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Centrifuge models of tunnel construction and compensation grouting

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ABSTRACT: The soil deformation mechanisms induced by tunnelling and grouting have been explored using centrifuge model testing. Examples of actuators and model systems representing significant elements of tunnel construction processes are described. A new technique for simulation of segmental tunnel construction in 3-D in a drum centrifuge is also described. Using this technique it is possible to model a propagating settlement trough at ground level caused by tunnel excavation. Simulation of complex tunnelling processes such as NATM is also possible using this technique. Model test data which demonstrate the effectiveness of these systems are presented. The results of centrifuge tests on compaction grouting show that injections must not be made too far ahead of the face if they are to be effective in preventing subsidence above the face of a tunnel.

1 INTRODUCTION

Underground excavation may be simulated in centrifuge models in at least four distinct ways:

(a) 2-D plane strain simulation (e.g. Mair, 1979). The tunnel is pre-bored within a strong container that permits deformation only in the plane of the cross-section. The process of excavation is reproduced only as a reduction of internal support pressure. There is no tunnel face and therefore, no longitudinal arching.

(b) 2-D longitudinal plane strain. The plane of deformation would be the vertical plane of symmetry along the axis of the tunnel. The face, with an adequate length of tunnel behind it, would be created across the full width of the container prior to centrifuging and supported temporarily as in (a). There would be no lateral arching.

(c) 3-D stationary tunnel heading (e.g. Mair, 1979). A lined length of tunnel is pre-bored with its appropriate cross-section, or as a half-section using the vertical plane of symmetry, behind an unsupported heading which is supported with compressed air in the early stages of the centrifuge test. Full 3-D strain conditions are induced around the heading.

(d) 3-D travelling tunnel heading (e.g. Nomoto et al., 1994). The correct strain path and stress history is achieved by modelling the advance of the tunnel face. While Nomoto et al. (1994) describe a miniature shield tunnelling machine working in dry sand, we will show a simpler technique which simulates the essential features of a travelling face, and which can be used in any soil.

In this paper we first show the creation of a 3D settlement trough above a stationary tunnel face, following mode (c) above, and its compensation by compaction grouting using a sand injection above and ahead of the face. We then explain a novel technique for the simulation of a travelling wave of tunnel excavation giving rise to a progressively developing settlement trough.

2 COMPACTION GROUTING

In the present study, the 1:50 scale centrifuge tests were carried out using the CUED 10 m balanced beam centrifuge. Figure 1 shows the general arrangement of a typical centrifuge model. It consists of a strongbox containing a 215 mm (H) x 745 mm (L) x 150 mm (W) block of Speswhite kaolin clay which has been one-dimensionally consolidated to a maximum vertical pressure of 125 kPa. Near the bottom of the strongbox is attached a tunnel unit capable of simulating volume loss into a 75 mm diameter face. A grout pump which can inject sand into the block of clay is mounted on the top of the strongbox. The pump can be mounted at a horizontal distance of between 50 and 100 mm from the face of the tunnel to make injections at any required depth.

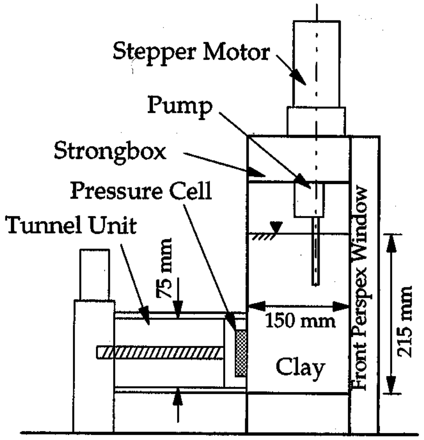

Figure 1 General arrangement of centrifuge model

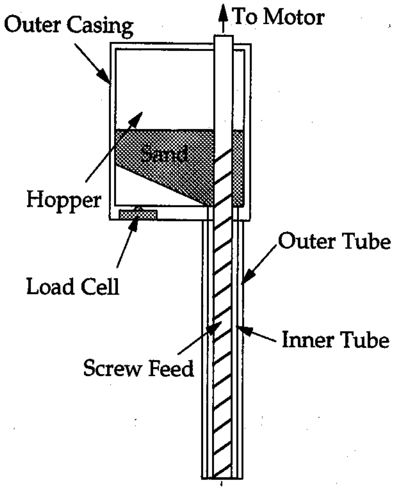

Figure 2 The grout pump

2.1 *Tunnel unit*

A typical tunnelling activity in the field involves a front face which is gradually moving forward by continuous excavation of soil. To design and construct a centrifuge model capable of exactly simulating this activity would require enormous effort and may not contribute significantly towards improving the understanding of tunnelling due to the complex nature of the results obtained from such a model. However, the stress relief at the front face followed by inward flow of soil can easily be simulated by mounting a mechanically retractable shore with a pressure measuring device against the face of the soil. This shore is shown as the tunnel unit in Figure 1. The tunnel unit is basically a modified car jack powered by an Escap 34L11 d.c. motor. A displacement transducer is attached to the back of the shore for recording its horizontal movement. A total stress measuring device (called TED) was designed and mounted on the front. The design of TED has been described in detail by Lu (1996). It consists of a pore pressure transducer encapsulated inside a sealed cell containing water and having a 100 µm thin dural membrane on the end facing the clay. During the assembly of TED, care was taken to prevent any air bubbles being trapped inside the cell.

2.2 *Grout pump*

A schematic diagram of the grout pump is shown in Figure 2. Its operation is similar to that of an Archimedean screw pump commonly used to transport water. It is capable of injecting dry granular material into the clay lying above and in front of the tunnel unit. A stepper motor drives a surface-toughened mild steel screw which collects dry sand from a surrounding hopper and pushes it in to the clay. The hopper bears on PTFE glides and the weight of sand contained in it is measured using a load cell located underneath its base. The pump is capable of injecting 125 g of sand (volume = 75000 mm^3) in 2 minutes. Such a fast injection is necessary if the clay is to remain undrained during grouting.

2.3 *Other instrumentation*

Other instrumentation consisted of several pore pressure transducers (PPTs) installed at various locations in the clay layer and an array of LVDTs mounted on the top surface of the clay layer. In addition, several horizontal and vertical lead threads were installed in the clay layer for recording its internal deformation pattern after the test using the X-ray method.

2.4 *Test Procedure*

To obtain the clay block, Speswhite kaolin powder was mixed with 120% (by weight) deionised water under conditions of partial vacuum. The resultant slurry was consolidated one-dimensionally in a plane strain consolidometer to a maximum vertical pressure of 125 kPa. PPTs were inserted prior to the final stage of consolidation. Two days before the day of the centrifuge test, the clay layer was unloaded, taken out of consolidometer, trimmed to the dimensions of the model and placed inside the strongbox. The tunnel unit, grout pump and the array of LVDTs were then attached to the strongbox. The package was then loaded on the swing of the centrifuge. A typical test was started by first bringing the clay layer in a state of hydrostatic equilibrium under an acceleration of 50 gravities with the water table at the ground surface. This was followed by the retraction of the tunnel face which in turn was followed by grouting. Surface settlements of the clay layer were constantly monitored and the grouting was stopped when the surface elevation prior to tunnel retraction was restored. Four tests were carried out. Table 1 gives the details of each test. An ideal prototype can be derived by scaling all lengths and displacements by factor 50; stresses and pressures remain unaltered.

Table 1 Compaction grouting centrifuge tests

Test Code	Description
YCL01A	8 mm tunnel retraction, no grouting
YCL01B	no tunnel retraction, only grouting
YCL03A	2 mm tunnel retractions followed by grouting, pump at 1.33D from tunnel face (D - diameter of tunnel).
YCL03B	2 mm tunnel retractions followed by grouting, pump at 0.67D from tunnel face

2.5 *Results*

Figure 3 shows settlements at the clay surface caused by the retraction of the tunnel shore in test YCL01A. It can be inferred from Figure 3 that for small retractions, the settlement is proportional to the retraction indicating a single plastic deformation mechanism. There was some reduction of settlement with distance ahead of face, but not as much as for a heading in field. This can be attributed to the fact that inside surface of the perspex window was lubricated and that it could not provide any supportive drag on that vertical plane.

Relating settlement above a stationary face to "ground loss" is not straightforward. But note that for 2 mm retraction we have 0.38 mm of maximum settlement in the trough. If the retraction is thought to be equivalent to constructing the full 150 mm section of tunnel, the area of the trough (71.25 mm^2) divided by the area of the tunnel cross-section (4418 mm^2) could be expressed as 1.6 % ground loss.

Figure 4 shows surface heave due to injection of the grout in test YCL01B. It can be seen that no significant heave occurred for the first 2000 mm^3 volume of grout but that all indicators then started responding. This can be explained on the basis of the argument that the first 2000 mm^3 of grout was to charge the threads of the screw, and can not be regarded as part of the injection. It is evident from Figure 4 that the surface displacements begin by being proportional to the injected volume. This implies a single mechanism of plastic flow into a heaving dome of constant plan area as shown in Figure 5. Since the width of the dome remains

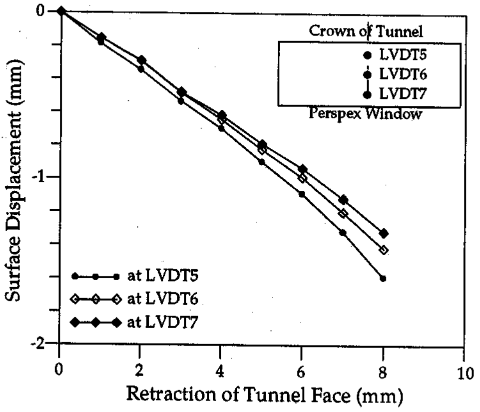

Figure 3 Surface settlements following tunnel retraction (Test YCL01A)

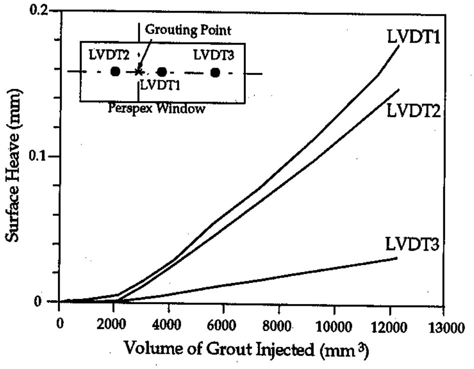

Figure 4 Surface heave following compaction grouting (Test YCL01B)

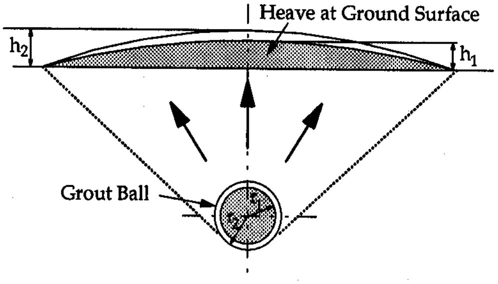

Figure 5 Plastic flow mechanism associated with compaction grouting

roughly constant, its volume can be taken to be proportional to the maximum heave at the centre of the dome. Therefore, the relationship between the volume of grout injected and the amount of surface heave observed is linear.

In tests YCL03A and YCL03B, there were episodes of retraction followed by injection. Figure 6 shows a typical compensation in test YCL03A where the pump was located 1.33D (D - diameter of tunnel) ahead of the face, and in YCL03B where it was 0.67D ahead. In the first 25 seconds, the tunnel shore was retracted 2 mm and in the next 50 seconds the pump injected sand to compensate. Although it was possible to compensate for settlement above the face in test YCL03A, this was only achieved at the expense of creating excessive heave above the injector. On the other hand, with the injector close enough to the face in test YCL03B a much more uniform compensation was achieved as can be seen in Figure 7 showing the pre and post-compensation contours of surface profiles for tests YCL03A and YCL03B.

The clay layer experienced some long-term settlements after initial compensation as can be seen in Figure 6. Figure 8 makes clear that these settlements accompany the dissipation of pore pressures induced in the clay layer due to grout injection. After initial reductions in pore pressure

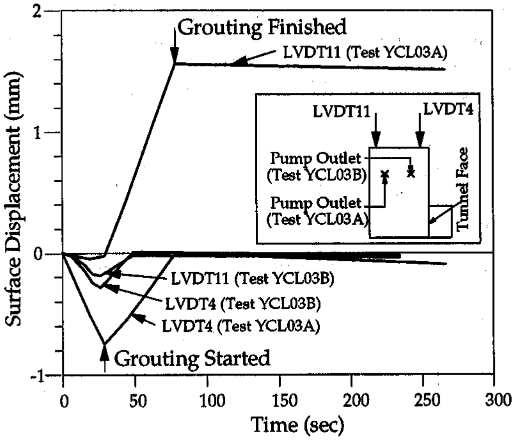

Figure 6 Surface displacements during tunnel retraction and compaction grouting

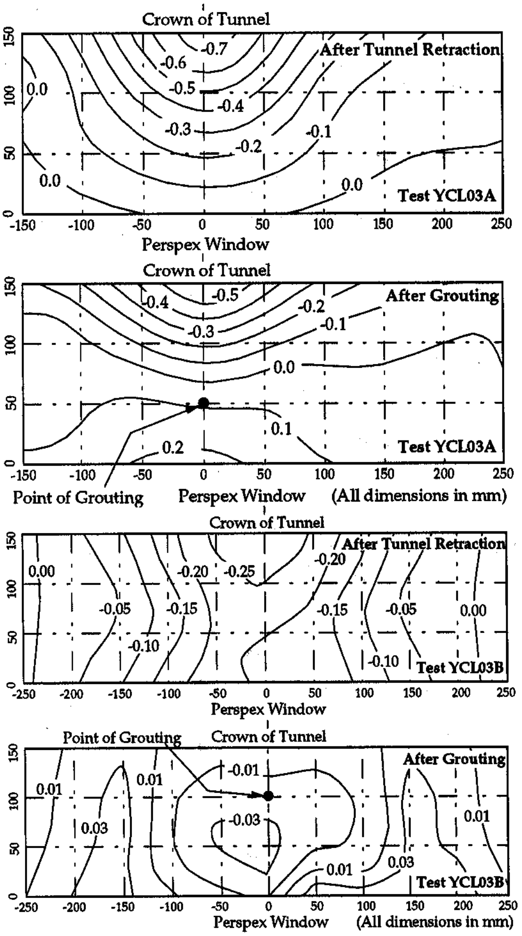

Figure 7 Pre and post-compensation contours of surface profile (tests YCL03A and YCL03B)

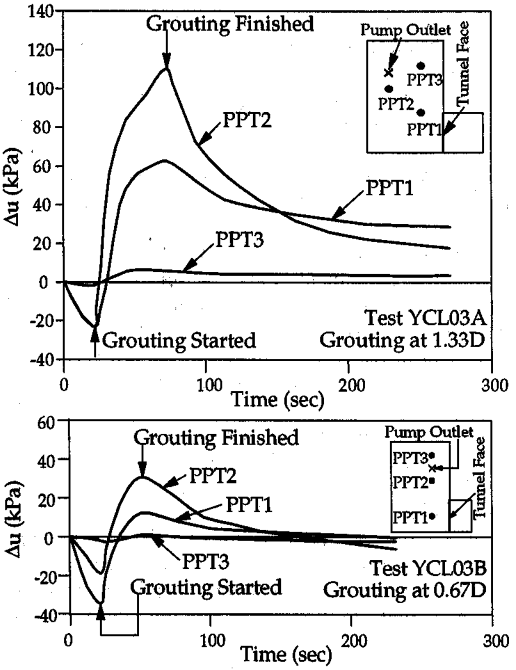

Figure 8 Change in pore pressure during tunnel retraction and compaction grouting

due to simulated tunnel excavation, the injection caused increases of up to 130 kPa in test YCL03A but only up to 55 kPa in test YCL03B. Obviously, the massive injection required at the too-remote position in test YCL03A caused excessive local pore pressures.

Figure 9 shows the total stress changes recorded by TED on the tunnel face in test YC0L3A. On the x-axis we have the difference between the volume of grout injected (V_g) and the volume of soil flowing in to the face (V_t). On the y-axis we have the change of horizontal support pressure ($\Delta\sigma$) normalised by the average undrained shear strength of the clay (c_u). Starting at the origin, the initial retraction reduces face pressure; this then increases as grout is injected. This plot will lead to analyses of the influence of compensation grouting on face stability.

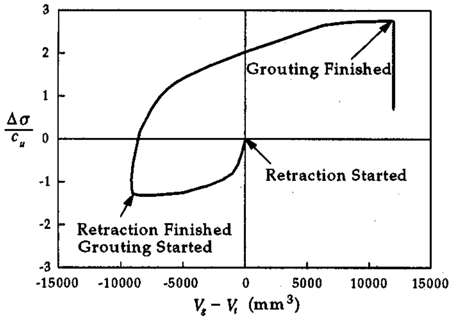

Figure 9 Change in total stress at tunnel face due to retraction of shore and compensation grouting

3 MOVING TUNNEL HEADING SIMULATION

A reasonably accurate simulation of tunnelling activity must have two essential features: (a) a moving tunnel heading, and (b) a progressively developing settlement trough. It is widely accepted that simulation of a moving tunnel heading in a small-scale centrifuge test is prohibitively difficult and expensive. Due to the complex nature of such an experiment, it may not contribute significantly towards our understanding of the tunnelling process unless great control is exercised and the equipment used is highly reliable. This is evident from the only attempt to date at such a modelling (Nomoto et al., 1994). However, from the point of view of environmental impact, the modelling of a progressively developing settlement trough is more important. In this section, a new technique is described which can simulate a propagating settlement trough in a drum centrifuge. This technique is extremely simple to use and models essential features of a moving tunnel face at a fraction of the cost and effort required for simulation of a moving tunnel heading attempted by Nomoto et al. (1994). This section also includes the details of a new laser-based device which can scan the entire surface profile with a resolution of ±10 µm. Some data from a series of preliminary tests are also presented which demonstrate the effectiveness of the technique.

3.1 *The technique*

The technique has been described in detail by Sharma and Bolton (1995). It is based on the observation that a piece of polystyrene foam (similar to that used in making model aeroplane wings) dissolves quickly when it comes in contact with an organic solvent. The idea is to use polystyrene foam as the core of model lined or unlined tunnel sections, install these sections at a certain depth in soil and dissolve the core in flight using an organic solvent to simulate tunnel excavation. In the present series of tests, a low density polystyrene foam having a modulus of 1500 kPa was used. This foam was found to be stiff enough to withstand overburden pressure of soil without causing any settlement at the surface before it was dissolved. The organic solvent used was 1,1,1-Trichloroethane (CH_3CCl_3), commonly known as methyl chloroform or Inhibisol.

3.2 *Test arrangement*

The general arrangement of a typical drum centrifuge test carried out in the present study is shown in Figure 10. The system can be divided into the following functional components: (a) model tunnel sections, (b) solenoid manifold and solvent reservoir

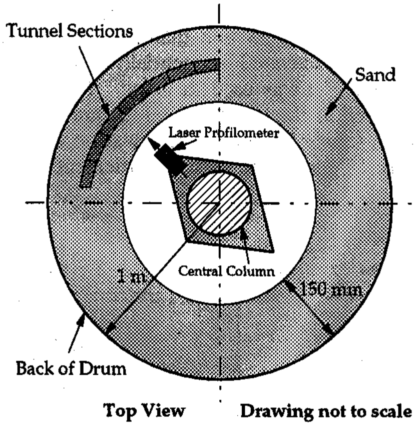

Figure 10 General arrangement of models for drum centrifuge tests on tunnels.

(not shown in Figure 10), (c) laser profilometer and (d) data acquisition system. The unlined sections were obtained by pasting brown paper around the periphery of cylindrical polystyrene segments cut using a 0.5 mm diameter hot Nichrome wire. The lined sections were obtained by wrapping a brass foil around unlined sections and soldering the lap joint using tin solder. Prior to wrapping, strain gauges were attached to the brass foil. The ends of each tunnel section were sealed by silicone rubber.

Once the silicone rubber cured, a plastic tube was inserted into the core of the tunnel section just below its crown (Figure 11). For controlling the flow of solvent into each model section, a manifold containing 8 solenoid valves was built and mounted at the base of the drum centrifuge. The inflow tube of each model tunnel section was connected to the outlet of the solenoid valve and the inlets of all the solenoid valves were connected to a solvent reservoir. The opening and closing of the solenoid valves could be done either manually or using a PC via the RS232 port and a D/A card. For recording the surface profile of the settlement trough, a laser profilometer was designed and commissioned. At the heart of the laser profilometer is a Laser Displacement Sensor (LDS) mounted on a carriage which can roll on a vertical rail. At any instant, its vertical and radial position is measured by two rotary potentiometers - one mounted on the laser profilometer and the other mounted on the central column of the drum centrifuge. The LDS has a measurement range of 60 to 140 mm at high response speeds of up to 0.7 ms and at resolution of up to 10 μm.

3.3 Test procedure and results

The 150 g centrifuge test (code TUN1) involved four tunnel sections (three unlined sections followed by a lined section; each 35 mm diameter, 70 mm long) which were excavated sequentially. A brass foil (0.15 mm thick) was used as lining. These sections were located at the centre of a 115 mm thick damp sand layer (cover 35 mm). There was no water table.

Figure 12 shows the surface settlements recorded by LDS after the injection of the solvent. Most of the "excavation" for each section was complete within 200 seconds resulting in collapse of the unlined sections and induction of stresses in the lined section. Figure 13 shows the settlements above the centreline of the tunnel, plotted after the excavation of each section. A good simulation of the progression of the trough has been achieved.

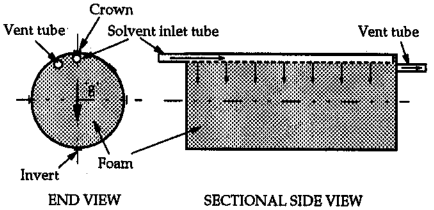

Figure 11 Arrangement of inflow of solvent

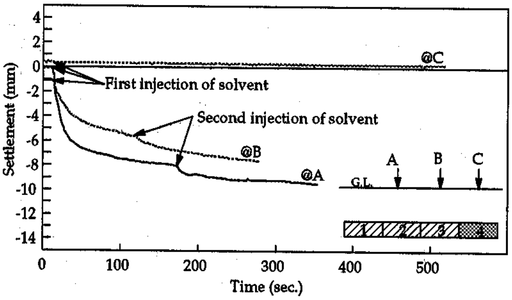

Figure 12 Settlements after injection of the solvent

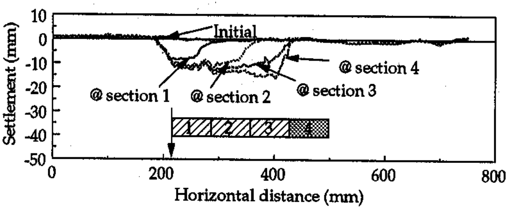

Figure 13 Progressive development of settlement trough above tunnel centreline

4 CONCLUSIONS

The creation and compensation of a stationary settlement trough has been demonstrated. The data show that null displacement above the heading can be achieved if the injection is properly sited. However, excess pore pressures induced around the injection dissipate to create long-term settlements. A technique for creating a progressive 3-D trough has been developed. It will be capable of resolving many uncertainties regarding tunnel construction effects.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Lu, Y.C. (1996). Compaction grouting. Forthcoming Ph.D. thesis. Cambridge University.

Mair, R.J. (1979). Centrifugal modelling of tunnel construction in soft clay. Ph.D. thesis, Cambridge University.

Nomoto, T., Mito, K., Imamura, S., Ueno, K. and Kusakabe, O. (1994). A miniature shield tunnelling machine for a centrifuge. Proceedings of Centrifuge'94, Singapore, pp 699-704.

Sharma, J.S. and Bolton, M.D. (1995). A new technique for simulation of collapse of a tunnel in drum centrifuge. Technical Report No. CUED/D-Soils/TR286, Cambridge University.