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Use of soil nailing in stabilisation of a freeway embankment

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ABSTRACT: The paper describes the first large scale use of the soil nailing technique for highway slope stabilisation in Australia. Results of short term pull-out tests and long term monitoring are presented and discussed. It is concluded that the observed behaviour of the nail wall can be reasonably predicted with the parameters obtained from these short-term tests.

1 INTRODUCTION

The Roads and Traffic Authority of New South Wales has successfully completed a major soil nailing project on the F3-Sydney to Newcastle Freeway at Mt. White, 55.6 km north of Sydney. At this location the road embankment is about 30 m high and 140 m long. The embankment was constructed about 25 years ago at a slope of 1.5 (H) to 1 (V) using compacted clayey silty sands and ripped sandstone, with armour rocks for surface protection. Both northbound and southbound carriageways are supported by the embankment and have a split gradeline level as shown in Figure 1. A two lane highway (Pacific Highway) runs close to the base of the freeway embankment.

The fill slope became unstable after prolonged heavy rainfall in early 1989 with the head of the slip threatening the integrity of the embankment and road structure. Further regression of the slip was likely and would have resulted in closure of part or all of the southbound carriageway, causing massive disruption to traffic flow.

A detailed geotechnical investigation was undertaken to determine the cause of failure and a number of schemes to repair the slope proposed. After consideration of these alternatives, the technique of soil nailing was adopted based on expediency, practicality of construction and cost. Soil nails were installed at the upper batter of the distressed embankment, followed by the construction of a retaining wall at the base in conjunction with backfilling to flatten the gradient of the batter below the soil nailed structure.

2 DETAILS OF REMEDIAL WORKS

A typical cross-section showing the proposed remedial works is given in Figure 1. Listed below is a summary of the construction details.

1. The top 2 benches were each 120 m long. The bottom 2 benches were 60 m long.
2. Two rows of soil nails were required per bench. Spacing of the soil nails was at 2 m centres and staggered at 1 m centres between rows (see Figure 2).
3. Soil nails were manufactured from 20 mm deformed bar, 12 m long and grouted in 75 mm predrilled holes 12.5 m deep. Soil nails were installed at 10 degrees from the horizontal into the slope. Ultimate tensile capacity of reinforcements is 125 kN and the working load was taken to be 70 kN. The soil nails were hot dip galvanised for corrosion protection. Each nail was also properly centralised when it was inserted to the hole to ensure uniform grout cover around its length.
4. Mesh reinforced shotcrete with a total thickness of 150 mm was applied in two layers to the slope surface. Against the surface of the first shotcrete layer, the soil nails were fastened with nuts and bearing plates by applying a nominal load of 10 kN using a torque wrench. The complete head assembly was finally covered by a second layer of shotcrete. The shotcrete

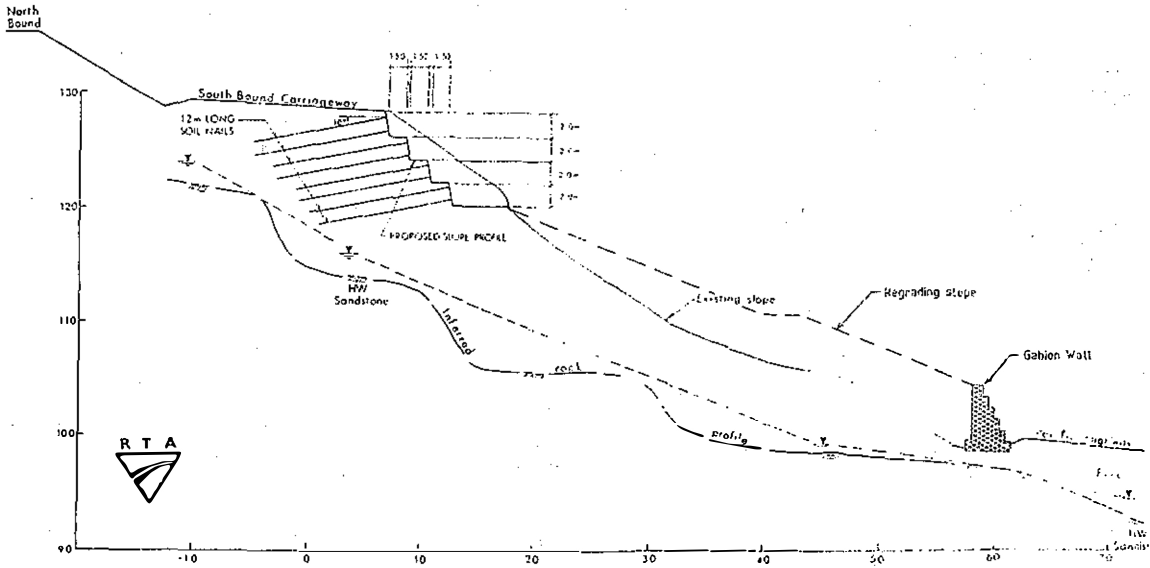

Figure 1 Typical cross-section of the site

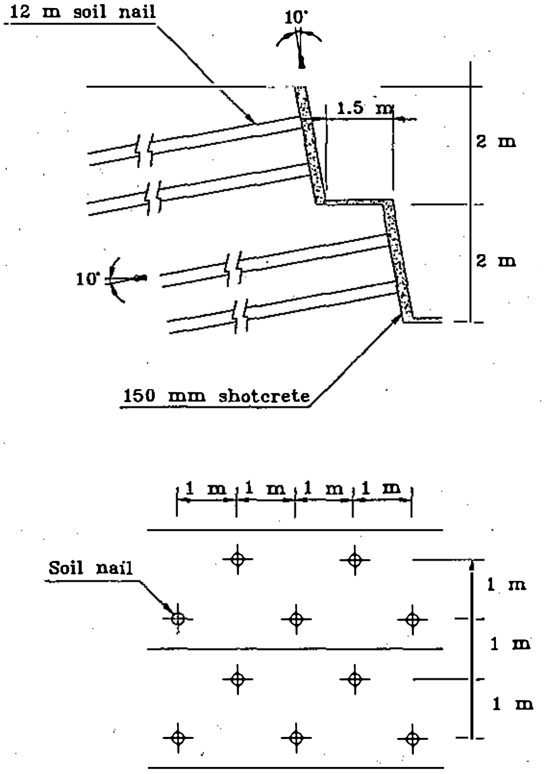

Figure 2 Typical details of soil nails

was designed to act as structural diaphragms which would increase the effectiveness of the soil nail system.

5. After the installation of soil nails, a gabion wall with a maximum height of 7 m was constructed at the toe of the embankment. Excavation into the existing fill was required for the placement of the gabion units, and the temporary stability of the overall embankment and the freeway was provided by the reinforcing action of soil nails. The slope behind the retaining wall was finally regraded to a gradient of 2 (H) : 1 (V) with compacted granular fill extending up to the base of the fourth soil nailed bench.

3 DESIGN METHOD

The design of the remedial work was based on the concept of slope stability using the limit equilibrium method, taking into account the effects of soil nails as external force acting on the slope. Different potential failure surfaces passing through either the reinforced or unreinforced zone were analysed in order to obtain the critical slip surface and the lowest factor of safety of the slope.

It is considered the soil nails would improve the slope stability by the mobilisation of axial force, the shear and bending capacities of the reinforcement being negligible as discussed by Jewell (1990). The axial capacity of soil nails available at the slip surface is limited by the lesser of either the tensile strength of the reinforcements or the pull-out resistance due to frictional shearing between the bars and surrounding soil behind the slip plane. The pull-out resistance provided by each row of nails was calculated by an effective stress approach given by Cartier & Gigan (1983).

The distressed embankment was assumed to have a factor of safety equal to unity under the worst groundwater conditions in its performance history. The soil nailing system was designed to improve the global factor of safety of the embankment to the level of 1.2 in the short-term, taking into account the adverse effects caused by the excavation at the toe for the retaining wall. The second stage of remedial works which involves a retaining structure with slope regrading would result in a factor of safety greater than 1.4 for the entire embankment. In the long-term stability analysis, a sacrificial thickness of 2 mm was allowed on the bar diameter of soil nails for corrosion effects.

4 MONITORING AND TESTING PROGRAM

A comprehensive monitoring program was implemented to evaluate the performance behaviour of the embankment soil nailing system under service conditions. Monitoring commenced early during the construction (May 1990) and is continued up to the present time.

4.1 Inclinometer monitoring

Prior to the start of construction work, six vertical inclinometers were installed at road level down through the embankment into the bedrock. During the construction three of the inclinometer holes were intersected by soil nailing drilling operations and could not be used. However monitoring results from the remaining holes indicate that during the six month construction period (May to December 1990) the maximum movement near the front of the soil nailed structure was of the order of 3 mm. Since the completion of soil nailing works, no further slope movements have been detected by the inclinometers (see Figure 3).

4.2 Strain instrumentation of soil nails

A total of six fully instrumented steel soil nails were installed in the slope with the first pair installed in the second bench. The second and third pairs were installed on benches 3 and 4 respectively (see Figure 4).

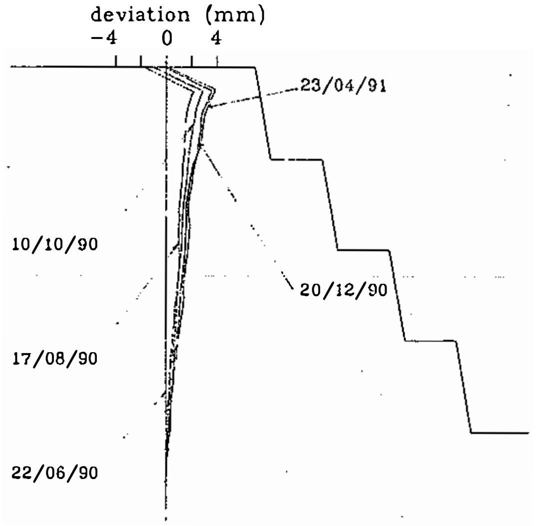

Figure 3 Inclinometer readings

Weldable strain gauges were micro welded at 2 m intervals so that each bar contained 5 measurement points to monitor the change in strain along the length of the soil nail after installation. The two instrumented nails in the second bench were equipped with two strain gauges diametrically opposite to each other at every measurement point to detect any induced bending of the steel bar. A quarter wheatstone bridge (three-wire) configuration was used with temperature compensated resistors buried at depth in the embankment slope. A great deal of care was taken in the process including lead wire configuration, continuity checks, waterproofing and sealing to ensure proper strain gauge performance.

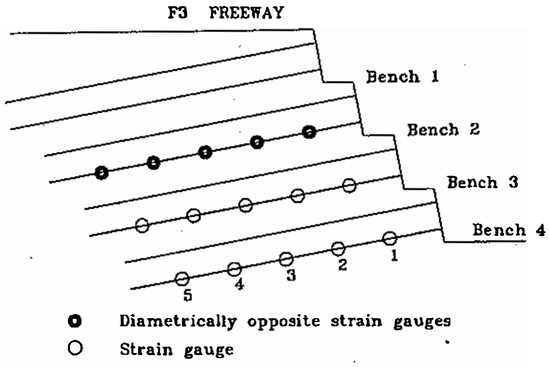

Figure 4 Instrumented soil nails

Four dataloggers were installed on site to monitor the six instrumented nails every 3 hours. The logger temperature at the reading time was also recorded to assist in the interpretation of the data. Lengths of soil nail were strain-gauged tested in the laboratory to calibrate axial force measurements against strain gauge readout.

Soil nail force monitoring started when the construction of the second bench was completed. It is noted that about 40% of the instruments malfunctioned during the 2 years monitoring period. However, allowance had been made for strain gauge redundancy. The data recorded from the remaining strain gauges have been proved to be reliable and consistent.

4.3 Pull-out tests

Short duration proof load tension tests were carried out for soil nail bars. Lengths of bars for these tests were either 4 or 6 m, and located on the second and the fourth benches. One 6 metre bar (installed on fourth bench) was instrumented with 3 strain gauges so that strain development along the bar could be measured during the test. All tests were performed 14 days after the nails were installed to ensure adequate grout strength and bonding.

4.4 Long term corrosion monitoring

A number of steel soil nails (lengths of 5 m) have been installed on the fourth bench for long term durability monitoring to assess corrosion. It is anticipated that these bars be extracted at 2, 5, 10 year intervals to monitor any long term corrosion and check on the effectiveness of the zinc galvanisation.

5 RESULTS AND DISCUSSION

5.1 Pull-out test

Results of a pull-out test on a fully instrumented soil nail (6 m length) is shown in Figure 5. The graph shows the development of axial force along the soil nail at 1.5, 3 and 4.5 m due to the applied load at the soil nail head. A maximum load of 105 kN was achieved when soil nail displacements reached approximately 8 mm. However, in the elastic range (which covers about 50% of the ultimate capacity) the required displacement is less than 2 mm. It is worth noting that the test was terminated when slippage occurred between the threaded head of the bar and the jack anchorage.

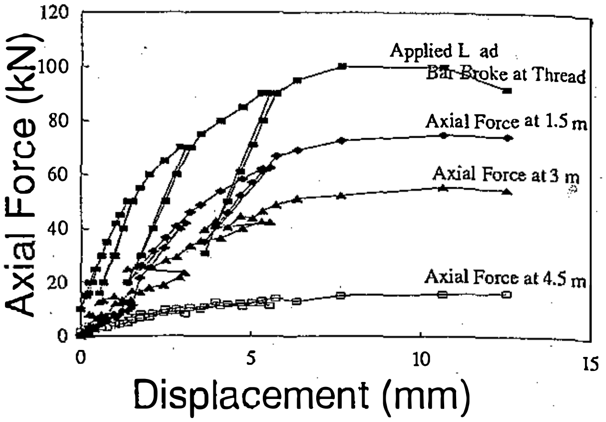

Figure 5 Pull-out test : Load - displacement

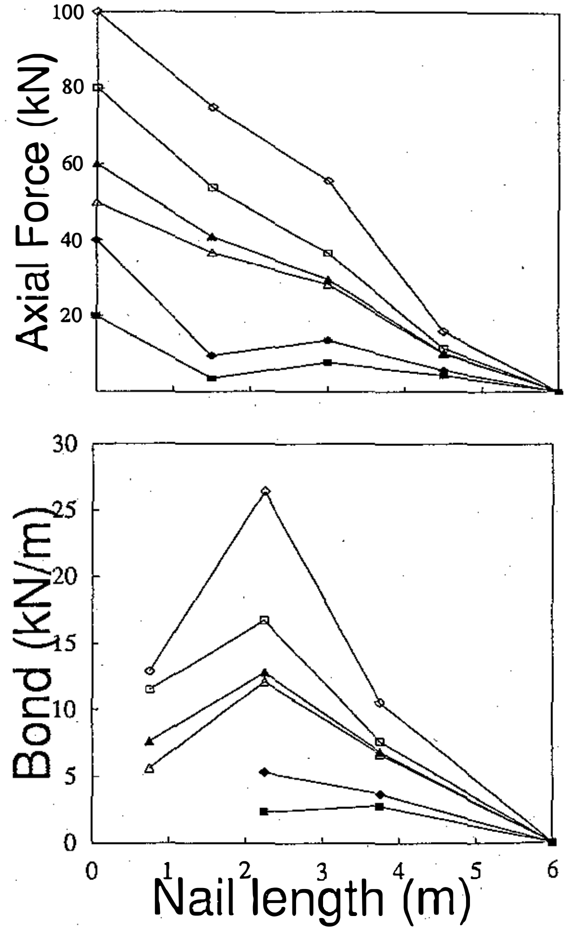

Figure 6 Pull-out Test: Load & bond distribution

The measured load distribution along the soil nail is shown in Figure 6. In general, the curves demonstrate a decrease in tensile stress along the length of steel bar at each load cycle, and an increased mobilisation of bond stress with increasing test load. However, at test loads less than 50 kN, there is a reversal of stress gradient at 1.5 m length, which may have been caused by the residual stress in the bar or the drift error of strain gauges.

From the curves of bond stress distribution, it is apparent that the maximum stress was developed between 1.5 m and 3.0 m. The bond strength for the initial 1.5 m length of soil nail is expected to be lower because of the reduction in overburden stress due to the 1.5 m wide berm above the nail. It is inferred that pull-out failure of the soil nail was not imminent at the end of the test, and the ultimate bond stress is likely to be greater than 25 kN/m where the depth of soil overburden is greater than about 7 m.

5.2 Nail force monitoring

A comprehensive strain monitoring program enabled axial tensile forces in selected soil nail to be tracked over time (1.7 years), as shown in Figure 7. Strain gauge data were calibrated to a standard temperature of 25°C ± 0.5°C. Only limited strain gauging was available from the datalogger installed on bench 4.

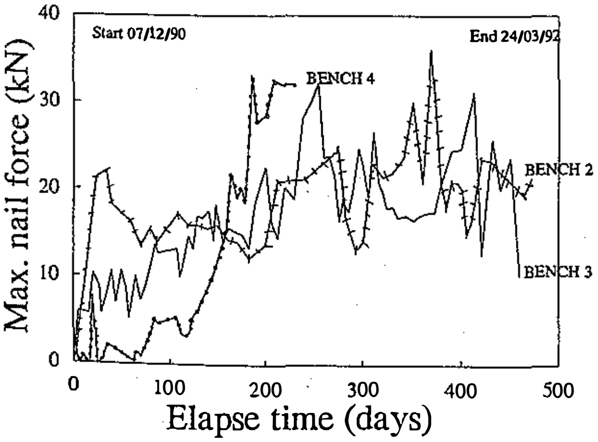

Figure 7 Development of maximum nail forces

Results show that the instrumented soil nails gradually developed tension (range 15 - 35 kN) during the construction phase as each bench was progressively excavated. Tension forces in the soil nails have remained fairly constant after the soil nail construction within this range and are well within their designed capacity. In general, nail forces in the lower benches are somewhat higher and appear to be more uniformly distributed along the nail length (see Figure 8).

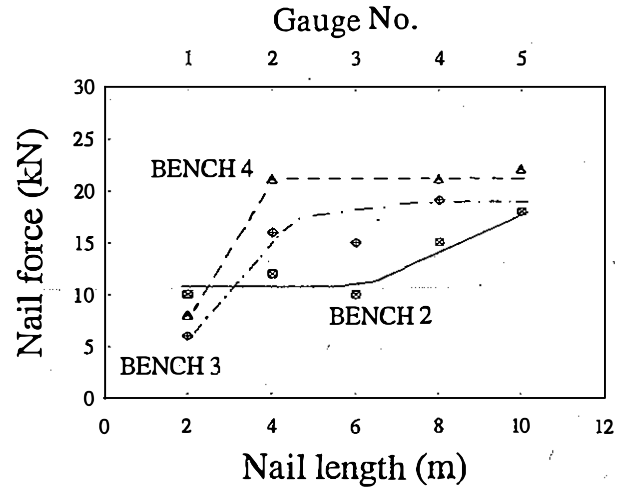

Figure 8 Observed nail force distribution

The phenomenon is also consistent with the horizontal movements recorded by the inclinometers. The measurements indicated that a small amount of outward movement (3 mm) occurred during construction but has now stabilised indicating the efficacy of soil nails.

6 NUMERICAL MODELLING

The terraced soil nail structure together with the freeway embankment were numerically modelled using the "FLAC" Finite Difference package (Cundall, 1991). The soil was modelled as a Mohr-Coulomb elasto-plastic material which yields according to the non-associated flow rule. The nails were represented by cable elements of which the parameters for bond stiffness and strength were derived from results of pull-out test. Nails were assumed to be pinned to the shotcrete layer at the bench face and free at the other end. The numerical model also considered the effect of the groundwater table and the traffic load on the freeway.

Numerical modelling results of soil nail forces (see Figure 9) compare favourably with actual field measurements. Predicted axial forces along the soil nail are slightly higher than the measured values and they show similar trends along the soil nail length.

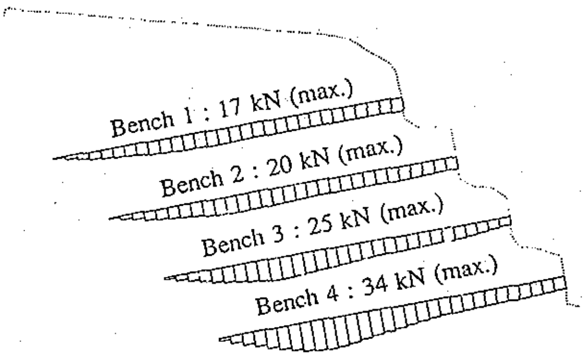

Figure 9 Predicted nail force distribution

7 CONCLUSIONS

The paper describes the successful application of soil nailing to repair an unstable road embankment. The technique has been found to be practical and cost effective given the constraints imposed by the existing carriageways above and below the embankment on this site.

The results of field monitoring are presented and agree well with the design assumption. The numerical model based on pull-out test parameters was found to reasonably predict the observed behaviour of soil nailing wall.

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