International Conference on Case Histories in Geotechnical Engineering

(2008) - Sixth International Conference on Case Histories in Geotechnical Engineering

14 Aug 2008, 4:30pm - 6:00pm

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Recommended Citation

Kwong, A. K. L. and Lee, C. F., "A Field Test Study on Instrumented Soil Nail Installed in Cut Slope" (2008). *International Conference on Case Histories in Geotechnical Engineering*. 2.
https://scholarsmine.mst.edu/icchge/6icchge/session02/2

6th International Conference on
Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008

A FIELD TEST STUDY ON INSTRUMENTED SOIL NAIL INSTALLED IN CUT SLOPE

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ABSTRACT

Soil nailing is a technique routinely used in Hong Kong whereby closely spaced steel bars are installed into a slope so that its stability conditions can be improved. A full-scale field test has been carried out by The Department of Civil Engineering of The University of Hong Kong to study the development of passive load along the full length of soil nails when subjected to induced rise in groundwater table. The cut slope was formed to a very steep angle of 55° and 10 m high in completely decomposed volcanic material. Grouted curtain was also formed behind, at the bottom and on both ends of the slope in order to form an impermeable barrier that would allow groundwater table to increase artificially by injecting water into slotted PVC pipes. Nine number of soil nails (in regular 2 m c/c spacing of 3 rows and 3 columns) of 6 m long high yield steel bar were installed at 15° from horizontal into the formed cut slope. Instrumentation included strain gauges along the nails, inclinometers, piezometers, and settlement prisms. This paper describes the method of construction and the load developed along the soil nails when the groundwater table was raised to the ground surface. It was found that the measured passive load along the soil nail was smaller than the commonly assumed design parameters, an indication that substantial savings can be achieved if mobilization of shearing resistance along the full length of the soil nail was considered in routine design. Finite element analysis has also been carried out to compare the measured load with the simulated load and the stability factor is compared with the factor of safety at each stage of loading.

INTRODUCTION

Soil nailing is a technique whereby closely spaced steel bars are installed into a slope to improve its stability conditions. This method has been routinely used in Hong Kong and overseas, and the analysis and design of the soil nails are mostly based on limit equilibrium approach which compares the resisting moment and force with the driving moment and force on the most critical slip surface. A safety factor is usually applied in the design so that the resisting moment and force will be larger than the driving moment and force.

By dividing the soil masses into vertical slices, a resisting force is usually applied to the base of each slice when it intersects the soil nails. This resisting force is usually checked against the tensile strength of the nail, the shearing resistance between the nail and the grout, the shearing resistance between the grout and the soil, and the shearing resistance of the soil only. In routine design, it is usually the shearing resistance of the soil governs the maximum force that can be applied. However, this limiting equilibrium approach does not consider how much deformation will be generated in the soil mass before the passive force can be fully mobilized in the soil nail. It has also not considered the relative stiffness between the soil and the steel bars.

To date, there has not been any field tests in Hong Kong conducted on slope comprises in-situ soil where load development along the steel bars are monitored during each stage of rise in groundwater table to the point of failure of the whole soil mass. Thousands of slope in Hong Kong have been upgraded using soil nails but they are not monitored. The only available field measurement of soil nail forces in Hong Kong was in a report given by Yim and Yuen (1998) where a 7 m high slope in completely decomposed volcanic was cut to 70° and the working loads developed in the 4 rows of nails were only 7% (10 kN) to 52% (70 kN) of the design working load (134 kN) of the nails because pore water pressure remained low during the monitoring period. No movements were observed.

Li (2003) summarized the current design and installation practice of soil nails in Hong Kong and described the construction and instrumentation of a loosely compacted soil-nailed slope. Li (2003) concluded that although the loads developed in the nails were small and at the working stage (40 to 70 kN), it had significantly reduced the slope deformation by preventing the formation of shear band or distinctive slip surface. Failure of the slope was governed by excessive movement (both lateral and downward due to surcharge at the top) rather than due to failure of the nail or failure of the bond between the nail and the soil.

Using a strength reduction technique, Cai and Ugai (2003) modeled an idealized slope reinforced with a single row of nail and compared the safety factors calculated by Bishop’s method. A range of nail orientation, spacing, and shear strength of the soil-grout interface was analyzed and reasonable agreement was achieved on the factor of safety (FOS).

However, field measurements are not available to compare the load developed in the nail and the deformation of the soil-nailed slope at failure with that predicted by the finite element method. It is imperative that the load and deformation predicted in the model is checked and calibrated against field data before it could be adopted for use in the practice. In this regard, a research involving a full-scale field test has been carried out with instrumentation mounted at strategic locations in order that the failure mechanism and the soil-nail interaction can be fully understood.

This paper describes the full-scale field test carried out at the Kadoorie Agricultural Research Centre of The University of Hong Kong, where groundwater table was artificially raised to the surface to study the development of loads in the soil nails and compare with that obtained using a finite element approach.

The objective of the research is to develop an in-depth understanding of the failure mechanism and load development along the nail at each stage of the loading step, based on a full-scale test with dimensions compatible to the common slope upgrading work in Hong Kong. Based on the instrumented results and the calibrated numerical model, it is hoped that savings can be achieved in the future design of soil nails in Hong Kong.

CONSTRUCTION OF FULL-SCALE FIELD LOAD TEST

Construction Procedure

At the Kadoorie Agricultural Research Centre of The University of Hong Kong, a cut slope was formed to a very steep angle of 55° and 10 m high in completely decomposed volcanic material (see Figure 1 for location). Two boreholes were drilled at the crest and the slope comprised 1.5 m of fill overlain 1 m of residual soil above the completely decomposed volcanic (CDV) layer. The residual soil can be described as firm, moist, brown, grayish brown, slightly sandy silt with some angular to sub-angular fine to coarse gravel, whereas the CDV can be described as extremely weak, light grey, completely decomposed fine ash crystal TUFF (slightly sandy silt with occasional angular to sub-angular fine gravel). Grouted curtain was first formed behind, at the bottom and on both side ends of the slope in order to form an impermeable barrier that would allow groundwater table to increase artificially by injecting water into slotted PVC pipes. The grout curtain at the back of the slope comprised 14 m long, nine numbers of 100 mm diameter hole, spaced at 1.0 m c/c. The grout curtain at both ends of the slope comprised 11 m long, fifteen numbers of 100 mm diameter hole, spaced at 1.0 m c/c (see Figure 2 for arrangements). The grout curtain at the bottom of the slope comprised 12 m long, seventeen numbers of 100 mm diameter hole, spaced at 0.5 m c/c. After all the grout curtains were formed, the slope was excavated from top to bottom to form a very steep angle of 55° (see Figure 3 for slope after excavation). After that, nine number of soil nails (in regular 2 m c/c spacing of 3 rows and 3 columns) of 6 m long high yield steel bar were installed at 15° from horizontal into the formed cut slope. A U-channel was constructed at the toe to collect and divert any surface water away from the floor and toe. Instruments including strain gauges along the nails, inclinometers, piezometers and settlement prisms were then installed (see Figure 4 for soil nails and inclinometers).

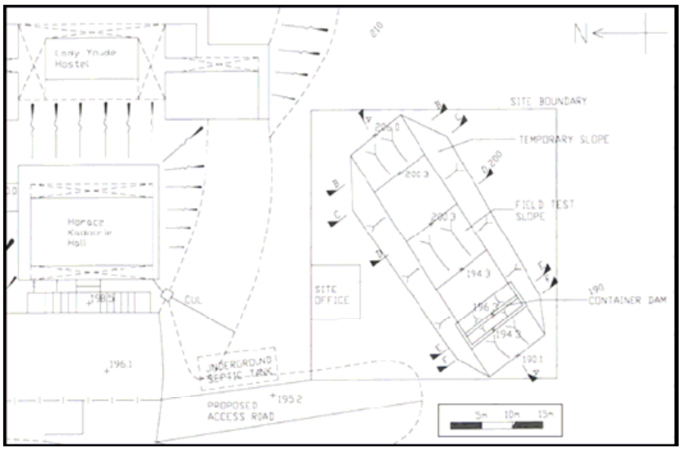

Figure 1. General site location plan at Kadoorie Agricultural Research Center.

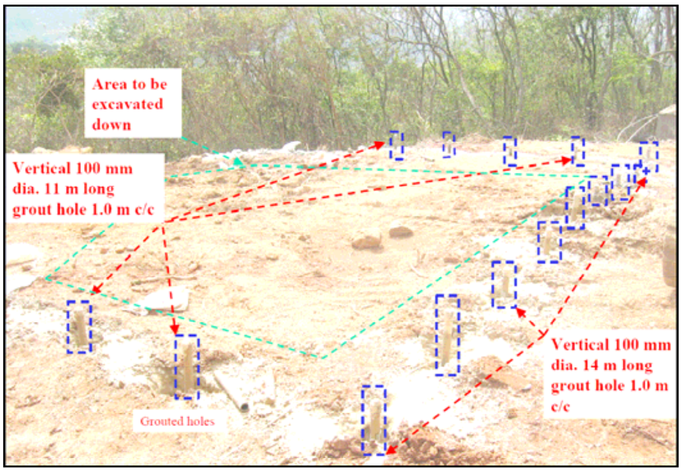

Figure 2. Grout curtains formed at the back and both ends of the slope.

Figure 3. Overall view of slope after excavation.

Figures 5 and 6 show the location of the instrumentations in plan view and sectional view respectively.

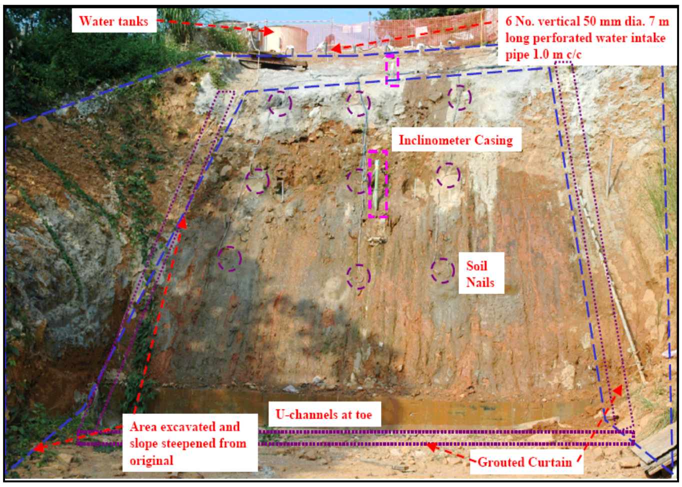

Figure 4. Overall view of cut slope with soil nails and inclinometers installed.

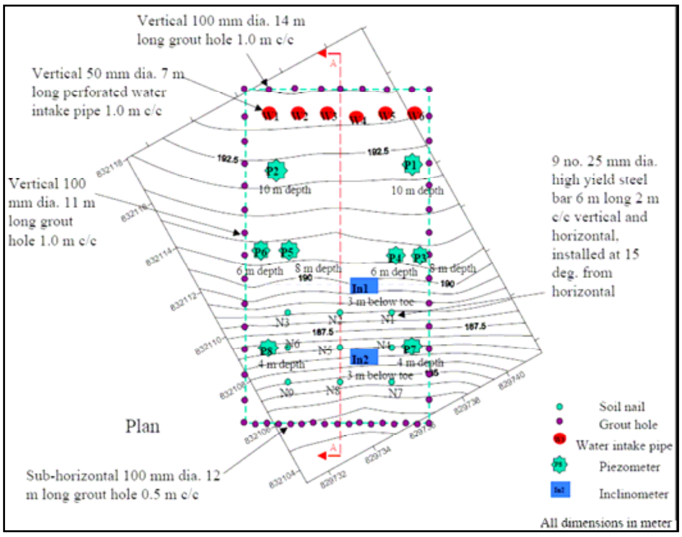

Figure 5. Plan view of instruments installed.

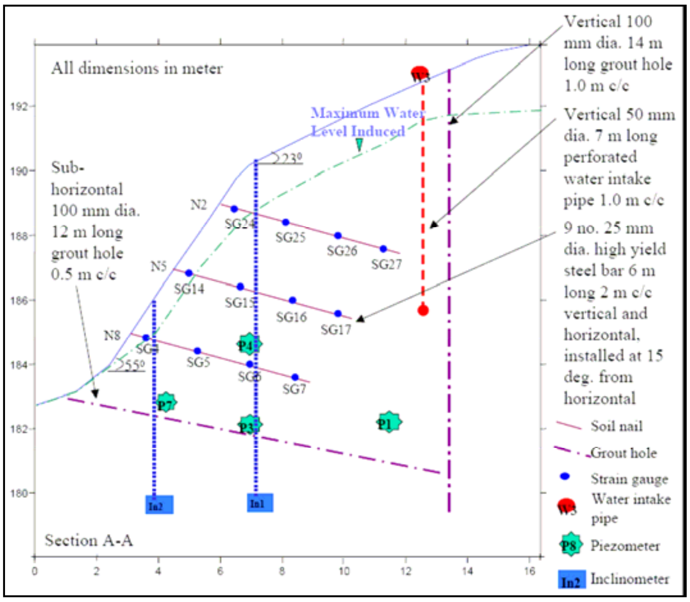

Figure 6. Sectional view of instruments installed.

Measurements of Pore Pressure, Loads and Movements

Although an impermeable barrier was formed by grouting on 4 sides of the slope (1 back face, 2 side faces and 1 bottom), the use of four number of small diameter grout pipes (25 mm diameter perforated pipes) could not provide sufficient water inflow into the slope to induce a rise in groundwater table when the test was first carried out in September 2005. Subsequently, six numbers of 7 m long pipes spaced at 1.0 m c/c (50 mm diameter perforated pipes in 100 mm diameter hole) were installed in October 2005 and with a 24-hour supply of water (with an average flow rate of about 30 l/min per pipe) continuously in 12 days, the groundwater table was finally raised to the bottom of the fill layer, approximately 1.5 m below the surface.

Figure 7 shows the setup of the water intake pipes and Table 1 shows the quantity of flow delivered into the pipes during the test period between 20 October 2005 and 31 October 2005.

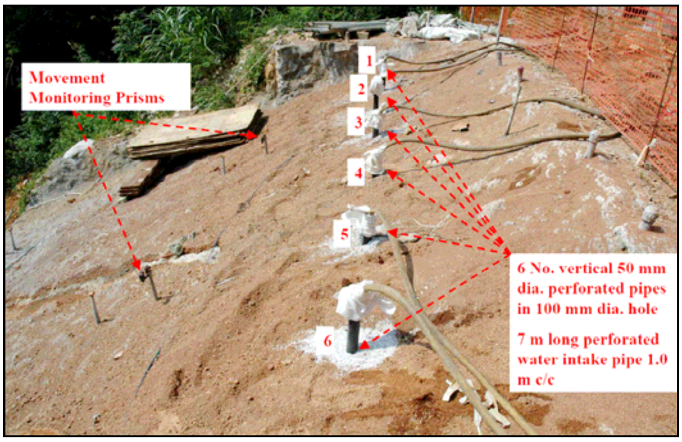

Figure 7. Water intake pipes installed.

Table 1. Summary of water intakes rate during test period.

Inflow in l/min	Pipes						
Date in 2005	1	2	3	4	5	6	Total
20-Oct.	3	3	3	3	3	3	18
21-Oct.	5	3	5	6	7.5	5	31.5
22-Oct.	10	15	10	15	6	5	61
23-Oct.	10	15	10	15	6	5	61
24-Oct.	12	17	12	17	6	5	69
25-Oct.	28	30	18	19	5	5	105
26-Oct.	28	30	18	19	5	5	105
27-Oct.	30	32	20	21	5	5	113
28-Oct.	30	32	20	21	5	5	113
29-Oct.	32	34	22	23	7	7	125
30-Oct.	40	40	45	36	12	11	184
31-Oct.	40	40	45	36	12	11	184

Figure 8 shows the maximum pore water pressure recorded in the piezometers (P2, P5, P5 and P8 location refers to Figure 5) and Figure 9 shows a typical plot of the maximum load developed in the nails (N9 location refers to Figure 10) between 20 Oct. and 31 Oct. 2005.

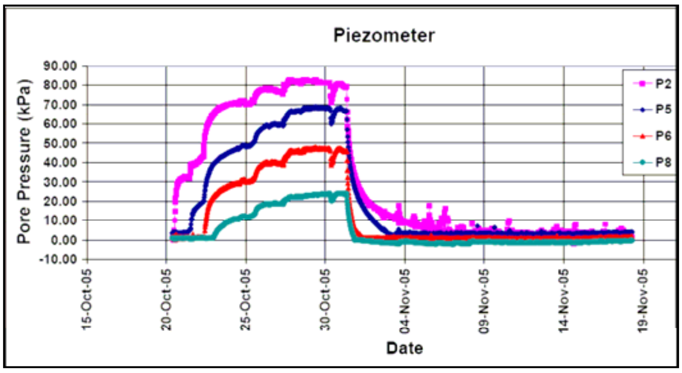

Figure 8. Pore pressure recorded during induced rise in groundwater table.

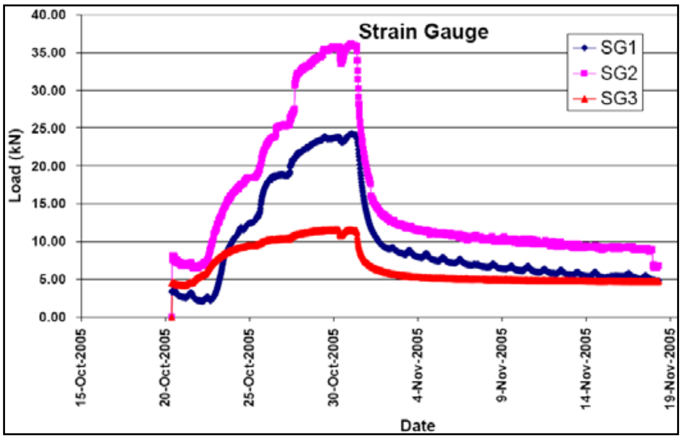

Figure 9. Load recorded in soil nails during induced rise in groundwater table.

The maximum developed force at each strain gauge location is shown in Figure 10.

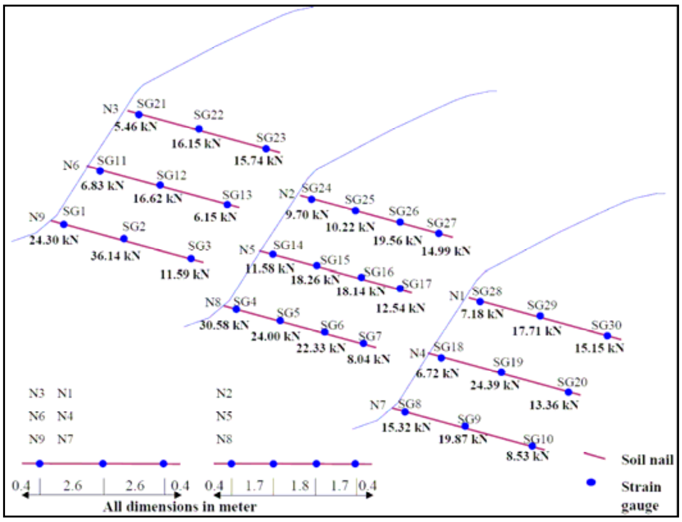

Figure 10. Load recorded in soil nails during induced rise in groundwater table.

Seepage Breakthrough Grouted Curtain at Bottom of Slope

Testing was started on 20 October 2005 and continued until 31 October 2005. During this period, water was continuously injected into the pipes with flow rate as shown in Table 1. The response of the pore water pressure within the soil masses and the load developed in the nails were spontaneous and synchronized, as reflected by the gradient of the curves in Figures 8 and 9.

Based on the elevations of the piezometers tip and the measured pore water pressures, piezometric elevation reached a maximum level equivalent to the base of the fill layer between the morning of 29 October 2005 and the evening of 30 October 2005. Water was observed seeping out at the toe and at the mid level of the slope on around 28 October 2005. When the water level reached the base of the fill layer on 30 October 2005, water was observed seeping out through the entire slope face and at the interface layer between the fill and the residual soil. The test was stopped on 31 October 2005 because any further injection of water into the slope would only cause water to seep out through the base of the fill layer, and would not cause any further increase in the piezometric elevation. After water was shut down on 31 October 2005, the water level was allowed to gradually reduce to its original level, which was below the base of the slope.

Figure 11 shows the entire slope surface was wet on 29 October 2005. A close-up view of the water seeping out at the slope face is shown in Figure 12.

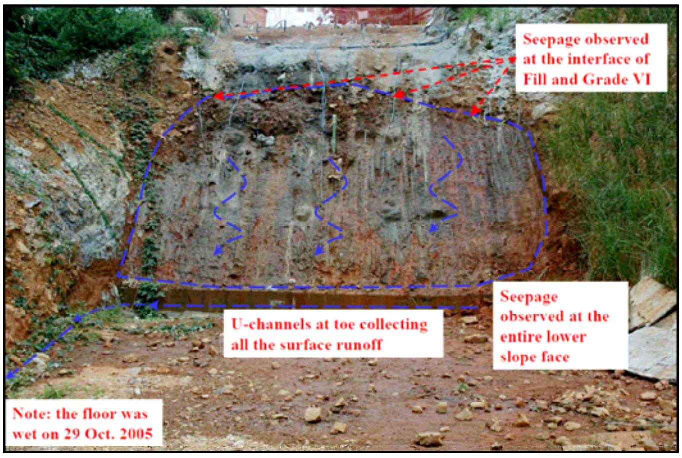

Figure 11. Observed seepage at the face of the slope.

Figure 12. Close-up view of observed seepage at the face of the slope.

The purpose of the grout curtain was to retain the injected water within the soil masses and to induce a rise in piezometric elevation. Its construction was successful as demonstrated by the piezometer readings described and the seepage observed. With a very close spacing of 0.5 m c/c at the base of the slope, the grouted holes have formed a relatively impermeable layer and allowed the water level to rise. As noted earlier, a U-channel was constructed at the toe of the slope to receive the surface runoff and to divert it away from the toe of the slope. It was very interesting to note that the floor was wet on the morning of 29 October 2005 (see Figure 13). Water could not have come from the slope surface because they were intercepted by the U-channel. The water was in fact came from below the base of the slope, as demonstrated by the water path indicated by the arrows in Figure 14. When the water level was very high on 29 October 2005, there was significant water pressure built up within the soil masses. Water eventually passed through the spaces between the bottom grouted holes, entered below the bottom of the slope and exit to the floor.

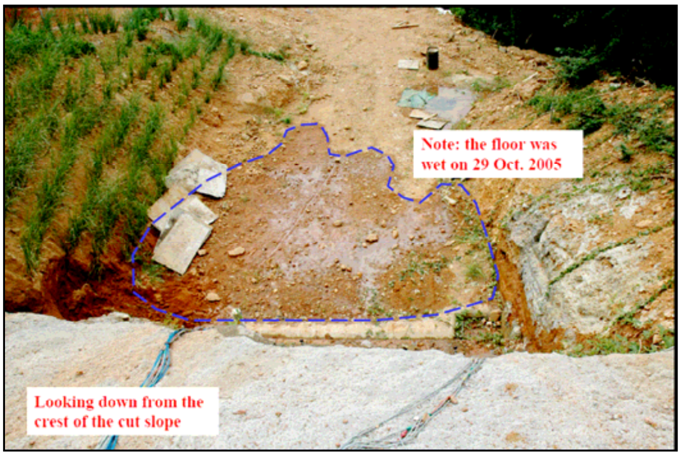

Figure 13. The floor of the slope was wet on 29 October 2005.

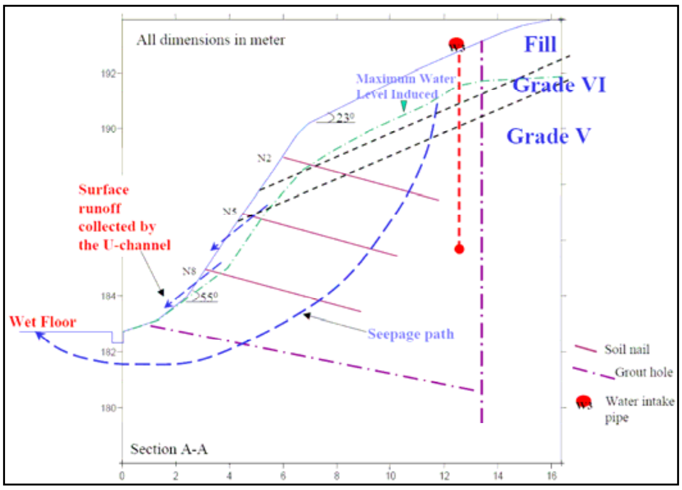

Figure 14. Flow path breaking through the bottom rows of grouted holes.

NUMERICAL MODELLING

Based on the measured piezometric levels and the movement observed from inclinometer readings, numerical modeling was carried out to simulate and to compare with the measured nail forces in order to assess the safety margin of the slope and whether it was approaching failure. Computer program GeoStudio 2004 was used and the results of the analysis were described in Kwong and Lee (2008).

The numerical assessment started with a routine design of the soil nails using limit equilibrium approach based on the geometry of the constructed slope and the determined laboratory shear strength parameters.

For a 10 m high slope with a steep angle of 55°, nine number of soil nails (in regular 2 m c/c spacing of 3 rows and 3 columns) of 6 m long high yield steel bar were needed in order to achieve a Factor of Safety (FOS) equal to 1.104 under the maximum measured water level.

Routing calculation was carried out to check the maximum nail forces that should be developed to achieve a marginally stable slope with a FOS equal to 1.104. As stated before, the resisting force is usually checked against the tensile strength of the nail, the shearing resistance between the nail and the grout, the shearing resistance between the grout and the soil, and the shearing resistance of the soil only. The results of this assessment are summarized as shown in Table 2.

Table 2. Summary of FOS using limit equilibrium method

	FOS without nail = 0.689			
	FOS with nails = 1.104			
	Maximum force allowed based on tensile strength of nail (kN)	Maximum force allowed based on shearing between nail and grout (kN)	Maximum force allowed based on shearing between grout and soil (kN)	Maximum force allowed based on shearing of the soil only (kN)
Upper Nail	81	424	57	17
Middle Nail	81	424	57	20
Lower Nail	81	424	57	25
Piezometric head shown in Figure 6.				

A finite element study was then carried out to investigate whether the measured loads were close to the design loads.

COMPARISONS OF FIELD MEASUREMENTS WITH NUMERICAL SIMULATIONS

Table 3 shows a comparison of the maximum and average load measured with that from the finite element results at the three rows of the nails.

Very close agreement can be found between the ones generated from the finite element with those measured in the field.

Table 3. Comparison of maximum and average load measured in three rows of nails with that from finite element results.

	Maximum Measured Load	Maximum Simulated Load	Average Measured Load	Average Simulated Load
	kN	kN	kN	kN
Upper Nail	19.6	29.2	13.2	15.9
Middle Nail	24.4	24.6	13.5	11.4
Lower Nail	36.2	31.4	20.1	19.5

Findings from Numerical Simulations

With the proper selection of soil parameters that have been calibrated with field measurement, and numerical simulation procedure following closely to that in the actual construction sequence, it has been demonstrated that the load simulated in the finite element model can replicate those in the field with close agreement. However, there is significant implication in practice if we then assess the stability condition of the slope with the developed nail forces. Is the slope approaching failure when the load developed is less than that assumed in the design and when the factor of safety and stability factor are so close to 1.0?

It was discussed in Kwong and Lee (2008) that if the average loads measured in the field (13 kN, 14 kN and 20 kN for the upper, middle and lower nails respectively) were used in limit equilibrium method, the corresponding FOS is equal to 0.966. Theoretically, the slope should have failed but it had not.

The stability factor (SF) of a slope by finite element stress method is defined as the ratio of the summation of the available resisting shear force to the summation of the mobilized shear force along a slip surface. This method was used and SF was equal to 1.030 at the highest water level.

This paper focused on the constructional aspects of the field test and detailed numerical assessment can be found in Kwong and Lee (2008).

CONCLUSIONS

The following conclusions can be made based on the field measurements and numerical works.

1. Rise in groundwater level was successfully induced, thus allowing the loads developed in the soil nails accurately measured.
2. Measured movement and load allowed proper calibration of material properties for numerical works.
3. The average loads at different rows of the nails from the numerical simulation compares very well with that measured, although some differences appear in the distribution along the entire length.
4. Although the FOS (based on limit equilibrium method) was close to 1.0, there was no sign of significant movement or distress observed. This may be due to the fact that soil nails have prevented the formation of shear band or distinctive slip surface. Failure of the slope may be governed by excessive movement rather than due to failure of the nail or failure of the bond between the nail and the soil. Conventional limit equilibrium method, by dividing the soil masses into vertical slices and applying a resisting force to the base of each slice, may not represent the actual soil structure interaction and a change in governing failure mechanism from distinctive slip surface to general yielding and excessive movement.
5. SF may be a good approach to use because its changes are gradual and the method considered the relative stiffness and movement between the steel and the soil.

ACKNOWLEDGMENT

The financial support by the Research Grant No. HKU7109/04E provided by the Research Grants Council of the Hong Kong Special Administrative Region, China is greatly appreciated.

REFERENCE

Cai, F. and Ugai, K. [2003]. "Reinforcing mechanism of anchors in slopes: a numerical comparison of results of LEM and FEM". International Journal for Numerical and Analytical Methods in Geomechanics, 27, pp. 549-564.

Kwong, A. K. L. and Lee, C. F. [2008]. "A numerical case study on load developments along soil nails installed in cut slope subjected to high groundwater table". The 10th International Symposium on Landslides and Engineered Slopes, June 30 to July 4, 2008, Xi'an, China (accepted).

Li, J. [2003]. "Field study of a soil nailed loose fill slope". Ph.D thesis, The University of Hong Kong, 218p.
Yim, K. P. and Yuen, K. S. [1998]. "Design, construction and monitoring of a soil nailed slope in decomposed volcanics". Slope Engineering in Hong Kong, Balkema, pp. 67-73.