MODELLING REINFORCEMENT RESPONSE IN A SOIL NAILED EXCAVATION

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The main purpose of shotcrete facing in soil nailed excavations is generally held to be the control of local failure in the soil between the nails. This relatively non-essential role has meant that facing design has remained reasonably rudimentary. In this paper shotcrete facings in soil nailed excavations have been analysed using a purpose built three-dimensional finite element program. A full-scale experimental soil nailed wall, constructed as part of The French National Research Project Clouterre, has been modelled using the program and comparisons between calculated and observed behaviour are presented and discussed. The parameters used in the simulations are justified using published data. Good agreement is found between calculated and published displacements, nail forces, stresses and failure mechanisms.

1 INTRODUCTION

Ease of construction, flexibility of design and economic competitiveness have meant that soil nailed excavations have become increasingly accepted as a feasible means of excavation support. However, despite there being a large pool of published data describing actual walls constructed and at least three widely accepted design codes, (Japanese design code (JHPC 1987), recommendations of Clouterre (FHWA 1993), British standards (BS 8006:1995)), there still remains much to be learned regarding working stresses within the reinforcement system. In particular, the earth pressures experienced by the shotcrete facing are largely unquantified.

Facing design for soil nailed excavations is presently based upon a number of simplifications of soil behaviour, or empirical rules of thumb. The existing design methods utilise three main techniques:

- Assume the earth pressures at the face are equal to a percentage reduction in the Rankine active earth pressure.
- Assume that the effect of overburden is negated by the action of the soil nails and design the facing to retain an active soil wedge forming between the nails.
- Assume the maximum nail tension forces are equal, or proportional to the expected total load at the face.

Little is understood about which parameters have the greatest effect on facing loading.

This paper presents a three-dimensional (3D) finite element program, capable of directly calculating the reinforcement response in a soil nailed excavation. Results regarding the determination of earth pressures at the facing will not be presented, rather the programs ability to accurately model; deflections, nail forces and failure modes experienced by a soil nailed excavation will be verified through comparisons of observed and calculated responses.

2 PROGRAM DESCRIPTION

For the analysis, a 3D finite element program, capable of simulating construction of soil nailed excavations was developed. A 3D simulation was considered necessary, so that the nails could be modelled as bars, (a 2D simulation represents the reinforcements as continuous flat sheets). When considering the moments induced in the facing, it was important that the 'point' restraint provided by the soil nails be reflected in the simulation.

Three types of element are used by the program; a twenty noded elasto-plastic 'soil' element, an eight noded isoparametric Mindlin Shell 'shotcrete' element and a two noded beam 'nail' element. The reinforcement elements share nodes with the main soil elements. As such, slip between the soil and reinforcing elements is not modelled. Inclusion of separate soil nail and shotcrete elements has meant that induced moments and forces in the support elements can be directly calculated.

Soil behaviour is characterised by an elasto-plastic (elastic - perfectly plastic) response curve. The Sloan and Booker (1986), modified Mohr-Coulomb yield surface is used to describe the failure criterion, and a Von Mises' plastic potential surface is used to define strain orientation at failure. Use of Von Mises' plastic potential means that soil dilation is not considered.

Excavation is simulated in steps, using Brown and Booker's (1985) virtual work solution to calculate the induced forces. A skyline solver has been incorporated, in order to reduce the memory required to run the program.

3 EXCAVATION SIMULATION

For simulation of excavation in elasto-plastic soils, it is essential that excavation be carried out in steps that reflect the actual excavation process. There are two reasons why this is necessary in soil nailed systems.

- During a stepped excavation the soil will experience stress states, which are different to its final stress state. As such, the simulated excavation process needs to properly reflect the actual excavation process, so that any plastic deformation and resulting permanent strain, experienced in intermediate construction stages is incorporated in the total excavation response.
- Without a stepped simulation process it would not be possible to properly model the influence of the incremental construction process. The layered nature of soil nailed wall construction, means that each layer of reinforcement has a unique zero stress position. This phenomenon needs to be properly mirrored in any simulation for meaningful results.

The incremental nature of a soil nailed wall's construction, has some bearing on the applicability of any simulation of a soil nailed system. In reality, the shotcrete and nail annulus, are placed wet onto the deforming excavation. All stresses within the reinforcement are induced by displacements after the shotcrete and grout have hardened. In the simulation, the time dependent nature of the displacements is not modelled. The reinforcements are either placed before the current excavation step is completed or alternatively, they are placed after all the displacements associated with the current step have occurred.

Figure 1 illustrates the two simulations for one excavation step. These two cases represent the limits of the actual behaviour. For case A, the stresses in the reinforcements are induced by displacements associated with the current step as well as displacements induced by following steps. For case B, the displacements due to the current step are said to have occurred before the reinforcing is placed. As such, the stresses in the reinforcement are only due to displacements induced by following steps. The actual behaviour of an excavation most likely sits between these two limits.

For this simulation, case B is taken to represent the excavation's behaviour, because it is believed that this case more closely represents reality.

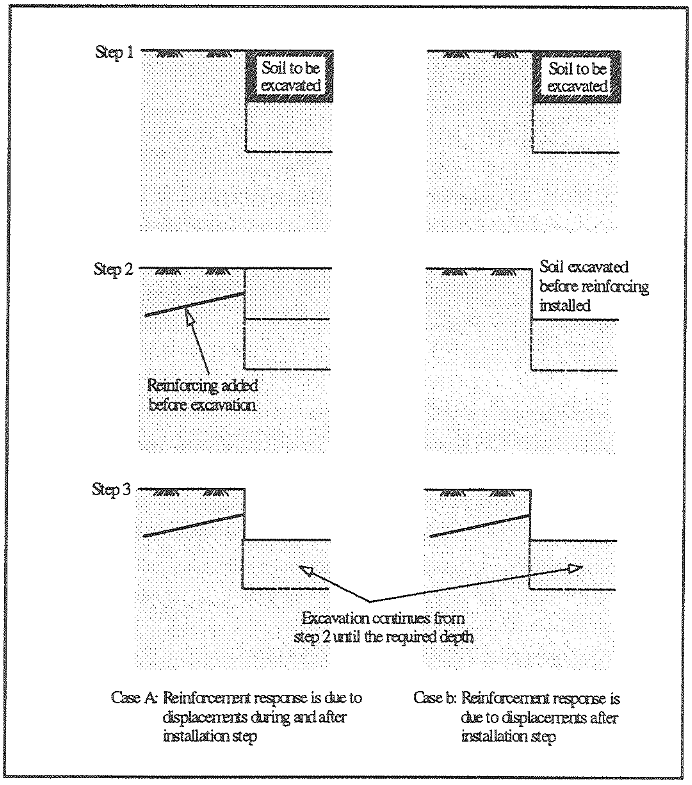

Figure 1 Excavation simulation

4 FULL SCALE EXPERIMENTAL WALL

Unterreiner et al. (1997), Schlosser et al. (1992) and Plumelle et al. (1990) present the results of a full scale experimental soil nailed wall constructed as part of the French National Research Project CLOUTERRE. Figure 2 shows a cross section of an embankment built for the project. The soil nail wall was constructed out of the embankment. Construction was incremental, with 1m high layers of the wall being built at a time. Nails were inclined at 10° to the horizontal, with nail length ranging from 6 to 8m. The facing was constructed of 100mm thick mesh reinforced shotcrete. The homogeneity and density of the backfill used to construct the embankment was tightly controlled. Excavation induced displacements were measured using inclinometers, positioned as shown.

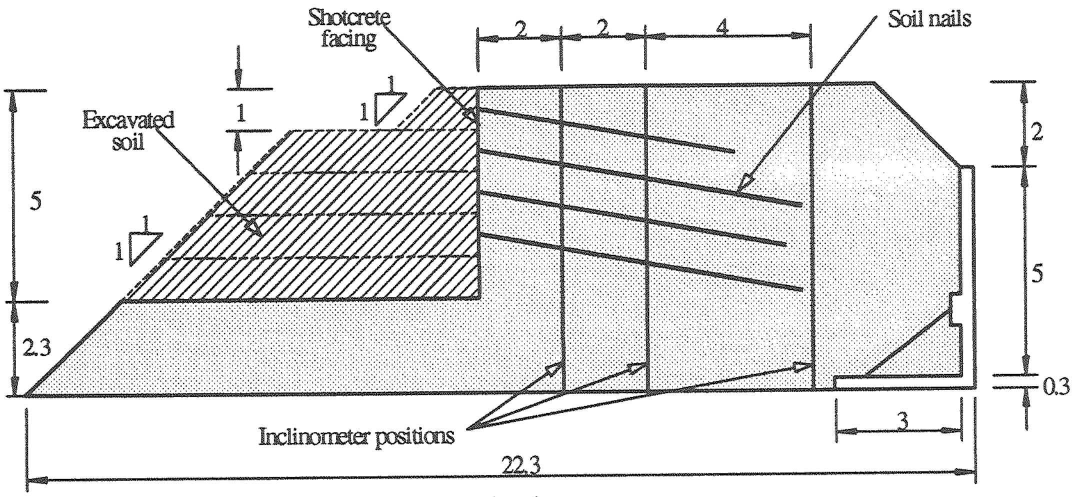

Figure 2 Embankment dimensions

Extensive testing was used to determine soil strength parameters. A Menard pressuremeter was used to calculate soil modulus and triaxial testing to determine the friction angle.

4.1 SIMULATION OF EXPERIMENTAL WALL

The large amount of testing conducted as part of the Clouterre project, and the controlled nature of the embankment fill in which the soil nailed wall was built, meant that a high degree of confidence could be placed in the soil parameters reported by Clouterre. As such the simulation makes use of these parameters wherever possible.

Table 1, shows comparisons of reported and simulated soil parameters. Figure 3, shows a comparison of the measured and simulated Young's Modulus. Initial stresses were considered to be geostatic, with K_o calculated using the relationship shown in Table 1.

	Reported	*Simulation*	*Method of determination*
φ	36°-40°	38°	Triaxial tests
C	3-4 (kPa)	3 (kPa)	Triaxial tests, water content
K_o	0.38	0.38	$K_o = 1\text{-}\sin\varphi$
γ	16.1 (kN/m^3)	16.1 (kN/m^3)	Avg. unit weight

Table 1 Soil parameters used

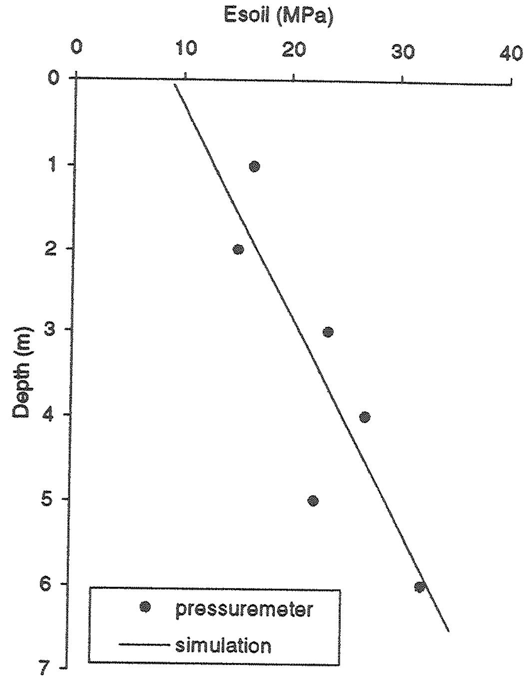

Figure 3 Measured and Simulated E_{soil}

4.2 COMPARISON OF RESULTS

Figures 4 (a)-(d) show the comparison of calculated and observed horizontal displacements. Results for two excavation stages (wall heights, 3m and 5m) are shown in each figure. Figures 4(a) and (b) (displacements for the facing and 2m behind face) show excellent agreement. In Figures 4(c) and (d), differences appear between the calculated and observed readings. Inconsistencies in the observed data suggest that some of the inclinometer readings are erroneous, particularly the observed displacements for the 5m deep excavation in Figure 4c, where the inclinometer data shows the soil moving away from the excavation.

Figures 5 (a)-(d) show comparisons of observed and calculated nail forces. A fair agreement is found for the size of the nail loads. Figures 5(b) and (c) in particular show that the program can over estimate the size of the nail forces. This is most likely attributable to the assumption of full fixity between the nails and soil. There is however a good agreement between the shapes of the observed and calculated nail force distributions. The position of the maximum nail force gives an indication of where the failure plane intersects the nail. As such, the good correlation between the positions of observed and calculated nail force maximums, shows that the program is properly simulating observed failure mechanisms.

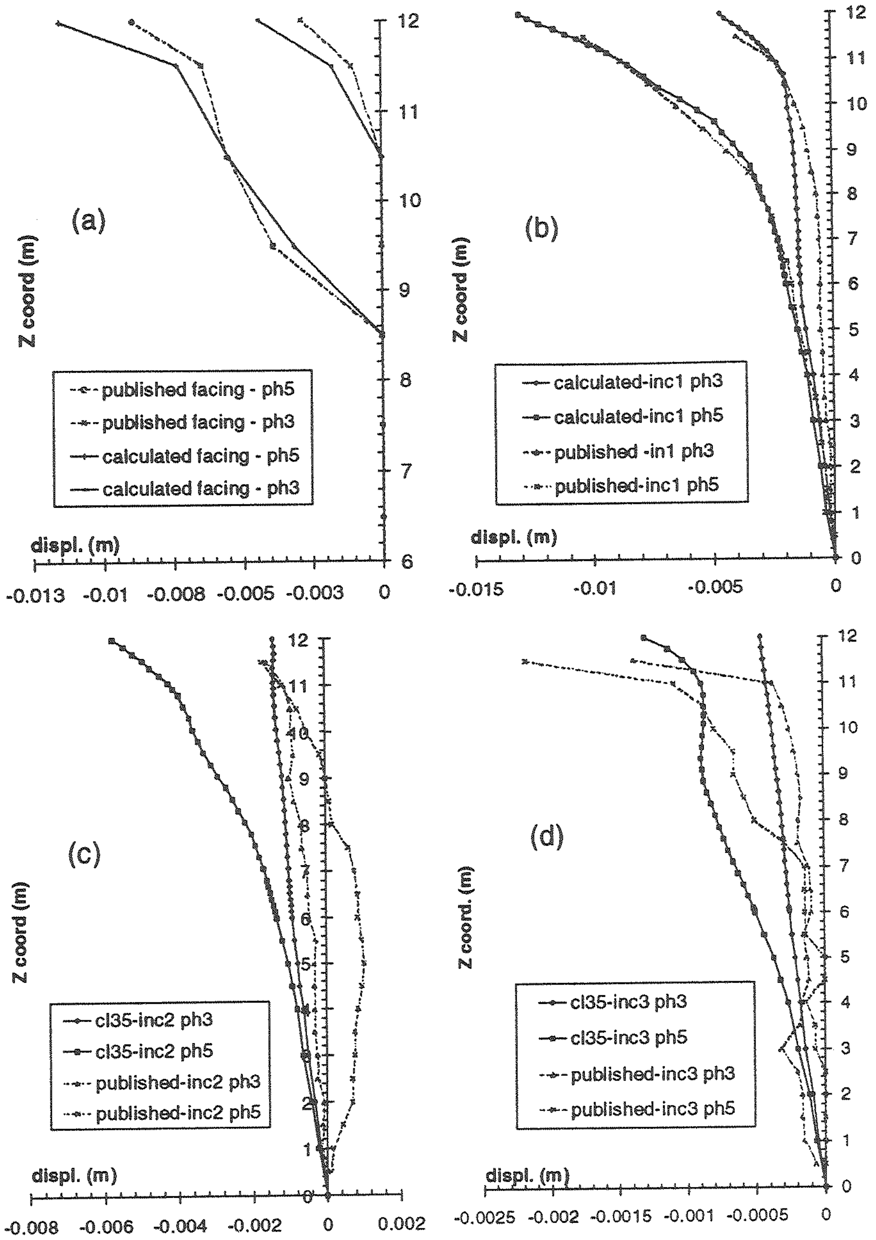

Figure 4 Horizontal displacement (a) at face (b) 2m from face (c) 4m from face (d) 8m from face.

5 DISCUSSION

Comparisons between observed and calculated; displacements, nail loads and failure mechanisms show that soil nailed excavations can be simulated using the presented 3D finite element program.

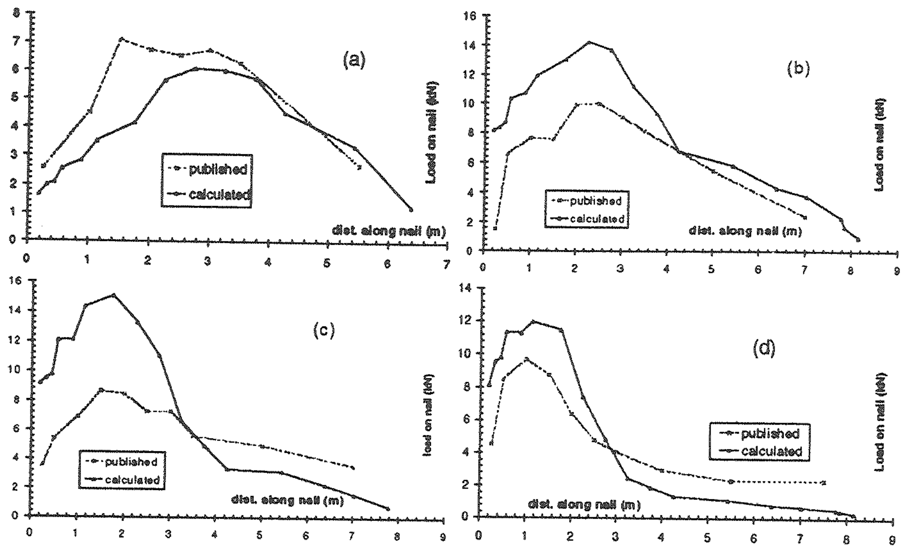

Figure 5 Force distribution in nails (a) top nail (b) second nail (c) third nail (d) bottom nail.

6 REFERENCES

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