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Compensation grouting

M. D. Bolton, C.Y. Chin & Y.C. Lu
Cambridge University, UK

ABSTRACT Two grouting devices have been commissioned which are capable of making injections in centrifuged models. One is capable of pumping sand from a hopper above the surface of a package accelerating on a beam centrifuge. The other can create hydro-fractures through the injection of fluid from a syringe mounted on a central turn-table in a small drum centrifuge. They are to be used to explore the prevention of ground subsidence due to tunnelling. The means of simulating a subsidence trough is also explained.

1 INTRODUCTION

Interest in the UK is being shown in the use of displacement grouting to compensate for subsidence caused by tunnelling, shown exaggerated in Figure 1. Grout is injected at an intermediate level between the tunnel crown and the ground surface, as the heading advances: see Figure 2. The grout is intended to support the overburden without de-stabilizing the tunnel face. Since the support must not be lost when the grouting pressure is relaxed, displacement grouting is generally done with granular material.

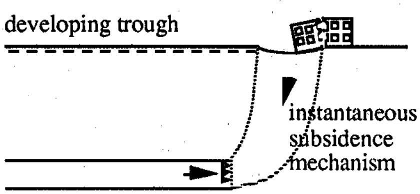

Fig 1 Subsidence due to tunnelling

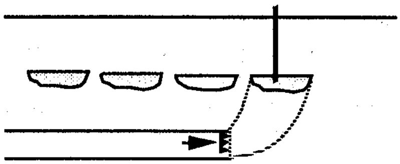

Fig 2 Compensation grouting

Two extremes may be recognised in the nature of these granular injections. They may be drained injections of a granular mortar (sand, cement etc) which behaves as a frictional material, or they may be undrained injections of a slurry of suspended particles (silica flour, PFA, cement, bentonite etc) which behaves as a viscous fluid during injection. These extremes are exemplified in the contrasting techniques of compaction grouting and hydro-fracture grouting.

2 MODELLING A SUBSIDENCE TROUGH

The objective is to simulate the typical subsidence trough which might be experienced above a 3.75 m diameter tunnel heading, with 7m of cover. Figure 3 shows a simple method of generating a given amount of ground loss, at a predictable rate. Working at 1:50 scale, a 75 mm diameter motorised tunnel facing-shore is initially held flush with the back face of a container (long, into the paper) which holds a block of clay 150 mm wide along the line of movement. Subsidence can be initiated by retracting the shore, permitting soil to flow plastically into the volume thereby created.

It must be recognised that the local pattern of subsidence will be different in the case of a retracting shore, compared with that of soil squeezing into an advancing heading. Nevertheless, the settlements for soft kaolin clay recorded in plan in Figure 4a, and sketched in section in Figure 4b at exaggerated scale, are roughly consistent with the empirical Gaussian

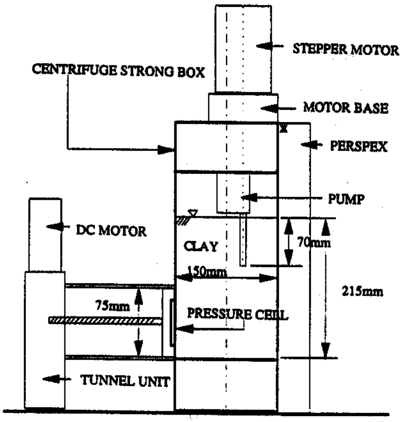

Fig.3 Tunnel and pump assembly.

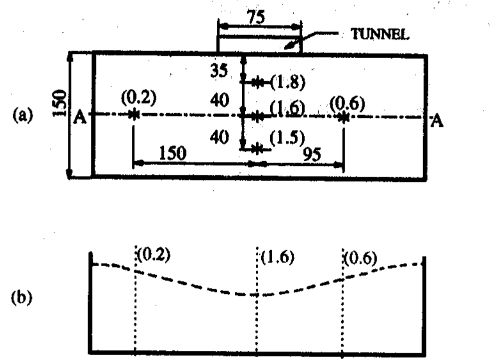

Fig.4 Surface settlements for 8mm tunnel retraction
(a) Plan with spot levels (in mm, shown in brackets)
(b) Settlement profile for section AA.

profile usually assumed, and those observed previously in centrifuge models of tunnels: Mair et al (1993). The maximum settlement above the tunnel was about 1.8 mm (90 mm prototype scale) for an 8 mm retraction. Figure 5 shows an approximately linear relationship between tunnel displacement and surface settlement one diameter ahead of the face, with a ratio between the two of about 5.

The volume of the 150 mm length of trough was found to be roughly equal to the 37 ml of retraction. The full 8 mm of retraction per 150 mm of model section may be expressed as a proportional volumetric change of 8 / 150, but "ground loss" is more properly defined as the ratio to the cross-sectional area of the tunnel of the cross-sectional area of the fully developed trough, rather than the attenuated trough ahead of the face. Taking the appropriate areas at the plane of the tunnel shore, the maximum equivalent ground loss would be approximately 7.5%. This would be two to four times greater than should be obtained with appropriate tunnelling techniques, and offers a useful range within which compensation grouting can be assessed.

The scatter in Figure 5 is quite small, confirming the controllability of subsidence using this technique. The retraction of the shore at a constant rate provides a constant rate of ground loss for trial compensation, at least in the case of soft clay ($c_u \approx 20$ kPa), as used here. A total pressure cell is incorporated into the model shore, as shown in Figure 3, so that the equilibrium of the whole plastic mechanism can be assessed. Pore pressure transducers buried at various locations in the clay are used as sensitive indicators of change, and to assist in back-analysis.

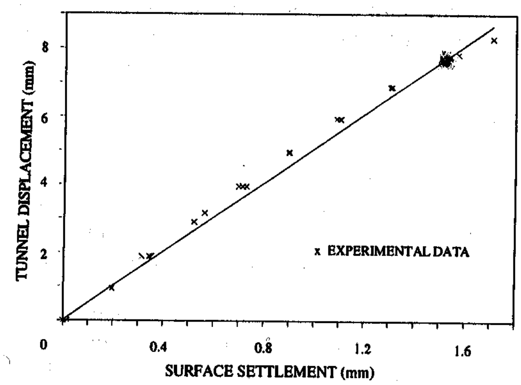

Fig.5 Tunnel displacement vs. surface settlement.

3 COMPACTION GROUTING

Figure 3 showed a sand pump located above the soil surface, capable of injecting dry granular material above and in front of the tunnel unit. Figure 6 shows a schematic section of the sand injector which has been used to simulate compaction grouting in clay at 50g on the Cambridge beam centrifuge. A stepper motor drives a screw feed which collects dry sand from a surrounding hopper. The inner hopper is located on PTFE guides, and the weight of sand inside is monitored by a load cell.

The pump is installed just before the package is mounted on the centrifuge. The outer tube is first inserted to the correct depth from the clay surface, the material inside being augured away. The unit is then lowered into place.

The pump was used to force uniform 0.8 mm Leighton Buzzard sand into kaolin clay, precompressed to 125 kPa, with $c_u \approx 20$ kPa at a depth of 70 mm at 50g. An injection of 125 g of sand occupying roughly 75 ml was carried out in a period of 2 minutes. Such a fast injection must leave the clay undrained; some allowance for strain-rate effects may be necessary in analysis.

As with the tunnel simulator, local pore pressures and surface displacements were monitored. There is some uncertainty over the quantity of sand trapped in the threads of the screw at any stage, but the final situation can be determined by direct physical examination, and intermediate states can be interpolated from the number of revolutions of the motor. Figure 7 indicates the ball of sand eventually exposed within the clay after the commissioning test. In this case, no subsidence was occurring during the injection, but the crown of the ball nevertheless remained at the opening in the delivery tube. The ball was pushed down as it expanded, causing regional

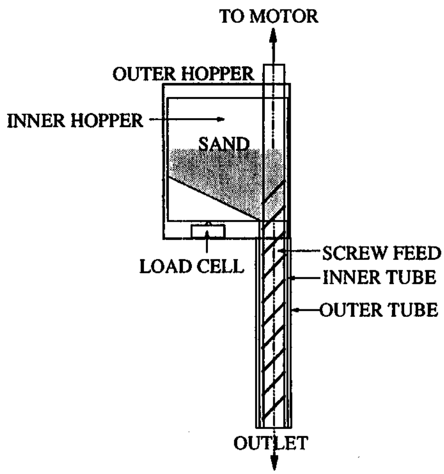

Fig.6 Pump for compaction grouting.

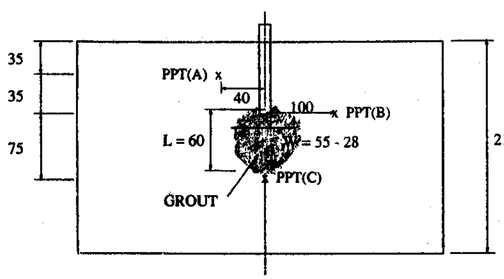

Fig.7 Section through sand injection, showing pore pressure transducer locations (all dimensions in mm).

rather than local heaving, which was monitored by LVDTs. Pore pressure in the clay below the injector, at C in Figure 7, rose by 150 kPa during pumping.

The sand pump will be used to create simple one-shot compensations for tunnelling subsidence. The intention is to study the mechanisms of plastic flow from around the injector towards the tunnel unit, and to vary conditions in order to assess the sensitivity of residual surface displacements to the location, magnitude, and timing of injections.

4 HYDRO-FRACTURE GROUTING

The injection of cement grout to fracture clay and induce permanent heave is well established as a remedial technique. The Tube à Manchette (TàM) system is usually used in which a grouted annulus around a perforated tube, sealed externally with rubber sleeves, is selectively burst by high pressure grout retained in sections by a packer system. The system has also been used ahead of an advancing tunnel face to compensate for subsidence as it occurs, through the monitoring of structures and the extensive use of ground instrumentation. Many injection tubes are used, usually fanning out from drilled shafts, to guarantee control of surface displacements.

The proper range of application of the technique, and the most efficient means of effecting it, are not yet clear. The mechanisms of hydro-fracture initiation and propagation in different soils, using grouts of different composition, are not well understood.

Preliminary hydro-fracture grouting tests have been carried out in a small drum centrifuge. Adhesives rather than particulate suspensions have been used in the first instance to investigate fracture mechanisms in kaolin, at different over-consolidation ratios.

The ANS&A mini-drum centrifuge, Figure 8, is an 800 mm diameter drum driven by a DC brushless servo motor capable of 1000 rpm. A ring channel holds containers of soil. The injection equipment sits centrally on a turn-table which can rotate in synchronisation with the ring channel. For these experiments two containers were used, one to accept grout and one to act as a counter-weight.

The injection equipment consisted of a 24 volt DC motor driving two pulleys via a belt. This provides linear motion to a screw feed, pushing against a plunger in a medical hypodermic syringe filled with the adhesive Loctite 241, which has a viscosity of 100 cP at 20°C. A 5 mm OD nylon tube connects the syringe to an aluminium nozzle embedded 50 mm in

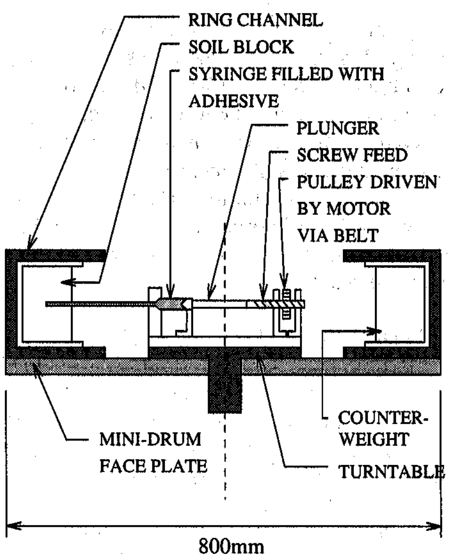

Fig.8 Cross-section of ANS&A mini-drum centrifuge with fluid injection equipment.

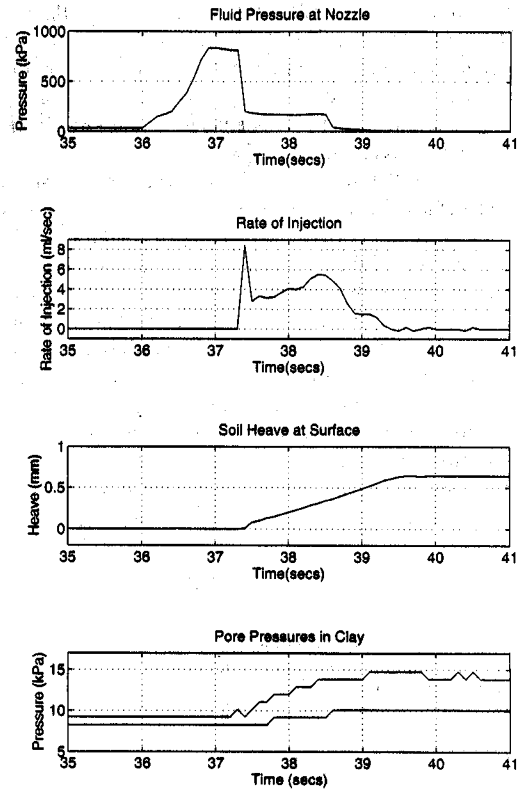

Fig 9 Data of hydro-fracture from test CYC 10.

range 250 - 750 kPa, simulating the puncture of a grout annulus.

The instrumentation consisted of LVDTs to measure the rate of injection and heave of the soil surface, pore pressure transducers in the soil at the level of the injection, and strain gauges on the plunger to monitor the pressure in the syringe.

5 MINI-DRUM HYDRO-FRACTURE TESTS

Dry Speswhite kaolin was mixed to 120% water content with de-ionised water, under vacuum. The soil containers were positioned in a consolidometer, and the clay slurry was poured over to cover them. The clay was consolidated in stages to 60 kPa. The containers were then extracted and placed in the mini-drum centrifuge. Varying over-consolidation ratios could be achieved by varying the rotational speed of the mini-drum. The sample was brought into a known water pressure condition prior to the injection being carried out.

Figure 9 shows the data of an injection conducted at 25g in test CYC 10 on clay at an OCR of 7.2. Prior to injection the clay at the point of injection had been permitted to swell back into equilibrium at $\sigma_v' = 8$ kPa.

At t = 36 seconds the motor was started. This caused an increase of pressure in the syringe, as an air bubble trapped below the piston was compressed. At 37.4 seconds the ball was ejected at a pressure of about 800 kPa, and the soil was fractured. From 37.4 to 39 seconds the grout was injected at a rate of about 4 ml/sec at a nozzle pressure of about 175 kPa, more than sufficient to lift the soil block above against its self-weight and boundary shear strength. During the injection, the ground close to the injector heaved at a roughly constant rate, reaching 0.6 mm, while pore pressures in the clay on either side of the injector were seen to increase. The plunger hit the bottom of the syringe at 38.5 seconds, but the trapped bubble of compressed air was able to sustain the injection for another second. Thereafter injection stopped but the heave remained.

Following each test, the clay sample was removed and baked for 1 hour at 150°C to allow the adhesive to set. The adhesive being blue, it was possible to trace its extent in the clay. Figure 10 shows the sub-horizontal fracture surface from test CYC 10: it consists of three zones. The central circular mark is the impression of the nozzle. The larger circular patch enclosing it, dark due to its being full of blue adhesive, was inflated to a thickness of about 5 mm, presumably in the pumping phase which followed initial hydro-fracture. The larger fracture zone to the right of this, with lighter colour due to its being only about 2 mm thick, was held to be the maximum extent of hydro-fracture created when the ball was first ejected from the tube. This hypothesis must be explored in further tests.

The injection in CYC 10 was conducted on heavily over-consolidated clay, OCR ≈ 7.2, at which the effective stress ratio K_0 should have been about 1.5. It was found that injections at OCR > 3, on the dilatant side of critical states, always resulted in sub-horizontal fractures, whereas for OCR < 3 the adhesive was found to have created a ball around the nozzle, rather reminiscent of the compaction grouting described earlier. This is consistent with the view that fracture requires the soil state to be strain softening, and that the fracture surface runs normal to the direction of minimum compressive total stress.

6 SIMILARITY CONDITIONS FOR FRACTURE

Before centrifuge tests can properly be described as models, the similarity conditions must be known. Before dimensionless groups can be formed, the physics of the phenomenon must be imagined. Then the essential dimensionless groups can be derived, and the whole modelling hypothesis validated in centrifuge tests.

Two phenomena need attention – fast fracture when the pumping rate is high enough to create a dynamic event, and inflation at a steady pressure just sufficient to lift the overburden above a pre-existing fracture. No criterion for fast hydro-fracture propagation currently exists which treats soil as a two-phase material subject to effective stress analysis, though recent work by Murdoch (1993) draws attention to the role of fluid pressures and fluid migration into the tip of a slowly propagating fracture. However, especially if TàM grouting is to be used, it seems necessary to consider the possible lateral extent of fast fractures caused during the period in which injection pressure exceeds that necessary for slow propagation.

Consider the following hypothesis, therefore. Since the soil aggregate is "cracked" at the outset, with complete freedom of particles to separate on any surface, fracture must relate not to the solid phase but to the fluid phase. A consistent physical description of fast hydro-fracture, sketched in Figure 11, would therefore be the prying open of a crack which begins to propagate like a pair of shear waves, back to back,

Fig.10 Fracture surface observed in test CYC 10.

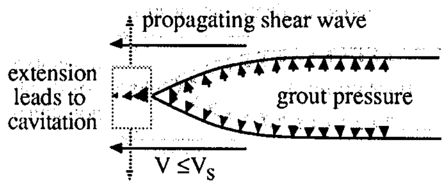

Fig.11 Fast hydro-fracture hypothesis.

at the shear wave velocity V_S. A zone of soil in front of the crack tip begins to extend in a direction normal to the propagation direction. Transverse tension, together with fast shearing on inclined planes if the soil is dilatant, leads to the creation of strong negative pore pressures ahead of the tip. If the ambient pore pressure was small enough, this can lead to cavitation or de-gassing, followed by the invasion of grout from the crack tip into the vapour-filled cavities, and therefore to the continued propagation of the fracture.

The propagation rate V will depend on the velocity of shear waves. Any such surge of grout of density ρ and viscosity μ will induce a shear stress τ on the sides of the crack which will tend to reduce grout pressures at the tip. If the crack is of mean thickness h, τ for a turbulent boundary layer may be written

$$\tau = \frac{\rho V^2}{R^m}$$

where m is some exponent less than unity to be applied to Reynold's number, defined as

$$R = \frac{\rho V h}{\mu}$$

From the foregoing discussion, it will be necessary to achieve a correct stress history, and correct effective stresses and pore water pressures prior to modelling fast fracture. Then the speed of stress waves will be replicated and, in the scenario traced above, grout velocities in the model should equal those in the prototype.

The criteria governing the thickness h of a fast hydro-fracture are not clear, and require examination. Ideally, however, the full-scale thickness would be reduced by factor n, together with the radius r. Since grout volumes should be scaled down by n^3, and cross-sectional areas by n^2, the duration of fast pumping must ideally be reduced by factor n in the model to achieve full-scale grout velocities. If the grout in the model has similar density ρ and viscosity μ to the grout in the field, the Reynold number will be reduced by factor n, which will tend to increase fluid friction. This will tend to cause a more significant pressure drop in the model, so injection pressures would be higher than those needed at full scale to extend a scaled-up fast fracture.

Conditions for slow inflation of a pre-existing fracture will be similar to those for compaction grouting. Grout viscosity will be negligible but the transient flow of pore fluid in the soil, or bleed from the grout, may be significant. The usual reduction factor of n^2 for the duration of an event subject to a diffusion process should theoretically be applied in this phase if the precise degree of transient flow were required in prototype materials are placed in a model. However, as with other dynamic centrifuge models, it will usually be possible to conduct meaningful tests with a time reduction of n. Bleed in cement grouts can be reduced by using micro-fine cement, or additives such as bentonite. Seepage in clay soils will be negligible even at time factor n, and the degree of transient flow in sands can be replicated using a d_{10} particle size scaled down by factor $\sqrt{n}$. Strain rates in the model will then be n times higher than the prototype, so element tests for model analysis should ideally be conducted at equivalent fast rates. It will be an objective to demonstrate the validity of this modelling of the slow inflation process, which should be capable of careful pressure control, and to determine whether it offers the required pattern of compensation.

7 CONCLUSIONS

The proper scaling of grout injections will require further study. A working hypothesis is that the duration of pumping should be reduced by the scaling ratio n in models centrifuged at n gravities. Fast fracture propagation would be correctly modelled only if the viscosity of the grout were similarly reduced by n in models, which is practically impossible, but it remains to be determined whether viscosity is a strong or weak parameter.

Devices have been commissioned to make single-phase injections. A screw device has been used successfully to perform compaction grouting of sand injections in soft clay. A syringe has been used to perform injections of a fluid.

Compaction grouting has been seen to lead to the expansion of a ball of sand which is pushed outwards and downwards beneath the delivery pipe. Fluid injection has been seen to lead to simple cavity expansion in lightly over-consolidated clay on the "wet" contractile side of critical states, and to fracture propagation in heavily over-consolidated clay on the "dry" dilatant side of critical states.

A small and convenient drum centrifuge has proved effective in permitting a rapid development of the concepts concerning hydro-fracture, which required ad-hoc adaptations of technology and a fast turn-around time. A large balanced beam centrifuge has proved effective in the development of models at larger scale which will permit a complex simulation of compensation grouting for the elimination of subsidence due to tunnelling.

8 ACKNOWLEDGEMENTS

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