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Model testing to evaluate the performance of soil nailed structures

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ABSTRACT: Soil nailing was introduced in the United Kingdom in the mid 1980's. In situ strengthening of the ground has proved to be cost effective and applicable to stabilise new and existing embankments and slope cuttings, and strengthen existing retaining walls. At first the take up of the use of soil nailing in the UK was hindered by a lack of both a fundamental understanding of the behaviour of soil nailed systems and comprehensive design guidance. The publication of HA68/94 and BS 8006:1995 has led to a steady increase in utilisation since the early 1990's. Nevertheless, there remains a concern that these guidelines are not fully comprehensive for UK construction conditions and practice. To address this issue a study of mechanisms associates with soil nailed systems has been conducted that was centred on a number of series of centrifuge model tests. The major findings of these studies are presented.

1 INTRODUCTION

In recent decades soil nailing has become increasingly more popular worldwide as a technique for reinforcing soil to form retaining structures in cut and to create, steepen or strengthen existing slopes. However, as has been reported in the best practice guide for soil nailing recently published in the UK by CIRIA (2004), in the UK soil nailing has been adopted more slowly as a construction technique than elsewhere in the world; particularly in other comparable European markets (i.e. France and Germany) and in the USA. Statistics assembled during the writing of the CIRIA guide, Figure 1, indicate that. Although soil nailing was first used in the UK in the mid 1980s, the face area of soil nailing installed in the UK did not start to increase significantly until the latter half of the 1990s. The slow acceptance of the technique in the UK prior to this date is partly attributable to a debate amongst British academics and practitioners about the mechanisms of soil nail/soil interaction and concerns about the potential corrosion of steel nails, but more probably resulted from a lack of UK guidance until the publication of the design manual for the reinforcement of highways slopes, HA68/94, in 1994 and the British Standard for reinforced soil BS8006, in 1995. In contrast, major national research projects conducted in France and Germany – the Clouterre (1991) and Bodenvernagelun (Gassler & Gudehus 1981) projects, respectively – and, later, in the USA, FHWA (1996), provided designers with not only design guidelines but also confidence in the technique of soil nailing resulting from the experience obtained from well instrumented case histories.

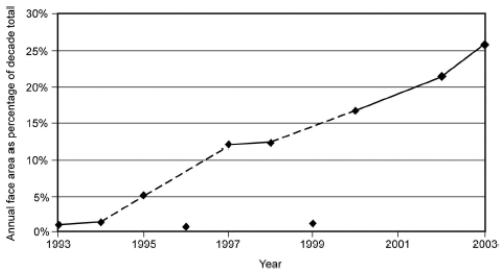

Figure 1. Growth of the UK soil nailing market in the decade up to 2003 (after CIRIA 2004).

As with other reinforcement techniques for retaining structures and slopes, the major components of soil nailed structures can have a number of different forms. Although most commonly formed from steel, soil nails can be made out of different materials (e.g. polymers), and they may be in direct contact with the soil or be surrounded by an annulus of grout. To prevent corrosion the surface of the nail might be treated with an epoxy or by galvanising, and there might be secondary protection in the form of plastic tubes (typically PVC or HDPE) surrounding the nail. Whilst the vast majority of nails are installed by being grouted into predrilled holes, different methods for placing nails exist; including self-drilled and driven installation techniques. The component of a soil nailed retaining structure that is most visible is the facing and these may be categorised into three major types: soft facings, flexible structural facings and hard structural facings. The materials used for these range from geofabrics to sprayed concrete reinforced with steel mesh

depending on the requirement of the facing and the amount of facing deformation that can be permitted.

Although the technique of soil nailing is becoming more widely applied internationally there still remain aspects of the technique that are not fully defined and this lack of understanding has resulted in a number of both serviceability and ultimate limit state failures of soil nailed structures. In the survey of problems with soil nailing construction in the UK (CIRIA 2006) failure were attributed to two major causes. The first was construction details (such as inadequate control of construction operations) and the second to a lack of understanding of mechanisms – this included poor facing design (particularly flexible facings) and a lack of appreciation of the interrelationship between nail spacing and type of facing.

Whilst problems associated with construction details can be eliminated with tighter control of construction operations, improved understating of the mechanisms requires a systematic study of soil nailed structures. However, since such tests are expensive to conduct at prototype (i.e. full) scale, this has restricted the scope of such investigations. Monitoring of in-service structures may also be conducted but, clearly, it is not possible to investigate the performance of such structures under failure conditions, However, it is possible to gain a greater understanding into the mechanisms of soil nailed systems in carefully controlled, correctly scaled model tests which can be achieved using the technique of geotechnical centrifuge modelling. This paper describes results from a number of studies conducted by the author and his research students to gain a greater understanding of a number of the key mechanisms of soil nailed systems. These include the development of global deformations and stresses induced in the inclusions – both during construction of soil nailed structures and during subsequent loading of the structure – and the influence of geometric parameters (e.g. slope angle, nail orientation and nail spacing) on these. The paper also considers the effects on nail forces and global deformations of changing the effective stress in the retained soil.

In addition, this purpose of this paper is to illustrate more generally, using the example of soil nailing, how the technique of geotechnical centrifuge modelling may be used to systematically investigate mechanisms in a range of ground reinforcement applications (such as goesynthetic reinforced slopes, e.g. Zornberg et al 1998, Zornberg & Arriaga 2003).

2 GEOTECHNICAL CENTRIFUGE MODELLING

2.1 *Centrifuge scaling laws*

The stress/strain behaviour of granular soils is highly non-linear, stress level dependent and stress history dependent. Accurate scale modelling therefore requires both similitude between material properties in the prototype (i.e. the full scale structure) and the model and the correct stress distribution within the model. If a model is constructed at 1/N scale using soil from the prototype (i.e. providing similitude in soil properties), and accelerated in a centrifuge so that the model experiences an acceleration N times Earth's gravity, stress similitude in model and prototype may be demonstrated (e.g. Taylor 1995) as follows:

Table 1. Scaling factors for centrifuge modelling.

Quantity	Full scale	Model scale
Linear Dimension	1	1/N
Stress	1	1
Strain	1	1
Density	1	1
Force	1	$1/N^2$

Prototype:

$$\sigma_p = h.\rho.g \quad (1)$$

Model:

$$\sigma_m = (h/N).\rho.(N.g) \quad = h.\rho.g \quad (2)$$

Therefore:

$$\sigma_p = \sigma_m \quad (3)$$

where σ_p and σ_m are self-weight stress in the prototype and model respectively, h is depth below the surface and g the gravitational field.

It can, similarly, be shown that the scaling law for force in a centrifuge model (such as the axial force in a soil nail) is given by

$$F_m = F_p/N^2 \quad (4)$$

A summary of centrifuge scaling laws appropriate to modelling soil nailed structures is given in Table 1.

2.2 *Experimental procedure*

2.2.1 *Centrifuge model*

The results presented in this paper were obtained from studies conducted at the Geotechnical Centrifuge centres at Cardiff University (Gammage 1997, Aminfar 1998) and the University of Dundee (Morgan 2002), Figure 2. The two machines have similar platform dimensions, with both able to accommodate a model package of up to 1 m × 0.8 m × 1.0 m; permitting relatively large models to be tested. This is an important factor in the study of reinforced soils where accurate modelling of the inclusions is required. The model scale selected for the experiments described herein was 1:20 (i.e. at an elevated gravity 20.g). This permitted

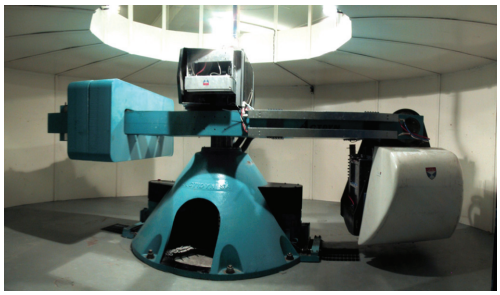

Figure 2. The University of Dundee geotechnical centrifuge.

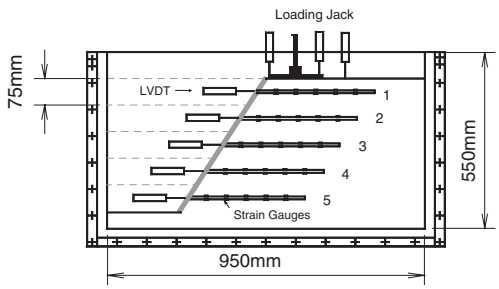

Figure 3. Centrifuge model – geometry and instrumentation (surcharge loading tests).

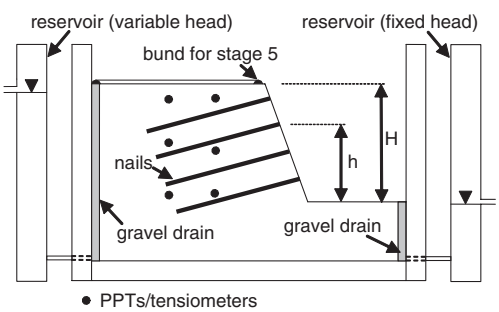

Figure 4. Centrifuge model – geometry and instrumentation (effective stress change tests).

prototype soil nail slopes and walls of up to 7.5 m high, and varying in slope angle between 45° and 90° to the horizontal, to be modelled whilst allowing dimensions and spacing of model nails to correctly replicate prototype conditions.

Each test consisted of two major phases. The nailed slope (or wall) was constructed in the first phase and then loading was applied in the second. During both stages instrumentation was monitored to provide information about the development of slope displacements and forces in the nails. The typical configuration of the models is shown in Figures 3 and 4. The models represent two different ways in which a soil nailed

Figure 5. Centrifuge model in strong box.

slope or wall was loaded following its construction. Figure 3 shows a model with loading in the form of a surcharge at the top of the slope (e.g. to represent construction at the top of the slope), whilst the loading in the model represented by Figure 4 was achieved by reducing the effective stress in the soil, by permitting water to flow through the slope. Figure 5 shows the photograph of a centrifuge strong box containing a model soil nailed slope with a flexible facing following an experiment (i.e. the "model package").

The soil used for the models was a fine sand, $D_{50} = 0.18$ mm, $c' = 0$ and $\phi' = 41.2°$. This was placed in the centrifuge strong box by pluviation to form a specimen with a uniform density typically of $\gamma = 17$ kN/m3. The front and rear faces of the strong boxes were fabricated from thick Perspex to permit observation of the model during testing.

2.2.2 *Soil nails*

It is experimentally very difficult to construct and reliably instrument a model nail which is an exact replica of the prototype. The nails to be modelled were 6.0 m long, 20 mm diameter steel bars grouted into a 160 mm diameter bore hole. This was replicated using an 8 mm diameter, 300 mm long acrylic bar designed to model the axial stiffness of the prototype nail (Gammage 1997, Morgan 2002). The model nails were coated with sand to replicate the soil/nail interface properties. The nails were instrumented with strain gauges on their upper and lower faces at five locations spaced at 50 mm intervals. These enabled both axial and bending strains to be measured; from which the axial force and bending moment distribution along the nail could be obtained.

2.2.3 *Facing*

A facing is required to prevent local failure occurring between reinforcements. To allow comparison between suites of experiments, the majority of the centrifuge models reported in this paper were constructed using a facing formed from a woven geofabric. The fabric used for the tests was typically a HF550 geotextile, manufactured by Don & Low. This has a tensile

strength of 25 kN/m and 16 kN/m in the warp and weft directions, respectively. As in a prototype structure, the geotextile was held in place by the nail heads, to form a flexible facing.

2.2.4 *Simulation of construction*

When constructing a soil nailed retaining structure the normal procedure is first to excavate a bench and then install the nail before, finally, applying the facing (although in situations where the unsupported face will not hold for a sufficient period to permit nail installation the second and third stages are sometimes reversed). It is not practically possible to simulate the soil nailing process exactly in a centrifuge model. However, in order both to investigate the construction process and to ensure that the construction displacements are equivalent to field conditions, two techniques have been used successfully by the author to achieve this. The first is to build a slope with the nails and facing in place on the laboratory floor and then place a flexible bag containing a solution of Zinc Chloride in the volume to be excavated. This is a technique that has been used by both for simulating excavation for soil nailing (e.g. Bolton & Stewart 1990, Jones & Davies 2000) and in other centrifuge model applications (e.g. Powrie & Daly 2002). If the Zinc Chloride solution is mixed to the same mass density as the soil, then this results in a lateral earth pressure coefficient, K_0, of approximately unity. Excavation may be simulated during centrifuge operation by draining the Zinc Chloride solution from the bag, halting to simulate the different stages of construction as required. In the second technique the model is also prepared on the laboratory floor with both nails and facing in location but in this case the same soil as that forming the slope is placed – at the same density and using the same placement technique – in the volume in front of the slope. Construction is then modelled in stages in a number of sequential centrifuge runs. Each stage of construction is achieved by excavating a layer of soil whist the centrifuge is stationary and then accelerating the model in the centrifuge to replicate the self weight loading of the reinforced soil system.

3 EXPERIMENTAL FINDINGS

3.1 *Mechanisms during construction*

3.1.1 *Development of displacements*

Figure 6 shows the displacement profile of the face of a model slope that developed during the sequential centrifuge runs of the construction phase in one of the experiments. In this experiment the prototype slope modelled was 7.5 m high with a slope angle of 60°. The wall was constructed in five lifts using 6 m long grouted soil nails inserted at vertical and horizontal spacing of $S_v = 1.5$ m and $S_h = 2.33$ m, respectively,

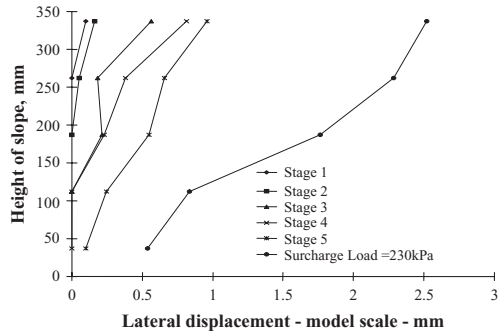

Figure 6. Development of lateral displacements (model scale).

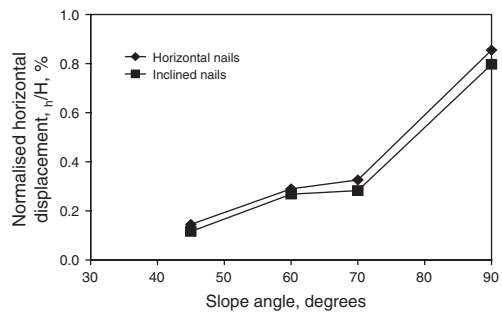

Figure 7. Variation in horizontal displacement at top of slope with slope angle.

at an angle of inclination of 15°. The figure indicates that there was a gradual development of lateral movement of the slope as excavation proceeded. The pattern of generally decreasing lateral displacement with depth conforms to observations of full scale soil nailed slopes. The maximum horizontal displacement of 0.95 mm is 0.25% of the slope height (i.e. 19 mm at prototype scale). Vertical deflections at the crest of the slope were of very similar magnitude. The displacement profile when a surcharge of 230 kPa was applied is also plotted in Figure 7. The figure shows that the front face of the wall bulged and the maximum lateral displacement was 2.50 mm; which corresponded to 0.67% of the slope height (i.e. 50 mm at prototype scale). In both phases of the tests the measured behaviour was in very good quantitative agreement with the results of the limited quantity of field measurements e.g. Gassler & Gudehus (1981), Clouterre (1991), Pedley & Pugh (1992) and Lazarte et al (2003).

The influence of both slope angle and nail inclination on horizontal displacement during the construction phase was investigated by conducting experiments on identical models in which these two variables were changed systematically. As can be seen from Figure 7, the maximum displacement at the top of the wall was reduced when the nail was inclined; but the reduction

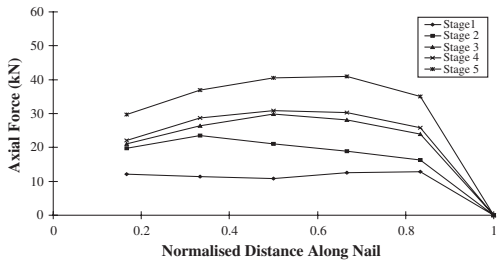

Figure 8. Axial forces in nail 2 during construction.

in displacement was relatively minor in all cases. The results do, however, indicate very markedly that, as would be expected, the measured lateral displacement of the soil nailed system increases as the slope angle is increased. This figure indicates that there appears to be a transition in behaviour at slope angles between 70° and the vertical as the soil nailed retaining systems moves from a reinforced slope to a reinforced soil retaining wall.

3.2 *Development of nail forces*

Results are presented in Figure 8 for axial force development in the nail located at level 2 i.e. the nail installed in the second stage (see Figure 2). As indicated above, the technique adopted for building the model resulted in the nails being located in the soil during model preparation. This permitted measurements of strain development in the nails to be monitored prior to the head of the nail being exposed by excavation. During this stage the nails showed a development of tensile force; which is attributed to the reduction in lateral stress in the soil beneath the excavation. At the second excavation stage, when nail 2 was exposed and began to act as a reinforcing element in the slope, it can be seen that the maximum axial force developed at a normalised distance of approximately 0.3 (1.8 m) from the face. As construction proceeded the location of maximum force migrated to 0.6 (3.6 m) from the face; indicating that the location of the potential failure surface moved, as would be expected, deeper into the slope. This observation agrees with the findings of centrifuge experiments of soil wall construction conducted by other workers e.g. Tei (1993).

The stress distribution in all the nails in the 60° slope may be observed by plotting the maximum axial force in each nail, T_{max}, (normalised by the tensile capacity of the prototype nail, T_p) against normalised height. The plot in Figure 9 shows that following construction the maximum stress recorded in the three nails located in the mid height of the slope were approximately 20% greater than that in the top and bottom nails. Lines representing the normalised active (K_a) and at rest (K_0) lateral earth pressure distributions are also plotted on Figure 9.

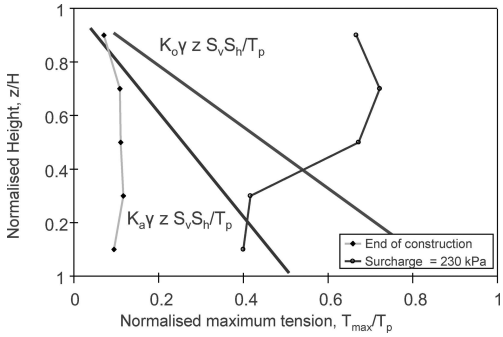

Figure 9. Normalised maximum axial force in nails following construction and surcharge of 320 kPa – 60° slope.

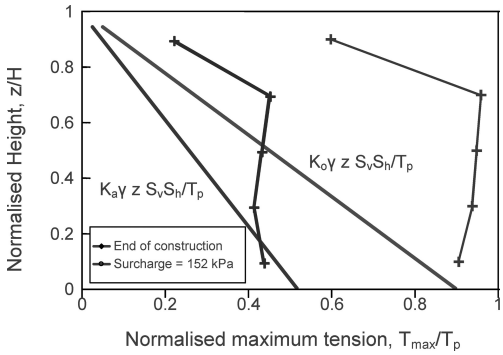

Figure 10. Normalised maximum axial force in nails following construction and surcharge of 152 kPa – vertical face wall.

Comparison of the maximum force distribution in the nails with these lines indicates that with the exception of the top nail the force carried by the nails is lower than would be required to maintain active conditions. In order to examine the influence of changing the angle of the slope on the distribution of maximum axial force in the nails, the normalised axial forces, T_{max}/T_p, recorded following construction of a vertical soil nail wall is shown in Figure 10.

Comparison of the distributions at the end of construction in this figure with that in Figure 9 indicates that the forces monitored in the wall were, as would be expected, significantly greater than those in the 60° slope. It is interesting to note that, with the exception of the top nail, the distribution of maximum force with depth is very linear. However, unlike the slope, the forces in all except one of the nails were greater that required to maintain active conditions. At the top of the wall the nails indicate axial forces above the K_0 distribution line. This implies that the nails are not acting to resist active earth pressures – in a mechanism analogous to that used for the coherent gravity method of analysis used in the design of reinforced earth – but

are involved in a more complex slip mechanism that is analogous to that used in the tie back method of reinforced soil design. This observation supports methods of analysis based on both wedges and slip circles that are widely used for the design of soil nailed systems, e.g. BS 8006 (1995). Estimates of the pullout capacity of the nails indicated that the top nail was very close to, or had reached, its maximum capacity and this explains why it contributed less to stabilising the wall than each of the other four nails.

3.3 *Mechanisms during loading*

3.3.1 *Surcharge loading of slopes and walls*

On the completion of construction a 150 mm wide rigid footing (the full width of the model), representing a 3.0 m wide strip load (this might represent, for example, the footing for a bridge abutment), was placed at the top of the slope; set back from the crest of the slope by 25 mm, Figure 2. Force was applied to the footing, via a 20 kN load cell, using displacement control.

The development of maximum axial force in each nail following application of a surcharge load may be investigated by comparing the distribution of axial force at the end of construction with that when a surcharge has been applied. For the case of the 60° slope the maximum axial forces in each nail when a surcharge of 230 kPa was applied to the top of the slope are plotted on Figure 9. During loading the maximum force was recorded in nail 2. This reflects a non-uniform distribution of shear stress along the potential shear plane; which was highest near the surface, where the load intensity due to the surcharge loading was at its greatest. Despite the very high surcharge loading the peak stress in all of the nails was significantly less than the tensile capacity of these nails, T_p. As has been described above, the surcharge loading resulted in the top of slope displacing horizontally by a prototype distance of 30 mm during this phase of the experiment.

Similarly, the maximum axial forces in each nail in the soil nailed wall following surcharging are plotted in Figure 10. In this case the test was stopped when the surcharge was 152 kPa. The test was stopped at this point because, as can be seen from Figure 10, a number of the nails were very close to rupture and therefore the wall was near to failure. Although the upper nail was at (or very close to) pullout following construction of the slope, application of the surcharge increased its pullout capacity allowing the nail to carry greater axial forces.

For the prototype slope and wall modelled in the experiments it would generally be expected that in the absence of a surcharge load the failure of nails by pull out would be more critical than by tendon rupture. A prediction of the factor of safety of the 60° slope at this end of the test was conduced using a circular slip analysis that incorporated the contribution of nails based on that proposed in BS8006 (1995) (Gammage 1997). The minimum calculated factor of safety was 1.6. A comparison of the predicted nail capacities with the peak measured axial forces is shown in Table 1. Although the predicted sum of the nail forces at the minimum factor of safety is very similar to measured value the distribution of forces in the nails was not predicted particularly accurately. The capacity of the top nail was greatly under predicted because the method of slices used in the analysis did not account for load spreading from the footing which increased the pull out capacity of the nail in the model. This indicates that the influence of surcharge has to be included when assessing the pull out capacity of a nail.

3.3.2 *Loading by changing the effective stress in the slope*

One of the applications of soil nailing is to stabilise slopes that are showing signs of impending failure or to strengthen slopes that have a calculated factor of safety that is considered to be too low. These conditions may be caused a variety of factors, including dissipation of negative excess pore water pressures generated during excavation and changes in hydrological conditions, e.g. Vaughan & Walbanche (1973). In addition to its application in stabilising existing slopes, soil nailing is also being used increasingly for the construction of new cuttings. Such new soil nailed slopes may also be subjected to changes in effective stress following construction – such as from increased rainfall intensity as a result of climate change, Hadley Centre (1998). There is a requirement, therefore, to establish the response of soil nailed systems to variations in effective stress in order to assess the long term serviceability of both existing slopes strengthened using soil nails and newly excavated soil nailed retaining structures. A study to investigate the mechanism resulting from variation in the effective stress of the soil forming a soil nailed slope has been reported by Davies & Morgan (2005) and the major findings reported in this paper are reproduced here.

The construction phase in these tests followed the same procedures as that described above for the surface loading tests. On completion of construction, the long term serviceability experiments were conducted by changing the drainage boundary conditions of the centrifuge models to examine the effects of both the increase and the cycling of pore water pressure in the slope. During and immediately following construction the water table was maintained at the level of the toe of the slope – stage 1. To reduce the effective stress in the model, in stages 2 and 4 of the test, the water level was raised in the gravel drain to the elevation of the top of the slope. In stage 3 the water level was returned to the same elevation as in stage 1. Finally, in stage 5 the model was subjected to a rise in ground water level combined with inundation from the top surface, achieved by forming a 1 cm high bund at the crown of the slope to impound water introduced to the

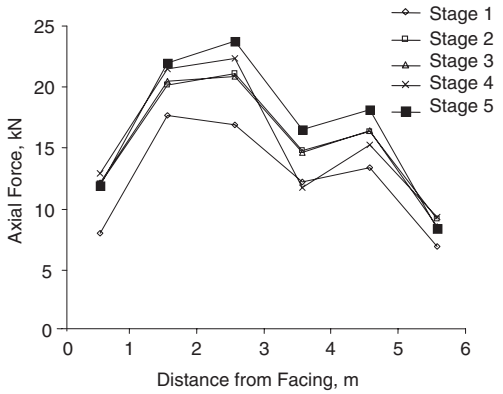

Figure 11. Axial forces along nail at elevation 0.375 at the end of each experimental stage.

top of the slope (Fig. 3). Stages 1 to 5 were applied to all the models except one in which an extra cycle of water table fall and rise was applied (i.e. repeat of stages 3 and 4). This phase of the experiment was completed without stopping the centrifuge.

3.3.2.1 Nail forces

Typical variation in axial force distribution along a nail during the experiments is shown in Figure 11. Immediately after construction (stage 1) the peak axial force in the nail is 17.65 kN, representing 19% of the predicted pullout capacity of the length of the nail located in the resistive zone of the slope. With the rise in water table in the upslope gravel drain in the model in stage 2 of the experiment, resulting in a reduction in effective stress in the slope, the force in the nail rose by 19%. However, on lowering of the water table to its original level – stage 3 – there was hardly any change in the force distribution in the nail, implying negligible rebound or settlement of the soil in response to the increase in effective stress re-loading of the soil.

Repeating the rise in water table (stage 4) resulted in extra forces being generated in the nail – the maximum change during this stage being 7% of the original loading. Finally, inundation from the top surface of the slope resulted in a further decrease in effective stresses resulting in additional forces (8%) being taken by the nail. The change in peak axial force, T, in each of the four nails reinforcing a 60° slope during an experiment are shown in Figure 12, from which it can be seen that all the nails in the slope were subjected to significant increases in axial load when water was permitted to flow through the slope.

The development of axial load in two nails in a 50° slope that was subjected to three cycles of effective stress reduction and increase, shown in Figure 13, indicates an increase in axial force with number of cycles. In common with all the other tests in the programme of experiments, the largest percentage change

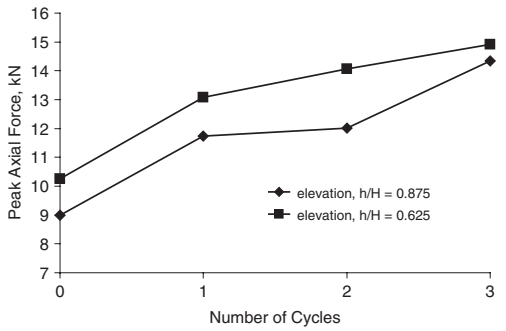

Figure 12. Peak axial forces (T) at each experimental stage (60° slope).

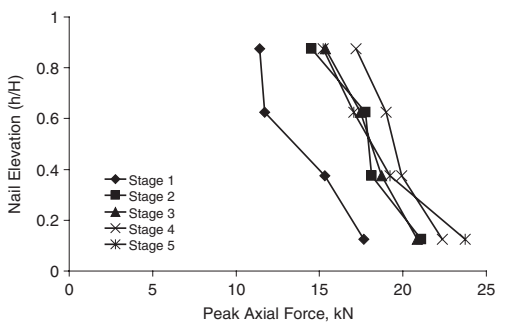

Figure 13. Peak axial forces in nails following cycles of water table rise in model (50° slope).

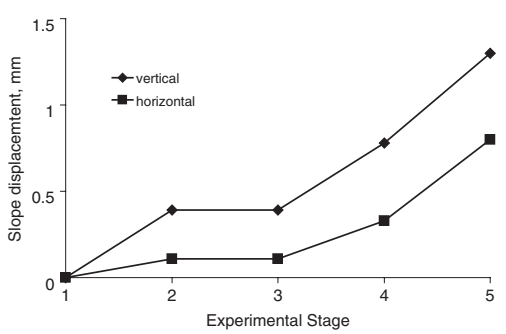

Figure 14. Vertical displacements at the top of the slope (0.7 m from the slope crest) and horizontal displacements measured adjacent to the head of a nail at a elevation of 0.625 (60° slope).

(i.e. increase) in axial force was induced during the first decrease in effective stress. Subsequent effective stress cycles increased the axial force in the nails.

3.3.2.2 Slope displacements

Examples of surface displacements measured on a 60° slope developed following stage 1 of an experiment are shown in Figure 14. Both sets of data show the

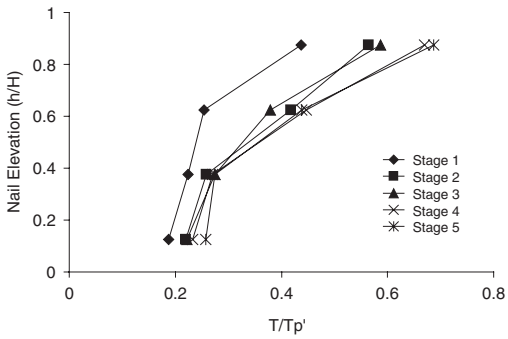

Figure 15. Comparison of measured peak axial forces (T) to theoretical pullout values (Tp').

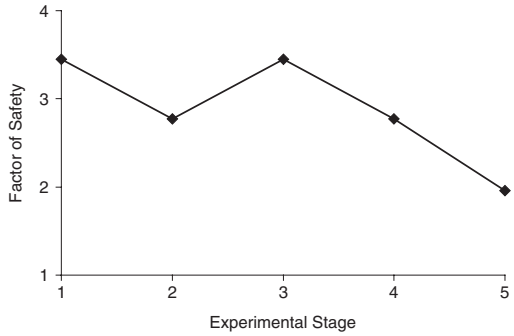

Figure 16. Predicted factor of safety (M_R/M_O) at each experimental stage (60° slope).

same trends. As can be seen in Figure 14, the slope displaced following the reduction of effective stress during stages 2, 4 and 5 of the experiment, but showed negligible displacement during the lowering of the phreatic surface in stage 3 – indicating a stiff response on re-loading. Since soil nails are passive inclusions, in order for forces to develop they have to be subjected to soil displacements and these measurements explain the sequence of axial force change in the nails presented above, i.e. when there are negligible displacements in the soil there is, similarly, negligible development of axial force in the nails. It is well established that cyclic shear loading of soils can result in the accumulation of deformation which can lead to serviceability limit state failure, such as in pavements, e.g. O'Reilly & Brown (1991). The results of the experiments indicated that there is the possibility that cyclic loading of soil nailed systems could lead to serviceability failure; however, this would depend on the number and amplitude of the cycles together with the geometry of and soil type forming the slope.

3.3.2.3 Nail pullout capacity

Since pore water pressures were measured in the experiments it is possible to assess the influence of change in effective stresses in the model on the pullout capacity of the nails. This may be achieved by comparing the measured maximum axial force in a nail, T, with the predicted pullout capacity of the length of nail located in the resistive zone of the slope, Tp'. Values of Tp' were calculated using values of pore water pressure interpolated from the spot values measured at the appropriate stage in the experiments. Values of T/Tp' for the four nails in the 60° slope at each stage of a test are shown in Figure 15, from which it may be seen that T/Tp' increased at all levels in the experiment during stages 2, 4 and 5. Figure 15 indicates that the ratio increased at all levels with each decrease in effective stress and that the axial force in the nail in the row nearest the top of the slope was approaching its pullout capacity.

3.3.3 *Stability analysis*

The effect of excess pore water pressure on the predicted stability of the model slopes was assessed in a limit equilibrium analysis, using a method of slices in which the critical slip surface was a log spiral. Pore pressures, measured at each stage of the experiments using miniature pore water pressure transducers, were applied at the base of the slices and the calculation was carried out to determine the out of balance moment, M_O. The resisting moment, M_R, was determined from the tension in the nails. The factor of safety is defined as M_R/M_O. The predicted factor of safety for the 60° slope is plotted for each experimental stage in Figure 16 from which it can be seen that, as should be expected, increase of pore water pressure in the slope leads to a reduction in the factor of safety; in this case by stage 5 the predicted factor of safety has almost halved. This analysis demonstrates the requirement to take into account in the design of soil nailed systems possible variations in pore water pressure within a slope, as monotonically increasing or cyclically changing pore water pressures might result in excessive deformations leading to serviceability failure.

3.4 *Nail spacing*

The effects of both nail spacing and facing stiffness on mechanisms associated with both walls and slopes is being investigated in the latest phase of the study. Aspects being investigated include both the forces developed in the soils nails and the stresses acting on the facing. The experimental procedure in these tests is the same as used for the investigation of the change in effective stress in the slopes, the only significant difference is that these slopes were built with four rows of nails as opposed to five in the experiments reported above. Tests were conduced on both walls and slopes with vertical nail spacing, S_v, of 1.5 m and with three horizontal spacings, S_h, of 1.4 m, 2.0 m and 3.4 m.

Figure 17 shows the measured maximum axial force measured in nails in a 70° slope for three horizontal

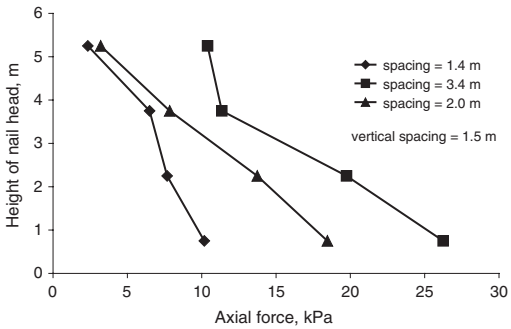

Figure 17. Distribution of maximum axial forces in nails at different horizontal spacings, S_h, (70° slope).

Table 2. Measured axial forces in nails at different horizontal spacings, S_h, (70° slope).

Height of nail head, m	Maximum axial force in nail, T_{max}, kN		
	$S_h = 1.4$ m	$S_h = 2$ m	$S_h = 3.4$ m
5.25	2.4	3.3	10.5
3.75	6.6	7.9	11.4
2.25	7.8	13.8	19.8
0.75	10.3	18.5	26.3
ΣT_{max}	27.0	43.5	68.0
T_{max}/S_h, kN/m	19.3	21.8	20.0

spacings following both construction and loading to stage 4 (i.e. water table is at the highest level within the slope). Although the configuration for this model is very similar to that for the other experiments presented herein, the facing was manufactured from horizontal strips of 2 mm thick aluminium. It can be seen that, as would be expected, the nails with the wider spacing carry higher axial load. The values of the maximum recorded axial forces are presented in Table 2 from which it can be seen that the sum of the nail forces in each of the models is almost identical. This result indicates that in the range of nail spacing investigated – which was typical of prototype conditions – there is no measurable interaction between the nails that might result in group action.

Miniature load cells attached to the rear of the facing permitted total stresses to be measured at different stages of the exponents. These are plotted in Figure 18 for two stages in each test, viz. immediately after construction ("excavate") and at loading stage 4 ("test"). These results show that immediately after construction of the walls with the two smaller spacings (1.4 m and 2.0 m) the stresses measured immediately behind the facing was very near to the active earth pressure; as indicated by the K_0 line which is also included on the diagram. However for the spacing of 3.4 m, the stresses are significantly higher that K_0 values. In all

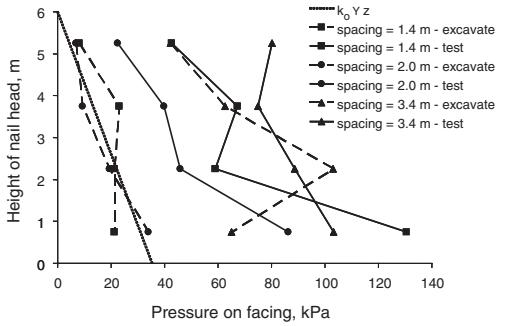

Figure 18. Distribution of measured pressure on facing at the end of construction and following reduction of effective stress for with different horizontal spacing of nails, S_h, (70° slope).

cases, Figure 18 shows that decreasing the effective stress in the slope results in an increase in the stress acting on the back of the facing to values above K_0.

4 CONCLUSIONS

The technique of soil nailing is now become established internationally as a technique for constructing earth retaining structures and for strengthening and steeping slopes. However, since the significant national studies conducted in the 1980s and 1990s there have been few opportunities for significant symmetric studies of the technique despite there remaining a number of unanswered questions about the mechanisms associated with aspects of the technique.

The technique of geotechnical centrifuge modelling allows studies of the mechanisms associated with nailed systems in experiments in which the major features of the prototype soil nailed systems are modelled correctly. The results of series of tests to investigate the performance of soil nailed systems during both construction and when subjected to different forms of load yielded the following conclusions:

1. The technique adopted for constructing the slope in a series of sequential centrifuge runs permitted the development of displacements of the slope and forces in the nails to be monitored following each stage of construction. Comparisons of the results with available data from field trials indicated that the models closely represent field conditions both during construction and the application of surcharge loading. In stability analyses the distribution of force in the nails was not well predicted.
2. Variations in effective stress within a soil nailed slope may result from dissipation of excess pore water pressures following excavation or through temporary or permanent – both natural and anthropogenic – changes in hydrological conditions. The results of the centrifuge model experiments

indicated that the axial force developed in soil nails may increase significantly to maintain stability of an excavation when effective stresses are decreased. This increase in nail load is caused by movement of the soil in the slope that could lead to serviceability conditions being exceeded or, in the extreme, ultimate limit state conditions being reached. The results indicate, therefore, that the level of possible reduced effective stresses within a soil nailed structure over time needs to be considered to assess any long-term effects on the structure, although initially a design may appear overly conservative.

3. Cycling of effective stresses within the model slopes led to an increase in axial forces in the nails resulting from accumulated deformations. The findings of the experiments indicate that repeated cycling of effective stress could lead to serviceability failure. In this experimental programme only a limited number of cycles of effective stress were applied to the model slopes and to assess the effects of a larger number of cycles and variations in boundary conditions this aspect is currently the subject of further investigation.
4. The results of the centrifuge tests indicate that the nail forces developed in a soil nailed system are influenced by the spacing of the nails. However, for the range of spacings examined to date – which are typical of dimensions used in practice – the axial force carried by the nails per unit width of the structure was found to be the same for all nail spacing. Increasing the spacing of the nails resulted in an increase in soil pressure acting at the rear of the facing.

Finally, the results of this study demonstrate the way in which the technique of geotechnical centrifuge modelling may be used to investigate a range of complex mechanisms associated with a particular construction technique. There are many other applications in the field of soil reinforcement where this technique may be applied to gain a greater insight into complex soil structure interaction mechanisms and provide quantitative data to validate analytical methods used in engineering design.

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