ON THE PHYSICAL MODELLING OF TUNNELS IN SOFT GROUND

Mohamed A. Meguid, Assistant Professor, McGill University, Montreal, Quebec, Canada
Joe Mattar, Graduate Student, McGill University, Montreal, Quebec, Canada
Miguel Nunes, Graduate Student, McGill University, Montreal, Quebec, Canada
Shoshanna Saxe, Undergraduate Student, McGill University, Montreal, Quebec, Canada

ABSTRACT

This paper summarizes some of the available experimental techniques used to investigate ground response to tunnelling in soft ground. Emphasis is placed on the recent developments of 1G and centrifuge models. A comparison between different tunnelling simulation methods is presented. The recently developed gravity scale model of tunnels excavated in soft ground at McGill University is also described.

RÉSUMÉ

L'article suivant décris les différentes approches utilisées dans le développement de modèles réduits de tunnels en terre souple. Une considération particulière sera faite pour les modèles réduits 1G et centrifuge. Une comparison des différentes méthodes de simulation de tunnels sera faite. L'article proposera aussi une nouvelle méthode pour la construction de tunnels réduits en terre souple développée a l'université McGill.

1. INTRODUCTION

Due to the dramatic increase in urbanization found all over the world, tunnelling has become a preferred method for the construction of urban transportation systems and the installation of cables and pipes. With so many tunnels being excavated in urban areas it is important to have a comprehensive understanding of soil settlement around a tunnel and the impact of tunnel construction on nearby buildings and utilities.

Analysis of onsite conditions during construction has yielded useful information. However, onsite investigation is limited by (a) instrument placement restrictions (e.g. depth restrictions, expense of instruments), and (b) safety concerns that prevent access to tunnels near collapse. Full-scale experiments are very expensive, difficult to run, and are hard to repeat (Chambon and Corte, 1994). Therefore, ground response to tunnelling is often studied using reduced scale physical models.

The construction of a tunnel is a complex three-dimensional process that involves many different events. Therefore, exact physical or numerical modelling of the tunnelling process is quite difficult and simplifications are usually necessary (Sharma *et al.* 2001). Laboratory model tests conducted under gravity, or in a centrifuge seem more suitable for this purpose. In fact they can single out the most relevant factors influencing the overall behaviour of the tunnel and provide valuable data for refining the chosen numerical model.

The objective of this paper is not to provide a comprehensive review of previous research or previous research or physical models developed for the simulation of tunnels in soft ground,. Rather the paper discusses selected techniques that have been successfully used to investigate the stability and induced deformations due to tunnelling in soft ground. Both gravity models (1G) and centrifuge models will be considered. The paper will also describe a new procedure developed at McGill University to simulate the tunnel excavation and lining installation in soft ground with the help of an assembled shield under 1G conditions.

2. GRAVITY VS CENTRIFUGE MODELING

Gravity Scale Models (GSM) are investigated under the normal 1G condition. GSM provide the flexibility of carrying out the test under controlled environment, whereas centrifuge testing is considered to be appropriate for tunnel modeling since the self-weight of the ground is a major factor influencing ground deformation. GSM are much more economical compared with centrifuge, full scale, or onsite investigations (Atkinson, *et al*. 1977). However, for a successful 1G scale model testing, correlations between the model and the prototype are necessary; at a minimum, they have to follow the same physical laws (Atkinson and Potts, 1977). The usefulness of GSM is limited by the fact that in situ stresses are not fully established. Despite this limitation GSM have long been successfully used in soft ground tunnelling research. In particular, they have been used as a preliminary method to predict the ground response to tunnelling. The results of GSM tests are useful as a comparison for accuracy in terms of stability calculations.

Centrifuge Models (CM) which originated in the Soviet Union, have since spread west and are now widely used in geotechnical testing (Atkinson and Potts, 1977). The in situ stress state can be accurately simulated in a centrifugal test as compared to a 1G test.

In a centrifuge the model is rotated with an angular velocity, ω (rad/s), at a radius R (see Fig. 1-a). This causes the model to experience an acceleration of $a = ng = \omega^2 R$, where g is the acceleration due to gravity ($g = 9.81$ m/s^2) and n is the scaling factor (Atkinson, *et al.* 1977). This means that in the centrifuge the model experiences forces due to gravity multiplied by n, where n depends on the speed of rotation. This effectively, as far as the values of in situ stresses are concerned, makes the model larger by a factor of n.

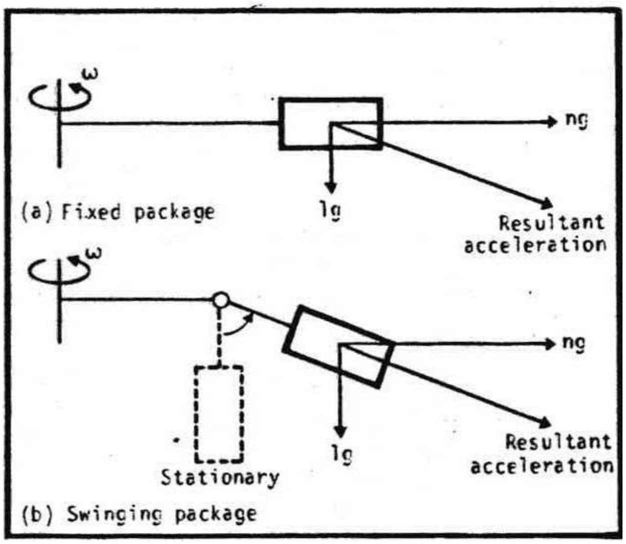

Figure 1 - Centrifugal acceleration of fixed and swinging package (Atkinson *et al*. 1977)

Validation of the scale model results requires a set of scaling relations that relate the experimental model to the prototype's behaviour. This relationship is described by the theory of scale model similitude.

There are several methods of scale modeling application (Kline, 1986), the use of these methods will lead to the definition of several scaling factors that will be taken into account when designing and then building scale models. Scale model similitude was also described specifically for problems in soil mechanics, and more specifically when constructing gravity models that provide soil scaling relations for centrifuge testing.

3. TUNNEL MODELING TECHNIQUES

Several modeling techniques have been developed to investigate different aspects of ground response to tunnelling. A summary of selected methods to simulate tunnel excavation in soft ground is provided below.

3.1 Trap Door

Trap door tests have been used to study the mechanics of 2D and 3D ground movements near the face of an advancing tunnel in different soils.

When a trap door (see Figure 2) that supports a granular material is lowered, the earth pressure acting on the trap door decreases and the earth pressure acting around the trap door increases. For clay deposits, the total earth pressure drops when the trap door is lowered and recovered when the trap door is suspended. The water pressure also decreases when the trap door is lowered (Adachi *et al*. 2003). If the trap door is suspended for a period of time, the water pressure rises to approximately that of its hydrostatic state. Trap door models are considered to be an approximate method to simulate the tunnel excavation process by controlling the ground volume loss induced by the process of lowering the trap door. It facilitates the evaluation of the surface settlement and the corresponding earth pressure on and around the trap door resulting from soil movement.

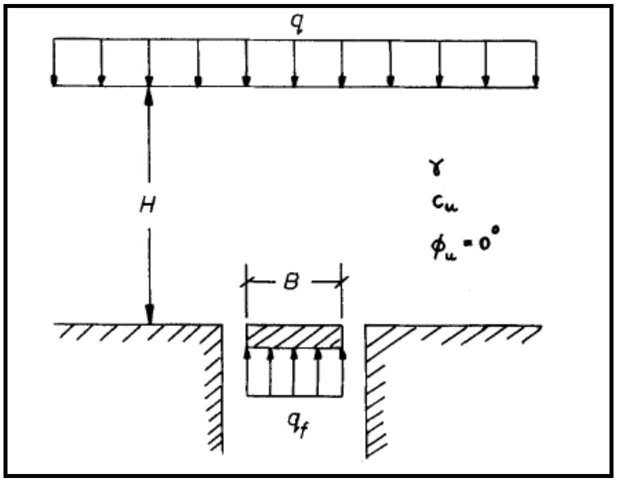

Figure 2 - The classical trap door problem (Sloan, 1989)

3.2 Bury and Cover

This is the simplest method for simulating a tunnel construction process. A tube is placed in the model container and soil is added to bury the tube (see Figure 3). The method has been used by several researchers (e.g. Chambon and Corte, 1994, and Nomoto *et al*. 1999). This method is limited to tunnel simulation in sandy soils and does not simulate the directional process of tunnelling.

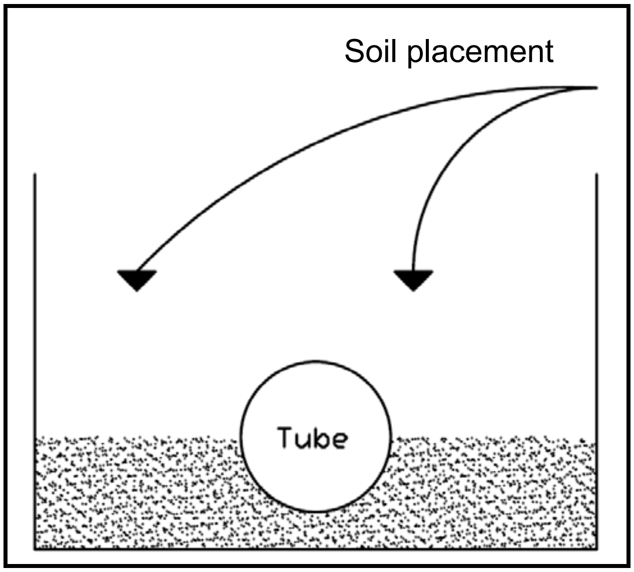

Figure 3 - Bury and Cover Model

3.3 Pressurized Air

Pressurized air in a rubber bag of negligible strength has been widely used in tunnel modeling (see Figure 4). A tube is pushed through the soil or buried during soil placement to make a tunnel; a rubber bag is then inserted into the simulated tunnel and pressurized. When testing unlined tunnels, the tube is usually removed from the soil. On the other hand, for testing lined tunnels the tube may be left in place. In the initial state conditions, the air pressure is equal to the overburden pressure. The air pressure is then lowered incrementally to simulate stress reductions experienced by the soil during tunneling until complete failure of the tunnel is achieved (Mair, 1982).

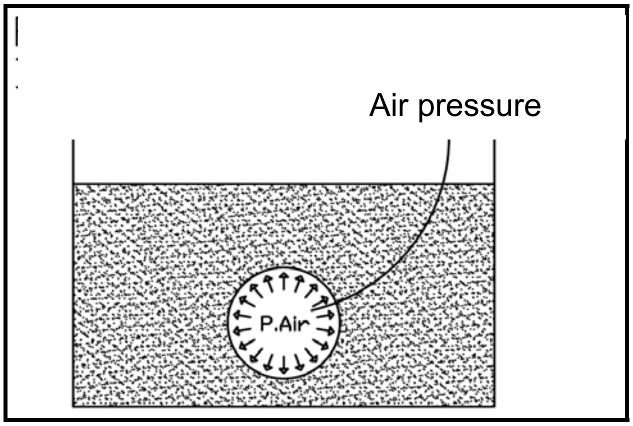

Figure 4 - Pressurized Air Model

3.4 Fluid Pressure

The stability of tunnel face in cohesionless soils has been investigated by several researchers (Chambon and Corte, 1994). The model usually consists of a rigid metallic tube with one end covered with a thin latex membrane as shown in Figure 5. A hydrostatic pressure is then used to simulate the pressure induced by a slurry shield.

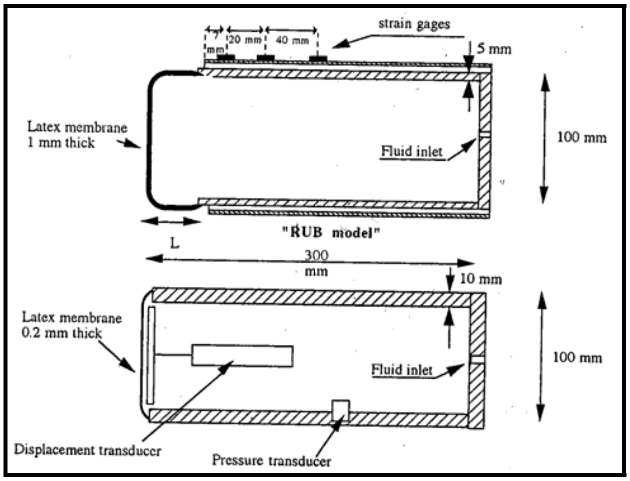

Figure 5 - Fluid Pressure Model (Chambon and Corte, 1994)

3.5 Heavy Liquid Drainage

Another approach similar to using air has been to fill the tunnel with a heavy liquid such as zinc chloride and then slowly drain it (Sharma *et al*. 2001). This approach requires that both ends of the tunnel be plugged and like the use of pressurized air does not account for the directional reduction of stresses experienced during tunnel advancement.

3.6 Polystyrene Foam and Organic Solvent

In this method, a stiff tube of polystyrene foam is buried in the soil (Sharma *et al*. 2001). In the initial state (pre-dissolution) the foam accurately simulates the in-situ stresses that would be applied to the surrounding soil before tunnel excavation. Once exposed to an organic solvent the foam dissolves quickly. The reduction of stresses applied to the surrounding soil as the foam dissolves models the stress reductions experienced during tunnel excavation.

3.7 Soil Augering

This method involves the use of a small soil auger to excavate an opening (see Figure 6) in reconstituted or natural clay material (Chapman *et al*. 2006). Soil (usually clayey materials) is typically consolidated in a tank under a specified pressure. An auger is then used to bore through the soil material in order to simulate the excavation process. Lining segments can be installed as the auger excavates to further model the tunnel construction process more accurately.

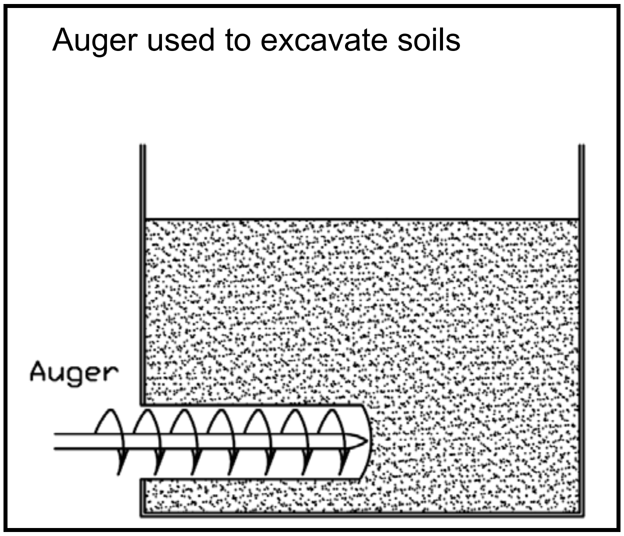

Figure 6 - Auger Excavation Model

3.8 Miniature Tunnel Boring Machine

Japanese researchers (Nomot *et al.* 1999) developed a miniature shield tunnelling machine, called the Mark IV (see Figure 7). This machine was designed to simulate the actual process of shield tunnelling as closely as possible. The machine is made up of the following three main components:

(i) The Shield: is made up of three tubes, a 100 mm diameter stainless steel tube houses a spiral conveyer with a cutting head to excavate and remove material, a middle tube of diameter 96 mm and 98 mm that serves as the tunnel lining (a series of load cells are inlaid on this middle tube), and a 100 mm diameter stainless steel pipe for simulating the tail void formation (this tube is removed after the complete advancement of the tunnel.)

(ii) The driving component: is made up of two motors, one for the forward advancement of the shield part and for removing the tail void tube, the other for driving the excavation cutter.

(iii) The strong box: is a 240 x 700 x 700 mm stainless steel box that houses the model and displacement measurement system.

The miniature tunnel boring machine is an impressive piece of technology. Unfortunately, for tunnel modeling purposes it has some serious limitations. It took four years to design and develop the machine, which is a time and financial investment that very few others could repeat. In addition, the testing limitations of the machine as it is limited to one specific tunnel diameter, 100 mm, and can only be tested up to 25g, meaning that this method can only be used to model prototype tunnels with a maximum diameter of 2.5m.

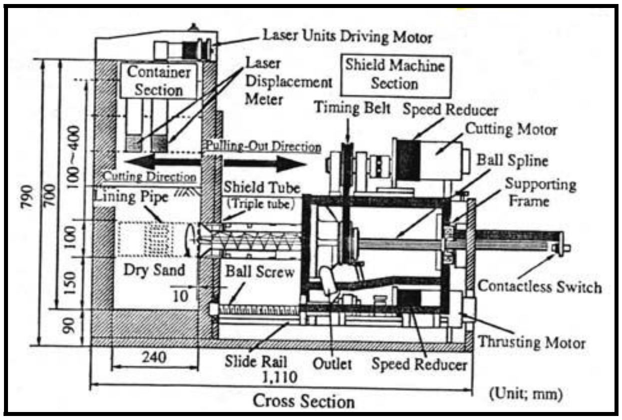

Figure 7 - Miniature TBM (Nomoto *et al.* 1999)

4. PROPOSED TUNNEL EXCAVATION METHOD

The proposed method of model tunnel simulation will involve a consolidated clay sample and a refinement of the soil augering method (see Figure 8).

The tunnelling procedure will introduce an alternative way of installing the lining: instead of pushing a solid cylinder/liner into the sample to facilitate excavation, the lining will be replaced by a series of thin rods, arranged in a circular flange, that will be pushed one by one all around the circumference of the proposed tunnel opening while excavation proceeds using an auger or a similar drilling head.

The proposed method will provide a significant improvement over other augering techniques by minimizing the soil disturbance prior to and after excavation as compared with the installation of a solid cylindrical lining.

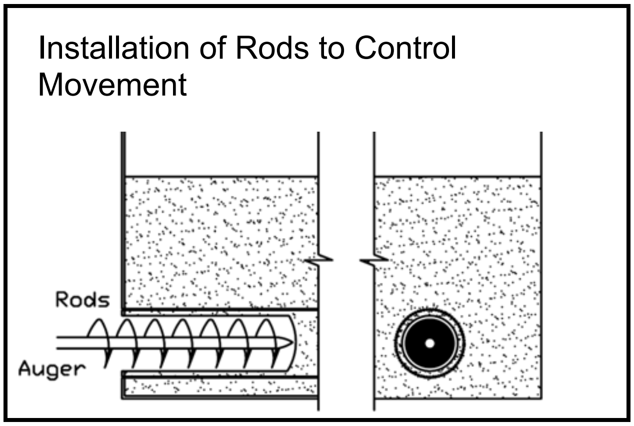

Figure 8 - Proposed Auger Excavation Model

5. CONCLUSIONS

Several tunnel excavation models were presented in this paper in addition to a proposed method that will be implemented at McGill University. The different advantages and disadvantages of these methods were investigated and it is expected that the proposed method will bring improvements to the technique of scale modelling and simulating in the area of geotechnical engineering.

6. ACKNOWLEDGEMENTS

This research is supported by the “Fond Québécois de la recherché sur la nature et les technologies” (FQRNT) and a McGill University Research Grant.

REFERENCES

Adachi, T., Kimura, M., and Kishida, K. (2003). Experimental Study on the Distribution of Earth Pressure and Surface Settlement Through Three-Dimensional Trapdoor Tests. Tunnelling and Underground Space Technology, Vol.: 18, pp 171-183.

Atkinson, Potts and Schofield (1977). Centrifugal Model Tests on Shallow Tunnels in Sand. Tunnels and Tunnelling. Cambridge, U.K.

Atkinson, J.H., and Potts, D.M. (1977). Stability of a Shallow Circular Tunnel in Cohesionless Soil. Geotechnique, Vol.: 27, No.: 2, pp 203-215. Cambridge, England and Rijswijk, Netherlands.

Chambon, P., and Corte, J.F. (1994). Shallow Tunnels in Cohesionless Soil: Stability of Tunnel Face. Journal of Geotechnical Engineering, Vol.: 120, No.: 7. Nantes, France.

Chapman, D.N., Ahn, S.K., Hunt, D.V.L., and Chan, A.H.C. (2006). The Use of Model Tests to Investigate the Ground Displacements Associated with Multiple Tunnel Construction in Soil. Tunnels and Tunnelling.

Kline, S.J. (1986). Similitude and Approximation Theory. Springer-Verlag, New York.

Mair, R. J. (1982). Ground Movement around Shallow Tunnels in Soft Clay. Tunnels and Tunnelling, Vol.: 14, No.: 5, pp 45-48. U.K.

Nomoto, Imamura, Hagiwara, Kusakabe and Fujii (1999). Shield Tunnel Construction in Centrifuge. Journal of Geotechnical and Geoenvironmental Engineering, Vol.: 125, No.: 4, pp 289-300. Japan.

Sharma, Bolton and Boyle, R.E., (2001). A New Technique for Simulation of Tunnel Excavation in a Centrifuge. Geotechnical Testing Journal, Vol.: 24 No.: 4, pp. 343-349.

Sloan, S.W. (1989). Upper Bound Limit Analysis Using Finite Elements and Linear Programming, International Journal for Numerical and Analytical Methods in Geomechanics. Vol. 13, pp. 362-282.