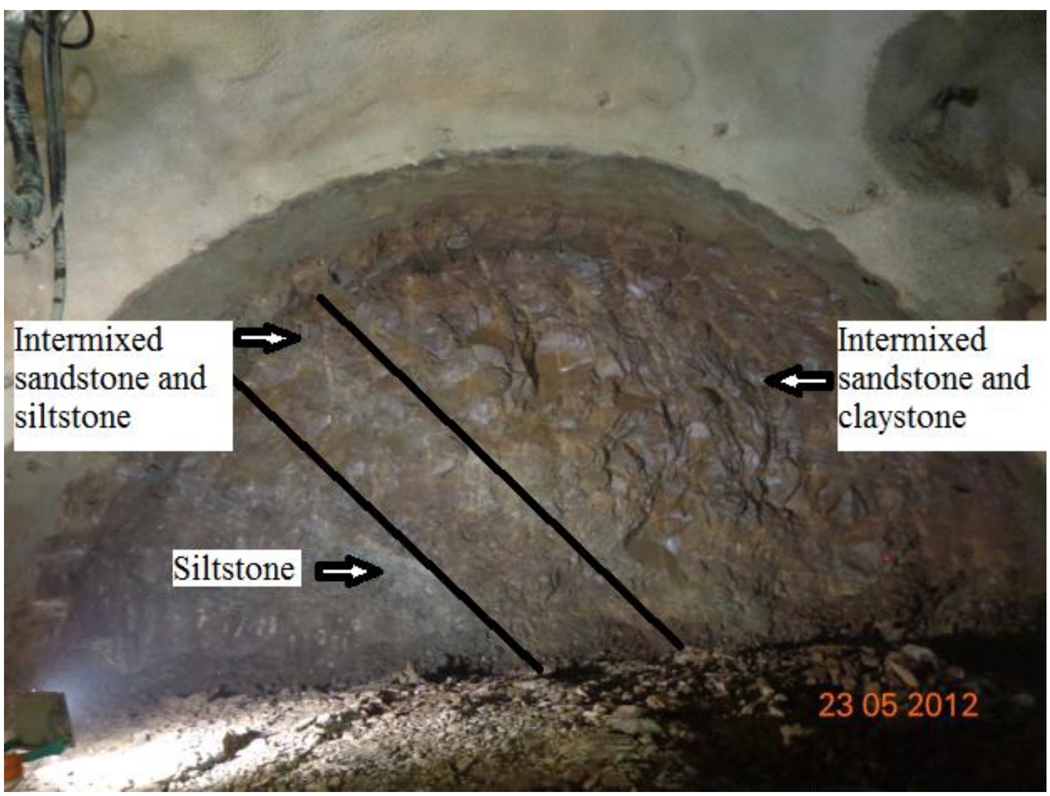

Figure 3.1.4 Murree formation of North face (Source: Goel et al. 2012)

3.2.3 Geotechnical Investigation of the material

Rock samples were collected from different places at the site to determine the properties of the material of tunnel surrounding. By performing geological investigations and tests in laboratory, the results show that the rock masses along the tunnel belong to the Lower Murree Formation. The Murree Formation is represented by a sequence of argillaceous and arenaceous rocks that includes a sequence of interbedded sandstones, siltstone/claystone beds with a thickness ranging from a few meters up to 10m (Facibeni et al. 2011)

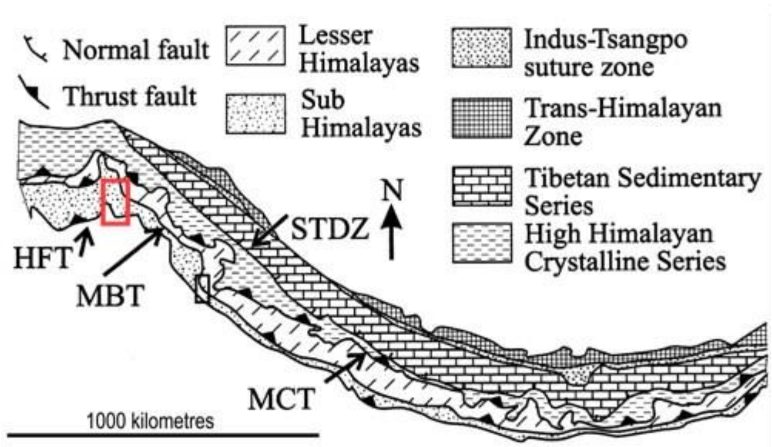

Figure 3.1.5 Geological features of the Site

Through investigation, it was found that the rocks along the tunnel are composed of sandstone, claystone and siltstone which were present at different locations along the tunnel.

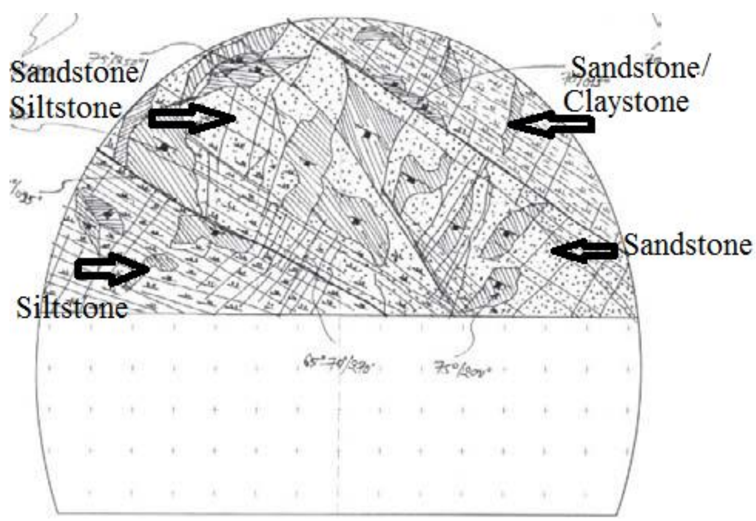

Figure 3.1.6 Geological face mapping

Table 3.1 Geo mechanical parameters of the Site (Source: Russo et al. 2013)

Lithology	UCS(MPa)	Elastic Modulus(MPa)	Poisson's ratio
Sandstone	100	6150	0.25
Sandstone/Siltstone	75	5032	0.25
Siltstone	50	4193	0.25
Siltstone/Claystone	15	839	0.30

3.2.4 Rock Classification of the Site

The rock masses along the project of the Chenani-Nashri tunnel belong to the Lower Murree Formation. The behavior classification of the rock mass has been performed using the quantitative approach proposed by Russo and Grasso (2007). The main advantage of the proposed probabilistic approach is that categorization of the deformational behavior is based on the results of the ground convergence curve with a relatively high degree of reliability.

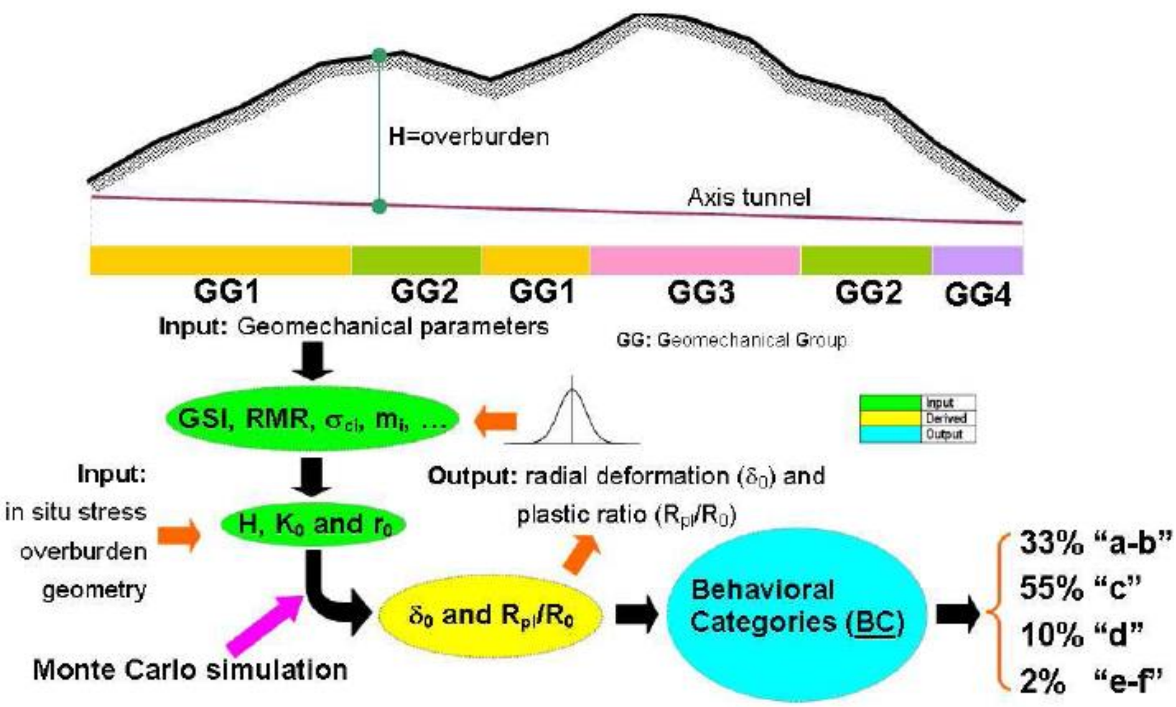

Figure 3.1.7 Quantitative approach by Russo and Grasso (2007)

3.2.5 Engineering properties of the Site

The geology of the rock at the site consists of a layer of Lower Murree formation which comprise of Sandstone and siltstone. The tunnel comprises of various layers of sandstone and siltstone in the Lower Murree formation. Various strength parameters of the rock at the site is obtained from Kim et al. (2014) which are as follows

Table 3.2 Properties of the Rock mass (Source: Russo et al. 2013)

Properties	Rock mass
UCS(MPa)	8-20
Elastic Modulus(MPa)	1200

3.3 METHODOLOGY

In this study, a model is adapted to study the effect of change in cover depth and lining on the tunnel in my study area. Further material and model is simulated with the prototype.

3.3.1 Scaling of the model and similarity

Similarity ratio is adopted according to the similarity theory which says the ratio of model and prototype should be same for all the dimensions i.e. geometric similarity, boundary conditions along-with material similarity. (Yongyan Wang 1997)

The scaled model is used to study the effect of cover depth and lining of the tunnel so it should have the similarity characteristics of the prototype which are overburden similarity, boundary conditions, geometrical similarity, loading conditions and material characteristics. These factors are important for the effective study of the physical model to study the load-deformation mechanism. Reasons for using POP for modeling are its similarity in UCS, Elastic modulus and Poisson's ratio of the prototype.

3.3.2 Laboratory tests

Laboratory tests have been performed to estimate the properties of the material used for physical modeling.

3.3.2.1 Dry Density test

To assess the degree of compaction, it is necessary to use the dry unit weight, which is an indicator of compactness of any material in a given volume. The laboratory testing is meant to establish the maximum dry density that can be attained for a given material with a standard amount of compactive effort.

Figure 3.2 Unconfined Compression Test sampler

In this test, dry density cannot be obtained directly. The bulk density and moisture content is obtained first and after that dry density is determined.

$$\gamma_d = \frac{\gamma_t}{1 + w} \tag{3.1}$$

Where γ_t = bulk density and w = water content

The dry density is obtained following the IS 2720 – Part 8 for obtaining the dry density of a material.

3.3.2.2 Compressive Strength Tests

Compressive strength test provides an idea about all the characteristic. By this single test one judge that whether casting has been done properly or not. Compressive strength depends on many factors such as water-content ratio, material strength, quality of material, quality control during production etc. Test for compressive strength is carried out either on cube or cylinder. Various standard codes recommend a cylinder or cube as the standard specimen for the test. Figure 3.4.1 is a compression testing machine (CTM) having a maximum load capacity of 2000KN.

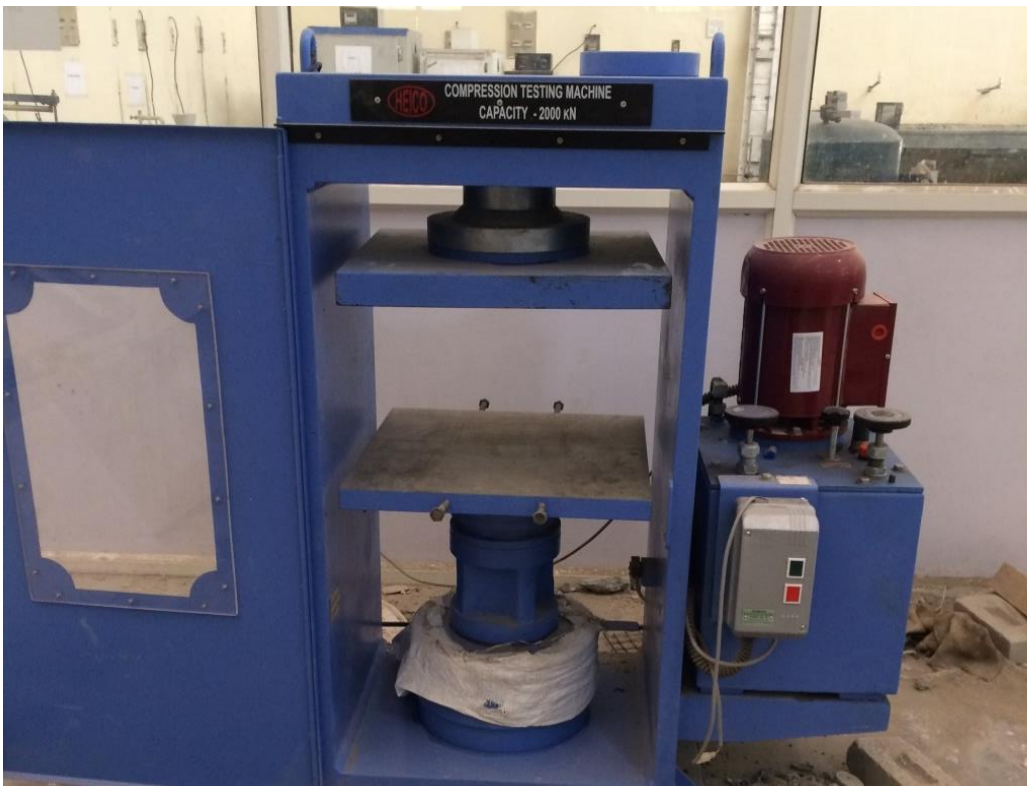

Figure 3.3 Compression Testing Machine

Figure 3.4 Compression Test for sample

3.3.2.3 Unconfined Compression Tests

Unconfined Compression Test (UCT) is a simple laboratory testing method to assess the mechanical properties of rocks and fine-grained soils. It provides a measure of the undrained strength and the stress-strain characteristics of the rock or soil. The unconfined compression test is often included in the laboratory testing program of geotechnical investigations, especially when dealing with rocks. The primary purpose of the Unconfined Compression Test is to quickly determine a measure of the unconfined compressive strength of rocks or fine-grained soils that possess sufficient cohesion to permit testing in the unconfined state. This measure is then used to calculate the unconsolidated undrained shear strength of the clay under unconfined conditions. In general, The UCT can be conducted on rock samples or on undisturbed, reconstituted or compacted cohesive soil sample. In the unconfined compression test, the sample is placed in the loading machine between the lower and upper plates. Before starting the loading, the upper plate is adjusted to be in contact with the sample and the deformation is set as zero. The load and deformation values are recorded as needed for obtaining a reasonably complete load-deformation curve.

Figure 3.5 UCS test

Table 3.3 Test results of UCS sample

LOAD(KN)	AXIAL STRAIN (10^{-6})	DIAMETRAL STRAIN(10^{-6})	STRESS(MPa)
0	0	0	0
0.2	185	63	0.17
0.9	432	146	0.79
1.9	1222	415	1.68
2.9	2401	816	2.56
4.1	3810	1295	3.62
5.9	5900	2006	5.22
7.3	7812	2656	6.46
7.9	8991	3056	6.99
8.2	9412	3200	7.25
8.3	9922	3373	7.34
8.25	10422	3543	7.30
8.15	12993	4417	7.21
7.94	13449	4572	7.02

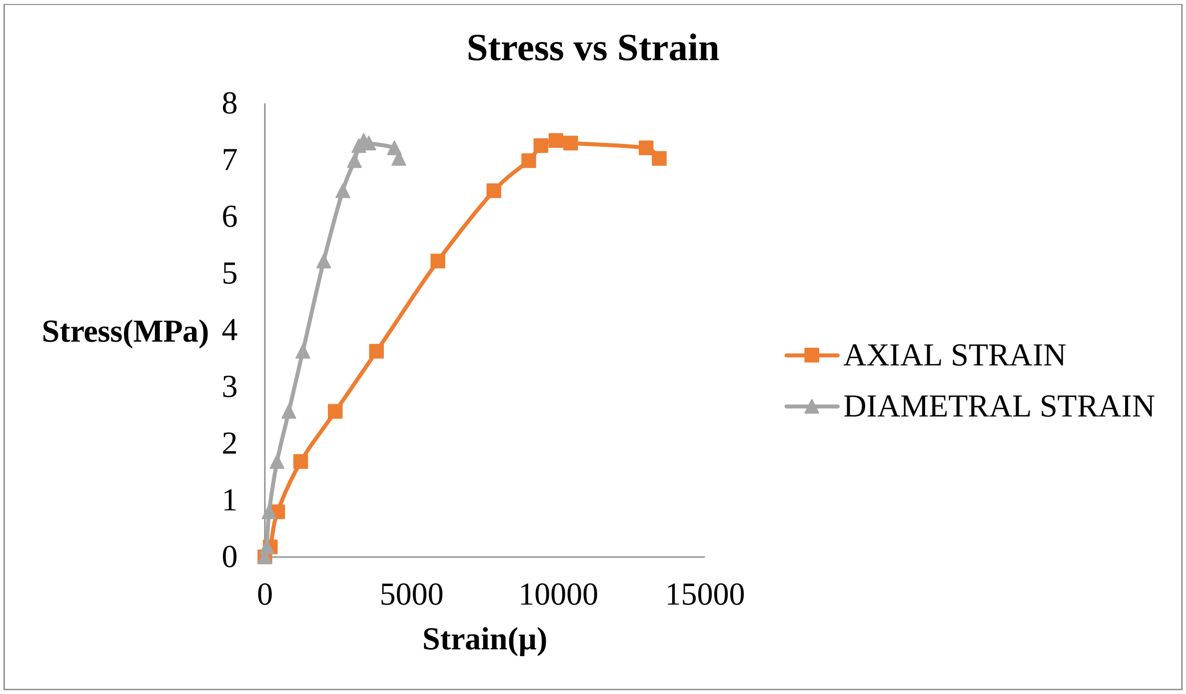

Figure 3.6 Stress vs strain for UCS sample

- ## Calculation of Dry density

Weight of the sample (W) = 200gm

Diameter of the sample (D) = 38mm

Height of the sample (H) = 76mm

Water content (w) = 0.60

Volume of the sample (V) = $\frac{\pi * D^2 * H}{4} = 86.19cm^3$

Bulk density (γ^t) = $\frac{W}{V} = 2.32g/cm^3$

Dry density (γ^d) = $\frac{\gamma t}{1+w}$ = $1.45g/cm^3$

- **Calculation of UCS**

Failure load (L) = 8.3KN

Cross-sectional area (A) = $\frac{\pi * D^2}{4} = 11.34cm^3$

UCS value = $\frac{L}{A} = 7.34MPa$

- **Calculation of Elastic Modulus**

Stress at 50% of failure stress value (σ) = 3.62MPa

Strain at 50% of failure stress value (ε) = $3810 * 10^{-6}$

Elastic modulus = $\frac{\sigma}{\varepsilon}$ = 950MPa

Elastic modulus = Slope of tangent modulus at 50% peak stress (Graphically)

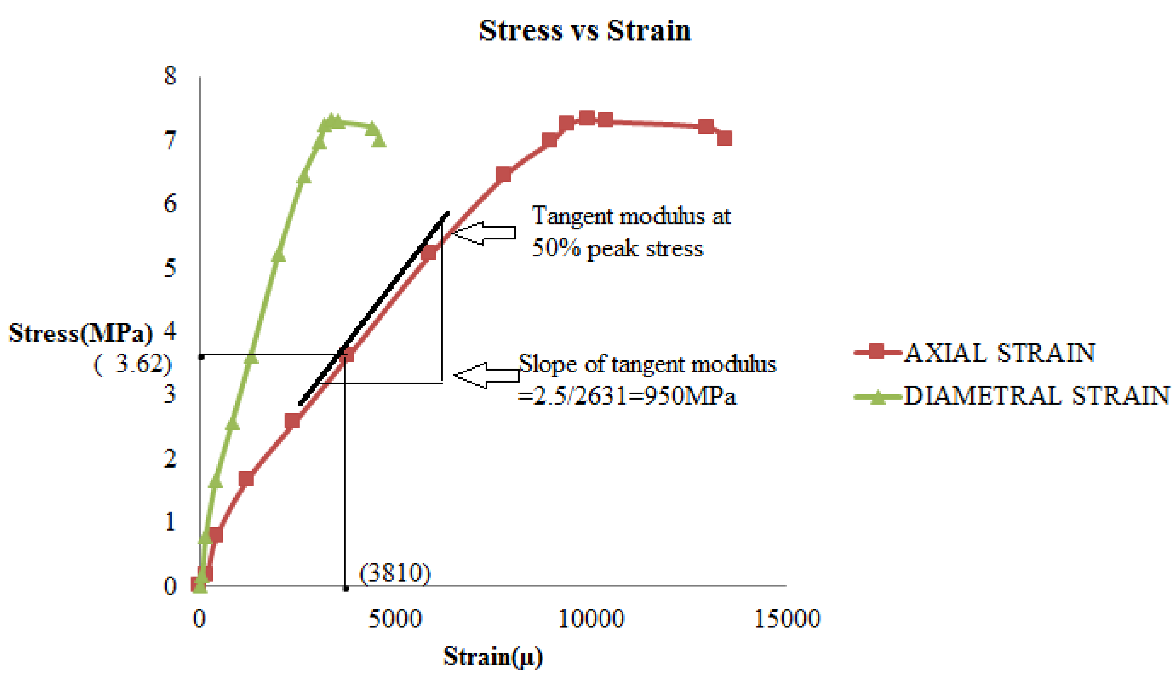

Figure 3.7 Tangent modulus at 50% peak stress

Elastic modulus = Tangent modulus at 50% peak stress (Graphically)

By above results, we can say that the selected material i.e. Plaster of Paris have a UCS value of around 7.34MPa and elastic modulus of 950MPa whereas the rock along the tunnel has a UCS of 8-20MPa and elastic modulus of 1200MPa. By approximation, we can consider the properties of site similar to the Plaster of Paris which justifies the material similarity.

Table 3.4 Material properties of Model Material

Property	Selected Material
Dry density(g/cc)	1.45
UCS(MPa)	7.34
Elastic Modulus(MPa)	950

3.3 Experimental platform

The experimental platform is designed as a frame using plywood sheets of 10mm thickness. The experimental setup includes experimental platform and strain gauges. In this test, the similarity ratio is taken 200 as the prototype is large. The experimental platform is a cubical box with dimensions to be 30cm long, 20cm wide and 20cm high which is designed on the criteria in IS: 4880(IV)-1971, i.e. a=3r where a= radius of the tunnel and r= distance from the tunnel and stress zones influence (Ahmed & Iskander 2011 and Terzaghi & Richart 1952), so as to determine the effect of loading under the sensitive zone of a rock mass when simulated in mountains for tunnels.

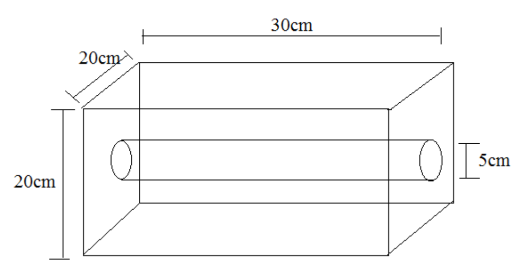

Figure 3.8 Schematic diagram of test model

CHAPTER 4

PHYSICAL MODELING

4.1 GENERAL

Physical modeling has played an important role in studies related to excavation of tunnels in soft ground. A variety of modeling techniques have been developed by researchers all over the world to study ground response to tunneling. It is a more effective and widely used method to explore stress mechanism to investigate the effect of variation of cover depth, lining, stress-strain analysis, and then forecast the stability of tunnels against deformations. (Meguid et al. 2008)

Tunnel modeling is one of the most important and effectively used method. The model is casted with similarity ratio using the similarity theory and can be tested under the CTM to determine the parameters such as stress, deformations, strains and many other mechanical properties such as stress-strain analysis which can help to check the stability of the tunnel. (Akinson et al. 1975; Potts. M. 2005; Mater et al. 2009)

Through previous researches, the models are further tested under the same loading conditions. The material properties have been determined through the UCS tests and the results show the material similarity with the prototype. The effect of variation in the cover depth and lining material on the tunnel is studied through the basic CTM tests on the physical model.

4.2 EXPERIMENTAL SETUP

The schematic diagram of the experimental platform has been shown in figure 3.5 which is made of plywood material. The setup geometry is similar to the model on which the tests are done results of which have been shown in the next chapter.

4.2.1 Frame wooden box

The frame box is designed using plywood of 10mm thickness for experimental work. The geometry scale is taken 200 as the prototype is large. The box is cubical which measures 30cm long, 20cm wide and 20cm high shown in the figure.

1cm=2m

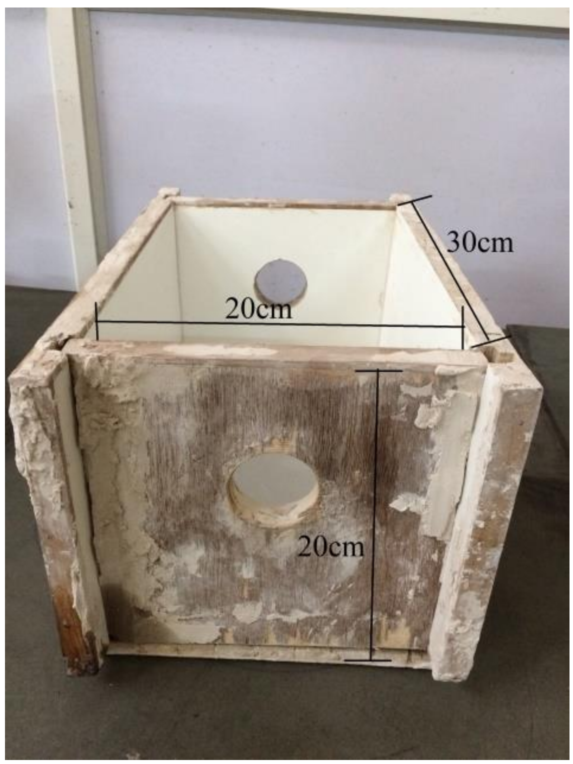

Figure 4.1 Experimental setup

4.2.2 Strain Gauges

To measure the value of strains at different points, strain gauges are installed in the tunnel model. The resistance of the strain gauges is 350Ω and size is 3mm.

Figure 4.2 Strain Gauges

4.2.3 Digital Multimeter

To measure the resistance of the strain gauges, a digital multimeter is required having input jacks. The dial can be rotated to change the parameter required to be measured, in accordance to the need of the experiment.

Figure 4.3 Digital Multimeter

4.2.4 Data Logger

For the display of the strains, a data logger is attached to the strain gauges with wires to determine the deformations. It has 4 channels which can be connected to 4 strain gauges although we have used only 3 strain gauges.

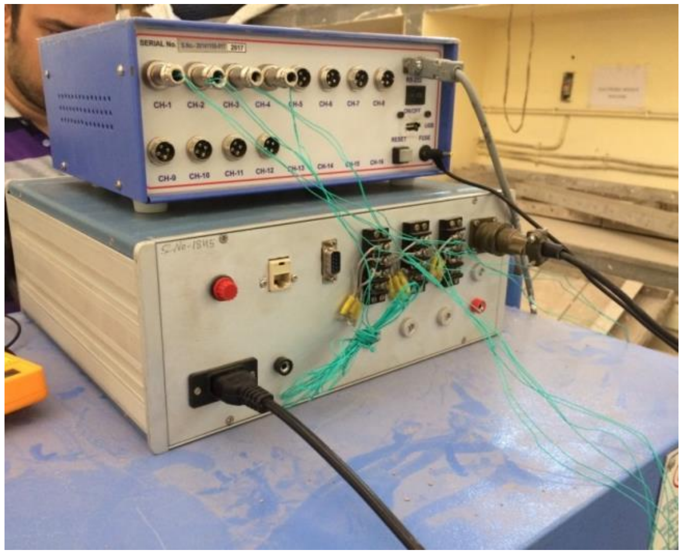

Figure 4.4 Data Logger

4.2.5 PVC pipes

The material used for lining of the tunnel is PVC pipe whereas the lining material provided in the tunnel is shotcreting along with wire mesh and nailing which is a restriction to the tests as the property of the lining material is different at the site.

Figure 4.5 PVC pipes

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 LOAD-DEFORMATION BEHAVIOUR AND STRAIN

In this study, the behavior of lined and unlined tunnel models under static loading is investigated. The material properties is compared to the rock along the tunnel at the site.

Table 5.1 Comparison of model and prototype

Property	Prototype	Model
Diameter(m)	10	0.05
UCS(MPa)	8-20	8.5
Elastic Modulus(MPa)	1200	950

After testing of material, CTM tests for cubical sample is done and load-deformation and stress-strain analysis for each model is performed. The strains are measured at three different places on the crown of the tunnel at L/4, L/2 and 3L/4 distances from the front face of the tunnel.

The results of the UCS test for 60% consistency have been shown in figure 3.6 and various properties such as UCS values, Dry Density, Elastic Modulus have been estimated shown in table 3.3. The blending at 40% consistency was attempted but the mix became so stiff that casting was very difficult to accomplish. Even the 50% consistency model was difficult to cast for a large-scale work.

5.2 STRESS-STRAIN BEHAVIOUR OF MODELS

5.2.1 Varying cover depth for Unlined Models

3cm cover depth unlined model

Table 5.2 Loading results for 3cm cover depth unlined model

LOAD(KN)	STRAIN 1(10^{-4})	STRAIN 2(10^{-4})	STRAIN 3(10^{-4})	STRESS(MPa)
0	0	0	0	0
1.3	101	147	114	0.14
1.7	130	189	147	0.18
1.9	152	221	118	0.21
2.7	210	305	163	0.29
5.2	421	610	475	0.58
11.5	921	1335	1041	1.27
22.2	1782	2583	2014	2.46
33.4	2686	3894	3037	3.7
36.6	3280	4755	3708	4.06
40.05	3534	5122	3995	4.44

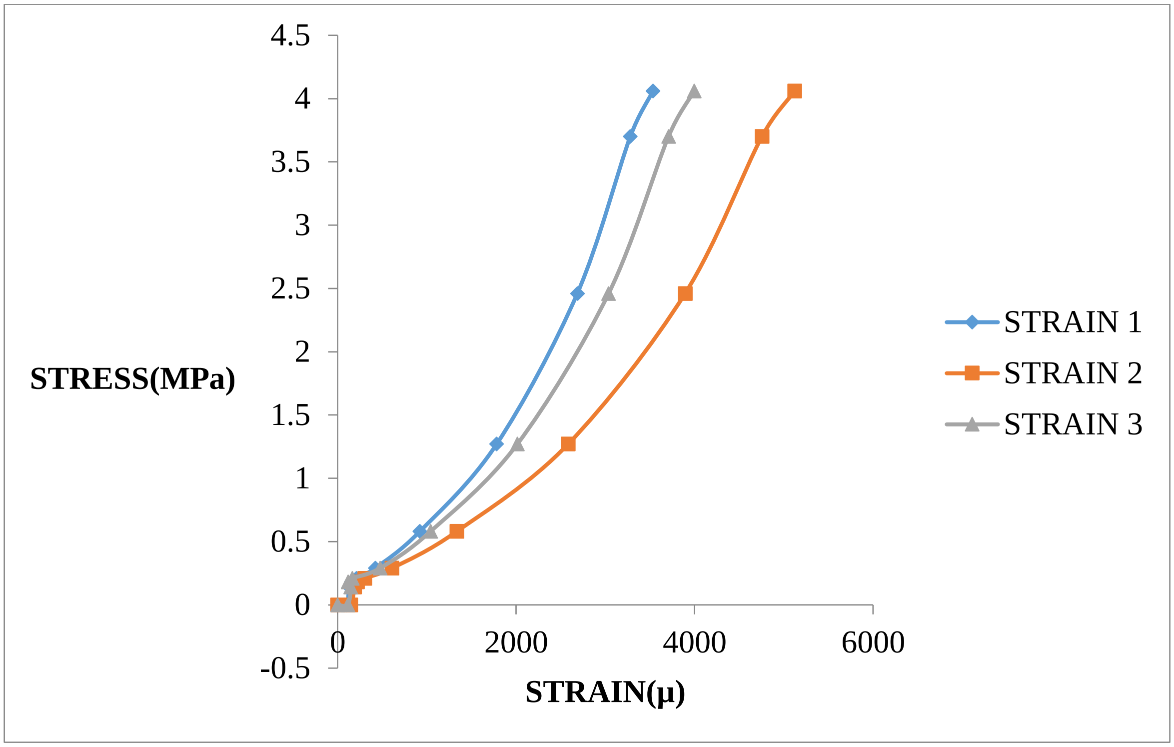

Figure 5.1.1 Stress vs strain at the 3cm cover depth unlined model

Figure 5.1.2 3cm cover depth before and after loading

5cm cover depth unlined model

The comparison of theload carrying capacity of unlined models is dependent on the cover depth as discussed earlier. Figure 5.2.2 shows the cover depth of models designed at 5cm from the top of the crown at 60% w/c. The model failed at a load of 50.05KN.

Table 5.3 Loading results for 5cm cover depth unlined model

LOAD(KN)	STRAIN 1(10^{-4})	STRAIN 2(10^{-4})	STRAIN 3(10^{-4})	STRESS(MPa)
0	0	0	0	0
0.8	54	84	11	0.08
4.5	334	515	261	0.49
15.9	1204	1853	963	1.76
31.7	2401	3694	1920	3.51
38.7	2928	4505	2343	4.28
41.7	3160	4863	2528	4.62
41.9	3174	4884	2539	4.64
44.5	3372	5189	2698	4.93
49.9	3739	5753	2991	5.52
50.05	3790	5831	3032	5.54

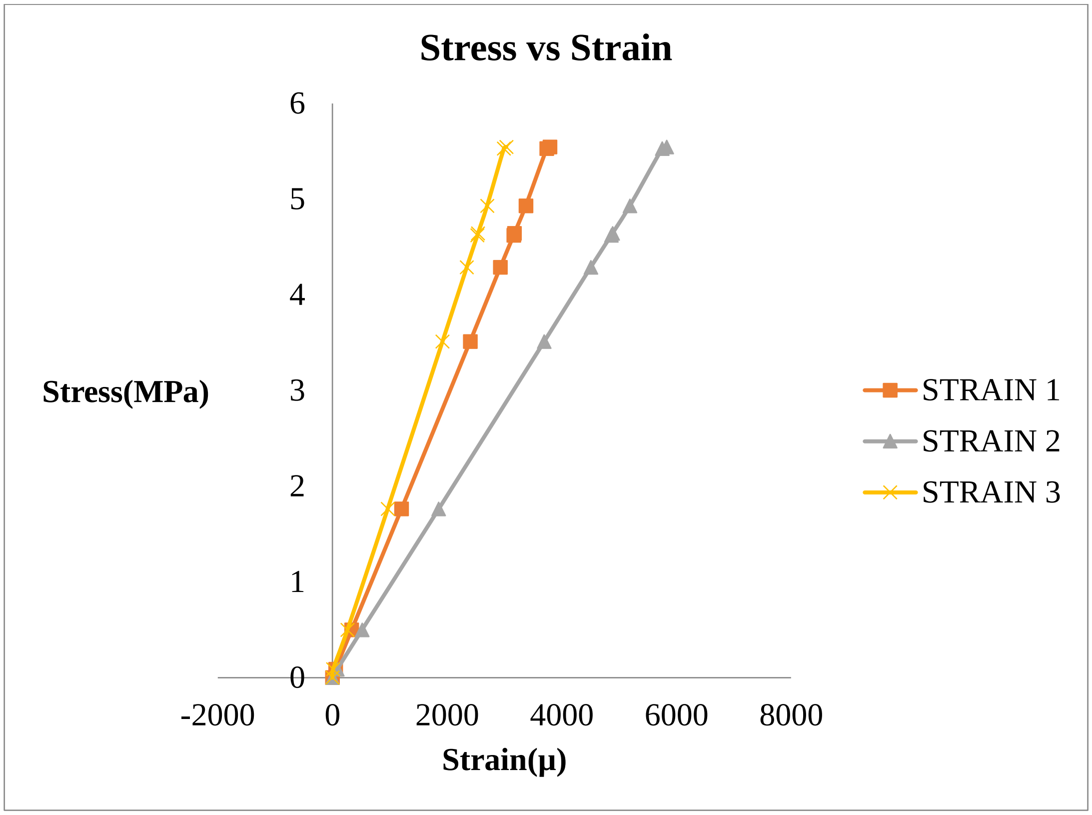

Figure 5.2.1 Stress vs strain at the 5cm cover depth unlined model

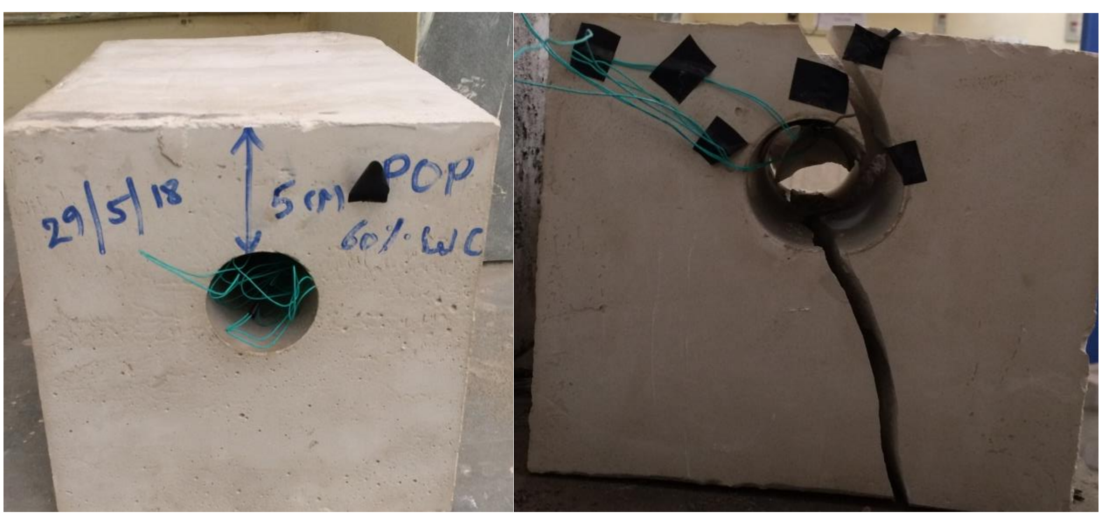

Figure 5.2.2 5cm cover depth before and after loading

5.2.2 Varying cover depth for lined models

The simulation for lined models for load-deformation behavior differs from the unlined models due to more load carrying capacity from lining material which has been tested at two cover depths as of 3cm and 5cm.

3cm cover depth lined model

Table 5.4 Loading results for 3cm cover depth lined model

LOAD(KN)	STRAIN 1(10^{-4})	STRAIN 2(10^{-4})	STRAIN 3(10^{-4})	STRESS(MPa)
0	0	0	0	0
0.5	10	23	10	0.05
0.6	32	63	35	0.06
0.8	45	84	47	0.08
1.5	87	168	95	0.16
2.7	158	305	173	0.29
9.8	590	1136	647	1.08
21.6	1307	2515	1433	2.39
37.4	2413	4642	2645	4.14
48.7	2950	5674	3234	5.39
48.8	2955	5684	3239	5.40

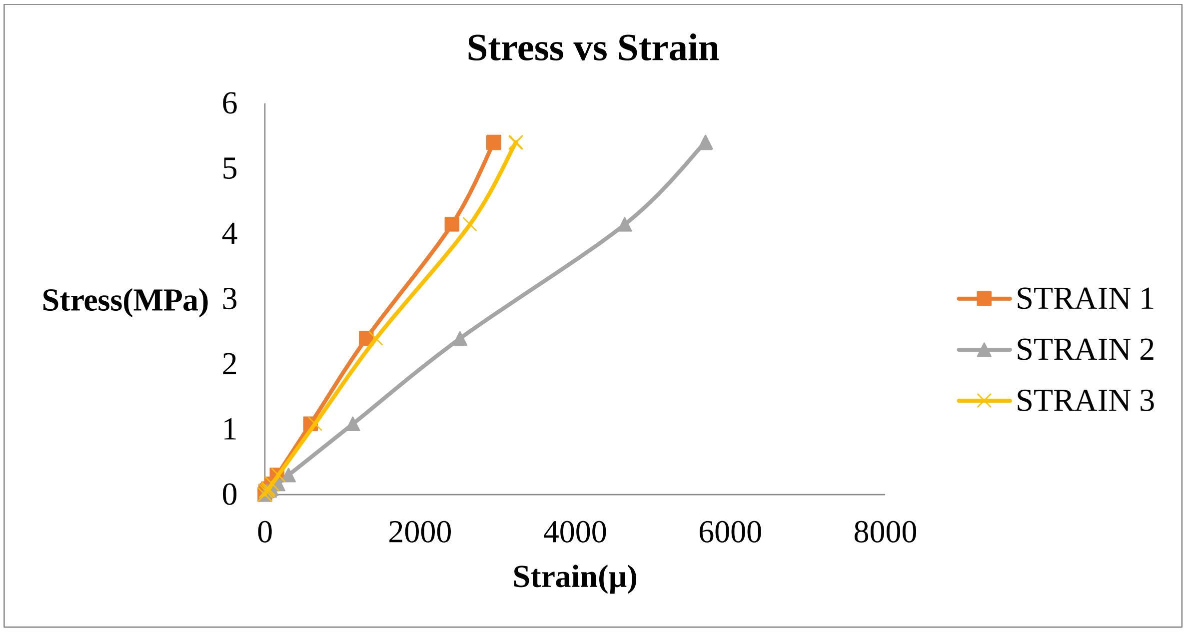

Figure 5.3.1 Stress vs strain at 3cm cover depth lined model

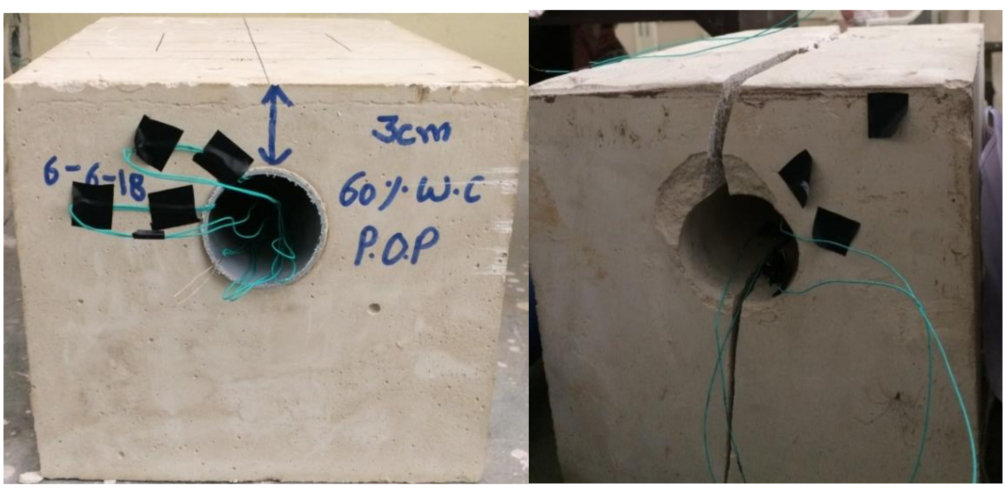

Figure 5.3.2 3cm cover depth before and after loading

5cm cover depth lined model

The comparison of a lined sample of 5cm cover depth for load carrying capacity is highly dependent on the cover depth as well as the lining material as discussed. Figure 5.4.2 shows the cover depth of models designed at 5cm at 60% w/c along with the lining material PVC. The model failed at a load of 63.5KN.

Table 5.5 Loading results for 5cm cover depth lined model

LOAD(KN)	STRAIN 1(10^{-4})	STRAIN 2(10^{-4})	STRAIN 3(10^{-4})	STRESS(MPa)
0	0	0	0	0
2.4	137	273	141	0.26
2.9	168	336	174	0.32
12.5	726	1453	755	1.38
29.7	1731	3463	1800	3.29
40.4	2352	4705	2470	4.47
44.1	2587	5136	2670	4.88
47.8	2784	5570	2896	5.29
52.6	3066	6133	3188	5.82
58.2	3388	6770	3520	6.44
63.5	3700	7400	3848	7.03

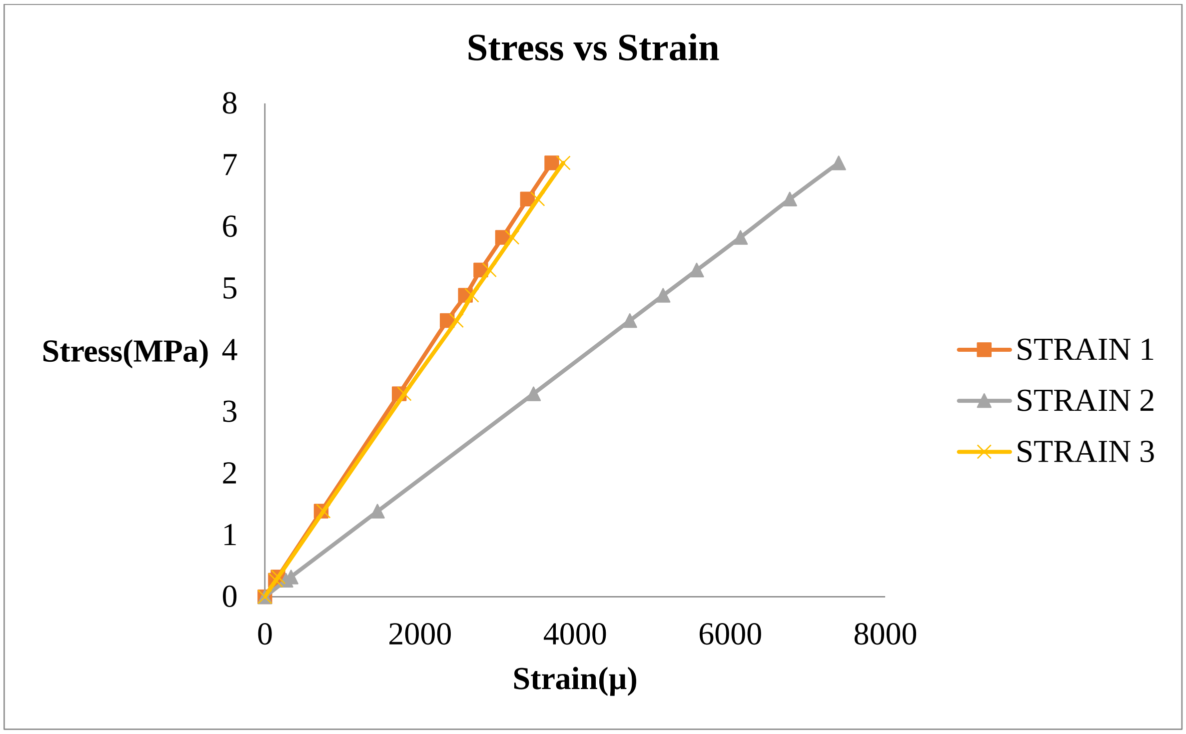

Figure 5.4.1 Stress vs strain at 5cm cover depth lined model

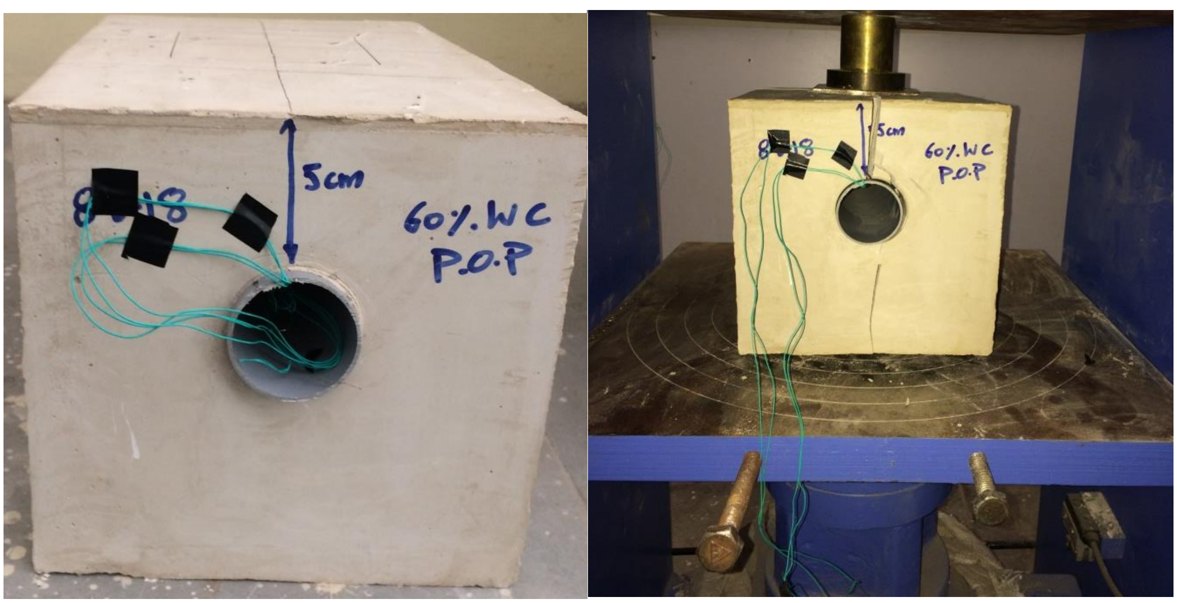

Figure 5.4.2 5cm cover depth before and after loading

5.3 SUMMARY

Through the past researches on the study of stresses on a circular hole in an infinite plate, the value of strains can be determined using the analytical equations (Duvall & Obert, 1967) which is the case of an infinite tunnel simulated in our study.

Boundary conditions:

- The stress is applied only in vertical direction, i.e. $\sigma_x = 0$
- The displacement is only in the vertical direction i.e. v = 0

Strain in the tangential direction, $u = \frac{2 * a * Sy}{E}$ (5.1)

Where, S_y = Vertical stress

a = Radius of the tunnel

E = Elastic Modulus

The input parameters for our model are as follows

a = 25mm

E = 950MPa

Using the equation 5.1, the standard values of strains are calculated and compared with the test results which are as follows

Table 5.6 Comparison of test results with standard analytical solutions (Duvall & Obert, 1967)

Stress value	Strain values from tests	Strain values from analytical solution
5.40 MPa	0.28	0.29
7.03MPa	0.37	0.37

The test results and analytical results have been compared and are found to be approximately equal, which justifies the test results.

CHAPTER 6

CONCLUSION

6.1 SUMMARY

In the present study, an attempt is made to understand the tunnel deformation behavior experimentally. The results provide a theoretical and scientific guidance for design of tunnels against deformation, better safety, lining material and effect of variation of cover depth on the tunnel.

Physical model test on induced tunnel stresses under variation of cover depth and lining in this experiment. The testing equipment have been opted through previous researches which were used for testing in an experimental platform and artificial tunnel models. The rocks along the tunnels are simulated with the material used for physical modelling.

Previous researches prove that this is an effective method for the determination induced stresses. The conditions and parameters for the tests are

- The consistency of material for modelling is kept to be 60%
- The strain gauges are installed at 3 positions in the tunnels i.e. L/4, L/2 and 3L/4 distances from the face of the tunnel.

Various conclusions have been drawn from the tests which are as follows

- The stress-strain relationship of POP is linear with an elastic modulus of 950MPa.
- The maximum stress on 3cm cover depth model was 4.44MPa whereas maximum stress on 5cm cover depth model was 5.44MPa which shows increasing the cover depth provides more stress.
- Stress on 3cm unlined model was 4.44MPa whereas the stress on 3cm lined model was 5.40MPa similarly stress on 5cm unlined model was 5.54MPa whereas the stress

of 5cm lined model was 7.03MPa, which concludes lining material increase the load-carrying capacity of the tunnel.

- The maximum deformation occurs at the center of the tunnel in the model, i.e. at the L/2 distance of the tunnel length which is observed in the results with maximum strain as $7400*10^{-6}$ which concludes that the center of the tunnel is the most critical spot and needs to be checked against deformation.

High induced stresses due to overburden pressure are the main triggering factor for the deformation of the Chenani-Nashri tunnel due to the height of the mountains above it which are also considered during the design of the tunnel, as they provide heavy stress on the tunnel due to which the tunnel may get deformed at the critical spots.

The behaviour of models with variation in the cover depth shows that with more cover depth the stresses on the tunnels are increased. This explains why such tunnels can be stable under less overburden pressure. However if the cover depth is decreased to a critical value, the tunnel deformation may be triggered due to the reduction in cover of the tunnel.

The probable initiation of deformation of the Chenani-Nashri is due to the overburden pressure of the mountains which begins at the centre of the tunnel. The combination of lining and optimum cover depth provides safety to the tunnel and cost-effectiveness.

6.2 FUTURE OUTLOOK

Although there are many limitations to this report such as the overburden above the actual tunnel is almost 1km high which cannot be simulated in the lab with simple physical modeling techniques. Also, the material used for the physical modeling exhibits some deviations from the inherent properties of the rocks at the site due to which results from these tests may differ from the actual estimated design. Still, this report provides pertinent results of the effect of change in cover depth as well as lining on the strength of the tunnel which provides a cost-effective design along with better safety and risk mitigation.

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