Experimental Setup for Studying Tunnels in Squeezing Ground Conditions

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ABSTRACT: Squeezing ground conditions in tunnels are often associated with rock mineralogy, strength, ductility/brittleness, excavation sequence, and magnitude of in situ stresses. Numerous methodologies and empirical correlations have been proposed in the past to determine the level of ground squeezing conditions in tunnels. Most of the correlations are problem-specific and limited in scope. In this work, a fundamental study of tunnel squeezing is carried out using an experimental approach to simulate tunnel boring machine (TBM) excavation in squeezing ground conditions. The experimental setup employs a cubical specimen of a soft rock/soil/synthetic material with each dimensions of 30 cm long. The specimen is subjected to a true triaxial state of stress with different magnitudes of principal stresses and stress levels corresponding to realistic in situ conditions. A miniature TBM is used to excavate a tunnel into the host rock (specimen) while the rock is subjected to true-triaxial state of stress. Embedded extensometers and strain gages glued on the surface of the tunnel liner are used to monitor tunnel response during construction. This paper presents the details of the experimental setup.

1 INTRODUCTION

The problem of squeezing involves time-dependent large deformation in tunnels, which may or may not terminate during construction and arises due to high in-situ stress around the tunnel and problematic geological and geotechnical properties (Barla 1995). Squeezing ground has intrigued engineers over the years in completing underground construction and resulted in the loss of time and money. Wiesmann (1912) first studied the effect of squeezing and since then it has been studied by many researchers including Singh et al. (1992), Aydan et al. (1996), Dube (1993), Barton & Grimnstad (1994), Goel et al. (1995), Yassaghi & Salari-Rad (2005), Gutierrez & Xia (2009), Khanlari et al. (2012), Dwivedi et al. (2012), and Shamsoddin Saeed & Maarefvand (2014).

The squeezing phenomenon in tunnels is still poorly understood (Kovari (1998), and Barla (2000)). Squeezing is associated with high overburden (H), rock mass quality (Q), the uniaxial compressive strength of intact rock (σ_c) and rock mass (σ_{cm}), competency ratio ($\sigma_c/\gamma H$) and tangential stress-strain response around the tunnel. Several definitions have been proposed based on combination of the abovementioned properties (Terzaghi (1946), O'Rourke (1984), Singh (1988), Aydan et al. (1996), Gioda & Cividini (1996), Kovari (1998), Barla (2000)).

To study squeezing problem, it is very important to get a better understanding of the trend in stresses and deformation that will develop around tunnels prior to the excavation. Over the decade's tunnel engineers have been dependent on the empirical methods with limited field data (Schmidt, 1974; Attwell, 1978; O'ReiIIy & New, 1982; Mair et al. 1993). Various empirical and semi-empirical developed over the years are problem-specific and often contradicts with one other.

Physical models to study two and three-dimensional behavior of the ground in response to tunneling were proposed by many researchers. A comprehensive review of such techniques for tunneling in the soft ground is provided by Meguid et al. (2008).

Figure 1 illustrates different physical models developed all over the world to study tunneling on soft ground and Table 1 lists all the advantages and disadvantages of the developed models.

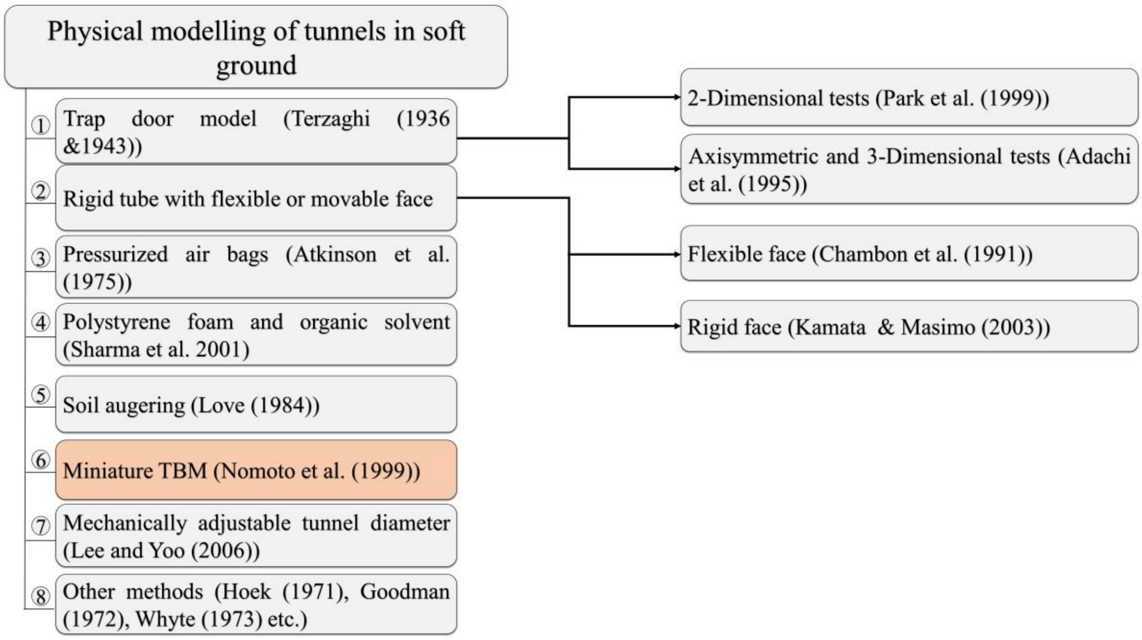


Figure 1. The various physical model developed to study tunneling in soft ground

Table1. Advantage and disadvantages of various physical models developed to study tunneling in soft ground conditions (modified from Meguid et al. 2008)

Method	Applications/advantages	Limitations
Trapdoor	• 2D and 3D tests can be performed under 1g and centrifuge.	• An approximate estimate of stresses and deformation. • Not the actual tunnel process.
Rigid tube with the flexible face	• Can study failure mechanism and face stability under 1g and centrifuge condition.	• No estimate of surface settlement behind the face.
Pressurized airbags	• Studies tunnel stability and induced ground motion around tunnels in 2D as well in 3D under 1g and centrifuge conditions.	• Can be used for unlined tunnels and does not simulate tunnel advance.
Polystyrene foam and organic solvent	• Simulated tunnel advance process under centrifuge conditions.	• Doesn’t give accurate results in underwater conditions.
Soil augering	• Tunnels advance process in 1g condition.	• Can be used for cohesive soils only. • Not mechanized for a centrifuge.
Miniature TBM	• Simulated tunneling under centrifuge condition.	• Only up to 25g gravitational acceleration can be applied.
Mechanically adjustable tunnel diameter	• Easy to operate 2D tunnel excavation process.	• It is manually controlled under the 1g condition for 2D models only.

In this study, a scaled physical model is proposed for the squeezing problem in tunnels. Experiments are carried out on a cubical specimen of a soft rock/soil/synthetic material with dimension of 30 cm on each side. The specimen is subjected to compressive true-triaxial stress state with $\sigma_1>\sigma_2>\sigma_3$. A miniature tunnel boring machine (TBM) is designed to simulate excavation similar to real in-situ tunneling. Monitoring is done using acoustic emission (AE), and strain gages that are installed in the TBM and embedded in the cubical specimen. The correlation developed from the experimental results may contribute significantly to better understanding of the tunnel squeezing in rocks. The uniqueness of this experiment is highlighted by the fact that tunnel is excavated in a specimen loaded in all three directions and with magnitudes load in the order of real field stresses.

2 EXPERIMENTAL SETUP

The objective of this experiments is to study the squeezing behavior of soft rock in response to tunnel excavation under true-triaxial stress state. Figure 2 shows schematically the experimental setup, which includes the true-triaxial cell, miniature tunnel boring machine (TBM), servo-controlled pumps and 115V constant speed AC motor for driving TBM, synthetic soft rock specimen (mudstone) and data acquisition system for monitoring deformations around the tunnel.

The mudstone specimen is loaded in true-triaxial stress state. The miniature tunnel boring machine is mounted on the top lid of the true-triaxial cell. The top lid of the cell has a 76 mm diameter circular opening which provides access to the rock surface for tunnel excavation. Required TBM thrust and torque are provided by servo-controlled pumps and electric motor, respectively. For continuous data acquisition, the cell is equipped with acoustic emission (AE) sensors and strain gages embedded in the specimen. All the important aspects and working of this experimental setup are discussed in the following sections.

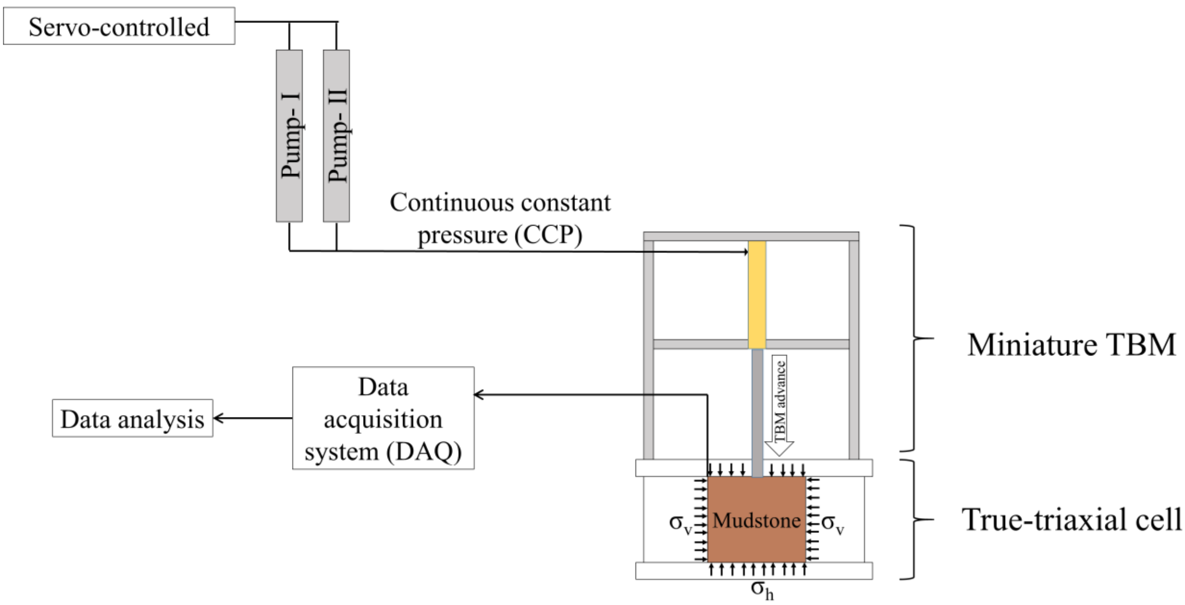


Figure 2. Schematic diagram of the proposed experimental setup to study TBM excavation in squeezing ground conditions.

2.1 *True-triaxial cell*

This experimental incorporates the use of true-triaxial cell developed by Frash et al. (2015) to study the enhanced geothermal system (EGS) at laboratory scale. The apparatus is capable of applying three independently controlled principal stresses up to 13 MPa to a 30x30x30 cm^3 rock specimen.

The apparatus was designed with a mixed flexible bladder (flat jack) and passive confinement system, shown in Figure 3. Each principal stress is applied via one active flat jack per principal axis when using the typical configuration for the apparatus. Specimen faces directly loaded by the flat jacks and the opposing reaction faces supported by the frame are hereby referred to as active and passive faces, respectively. The steel top lid was furnished with a 63 mm diameter port to pass electrical sensor wires and hydraulic tubing for internal sensors and jacks.

The reaction ring of the central body was constructed from A36 structural steel with the yield strength of 250 MPa. The lids were constructed from A514 steel with the yield strength of 700 MPa to reduce thickness requirements following stress design criteria. Sufficient lid thickness was provided to permit drilling multiple non-intersecting 10 mm holes through the lid while maintaining a safety factor greater than 2.0. The lid of the cell was effectively considered to be a sacrificial component. This lid is modified to conduct the TBM excavation in squeezing ground conditions.

Active face stresses are provided by flat jacks (350 mm diameter circular Freyssinet®) and an assembly of two 300 mm diameter round steel platens and one 300 mm square steel platen. Each flat jack is pressurized via an independent hand pump with active digital pressure monitoring. Using separate pumps bypasses pressure control issues which occur in single pump systems with manifold valves. The square platen's inward edges were beveled to mitigate binding with adjacent platens. A 25 mm thickness was specified for the square platens referencing elastic stress-deflection analysis and limit yield criterion for stress transmission to the specimen corners. The square platen also provided a protective housing for AE sensors. This design decision improved AE data quality by ensuring good face-to-face sensor contact with the specimen, reducing noise transmission through the sensor housing and reducing assembly time. A typical alternative AE sensor installation method in similar true-triaxial devices involves cutting shallow holes into the specimen with consequentially increased sensor alignment difficulty, increased assembly time, decreased stress uniformity and likely reduced AE measurement quality (Frash et al., 2015).

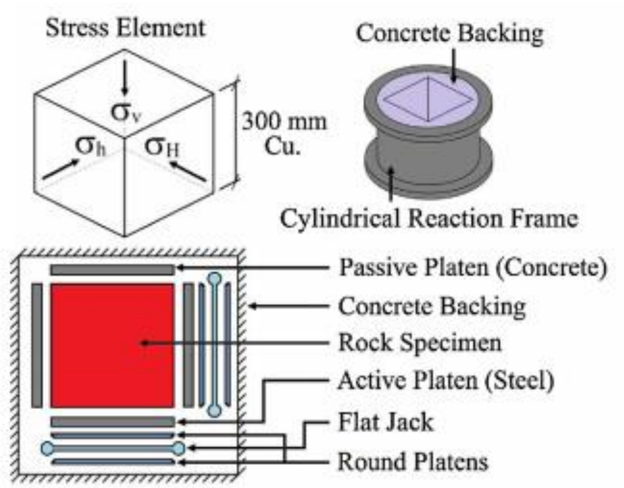


Figure 3. True-triaxial cell at Colorado School of Mines (modified from Frash et al. (2015))

2.2 *Miniature tunnel boring machine (TBM)*

The miniature TBM, shown in Figure 2, is an integral part of the experimental setup. The miniature TBM is designed keeping in mind different thrust and torque requirement at a different level of field stress. Figure 4 presents the miniature TBM designed and fabricated at the Colorado School of Mines. One of the important parts of this miniature TBM is the 100 kN and 200 mm stroke cylindrical hydraulic jack. The jack is controlled by a pair of D-series Teledyne ISCO pumps. The pump maintains the continuous constant pressure (CCP) at the jack and hence, constant thrust at the face of the TBM.

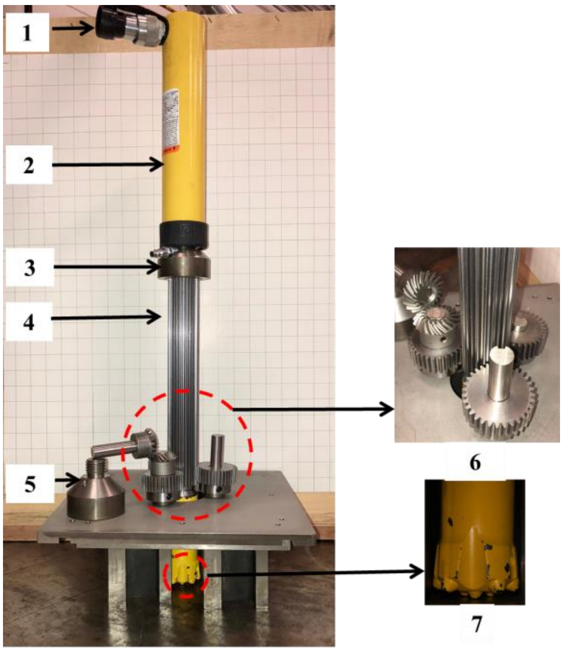
The plunger of hydraulic jack is connected to the rotatory shaft of the miniature TBM through a thrust bearing which allows relative rotation between the rotatory shaft and plunger of the jack. The rotatory shaft is mainly a 300 mm long spur gear with pitch (number of teeths per 25mm pitch diameter) is 16, pitch diameter of 38 mm and the pressure angle of 20°. The shaft (long spur) is connected to a 50 mm button type drill bit which provides the drag action to the rock surface similar to the soft ground TBM.

The required torque is provided by bevel and planetary gear assembly which is driven by a 115V single phase alternating current (AC) constant speed (rpm) AC motor. The main drive gear is the pair of bevel gear having pitch 16, pitch diameter of 38 mm and the pressure angle of 20°. A pair of bevel gear converts the rotation along the horizontal axis into the rotation along the vertical axis.

The vertical bevel gear is axially connected to a spur gear having pitch 16, pitch diameter of 50 mm and the pressure angle of 20°. This spur gear is coupled with the shaft (long spur) of the miniature TBM and provides the required torque to the cutter head at a constant rpm. The longspur is also coupled with two more spur gears (pitch 16, pitch diameter of 50 mm and the pressure angle 20°) which prevents the lateral deformation of the shaft of the miniature TBM (See Figure 4). Therefore, the required thrust and torque for driving this miniature TBM are provided by a pair of the servo-controlled pump at CCP and constant speed AC motor. The muck produced due to the tunnel excavation will be clear off from the excavation face using compressed air at regular intervals.

The whole assembly is supported by a reaction frame designed in such a way that the vertical deflection of miniature TBM at the maximum thrust level will be less than 1 mm. This reaction frame is mounted on the top of the lid of the true-triaxial cell and shown in the schematic diagram of the experimental setup (See Figure 2).

The tunnel advancement rate is measured by a pair of servo-controlled pumps which is continuously monitored. The torque applied by the cutter head is measured by the continuously monitored power output (as power if torque times rpm). Hence, this design of miniature TBM provides all the flexibility in terms of the application of thrust and torque, and at the same time continuously monitors all the essential operating parameters which are monitored in the field as well.



1. Feed in hydraulic oil using D-series ICSO pumps
2. Hydraulic cylinder (10 ton & 8” stroke)
3. Thrust bearing and water/compressed air supply assembly
4. 1 feet long Geared shaft (OD = 1.63”)
5. 115V, Single phase AC geared motor (actual motor not available yet)
6. Bevel and planetary geared assembly for shaft rotation
7. 2” diameter, miniature TBM cutter head

Figure 4. Miniature tunnel boring machine (TBM) designed and fabricated at Colorado School of Mines.

2.3 *Synthetic mudstone specimen*

A synthetic mudstone specimen is prepared in the laboratory using the methodology proposed by Johnston & Choi (1986). They prepared a synthetic soft rock to eliminate experimental scatter and high variable performance for laboratory model studies. They found the model material to be homogenous and isotropic with physical and mechanical properties well aligned to that of natural mudstone.

In this work, artificial mudstone is prepared in the laboratory by mixing type I/II cement (include cement provider name here), clay which is chemically hydrous aluminum silicate and water in the correct proportion. After performing various trials with different mix proportions, it was found that upon mixing equal proportions of cement, clay, and water with some superplasticizer, a highly workable, consistent and homogenous mix is obtained. The correct proportion of superplasticizer depends on the type and grade of the superplasticizer used. In this case, superplasticizer used is MasterGlenium 7920 supplied by BASF. Table 2 shows the quantity of ingredients required for preparing 1 m^3 of mudstone.

Table 2. Mix proportions for one cubic meters of synthetic mudstone

Ingredient (units)	Quantity for 1m^3 of mudstone
Cement (kg)	592
Clay (kg)	592
Water (kg)	592
Super plasticizer (ml)	24

The mix is poured in cylindrical and cubical molds. A cylindrical specimen of 51 mm diameter and 102 mm length were prepared to conduct uniaxial compression tests (UCT) and conventional triaxial tests at a confining pressure ranging from 1 MPa to 10 MPa (which is also the range of confining stress in the true-triaxial test).

Some preliminary compressive strength tests are performed on the five cylindrical specimens of mudstone. Average unconfined compressive strength (UCS) is observed as 6 MPa with a standard deviation of 1 MPa.

A cubical specimen of 30 x 30 x 30 cm^3 is prepared to perform laboratory scaled simulation of TBM excavation in mudstone at stresses equivalent to the stress in the field. Based on the deformation monitoring around the excavation, squeezing behavior of the mudstone will be studied.

2.4 *Instrumentation and monitoring*

The data acquisition system (DAQ) used to monitor and control the laboratory performed TBM excavation in squeezing ground conditions record all the essential operating parameters as is standard for the field application while also implementing some additional elements to take advantage of improving accessibility that an experimental setup allows. The following section presents the details of instrumentations and monitoring in the proposed experimental setup.

2.4.1 *Instrumentation for monitoring TBM output*

At the very basic level, as already discussed, the thrust of the TBM will be controlled by the two syringe pumps under continuous constant pressure (CCP) mode. This mean TBM will apply constant thrust at the face of the excavation. The advance rate of the TBM can be back-calculated flow rate (Q) and time (t) data of the servo-controlled pumps. The torque provided by the TBM will be continuously monitored by a separate DAQ which will record the power output from the AC motor running at constant revolutions per minutes (rpm).

2.4.2 *Acoustic emission (AE) to monitor damage*

AE events will be monitored using Physical Acoustic Corporation (PAC) AE monitoring system with six WSα sensor and three PCI-2 cards mounted in the Micro-II chassis. Six AE sensors are used because in case we do not get high quality data from two or three sensor, there should be high quality data from the minimum number of sensors required for geophysical characterization.

As shown in Figure 5, six AE sensors are typically placed on test specimen surfaces and attached directly to the specimen faces using a thin layer of vacuum gel for coupling, to attain direct AE measurement with minimal reflection, surface interference, sensor orientation error, or attenuation effects. The use of six sensors also enables the application of moment-tensor analysis to classify recorded AE events according to location and failure mode, which is either tensile dominated, shear dominated, or mixed-mode.

2.4.3 *Embedded strain gauges for monitoring strain around the excavation*

To monitor the strains around the excavation, various strain gauges will be embedded in a cubical specimen of mudstone. Due to the very high water content of the synthetic mudstone, there will be improper adhesion between strain gages and mudstone. Hence, strain gauges can't be directly embedded in the synthetic mudstone. A multiple point borehole extensometer (MPBEx) will be prepared using a thin flexible material like Teflon and an array of strain gauges as shown in Figure 6.

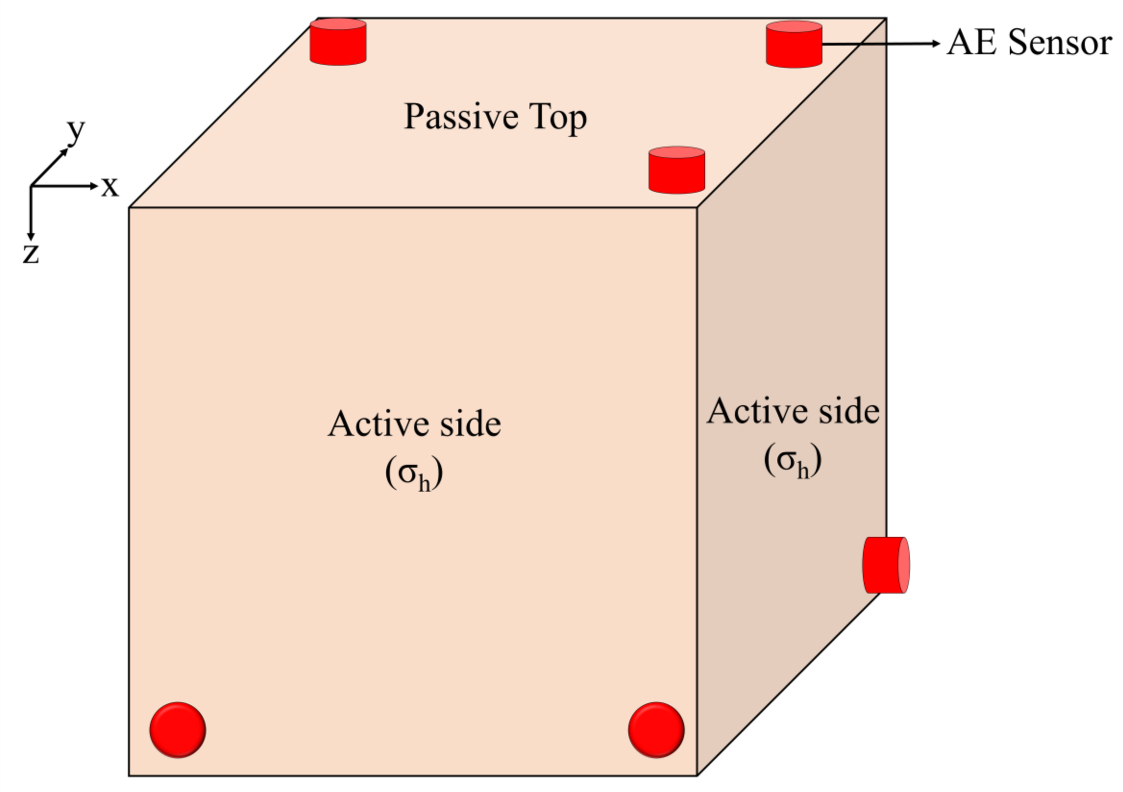


Figure 5. Six AE sensor position for true-triaxial testing on a cubical specimen.

Since the thin Teflon sheet is more flexible than the mudstone, the embedded strain gauges will show the deformation of the more competent member i.e. mudstone. However, this methodology should be validated by performing a conventional UCT on a cylindrical specimen of synthetic mudstone with embedded axial strain gauges and measuring axial deformation using a linear voltage differential transducer (LVDT). The axial strain measurements from the embedded strain gauge and LVDT should be comparable.

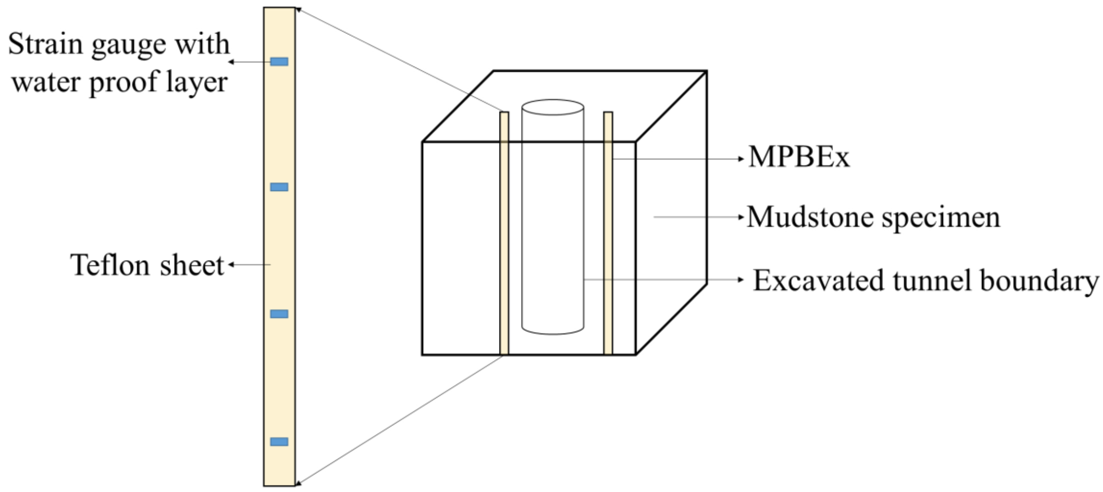


Figure 6. An array of strain gages (MPBEx) embedded in the synthetic mudstone cubical specimen

2.4.4 *Instrumentation in the tunnel liner*

After excavating a two inches diameter tunnel, a thin flexible cylindrical liner will be installed in the excavated tunnel. Elastic properties (Young's modulus and Poisson's ratio) of this liner material will be predetermined by conducting appropriate tests. Four strain gauges, equally spaced in the longitudinal direction, will be glued on the inner surface of the liner. The thin annulus gap between the liner and excavated tunnel will be filled with quick set epoxy with known elastic properties. Using the hoop stress and continuity equation at the tunnel and liner interface, tunnel convergence will be continuously monitored.

3 ANALYSIS AND SYNTHESIS OF THE EXPERIMENTAL RESULTS

Figure 7 shows the flowchart for the post-processing of the test results. Data from the continuous monitoring of the miniature TBM, embedded strain gauges (MPBEx), tunnel liner strain gauges and AE sensors will be closely monitored. Continuous monitoring of the miniature TBM will give the cutter head thrust, advance rate, speed (rpm) and torque with time. In this setup the cutter head thrust, and rpm will be constant throughout the experiment.

Monitoring of embedded strain gauges (MPBEx) will provide the strain around the excavated boundary during and after the excavation at multiple points. On other hand, the strain gauges installed in the liner will provide the tunnel wall convergence at multiple points after the excavation.

Post-processing the data from the continuous monitoring using six AE sensors, installed at the surface of the cubical specimen, will allow for the classification of recorded AE events according to location and failure mode.

The deformations and AE events will be continuously monitored even after the TBM excavation till the time no significant change is observed. Results from each test obtained during the excavation stage and the characterization of the samples after testing will be carefully analyzed and synthesized. New methods to predict tunnel squeezing will be formulated or existing ones will be validated and improved.

After the completion of each test, the loaded samples will be sliced into several sections along the tunnel longitudinal axis. Each section will then be imaged and analyzed in terms of deformations, failure and plastic zone formation around the excavation.

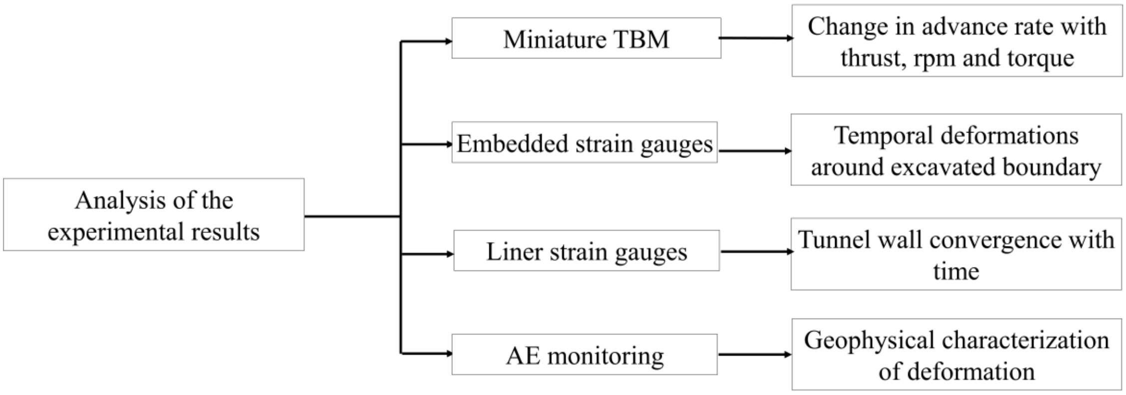


Figure 7. Flowchart for the analysis of the experimental results.

4 CONCLUSIONS

A novel experimental setup is proposed to simulate the TBM excavation in squeezing ground condition. This experimental setup is capable of monitoring tunnel advance and tunnel stability at a field stress level. Stress level up to 13 MPa stress can be independently applied in each of the three direction (which is approximately equal to 600 m of overburden pressure). The setup can simulate lined as well as unlined tunnels and will provide a fair estimate of stresses and deformation around the tunnel. This experimental setup also allows to take advantages of some additional features such as slicing of the specimen into thin sections to study the extent of the plastic zone around the tunnel.

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