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Review

Physical modeling of tunnels in soft ground: A review

M.A. Meguid *, O. Saada [1], M.A. Nunes [1], J. Mattar [1]

Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, Que., Canada H3A 2K6

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Abstract

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. These techniques range from the two-dimensional trap door tests to the miniature tunnel boring machines that simulate the process of tunnel excavation and lining installation in a centrifuge. This paper presents a review of selected physical models that have been developed and used in soft ground tunneling research. Furthermore, this paper discusses some of the various approaches used to record soil deformation and failure mechanisms induced by tunneling. Experimental setups and sample results are presented for each technique as described by original authors. A summary of the advantages and disadvantages of each method is also presented.

Keywords: Physical modeling; Soft ground tunneling; Centrifuge; Tunnel excavation; Soil displacements

Contents

* Corresponding author. Tel.: +1 514 398 1537; fax: +1 514 398 7361.
E-mail addresses: mohamed.meguid@mcgill.ca (M.A. Meguid), saadao@ufl.edu (O. Saada).
[1] Tel.: +1 514 398 1537; fax: +1 514 398 7361.

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1. Introduction

Due to the increase in urbanization found all over the world, tunneling has become a preferred construction method for transportation and underground utility systems. With so many tunnels being built, it is important to have a comprehensive understanding of the tunneling induced displacements and stresses and their impact on nearby structures. Tunneling technology has significantly advanced in the past few decades. Nevertheless, tunnel engineers are often relying on empirical methods (e.g. Schmidt, 1974; Attwell, 1978; O'ReilIy and New, 1982; Mair et al., 1993; etc.) based on limited field data in calculating surface settlement or lining stresses. These methods assume plane strain conditions and often do not account for the three-dimensional (3D) nature of the tunnel construction process. Numerical modeling (e.g. Mair et al., 1981; Rowe and Lee, 1989; Swoboda et al., 1989; Lee and Rowe, 1990; Leca and Clough, 1992; Chen and Baldauf, 1994; etc.) allows one to conduct more realistic analyses that take into account the tunnel-lining interaction, construction sequence and 3D face effects. Analysis of instrumented projects and field trials (e.g. Peck, 1969; Attwell and Farmer, 1974; Rowe and Kack, 1983; Lo et al., 1984; Harris et al., 1994; etc.) has yielded useful information. However, results are difficult to interpret. In addition, field investigation is limited by (a) 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. For all these reasons, ground response to tunneling should also be studied using reduced physical models.

Laboratory model tests conducted under gravity or in a centrifuge allow one to investigate the most relevant factors influencing the tunnel behavior. Testing results also provide valuable data for refining the chosen numerical model. Several 2D and 3D models have been proposed to investigate different aspects of tunneling in soft ground. Tunnels are usually modeled by either placing soil around and over a pre-installed tube and controlling the supporting pressure or precutting the tunnel opening and installing a lining system. Models have also been developed to study the face stability of tunnels in soft ground including the trap door method, a pre-installed tube with vinyl facing, a dissolvable polystyrene foam core, or a miniature tunnel boring machine.

This paper summarizes selected physical model experiments that have been developed and used in soft ground tunneling research. Furthermore, this paper will discuss the various approaches used to record soil deformation induced by tunneling. Testing setups are presented for each technique as described by the original authors. A summary of the advantages and disadvantages of each technique is also presented.

2. Physical modeling of tunnels

Although advances in computational techniques have led to extensive numerical and analytical tunneling research being conducted, geotechnical engineering researchers depend heavily on physical modeling to understand different phenomena related to tunneling, such as, deformation patterns and failure mechanisms. Tests are usually conducted under 1g conditions or in a centrifuge. 1g models allow one to investigate complex systems in a controlled environment and are considered to be more economical compared to centrifuge or field investigations. The usefulness of 1g models is limited by the fact that in situ stresses are not realistically simulated. Despite this limitation 1g models have long been used in soft ground tunneling research.

Centrifuge modeling is thought to be a convenient tool to reproduce gravity stresses in a small model. The idea was applied for the first time in 1930s by Bucky (1931) and Pokrovsky and Fedorov (1936). Centrifuge testing offers the advantage of using small size models with a great control up to failure. Using centrifuge in tunneling research has been very popular since early seventies (e.g. Cairncross, 1973; Orr, 1976; Potts, 1977;

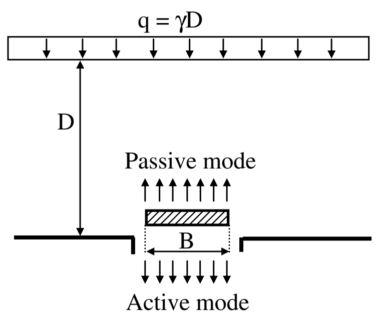


Fig. 1. The classical trap door problem.

Mair, 1979; Seneviratne, 1979; Bolton et al., 1994; Yoshimura et al., 1994; Nomoto et al., 1999; etc.). Limitations of centrifuge modeling include (Taylor, 1995): grain size effects in small models and inconsistency of scaling factors for different measured quantities (e.g. length, inertia force, creep, etc.). In addition, the radial forces induced during centrifuge testing are not the same throughout the model.

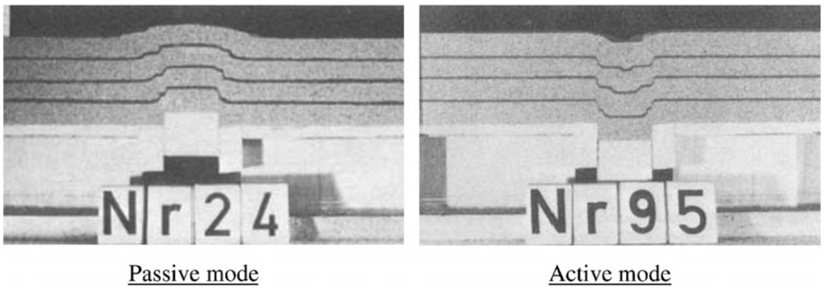


Fig. 2. Typical failure patterns under active and passive modes of trap door displacements (Vardoulakis et al., 1981).

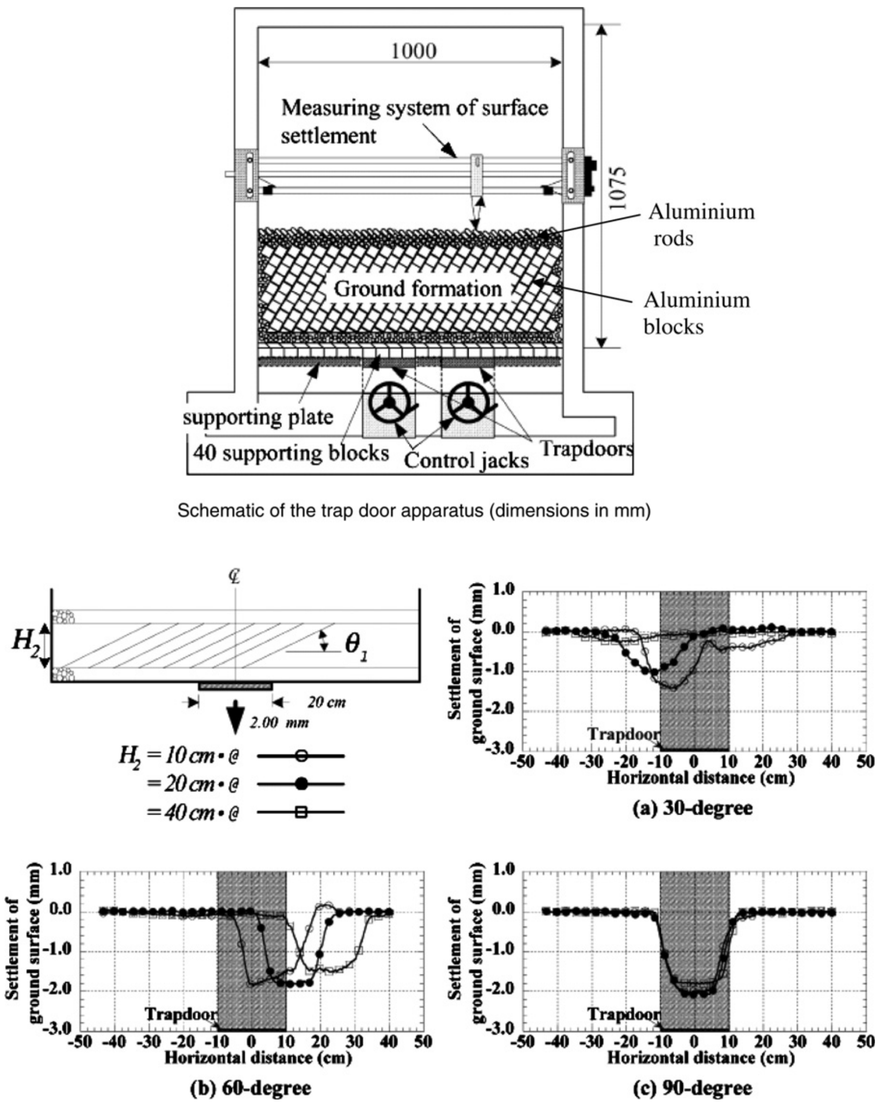


Fig. 3. Surface settlement measured for applied displacements of 1 mm and 4 mm (Park et al., 1999).

3. Tunnel modeling techniques

Several modeling approaches have been developed to investigate different aspects of ground response to tunneling. The tested soils are typically contained within an apparatus with rigid boundaries. The container is usually lubricated to limit the frictional resistance imposed on the soil. Often at least one of the faces is transparent to enable researchers to visually record the soil movements. A summary of selected physical modeling techniques used in tunneling research is provided below.

3.1. Trap door models

The problem of ground pressure against buried structures has been of great practical importance in civil engineering. Terzaghi (1936, 1943) explained the arching theory based on the translation of a trap door into the soil (passive mode) or away from it (active mode) as shown in Fig. 1. The passive mode can be used to evaluate of the uplift force of anchors and other buried structures that can be idealized as anchors. The active mode can be used to study the silo problem or the earth pressure on a tunnel lining. Following from Terzaghi's work several researchers conducted 1g trapdoor tests using either aluminum rods (e.g. Ladanyi and Hoyaux, 1969) or dry sand (e.g. Vardoulakis et al., 1981) to simulate the response of granular materials to trap door displacement under plane strain conditions. Typical failure patterns for the active and passive modes of trap door displacements are shown in Fig. 2.

In tunneling applications, trap door models are considered to be an approximate method to simulate ground response to tunneling. They facilitate the evaluation of the surface settlement and the corresponding earth pressure on a tunnel lining. To demonstrate the application of the trap door method in tunneling research, two experimental examples along with some testing results are given below.

3.1.1. Two-dimensional tests

2D trap door tests were conducted by several researchers (e.g. Terzaghi, 1936; Vardoulakis et al., 1981; Tanaka and Sakai, 1993; etc.). Park et al. (1999) conducted a series of 1g trap door experiments to investigate the response of inclined layers to tunnel excavations. The tested material consisting of aluminum rods (unit weight = 21.1 kN/m^3 and friction angle = 30°) and aluminum blocks (unit weight = 26.4 kN/m^3 and friction angle = 20°) was arranged in layers making angles, θ_1, of 30°, 60°, and 90° with the horizontal. The setup (shown in Fig. 3) composed of 40 supporting blocks, 2.45 cm in width arranged over a supporting plate installed along the base of the apparatus. Forty load cells were installed between each supporting block and the supporting plate so that the distribution of earth pressure on the trap door can be measured. The interaction between two adjacent blocks is avoided by setting the spacing at 0.05 mm. The tunneling process is simulated by lowering the trap door using a control jack. Fig. 3 shows an example of the surface settlement profiles induced by lowering the trap door 2 mm for different layer inclination angles and overburden pressures. The inclination angle was found to have a significant effect on the surface settlement trough. Symmetrical settlement profiles were observed for the vertically arranged blocks ($\theta_1 = 90°$). For the $\theta_1 = 30°$, the maximum surface settlement shifted towards a direction normal to the layer inclination angle (left of the trap door). Different behavior was found for the case of $\theta_1 = 60°$ where the maximum surface settlement shifted in the direction of the layer inclination angle (right of the trap door).

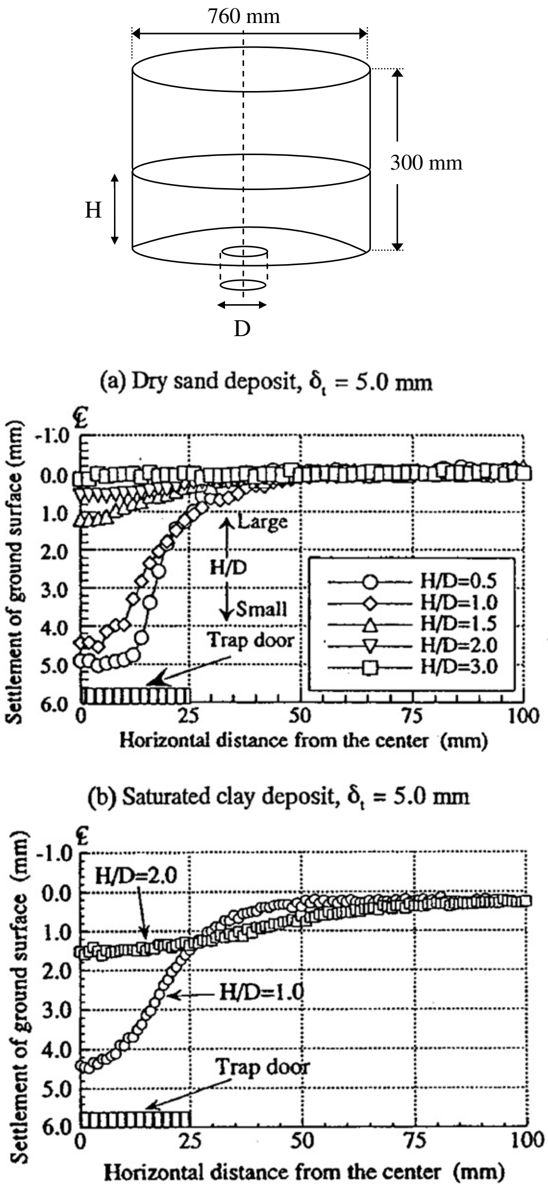


Fig. 4. Displacement patterns in axi-symmetric trap door test (Adachi et al., 1995).

3.1.2. Axi-symmetric and three-dimensional tests

Axi-symmetric trap door experiments were conducted by Adachi et al. (1995) under 1g and centrifugal conditions. The testing device, made of stainless steel, has a radius of 380 mm and a height of 300 mm. A schematic of the test setup is shown in Fig. 4. The center of the testing chamber has a circular trap door that (with a diameter of 5 cm) can be lowered by a screw jack and electric motor. Silica sand No. 6 (void ratio = 0.753, relative density = 70.94%, friction angle = 36°) was used for the model soil. Displacements and earth pressures at and around the trap door were measured. The surface settlement is measured using a laser displacement gauge when the trap door is lowered 5 mm. Displacement patterns for dry sand and saturated clays are shown in Fig. 4. Surface settlement generally increased when H/D ratio decreased and the largest settlement was recorded for H/D values of less that one. A similar setup has been used by Adachi et al. (2003) to investigate the 3D effect of the trap door system on the induced pressure and surface settlement under 1g condition. The soil used was silica sand No. 6 with friction angle of 36°. For a given overburden pressure and a trap door displacement the earth pressure measured around the 2D trap door was found to be greater than that measured around the 3D trap door tests.

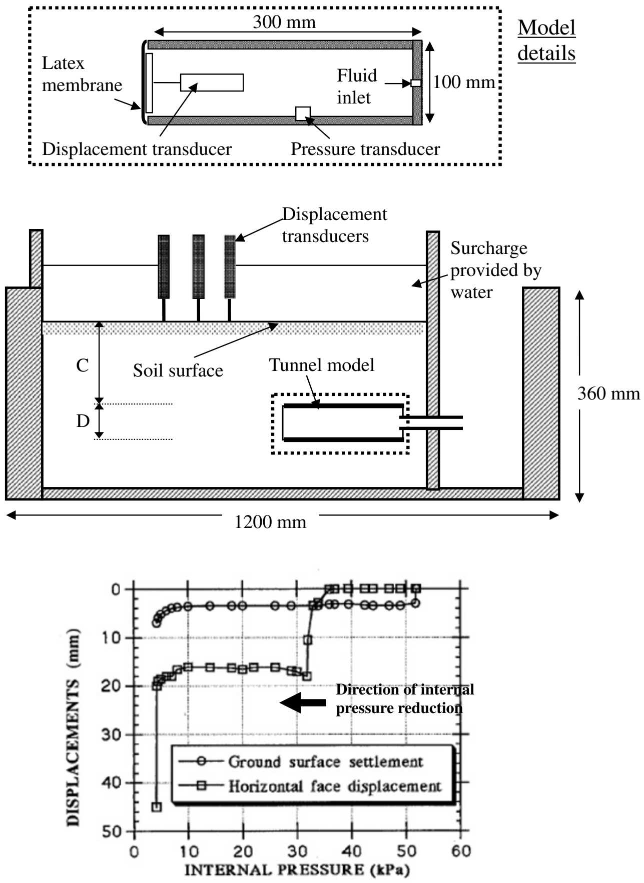


Fig. 5. Tunnel model and measured displacements (Chambon and Corte, 1994).

The above methods provided insight into the 2D and 3D arching mechanisms and ground response induced by tunneling in soft ground.

3.2. Rigid tube with flexible or movable face

This method has been used by researchers (e.g. Chambon et al., 1991; Sterpi et al., 1996; Sterpi et al., 1996; Kamata and Masimo, 2003; etc.) to investigate the near face stability of shallow tunnels and evaluate the stress transferred to the lining. A tube is typically placed in a container during the soil placement stage and buried as more soil is added to the container. The method is limited in its application to granular material since the presence of a rigid pipe makes it difficult to consolidate clays in the container. Examples demonstrating the testing methodology and sample results are provided below.

3.2.1. Flexible face

Chambon et al. (1991) conducted centrifuge tests to investigate the face stability of tunnels in soft ground. The physical model consisted of a metallic tube (100 mm

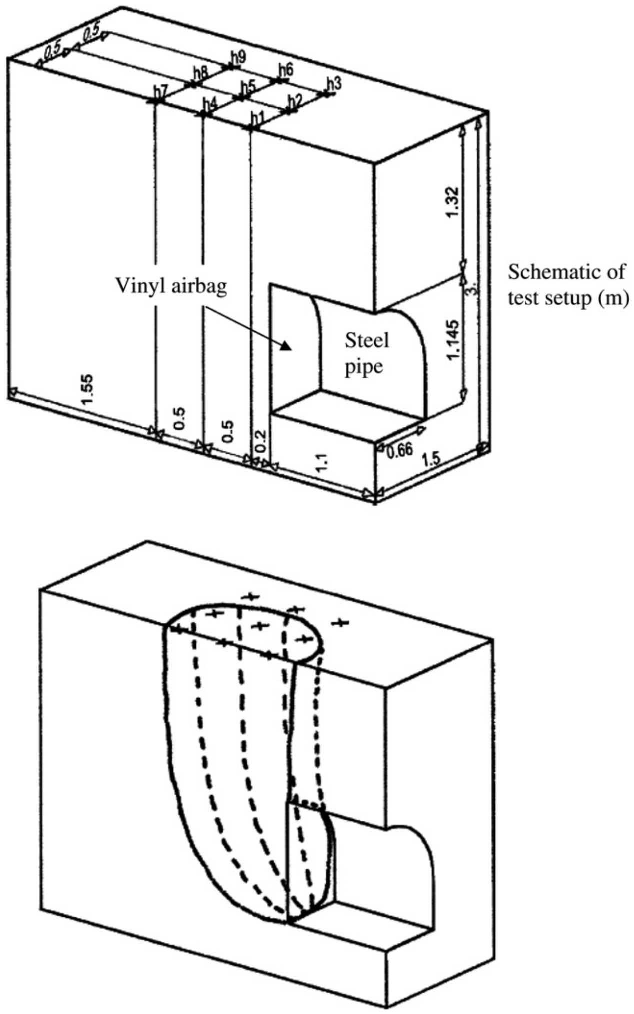


Fig. 6. Test setup and failure mechanism (Sterpi et al., 1996).

diameter) with a latex membrane (0.2 mm thick) representing the tunnel face (Fig. 5). The membrane was left slack to prevent mechanical influence on the displacement of the face. The face movements were tracked using a displacement transducer. Fine homogenous sand ($D_{50} = 0.17$ mm, uniformity coefficient = 1.47) was poured evenly into a rigid container and then the tunnel model is placed and more sand is added. The centrifuge testing was conducted under 50g, 100g and 130g. During the test, the pressure in the tunnel is gradually reduced until failure occurred. Tests were conducted for different soil cover to diameter ratios (C/D) as shown in Fig. 5. Face movement was observed when the internal pressure is lowered (from 36 kPa to 32 kPa). This corresponded to a local movement of the soil around the tunnel and did not affect ground surface. A limiting failure pressure of 5 kPa (associated with significant ground surface movement) was consistently observed for the range of C/D ratios used throughout the tests.

A large scale 3D model of a tunnel heading has been developed by Sterpi et al. (1996). This 1g model (see Fig. 6) consists of a 1.1 m long, horse shoe shaped steel pipe, with width and height of 1.32 m and 1.145 m, respectively. A vinyl bag is inserted within the pipe and air pressure is applied to support the tunnel face. The pluvial deposition technique was adopted to fill the container with medium uniform sand (friction angel = 32°) leveled in layers of constant thickness (about 30 cm). Fig. 6 shows the recoded failure pattern resulting from air pressure reduction at the tunnel face.

3.2.2. Rigid face

A physical model was developed by Kamata and Masimo (2003) to investigate the effect of face reinforcement on the face stability of shallow tunnels. It consisted of a semi-cylindrical acrylic shell 80 mm in diameter (see Fig. 7). Toyoura sand (unit weight = 15.1 kN/m^3, water

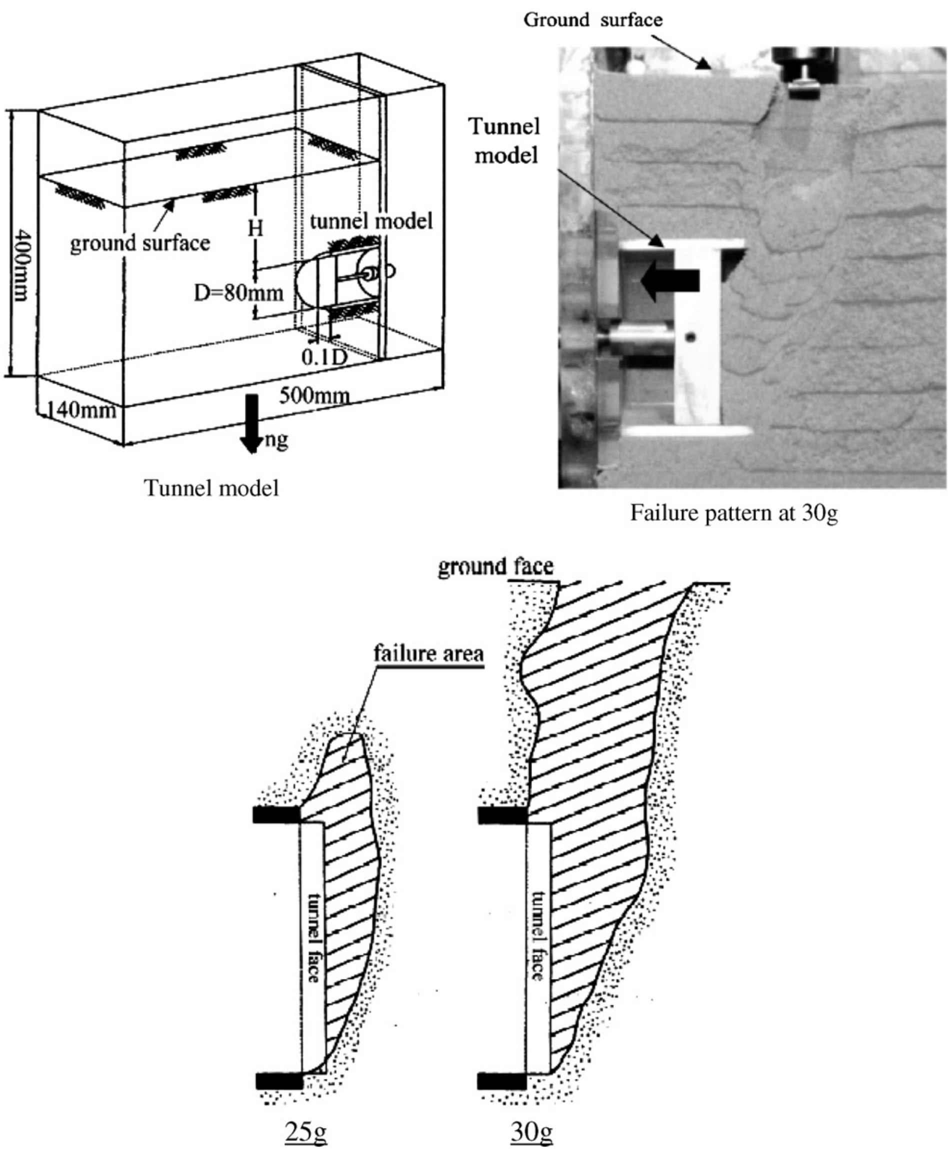


Fig. 7. Tunnel model and observed failure patterns (Kamata and Masimo, 2003).

content 6.5%, cohesion = 4.6 kPa, friction angle = 34.5°) was poured and compacted in 2 cm thick layers. The tunnel face is supported by a movable 25 mm thick aluminum plate. The model is placed in a container measuring 140 × 500 × 400 mm with a transparent acrylic panel. The overburden ratio (H/D) was kept at 1.0 for all tests and the face reinforcement was installed. A series of centrifuge tests were conducted and the stability of the tunnel face resulting from pulling the aluminum plate was observed. Failure was recorded when the centrifuge acceleration reached 30g. Failure patterns at 25g and 30g are shown in Fig. 7.

3.3. Pressurized air bags

Pressurized air in a rubber bag of negligible strength has been widely used by several researchers (e.g. Atkinson et al., 1975; Hagiwara et al., 1999; Wu and Lee, 2003; Lee et al., 2006). A tube is pushed through the soil or buried during the soil placement and a rubber membrane is then inserted into the tube and pressurized. In the initial stress state the air pressure in the bag is kept equal to the overburden pressure. The air pressure is then lowered incrementally to simulate stress reduction experienced during soil excavation until complete failure of the tunnel is achieved. While air-pressure can be effectively controlled, the method is mostly used under 2D plane strain conditions.

Atkinson et al. (1975) studied the stability of shallow tunnels using the pressurized air procedure. Eight tests were conducted on unlined tunnels in dense sands under 1g conditions. Leighton Buzzard sand (void ratio = 0.52) was poured into a test box in the direction of the tunnel axis. The pressure was introduced between two rubber membranes and the sand in the tunnel was removed causing the inner membrane to collapse and leaving the outer membrane as a flexible tunnel lining supported by the applied air pressure. The test was conducted by reducing the tunnel pressure in stages until collapse occurred. For each test collapse pressure and, in most cases, the final equilibrium tunnel pressure was recorded. The variation of tunnel pressure at and after collapse along with the observed collapse mechanisms are shown in Fig. 8.

The problem of tunneling in a multi-layer ground was studied by Hagiwara et al. (1999). A series of centrifuge tests of model tunnels in clay overlain by a sand layer was conducted. The soil sample was prepared by consolidating kaolin clay to a vertical pressure of 500 kPa in a plane strain box (550 mm × 200 mm). The tunnel cavity was cut through the clay and was lined with a latex rubber bag whose air pressure could be controlled. A schematic of the test setup is shown in Fig. 9. The figure also shows the settlement troughs at the surface and at the sand clay interface. It was found that the type and stiffness of the upper sand strata has a significant effect on the movement of the lower clay layer.

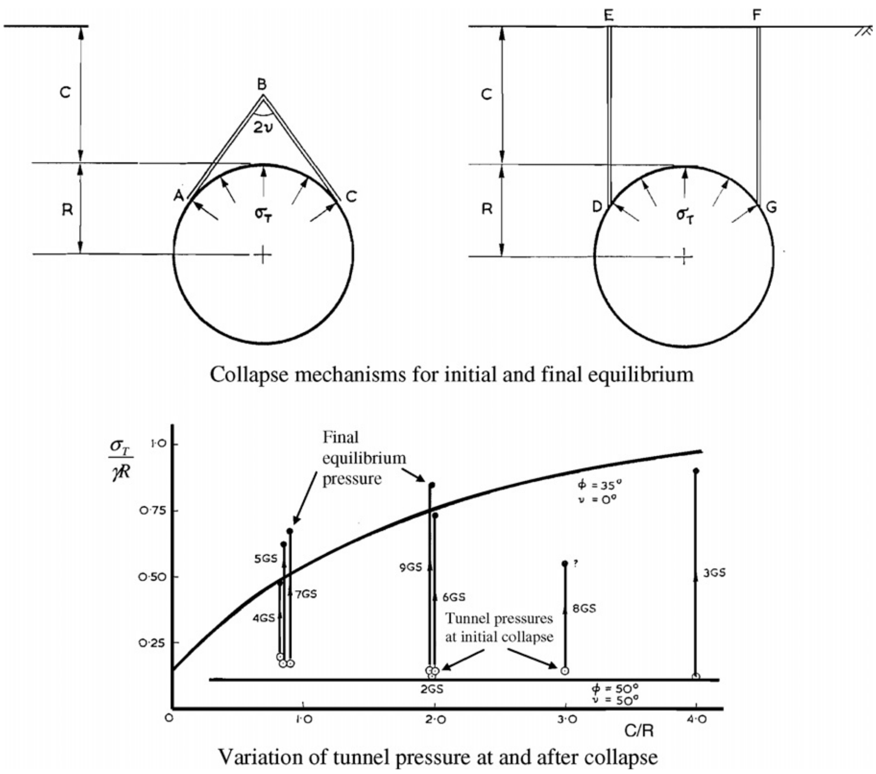


Fig. 8. Collapse of shallow unlined tunnel in dense sand (Atkinson et al., 1975).

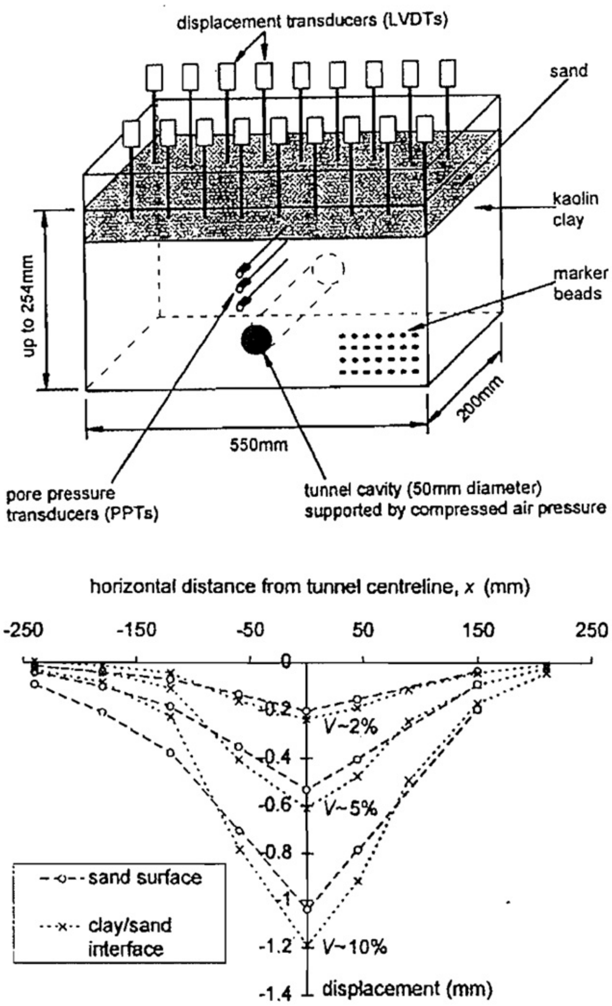


Fig. 9. Effect of overlying strata on ground movement induced by tunneling (Hagiwara et al., 1999).

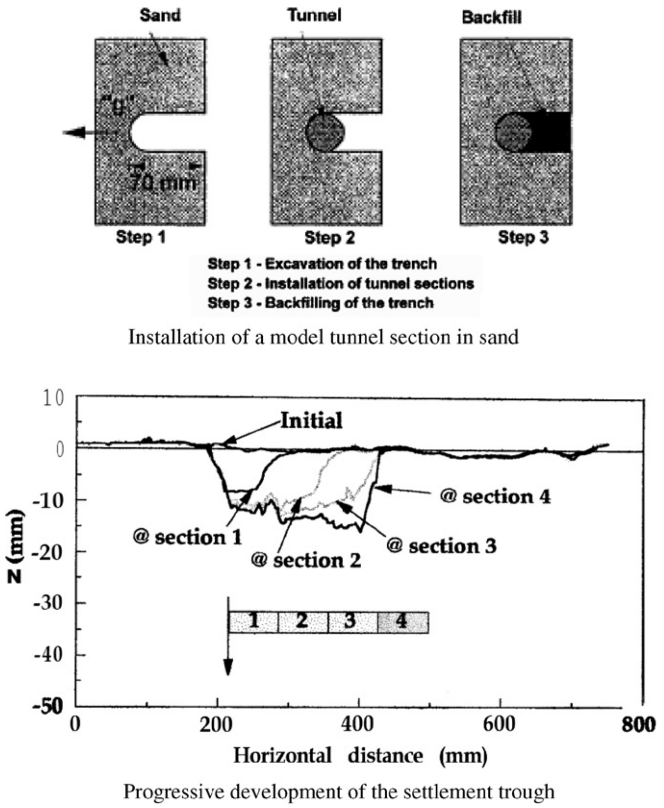


Fig. 10. The use of polystyrene foam in model tunnels (Sharma et al., 2001).

3.4. Polystyrene foam and organic solvent

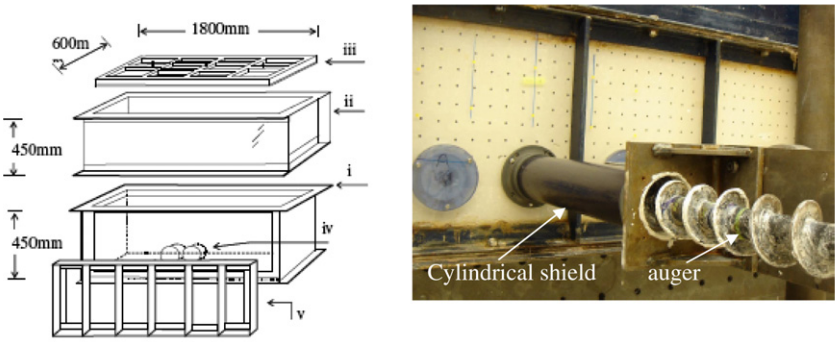
This method was developed by Sharma et al. (2001) to simulate tunnel excavation in a centrifuge. A stiff tube of polystyrene foam is buried in the soil. Once exposed to an organic solvent the foam dissolves quickly. The stress reduction induced as the foam dissolves is used to simulate the unloading condition experienced during tunnel excavation. Fig. 10 shows the procedures adopted to install a model tunnel in dry sands. The model tunnel consists of 35 mm diameter and 70 mm long foam cylinder with a Young's modulus of 1500 kPa. The model was buried in a sand medium (Leighton Buzzard sand, $D_{50} = 0.43$ mm). To simulate the lining, the foam was wrapped with hard brass foil; any gaps between the Polystyrene foam and the brass were filled in with a silicone rubber sealant. The flow of solvent into the tunnel model was controlled to allow for the dissolution of one section of foam at a time. This allowed one to simulate the progressive tunnel face advance. The developed settlement trough is shown in Fig. 10. Results were less satisfactory when the excavation was simulated under water.

3.5. Soil augering

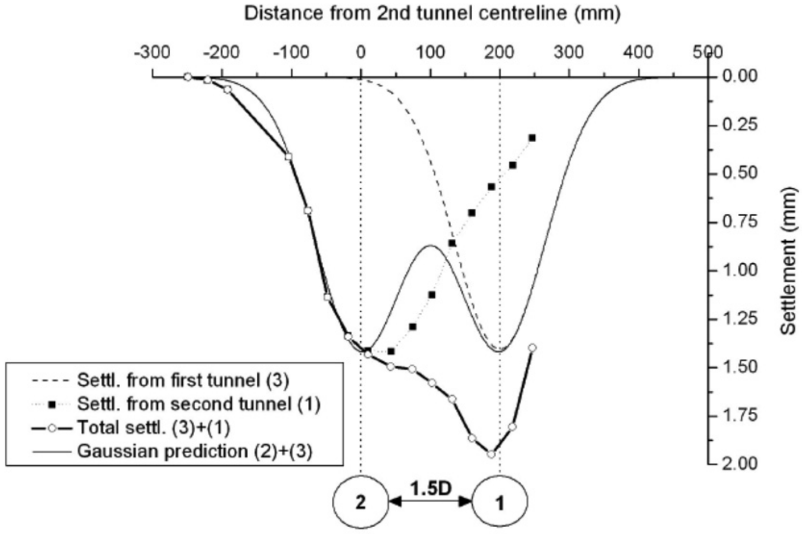
This method involves the use of a small soil auger to excavate a model tunnel in a reconstituted or natural clay material (e.g. Love, 1984; Kim, 1996; Champan et al., 2006). Soil is typically consolidated in a tank under a specified consolidation pressure. An auger is then used to bore through the soil and lining is installed. An over-cut in the tunnel diameter is usually made to facilitate lining installation which creates a gap between the soil and the lining. The tests reported by Champan et al. (2006) were conducted under 1g condition. Samples were prepared from Kaolin clay mixed at water content of 126%. The tested clay is lightly overconsolidated (OCR = 2.7). A water bag is used to provide surcharge pressure on the soil surface. The settlement trough resulting from the construction of two parallel tunnels is shown in Fig. 11. It was concluded that simply summing individual Gaussian curves to predict the settlement above closely spaced tunnels does provide a true reflection of the ground movements in clay soils.

3.6. Miniature TBM

Nomoto et al. (1999) developed a miniature tunnel boring machine (TBM) to simulate the process of shield tun-



General arrangement of the laboratory test tank



Individual settlement troughs generated by the construction of the two tunnels

Fig. 11. Experimental investigation of multi-tunnel construction in clay (Champan et al., 2006).

neling. As shown in Fig. 12, the shield consists of three tubes, a 100 mm diameter stainless steel tube houses a spiral conveyer with a cutting head to excavate soils, a middle tube of diameter 96 mm that serves as the tunnel lining, and a 100 mm diameter stainless steel pipe to simulate the tail void formation. The driving part is made up of two motors, one for the forward advancement of the shield and for removing the tail void tube, the other for driving the excavation cutter. The Strong Box is a $240 \times 700 \times 700$ mm stainless steel box that houses the soil and the displacement measurement system. The machine has been used to test a 100 mm diameter tunnel in a centrifuge under a maximum acceleration of 25g (2.5 m diameter tunnel). The developed settlement in the longitudinal direction is shown in Fig. 12.

3.7. Mechanically adjustable tunnel diameter

Lee and Yoo (2006) investigated the behavior of a tunnel adjacent to a row of loaded piles under 1g conditions. The 2D model test utilized a multi-sized aluminum rod mixture of various diameters (2 mm, 3 mm, 6 mm, 9 mm, 12 mm and 20 mm) with 75 mm in length. It represented a well graded, idealized granular material under plane strain conditions. Fig. 13 shows the tunneling device that can be adjusted to provide the desired volume loss. The model is 100 mm in diameter and consists of six segments forming a cylindrical shape. The segments can move inward by adjusting a mechanical knob to incrementally reduce the initial tunnel diameter.

3.8. Other methods

The methods discussed above do not represent a comprehensive review of all physical tunnel modeling techniques. Rather, they represent a brief description of selected methods that involve a distinct operating mechanism or investigate different aspects of tunneling. Other methods have been developed to simulate ground response to tunneling (such as the Base Friction method) are also of interest to geotechnical engineers. The base friction method has been used to reproduce the effect of gravity and visualize displacements in 2D physical models of mainly rock tunnels. Gravity is simulated by the drag of a belt moving

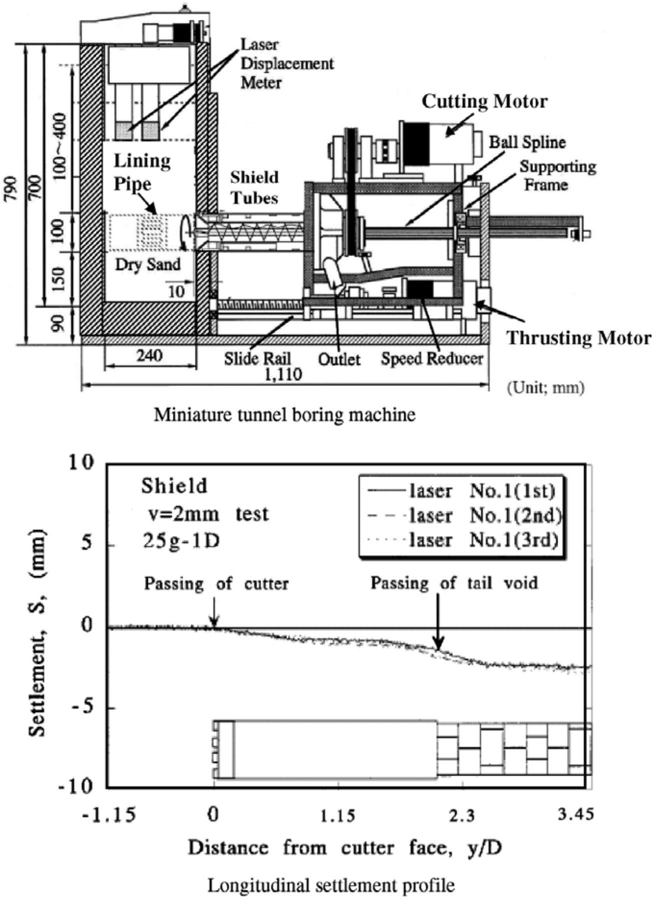


Fig. 12. Miniature shield tunneling machine (Nomoto et al., 1999).

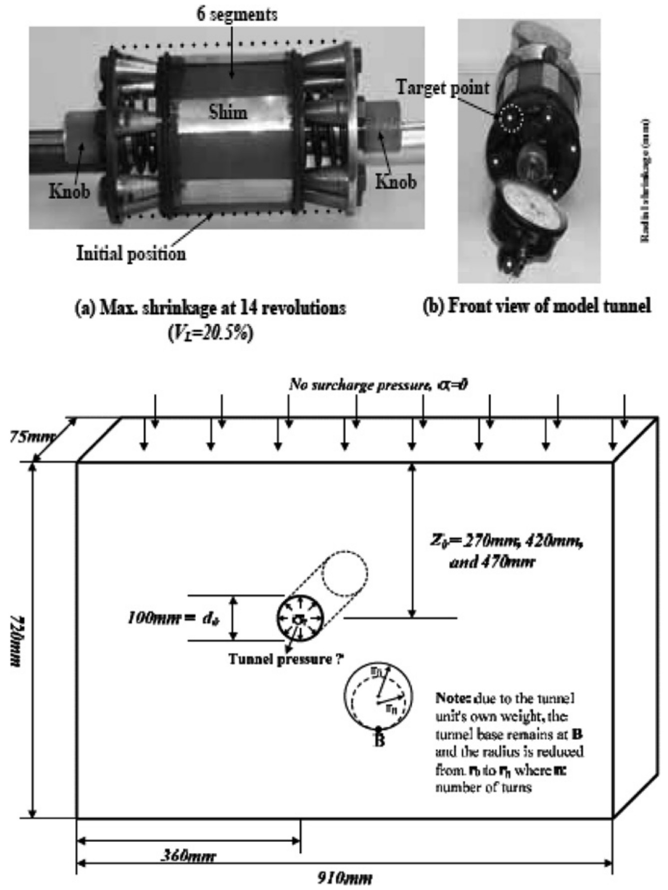


Fig. 13. Modeling bored tunnel using an adjustable device (Lee and Yoo, 2006).

along the model base (e.g. Hoek, 1971; Goodman, 1972; Whyte, 1973; Egger and Gindroz, 1979; Bray and Goodman, 1981; etc.). The method allows one to visually observe the ground movement and the failure mechanisms resulting from tunnel excavation. A cross section of the base friction machine and an example demonstrating the failure pattern around shallow tunnels is shown in Fig. 14.

4. Measuring soil displacement

One way to measure ground response to tunneling is to install conventional LVDT transducers at the soil surface to record the induced settlement trough. This method allows one to measure particular points at the surface and does not give comprehensive data on displacements elsewhere around the tunnel. Methods have been developed to measure displacements inside the soil medium during and after tunnel excavation. Some of these techniques are described below.

4.1. Lead shots and marker beads

The lead shots technique has been widely used to measure displacement pattern in sand models (Roscoe et al., 1963). The technique was successfully used to produce contours of shear and volumetric strain with a precision of 0.1% in large (2.0 m × 0.5 m) models (James, 1965). During soil placement, a grid of lead shots is placed in a plane perpendicular to the tunnel axis. By exposing radiographs to the lead shots at regular intervals and observing their movements, the resulting images allow one to measure displacement and strain fields in the soil. This is limited by the fact that only one plane can be examined at a time. As well it takes a significant amount of time (7–10 min) to fully expose the radiographs to the lead shots.

A similar method is to place visible markers (Atkinson et al., 1977) in the soil over the front plane of the box against a clear wall (Fig. 15). This works in much the same way as the lead shot method, with the position of the markers observed repeatedly over the progress of the test. Using marker beads has the added disadvantage that they can become obscured by the soil during deformation and can only be used on a visible plane (i.e. the face). Visible markers therefore have many of the same disadvantages as the lead shot method, on the other hand since the position of visible markers can be recorded by a normal camera they do not require nearly as long an exposure time as lead shot.

When using marker beads or lead shots placed in the soil, there is a concern that the presence of the beads or

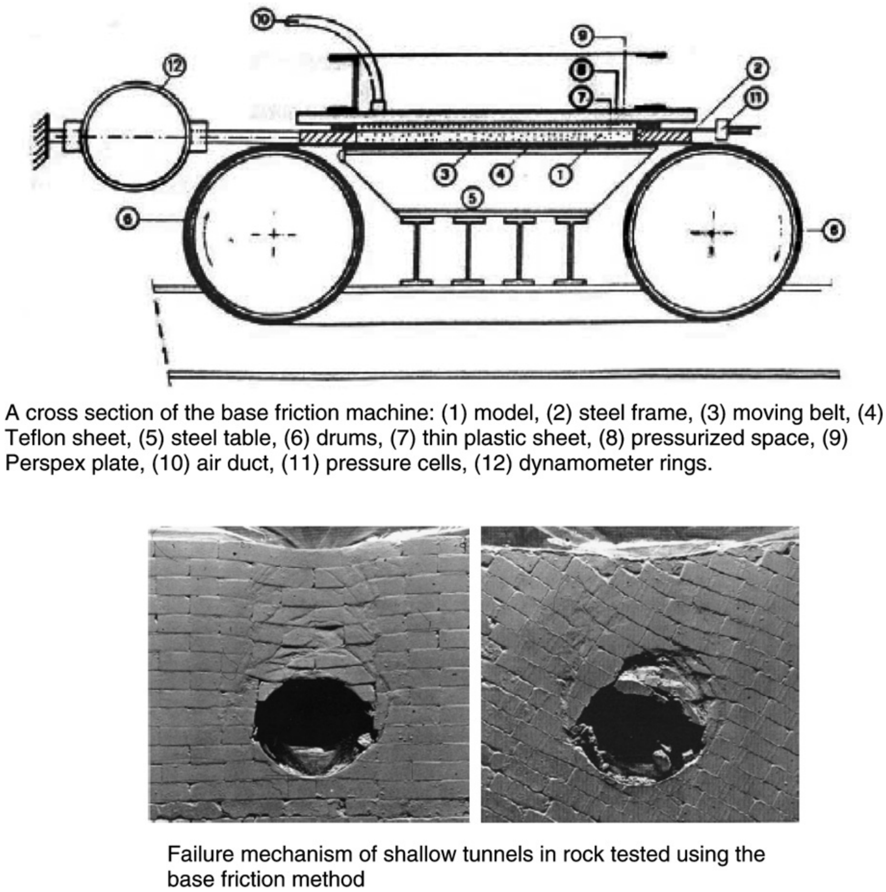


Fig. 14. The base friction model (Egger and Gindroz, 1979).

the lead shots in the soil affects the measured deformation. Using too dense a grid of marker beads may influence the soil deformation; on the other hand using a sparse grid of markers will only provide limited data. Additionally, it is difficult to use lead shots in a centrifuge because of the high speed of rotation and the insufficient amount of time available for the exposure of the radiographs.

4.2. Colored layers

Chambon and Corte (1994) used layers of colored sand to record the development of the failure mechanism. During the soil placement, layers of colored sand were inserted at known intervals. After completion of the test, the sand was cut into different vertical planes. The deformation of the colored sand layers allowed one to visually observe the failure mechanism (Fig. 15). The use of colored layers of soil provides a unique view of the soil deformation up to failure.

4.3. Colored spaghetti

Wu and Lee (2003) used colored spaghetti noodles to visualize the soil movement from the beginning of the test throughout failure. A series of marked spaghetti were placed in the soil. The spaghetti absorbs water from the soil and deforms along with it. After completion of the test, soil displacement was obtained by digging out the spaghetti and carefully recording the post-test position of each one of them. This method is innovative and is reported to have produced satisfactory results.

4.4. Soil photogrammetry

Photogrammetry has become a popular non-intrusive means by which ground displacement at the surface and around an excavated tunnel can be measured. Several investigators (e.g. Allersma, 1996; White and Take, 2002) have reported the usefulness of applying the particle image velocimetry (PIV) technique to geotechnical applications. PIV operates by tracking the texture within an image of soil through a series of images. The initial image is divided up into a mesh of test patches. To find the displaced location of this patch in a subsequent image a correlation between the patch extracted from the first image and a larger patch from the same part of the second image is evaluated. The location at which the highest correlation is found indicates the displaced position of the patch. Since PIV operates on the image texture, intrusive target markers need not be installed in the observed soil.

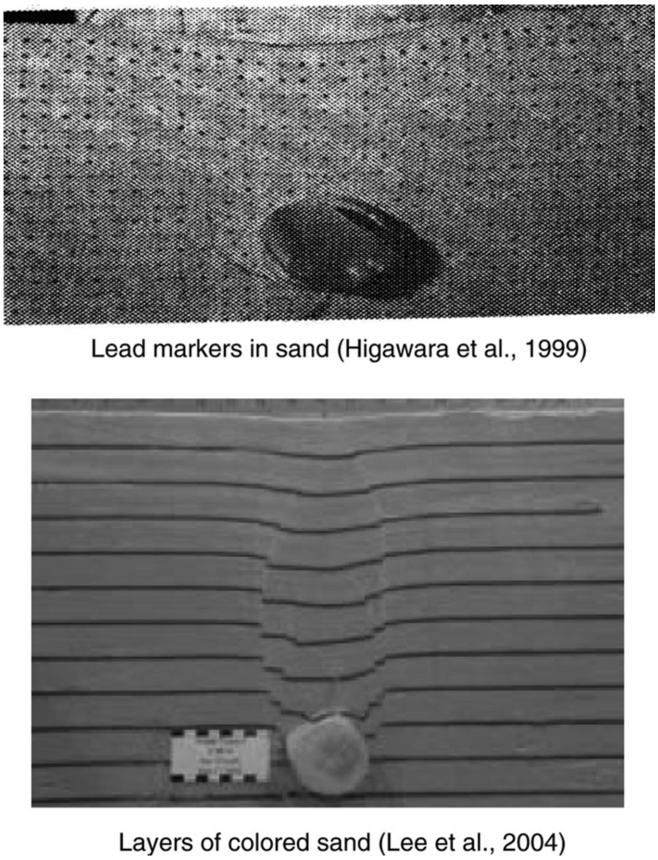


Fig. 15. Displacement measurement techniques.

5. Summary and conclusions

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. Vertical stresses as well as surface displacements can be investigated by lowering a trap door under 2D or 3D conditions. Stability of the tunnel face can be investigated using a rigid tube with flexible membrane at the face. Tunnel excavation is simulated, in this case, by reducing the air pressure inside the tunnel and monitoring the soil movements. Other methods include the dissolvable polystyrene core showed some success; however, the tunneling induced surface settlement was not uniform. In addition test results were less satisfactory when the excavation was made under water. Techniques based on hand or mechanical augering to represent tunnel excavation and progressive face advance seem more realis-

Table 1
Method comparison table

Method	Advantages and applications	Disadvantages
Trap door	• Used to evaluate surface settlement and pressure on the trap door simulating tunneling induced movement and lining stresses • Both 2D and 3D ground movement resulting from tunnel excavation can be evaluated under 1g and centrifuge conditions	• Does not simulate the actual tunneling process • Only 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 • Tests can be conducted under 1g and centrifuge conditions	• Does not provide information on the surface settlement behind the tunnel face
Pressurized air bag	• 2D and 3D tests that can be conducted under both 1g and centrifuge conditions • Used to study tunnel stability and induced ground movements around tunnels	• Used mostly for unlined tunnels • Does not simulate the tunnel face advance
Polystyrene foam and organic solvent	• Can be conducted in a centrifuge • Simulates the tunnel advance process	• Results were less satisfactory when the excavation was simulated under water
Soil augering	• Simulates the tunnel advance process • Easy to operate	• Used mostly for cohesive soils • Insertion of a shield is usually required • 1g only, not easily mechanized for a centrifuge
Miniature TBM	• Conducted in a centrifuge • Simulates the complete tunneling process	• Expensive • Limited gravitational acceleration (up to 25g) may be applied in centrifuge
Mechanically adjustable tunnel diameter	• Simulates the 2D tunnel excavation process • Simple to operate	• Manually controlled • Limited to 2D models under 1g condition

tic, however, mechanizing the test in the centrifuge is very expensive. Further experimental research is, therefore, needed to enhance the existing techniques and to develop new methods that allow one to simulate actual tunnel construction. Table 1 summarizes the advantages and disadvantages of the modeling techniques discussed above.

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