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# The effect of bending stiffness of soil nails on wall deformation

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ABSTRACT : Finite element analysis has been carried out on a trial soil nailed slope, in which the nails were modelled as tensile bars and as beams with different bending stiffnesses to take account of the reinforcing role of the grout. The results of the analysis show that the inclusion of bending stiffness has an insignificant effect on the deformation behaviour of the wall model.

## 1 INTRODUCTION

Soil nailing has been used extensively as an in-situ ground reinforcing technique, particularly in Japan where it is used mainly for slope stabilisation. Much research work to date has been directed towards establishing design methods for soil nailed walls (Gassler and Gudehus, 1981, Schlosser et al, 1983). The design methods have some commonality in that they are concerned with the overall and internal stability of the nailed mass at ultimate limit state. However, there are important differences concerning the assumed failure mechanism and the nail forces mobilised at failure.

The design method proposed by Gassler and Gudehus (1981) uses a two-wedge failure mechanism with only axial forces developed in the nails. In contrast, the method developed by Bridle (1989) adopts a log-spiral failure surface with both axial and shear forces considered to be mobilised in the nails at failure. The multi-criteria method developed by Schlosser et al (1983) also considers axial and shear forces developed in the nails and proposes four design criteria which are used to produce an envelope of limiting reinforcement forces.

The inclusion of reinforcement bending stiffness in limit state design methods has been firmly opposed by Jewell and Pedley (1990). They presented a theoretical study of the stresses and displacements in reinforcement bar across a rupture surface in sand, supported by direct shear tests, and concluded that the shear force developed in the nail up to failure is relatively insignificant compared with the axial force.

In recent years, there has been a renewed focus on the serviceability limit state for engineering structures. A serviceability limit state is reached when the deformation of the structure, or some other performance criteria, exceeds a specified limit. McGown et al (1993) proposed a design approach for reinforced earth based on strain compatibility of the various wall components. Clearly, a technique such as the finite element method which models pre-failure deformation can be useful in developing serviceability limit states for soil nailed walls.

This paper reports the results of a study of the deformation behaviour of a soil nailed wall, which was modelled using finite element analysis. In particular, a comparative study was made of the behaviour of the wall when different nail models were used. The nail models used were one which allowed axial forces only to develop, and a series which also allowed shear forces to develop with some account taken of the stiffening role of the grout.

## 2 THE FINITE ELEMENT SIMULATION

In order to test the efficacy of the finite element simulation, the results of a full-scale experimental soil nailed slope carried out by the Japan Highway Corporation at Tama were used (Sano et al, 1987). The ground profile comprised homogeneous volcanic clayey soil in which a 3m high slope was cut and reinforced by soil nails of the drilled and grouted type at 1m centres. The wall was then surcharge loaded incrementally to failure using hydraulic jacks acting on a loading pad of width 1.5m, placed with its leading edge 0.5m from the crest of the wall. The yield load was taken as the break point in the load-settlement relationship.

Measurements were taken of the top surface settlement, horizontal displacement of the slope face and the distribution of axial forces mobilised in the nails. Two trials were carried out with nails of 4m length and 2m length, details of which are given in Table 1.

Table 1. Details of the field experiments at Tama

| Trial No. | 1 | 2 |
|---|---|---|
| Slope Height (m) | 3 | 3 |
| Nail Vertical Positions (m) | 0.5 / 1.5 / 2.5 | 0.5 / 1.5 / 2.5 |
| Nail Spacing (centres) (m) | 1 | 1 |
| Nail/Hole Diameter (mm) | 25 / 45 | 25 / 45 |
| Nail Length (m) | 4 | 2 |
| Yield Pressure (kN/m$^2$) | 275.0 | 196.0 |

The finite element analysis was carried out using the Critical State Program (Britto and Gunn, 1990). Plane strain conditions were assumed in the model. Interface elements were provided along the upper and lower faces of the nail elements. The soil elements were represented as an elastic-perfectly plastic continuum with a Mohr-Coulomb failure criterion. The use of this model allowed the measured soil properties to be utilised. These properties are given in Table 2.

Table 2. Material properties used in the model

| Property | Value | |
|---|---|---|
| *Soil* | | |
| Friction angle, $\phi$ (°) | 22 | |
| Cohesion, c (kN/m$^2$) | 49.0 | |
| Unit weight (kN/m$^3$) | 13.14 | |
| Elastic modulus (kN/m$^2$) | 1.10x10$^4$ | |
| Poisons ratio | 0.35 | |
| *Reinforcement* | *Bar* | *Beam* |
| Elastic modulus (kN/m$^2$) | 1.44 x10$^8$ | 2.06 x10$^8$ |
| Poisons Ratio | 0.3 | 0.3 |
| Bar area (m$^2$/bar) | 1.59 x10$^{-3}$ | 2.87 x10$^{-1}$ |
| Moment of inertia of bar, $I_b$ (m$^4$/bar) | - | 6.53 x10$^{-9}$ |
| *Interface* | | |
| Friction angle, $\phi$ (°) | 22 | |
| Cohesion, c (kN/m$^2$) | 49.0 | |
| Modulus (normal direction), $K_n$ (kN/m$^2$) | 1.77 x10$^4$ | |
| Shear modulus, $K_s$ (kN/m$^2$) | 4.07 x10$^3$ | |
| Residual shear modulus, $K_{res}$ (kN/m$^2$) | 4.07 x10$^3$ | |
| Thickness (m) | 1.0 x10$^{-2}$ | |

The reinforcement was modelled using a three-noded bar element and a beam element. In the case of the bar element the stiffness in tension only is modelled (Bar). In the case of the beam element incorporating bending stiffness, the moment of inertia of the nail is also required. Representing a composite reinforcement comprising a steel bar surrounded by grout results in some difficulty. There is currently a lack of detailed information concerning the properties and behaviour of the grout and its reinforcing role. The most practicable approach is to use a single value for the properties of the composite material.

The study by Standing and Burland (1993) which considered the properties of the grout suggests a moment of inertia for the composite of approximately 1.5 times that of the steel bar alone (1.5$I_b$). However, the data given by Kakurai and Hori (1991) suggests that a much greater value of 20 times the bar alone would be appropriate (20$I_b$). In any case, irrespective of the accuracy of these values, their use in the model gives a good indication of the sensitivity of the wall behaviour to the bending stiffness of the nails. The values used for each beam element are given in Table 3.

Table 3. Properties of the beam elements

| Element | Beam 1 | Beam 2 | Beam 3 |
|---|---|---|---|
| Moment of inertia, I (m$^4$/bar) | 6.53 x10$^{-9}$<br>($I_b$) | 9.65 x10$^{-9}$<br>(1.5$I_b$) | 1.36 x10$^{-7}$<br>(20$I_b$) |

The interface element properties used in the model are given in Table 2. Due to the lack of pullout test information for this particular experiment, the stiffness parameters were obtained from the formulations suggested by Britto and Gunn (1984).

The surcharge loading applied in the model replicated the loading increments applied in the field trials, which was initial loaded in increments of 29.4 kN/m$^2$ with smaller increments applied close to the yield points.

## 3 COMPARISON OF EXPERIMENTAL AND PREDICTED WALL BEHAVIOUR

The results of the finite element simulation are presented for the case of deformations of the wall crest and slope face at the yield load. The predicted and experimental variation in the horizontal displacement of the slope surface are compared in Figure 1 for the wall with 4m long nails. The figure shows the predicted variation when the nail is modelled using bar elements (Bar) and when the nail is modelled using beam elements with three different bending stiffnesses (Beam 1, Beam 2, Beam 3).

It can be observed that there is little difference in the predicted horizontal displacement variation between

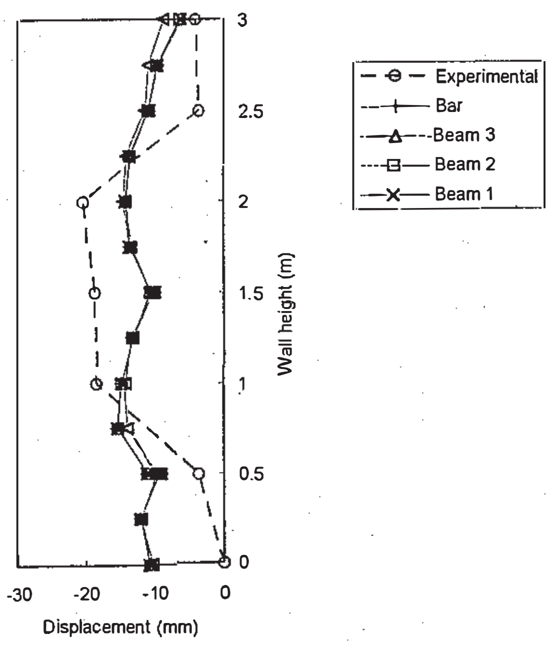

Figure 1 Experimental and predicted slope displacement for wall reinforced with 4m long nails

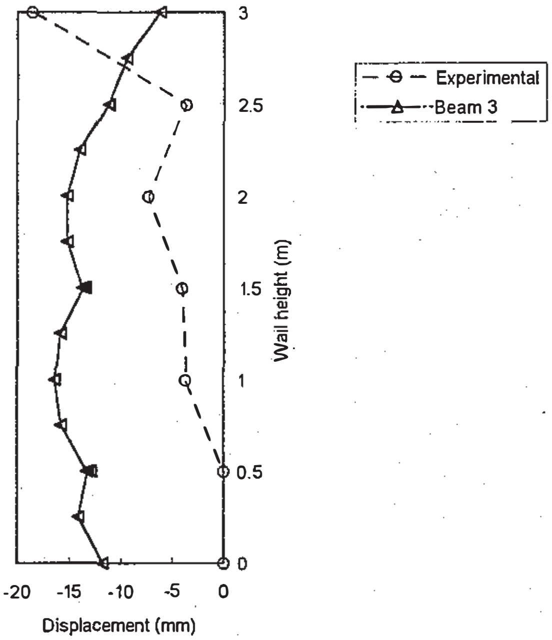

Figure 3 Experimental and predicted slope displacement for wall reinforced with 2m long nails

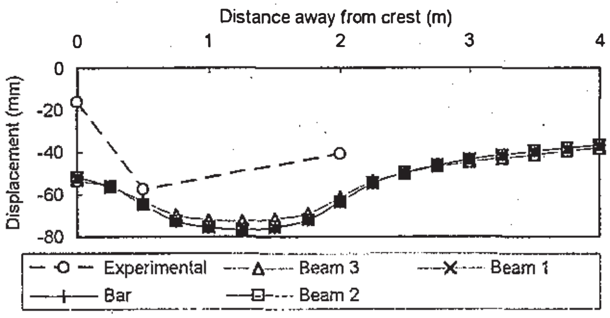

Figure 2 Experimental and predicted displacement of top of wall for wall with 4m long nails

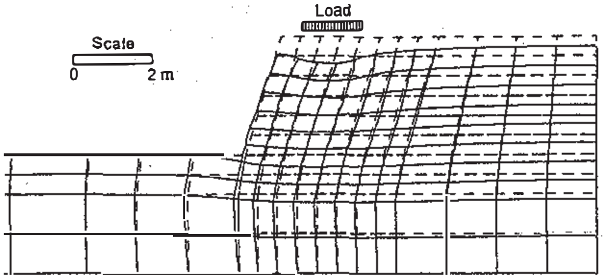

Figure 4 Undeformed and deformed mesh at yield load, for the wall with 2m long nails

each nail model. The model with the highest bending stiffness ($20I_b$) gave lower displacements in the lower half of the wall and higher displacements in the upper half particularly at the wall crest. This indicates that increasing the rigidity of the nail tends to produce more lateral displacement of the soil above the first row of nails.

The predicted and experimental variation in the settlement of the top surface of the wall is shown in Figure 2, where it can be seen that the model tends to overpredict the surface settlement. As previously, there is little effect on the surface settlement of incorporating bending stiffness into the nail model.

Similar results were obtained for the wall with the shorter 2m long nails. It can be seen in Figure 3 that the predicted horizontal displacement towards the base of the slope surface is greater than the actual displacement, suggesting that a greater degree of lateral restraint was available in the field than was provided by the model. The very large horizontal displacement at the top of the slope may be explained by a local failure which occurred beneath the inner edge of the loading pad (2m from the crest).

It should be noted that the experimental variation of horizontal slope displacement shown in Figure 3 is similar to that which can be anticipated for a structure which is constructed from the top downwards. However, the model at present does not consider the effect of the staged excavation process on the wall deformation.

For the wall with short nails, Figure 4 shows the undeformed and deformed mesh at yield load. The model confirms the tendency of the nails to rotate about their heads under surface loading and for the soil at the

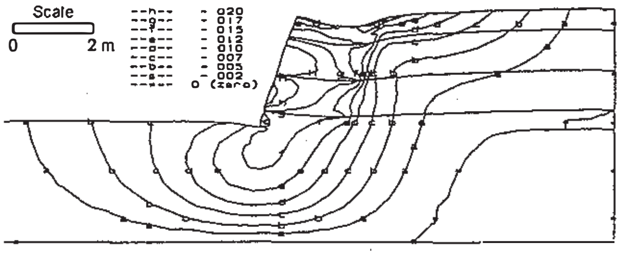

Figure 5 Horizontal displacement contours at yield load, for the wall with 2m long nails

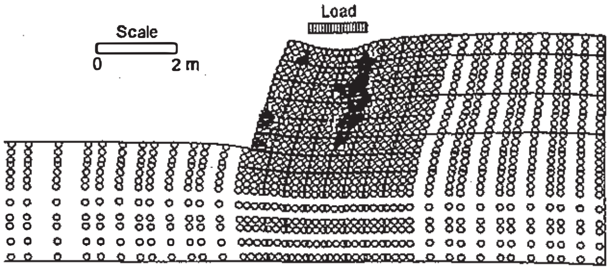

Figure 6 Extent of plastic zone at yield load, for the wall with 2m long nails

inner extremity of the nailed zone to be displaced away from the slope - a phenomenon also observed in the field experiment. This helps to explain why bending stiffness of the nails has little effect on the deformation behaviour of the wall.

Figure 5 shows the horizontal displacement contours at yield load for the short-nailed wall, showing clearly that the nailed zone acts more or less as a block with the soil yielding at the extremity of the nailed zone and the nails providing lateral restraint. This is confirmed by Figure 6 which shows the extent of the plastic zone in the soil. For the wall with the longer 4m nails, a plastic zone at the extremity of the nails did not develop. In this case the deformation pattern was more uniform beneath and away from the loaded area with the zone of plastic soil occurring mainly above the first row of nails.

## 4 CONCLUSIONS

The results of the finite element simulation show that the effect of incorporating bending stiffness into the nail model had an insignificant effect on the deformation behaviour of the wall up to yield load. The present study is therefore consistent with the conclusion reached by Jewell and Pedley (1990) that the bending stiffness of the nails can be safely neglected for ultimate limit state design. This further suggests that for serviceability limit state design, bending stiffness is unimportant and that the appropriate design considerations are the tensile forces developed and the soil/nail interaction.

Future work will consider the serviceability limit states appropriate for soil nailed structures. Such limit states have already been proposed for reinforced earth - a technique which shares many common principles with soil nailed walls, particularly if axial forces only are considered in the nails. Clearly, the most important difference between the methods is the construction sequence and its effect on the wall deformation. This work will assist in allowing the full economic benefits of soil nailed walls to be realised.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance and support of the Japan Highway Public Corporation.

## REFERENCES

Bridle, R.J. (1989). *Soil nailing - analysis and design.* Ground Engineering, London, September, pp. 52-56.

Britto, A.M. & Gunn, M.J. (1984). *Critical state soil mechanics via finite element modelling.* John Wiley & Sons.

Britto, A.M. & Gunn, M.J. (1990). *CRISP users and programmers manual.* Cambridge University.

Gassler, G. & Gudehus, G. (1981). *Soil nailing - some aspects of a new technique.* Proc 10th ICSMFE, Stockholm, Vol. 3, pp. 665-670.

Jewell, R.A. & Pedley, M.J. (1990). *Soil nailing design: the role of bending stiffness.* Ground Engineering, London, March, pp. 30-36.

Kakurai, M. & Hori, J. (1990). *Soil reinforcement with steel bars on a cut slope.* Proc Performance of Reinforced Soil Structures, BGS, Glasgow, pp 213-218.

McGown, A. et al (1993). *Limit state design of reinforced soil walls and embankments.* Proc Int Conf on Limit State Analysis, ISLSD, Copenhagen, pp. 275-284.

Sano, N. et al (1987). *In-situ loading test of artificial reinforced slopes with steel bars.* Report of the laboratory of the Japan Highway Public Corporation, Vol. 24.

Schlosser, F. et al (1983). *Soil reinforcement.* Proc 8th ICSMFE, Helsinki, General Report, Vol. 3, pp1159-1180.

Standing, J. R. & Burland, J. B. (1993). *Investigation of the interface resistance of soil nails in sands and clays.* TRL Report N00390, Transport Research Laboratory, UK.