INTERNATIONAL CONFERENCE ON REINFORCED SOIL

STRATHCLYDE UNIVERSITY, GLASGOW, SEPTEMBER 1990

THE RESPONSE OF NAILED WALLS TO THE ELIMINATION OF SUCTION IN CLAY

M.D.BOLTON MA MSc PhD MICE CEng
Lecturer in Department of Engineering
University of Cambridge

D.I.STEWART BSc MPhil PhD
Visiting Assistant Professor in Department of Civil Engineering
Oregon State University, Corvallis, USA

The long-term behaviour of nailed walls in overconsolidated clay has been simulated in centrifuge models. Excavation was represented by the drawdown of a heavy fluid from in front of a previously nailed face. Models with different nail lengths and spacings were permitted to approach drained equilibrium. In particular, the effects of swelling and softening following the elimination of negative pore pressures, due to inundation of the clay surface, were monitored.

INTRODUCTION

1. Nailed retaining walls constructed top-down *in-situ* are increasingly being advocated for excavation support, temporary or permanent. Many developments in the U.K. will involve heavily over-consolidated clay deposits. Initial conditions in London clay, for example, will initially be such that $K_o>1$ down to about 20m.

2. The process of excavation will first permit some relaxation of these large lateral stresses, with a consequential drop of pore pressure. Following insertion of the nails, the clay's substantial undrained strength will then be available in nail adhesion to resist any lateral pressures against the facing in the short term. Where the soil shears, further temporary suctions will be generated. Ultimately the soil will drain so as to achieve pore pressure equilibrium, which will depend on long-term hydrological conditions. Designers have had little guidance on the magnitude of possible ground movements in this ultimate phase.

3. This uncertainty will be compounded if the ground water level behind the wall is rising. Ground water levels in many urban areas (notably London, Simpson et al., Ref.1) are rising because of reduced industrial extraction from deep aquifers. Increase in pore water pressures may also be caused by leakage from damaged water mains or sewers (possibly as the result of construction activity). Seepage quantities in such circumstances might be negligible, yet the impact of future swelling pressures might be substantial. Centrifuge model tests were performed to investigate the deformations of nailed walls in stiff clay as pore pressures changed.

CENTRIFUGE MODELLING

4. Transient groundwater flow in a heavily overconsolidated clay deposit can take decades to complete in the field, so it was necessary to observe the behaviour of a 1/n scale model tested on a geotechnical centrifuge at an acceleration n times earth's gravity. All stresses and strains in an equivalent full-scale prototype are then correctly replicated, and the time scales for transient seepage are reduced by a factor of n^2; Schofield (Ref.2).

5. The centrifuge models reported in this paper consisted of a 200 mm thick slab of overconsolidated kaolin clay overlying a porous plastic sheet. When tested at 75g this modelled a 15 m thick layer of clay overlying a porous bedrock. The top surface of the clay was covered with a thin layer of sand to facilitate the supply of water to the top surface. This was then was covered by a thin sheet of latex rubber to reduced evaporation from the model. The preparation of the clay consisted of drained one-dimensional compression to a maximum vertical stress of 1200 kPa then one-dimensional swelling to a vertical stress of 200 kPa. The centrifuge model was then made by removing soil from the excavation, placing the wall facing against the exposed clay face, and inserting the nails through the facing.

6. It was decided not to adopt strict scaling of full-scale nails, but rather to use a smaller number of larger diameter units spaced at larger distances. This facilitated nail gauging, and speeded model building. Similarity could be achieved in terms of two area ratios: nail surface to tributary wall facing surface, and nail cross-section to nail surface. The bending stiffness of the nails was thereby increased, so it was additionally necessary to measure bending strains in an attempt to derive nail shear forces, to check whether dowel action remained small in comparison to tensions. Fig. 1 shows a model nail cross-section, with a steel hypodermic tube strain-gauged at intervals and protected by a plastic sheath.

7. Displacement transducers were placed in front of the wall to measure horizontal wall movement and two rubber bags were placed in the region that represented the excavation: see Fig.2. Before centrifuging, the rubber bags were

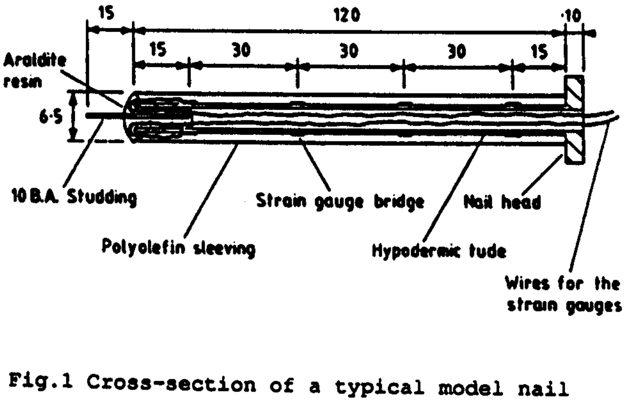

Fig.1 Cross-section of a typical model nail

filled with a dense liquid (zinc chloride solution) mixed to the same density as the clay. The model could then be brought into equilibrium on the centrifuge under its enhanced self-weight in conditions where K_0 was approximately unity. The model was restrained by the sides of the centrifuge strongbox, which were well lubricated so that the model represented a prototype that was very long in comparison with its height.

8. In addition to measuring wall movement, displacement transducers were used to measure the settlement. Black markers were placed on the cross-section, to be photographed through the perspex during the tests, so that internal displacements could be estimated. Miniature pore pressure transducers were inserted into the clay, and one column of nails was strain gauged to measure tension. Fig. 3 shows the fluid control system which permitted the independent supply of water at selected pressures to the top and bottom surfaces of the clay in flight.

CENTRIFUGE TESTS

9. Three model nailed retaining walls were tested (SSI02, 03 and 04), all retaining 200 mm (15 m prototype) of heavily overconsolidated kaolin, but restrained by different configuration of nails and subjected to different groundwater conditions.

10. Model SSI02 was restrained by twelve 120 mm long (9 m prototype) 6.5 mm diameter (0.5 m prototype) nails spaced 50 mm (3.8 m prototype) apart on a square grid. This model was supplied with water to both the bottom and the top boundaries from the start of the test. Steady, vertical percolation initially induced negligible pore pressures, as expected. "Excavation" took 160 seconds (approximately 10 days prototype scale), and was accompanied by an appreciable wall movement of 0.9 mm (0.07 m prototype). The model never quite reached equilibrium in the long-term, collapsing 6 hours after excavation (4 years prototype). Measured pore pressures never deviated much from zero, though it must be assumed that collapse eventually occured because the negative pore pressures induced on excavation were brought back towards their steady state of zero. Figure 4(a) shows the rupture planes observed through the perspex window after testing, along with the nail tensions and boundary displacements immediately before wall failure.

11. Model SSI03 was also restrained by twelve nails that were 6.5 mm diameter (0.5 m prototype) spaced 50 mm apart (3.8 m prototype) on a square grid, but in this test the nails were 350 mm long (26.3 m prototype). Initially model SSI03 was only supplied with water at the

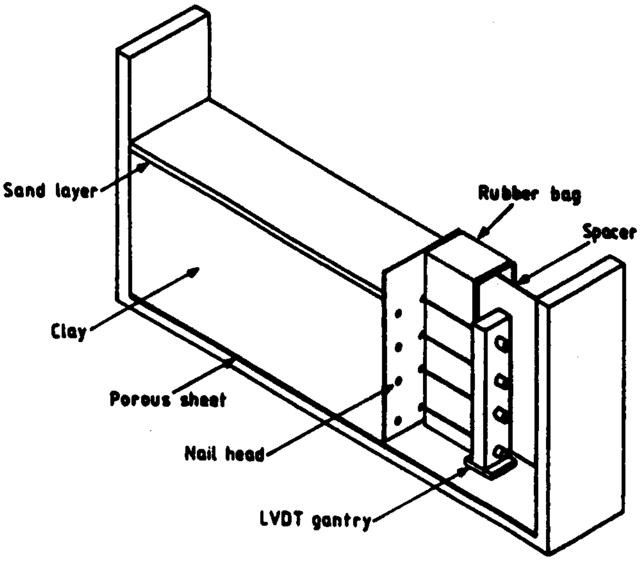

Fig.2 Cut-away view of a centrifuge model

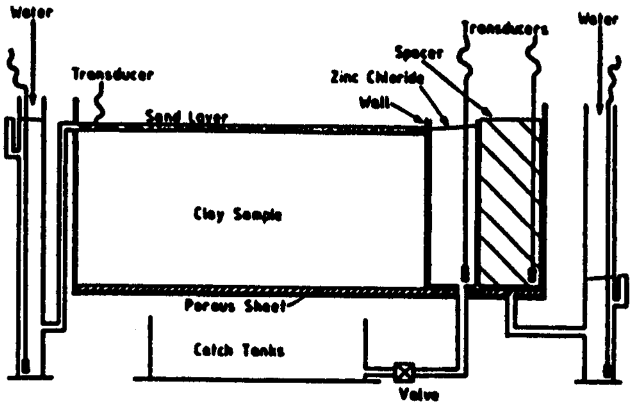

Fig.3 Fluid control system

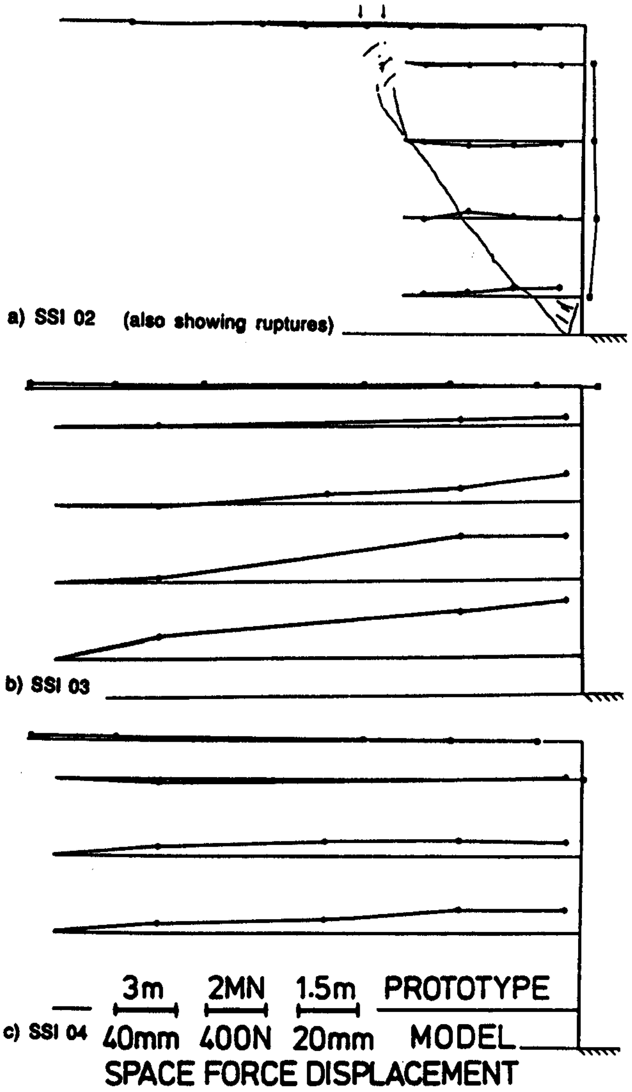

Fig.4 Soil displacements and nail tensions

base of the clay layer and pore water pressures measured in the clay above were increasingly negative, conforming to potential heads slightly below the water table as evaporation caused a small upward flow. Excavation took 314 seconds (approximately 20 days prototype). Immediately upon excavation there was little wall movement; the retained surface settled by approximately 0.3 mm (0.02 m prototype) at a distance of 30 mm (2.2 m prototype) from the wall. Model SSI03 reached a steady state 8.5 hours (5.5 years prototype) after excavation. The retained surface had then settled by 0.4 mm (0.03 m prototype) at a distance of 30 mm (2.2 m prototype) behind the wall. The pore water pressures at this stage were the same as those immediately before excavation. Next, water was supplied to the top surface of the clay. The changes of pore water potentials after 9 hours (5.8 years prototype), when the pore water pressures had reached a steady state, are shown in Fig. 5. These are commensurate with a flow-net for one-dimensional seepage from the top surface to the base of the clay layer, with zero pore pressures throughout. At the top of the clay, therefore, pore pressures had risen by at least 150kPa. The final nail tensions and boundary displacements of model SSI03 are shown in Fig. 4(b). Much larger tensions were mobilized in these much longer nails, compared with the previous model. Although sufficient to prevent collapse, even following the wiping-out of suctions, they were unable to prevent the wall crest displacing about 5 mm outwards (0.375 m prototype) as the clay swelled.

12. Model SSI04 was restrained by the same size nails as model SSI03 but twenty were used on a rectangular grid with a vertical spacing 50 mm (3.8 m prototype) horizontal spacing 30 mm (2.2 m prototype). Like model SSI03, model SSI04 was initially supplied with water only to the base of the clay layer. The pore water potentials in the model, once it had reached a steady state under its enhanced self weight, were close to base of the clay, so that negative pore pressure increased with elevation. Excavation took 216 seconds (approximately 14 days prototype). Immediately upon excavation there was very little wall movement; the retained surface settled by approximately 0.1 mm (0.008 m prototype) at a distance of 30 mm (2.2 m prototype) from the wall. Model SSI04 reached equilibrium 7.5 hours (4.8 years prototype) after excavation. At this stage the retained surface had settled by 0.2 mm (0.015 m prototype) at a distance of 30 mm (2.2 m prototype) from the wall. The steady state pore water pressures remained negative and hydrostatic. At this stage water was supplied to the sand layer on top of the retained clay. A difficulty with the water supply resulted in the top surface of the clay being only partially flooded. A flow-net for this condition was deduced from the pore pressure measurements as shown in Fig.6. The increasing pore water pressures resulted in clay swelling, with the retained surface heaving and the nail tensions increasing, but this was accompanied by very little wall movement. The final nail tensions and boundary displacements of model SSI04 are shown in figure 4(c). It will be appreciated that this model had both a greater proportion of nails, and smaller pore water pressures close to the face, than did SSI03. These two effects are responsible for the smaller nail tensions, and much smaller wall movements.

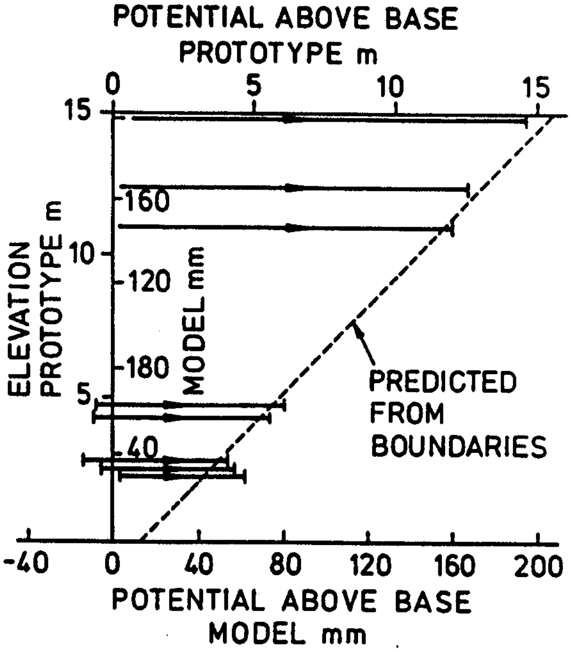

Fig.5 Increases in potential heads due to inundation of model SSI 03

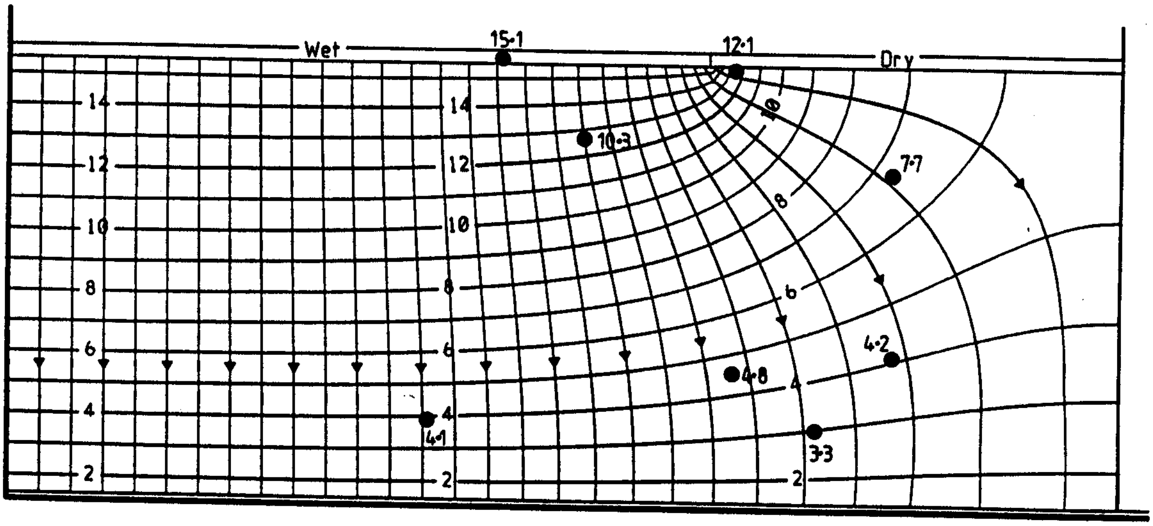

Fig.6 Ultimate flownet following inundation of model SSI04: potentials in m prototype

LIMIT EQUILIBRIUM ANALYSES

13. These tests were analysed by the limit equilibrium method. Two mechanisms were considered, a single slip plane passing through the base of the wall, and a trapezium driven by an active wedge: Fig.7. Gassler and Gudehus (Ref.3) found that the second type of mechanism was usually critical.

14. The nail pull-out capacity was calculated by summing the skin friction on that part of the nail surface projecting beyond the slip lines (Stewart, Ref.4). In undrained analyses the shear stress was taken to be $\tau=\alpha.c_u$ with $\alpha=0.5$ for the heavily overconsolidated clay, and in drained analyses $\tau=\sigma_v'\tan\delta$. The angle δ was measured in a direct shear apparatus to be 15°.

15. An undrained analysis of model SSI02 confirmed that this wall should have been stable upon excavation. An effective stress analysis then indicated that the model had grossly insufficient strength for long-term stability in the absence of suction. An angle of soil shearing resistance of 60° should have been required whereas the critical state angle, for example, was $\phi_{crit}=22°$. This does not exactly match with the model, which collapsed 6 hours (4 years prototype scale) after excavation, having apparently reached a long-term steady-state in the absence of suction, and having apparently mobilized the expected pull-out resistance of the lower 2 levels of nails. One possible explanation for the discrepancy is that excess suction due to shearing was assisting sliding stability in the dilatant soil, and that this local effect failed to register on well-spaced pore pressure transducers. Another is that dowel shearing was significant in a small region local to the slip surface, and could not be registered on occasional bending moment gauges.

16. A drained limit equilibrium analysis of model SSI03 indicated that this model did have sufficient strength for stability when the pore water pressures had reached a steady state under downward seepage with the very small pore pressures shown in Fig. 5. The critical slip surfaces would have had to mobilize an angle of shearing of 15.5°. This is not inconsistent with the observed behaviour of this model; the wall was stable at the end of testing but the clay swelling associated with flooding the top boundary caused a significant wall movement. When swelling is taking place at zero lateral strain, earth pressure coefficients will tend towards passive values, so that values of the order of 0.67, as here, are attainable only after some lateral relaxation.

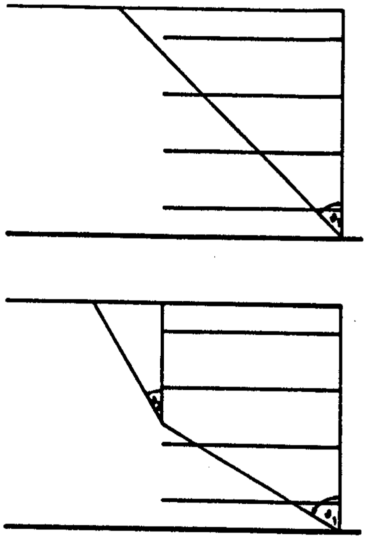

Fig.7 Failure mechanisms:
(Gassler & Gudehus, 1981)

17. The lack of wall movement in centrifuge test SSI04 was associated with a limit equilibrium analysis showing $\phi_{mob}=11°$, but the perseverance of suction near the wall was thought to be much more significant in this case than the reduced soil strength demanded by the more highly reinforced model. If the soil is remote from failure, its strains - and consequential structural displacements - are a function of its effective stress *changes* (here, due to the partial elimination of suction) rather than to the final values alone. No "factor of safety" against failure, however it is defined, can provide an accurate serviceability criterion.

CONCLUSIONS

18. Three centrifuge tests are insufficient to permit definite advice to be formulated. Certain observations can, however, be made.

i) A two-block failure mechanism was observed in model SSI02 in heavily overconsolidated clay. Limit equilibrium analyses based on undrained adhesion correctly indicated that the wall should have been stable prior to the clay softening. Simple drained analyses showed that the elimination of suction by downward seepage should have led to the early destruction of the wall. Its stability for a substantial period suggests that the pull-out strength of the nails was supplemented in some way. More intensive instrumentation would be necessary to determine the source of this extra strength.

ii) Deformations of nailed walls which are safe, even according to a possibly conservative limit equilibrium calculation, are not related simply to the "factor of safety". In these models which were investigated for swelling effects, the precise changes of suction were very significant. If the deformations of nailed or reinforced clays are to be predicted in the long term, it will be necessary to investigate swelling stress-strain paths. Serviceability failures, due either to swelling pressures damaging the facing of a highly reinforced mass, or to significant vertical or horizontal soil displacements, will have to be prevented.

REFERENCES

1. SIMPSON B., BLOWER T., CRAIG R.N. and CROFT D.D. The engineering implications of rising groundwater levels in the deep aquifer beneath London. CIRIA special publication 69, 1989.
2. SCHOFIELD A.N. Rankine Lecture - Cambridge geotechnical centrifuge operations. Geotechnique 1980, Vol. 30, No. 3, p.225-268.
3. GASSLER G. and GUDEHUS G. Soil nailing - some aspects of a new technique. Proc. 10th Int. Conf. on Soil Mechanics and Foundation Engineering, Stockholm, 1981, Vol.3, p.665-670.
4. STEWART D.I. Groundwater effects on in-situ walls in stiff clay. PhD Dissertation, Cambridge University, 1990.

ACKNOWLEDGEMENT

This work formed part of a research contract placed by TRRL with the senior author, and supporting the junior author. The views expressed are those of the authors, and are not necessarily those of the TRRL or the Department of Transport.