SOIL NAILING FOR PUBLIC ESTATES IN HONG KONG

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ABSTRACT

Quite similar to some areas in Greater Vancouver, Hong Kong is a hilly territory in which landslides of different magnitudes may occur during the rainy season. The consequences of landslides in Hong Kong can be devastating because of the dense population, a substantial portion of which is located on the hill sides because of limited flat lands and other reasons.

The Hong Kong Housing Society presently manages approximately 40 housing estates in Hong Kong with a population of about 140,000. Of the 40 housing estates, a few of them are located near slopes whose stability has recently been found to be unsatisfactory. Improvement works to the unsatisfactory slopes were implemented by installing soil nails.

This paper presents how the unsatisfactory slopes can be repaired or improved under the conditions of limited space and high costs of possible slope failures. Different stabilization methods are considered and the most efficient and/or reliable one is found to be soil nailing. The design and construction of the stabilization works of three cases, in which the slopes (up to 35 m high) close to residential buildings have been repaired, are presented.

INTRODUCTION

Hong Kong is similar to Greater Vancouver in topography. Both cities are hilly and landslides of different magnitudes may occur during the rainy season. Because of limited flat lands and the large population, many residential buildings are located on hill slopes or near the toes of hill slopes. Around the Central District and other commercial districts, large and tall (over 20 or 30 storeys) buildings have been constructed on sloping terrains, for reasons of proximity to commercial centres, good scenery, better air quality, etc. Even in areas farther away from the commercial centres, residential buildings on or near hill slopes are also commonly found. Thus slope failures in Hong Kong often lead to loss of lives, injuries, and loss of properties. The need for slope stabilization and maintenance has become apparent.

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The Hong Kong Housing Society presently manages approximately 40 public and private housing estates and properties in Hong Kong. The total population in these estates is about 140,000. Eleven of the properties are located near or on hill slopes. To ensure a safe physical living environment for the estate residents, the Society makes use of the services of different geotechnical consultants in the inspection, assessment and maintenance of the slopes. Recent assessments show that a few of the slopes do not have satisfactory safety margins. This paper presents how some of the unsatisfactory slopes can be repaired or improved under the conditions of limited space and high costs of possible slope failures.

Three cases in which the slopes (up to about 35m high) close to residential buildings have been repaired are discussed in this paper. In the following section, different stabilization methods are considered. After deciding that the most efficient and/or reliable one is soil nailing, the analysis and design of soil nailing is briefly described. Then the construction and monitoring of the slope stabilization works are presented, and finally comments and conclusion are made.

ALTERNATIVES FOR SLOPE STABILIZATION

In the three housing estates considered in this paper, slopes of considerable heights exist close to residential buildings. For example, in Tanner Hill Estate (see the following sections), the crest of a 18 m high slope is only 2 m away from a residential building. Also, quite often only limited access needed for slope repair works is available. Considering the alternatives for slope repairs in these cases, conventional gravity or inverted-T-shaped retaining walls are ruled out because of limited space and the large volumes of soil and rock which need to be excavated before the retaining walls can be constructed. Other alternatives are raking piles, cantilevered retaining wall, soil/rock anchors, support ties to existing buildings, and soil nails. The main pros and cons of each of the alternatives are:

Raking piles - There is considerable difficulty of mobilising heavy piling equipment at the top of the hill. Vibration due to piling may cause detrimental effects to slope. For example, loose boulders on slope may be affected. To the best of the knowledge of the authors, this technique has not been tried out in Hong Kong.

Cantilevered retaining wall - A caisson wall can have large stiffness compared to a gravity retaining wall. It is a proven slope stabilisation technique in Hong Kong, but the cost of construction is comparatively great. Also, there are considerable safety hazards for the caissons are hand-dug. Mechanically excavated walls (e.g. bored pile walls and diaphragm walls) are also expensive and there are large difficulties in mobilising the heavy machineries required in areas with limited space.

Soil/rock anchors - Soil/rock anchors can be used to stabilize a slope by tying the outer slope to the soil/rock mass deep into the slope. However, because the anchors are under high tension, strict and cautious maintenance and regular inspections are required.

Support ties to existing buildings - Steel or reinforced concrete support ties can be constructed between the slope face and the buildings nearby. Lateral resistance, mainly derived from the weight of the buildings and their foundations, can be used to stabilize the slope. However, the design for such stabilising system is complicated because it involves checking the foundation and structural strength of the existing buildings. Also, the ties have to be properly connected to the buildings, probably at the floor levels. Thus design and construction cost can be great.

Soil nails - Soil nails can be installed using relatively light machineries. Only small spaces are required for the works and disturbance to the existing slope is small. The construction cost is not large compared to other viable alternatives. The use of soil nailing in stabilizing slopes in Hong Kong has been proven to be effective in many cases (Watkins and Powell 1992; Chung et al 1991; Shen 1991).

Based on the above considerations, soil nailing is found to be the most efficient/reliable method in the stabilization of the marginally stable slopes.

BACKGROUND, ANALYSIS AND DESIGN OF SOIL NAILING

Background

Soil nailing was first used during the development of the New Austrian Tunnelling Method in which the strength of the ground mass itself was mobilized to help to stabilize tunnel excavations. Then about 30 years ago soil nailing was being used in Canada, France and Germany. Nowadays Germany, France, and the USA are the main practitioners of the technique. Soil nailing had been quite sparingly used in Hong Kong before 1987, when interest in soil nailing blossomed (Powell and Watkins 1992). Soil nailing in Hong Kong is mostly used to improve the stability of marginally stable slopes.

Analysis and design

Basically the soil nails act as tensile reinforcements in the soil which could prevent a potential slope failure during critical times such as the times just after heavy rainfalls. As opposed to soil anchors, soil nails are not tensioned after installation. Tension is only developed when the soil mass in the slope deforms under adverse loading conditions such as rising ground water levels or surcharging on the crest of the slope. The developed tension helps to bind the soil mass together and prevents failure.

In the design of the soil nail, different possible modes of slope failure under adverse loading conditions must be considered. Watkins and Powell (1992) classify the different failure modes into "external" and "internal" modes (Fig. 1). In the common practice in Hong Kong, the failure mass is considered to be in the form of a monolith, and a single sliding plane of failure is considered. Then the method of slices (usually Janbu's method [Janbu 1972] is used) is used for slope stability analysis to find the lowest factor of safety against sliding. The soil nailing is then designed so that the required factor of safety (usually 1.2 or higher) can be maintained. Sufficient factors of safety for the possible failure of the soil mass in the form of a gravity retaining wall (the external modes of failure) and the internal modes of failure have also to be maintained. The typical details of a soil nail is shown on Figure 2.

At this point it is interesting to notice that there is another design method that can be used. In this method, apart from the monolithic failure modes, another failure mode involving the equivalent gravity wall and an earth pressure wedge is considered (Gnilsen 1988) (Fig. 3). However, according to Gnilsen (1988), if the critical mode of failure involves a slip plane that lies within the nailed soil zone, then the two design methods will virtually give the same results. In Hong Kong most slope failures are shallow and provided that the soil nails are of sufficient lengths, the design method using a monolith is sufficient.

The stability of the three slopes presented below was analysed by Janbu's simplified method of slices. The design water table was assumed at one-third of the slope height. The design principle of the soil nails was to determine the stabilizing force required to increase the factor of safety of any particular slip plane to the required minimum safety factor. This force was then provided by tensile force in the soil nail through bonding with soil. The force was evaluated from slope stability analysis using Janbu's simplified method. The required stabilizing force was distributed to the nails in a triangular pattern. The internal stability of the soil nails was checked against the tensile failure, pull-out capacity, bond failure between soil and grout, and bond failure between grout and steel. The pull-out resistance between soil and grout was based on the equation proposed by Cartier and Gigan (1983) with a safety factor of 2.0.

A 2 mm sacrificial radius is allowed for long term effect of the reinforcement corrosion. The working tensile stress on the steel bar was assumed to be 50% of the ultimate tensile stress. Strength of grout and ultimate stress of steel bar of 25 MPa and 425 MPa, respectively, were adopted for the design.

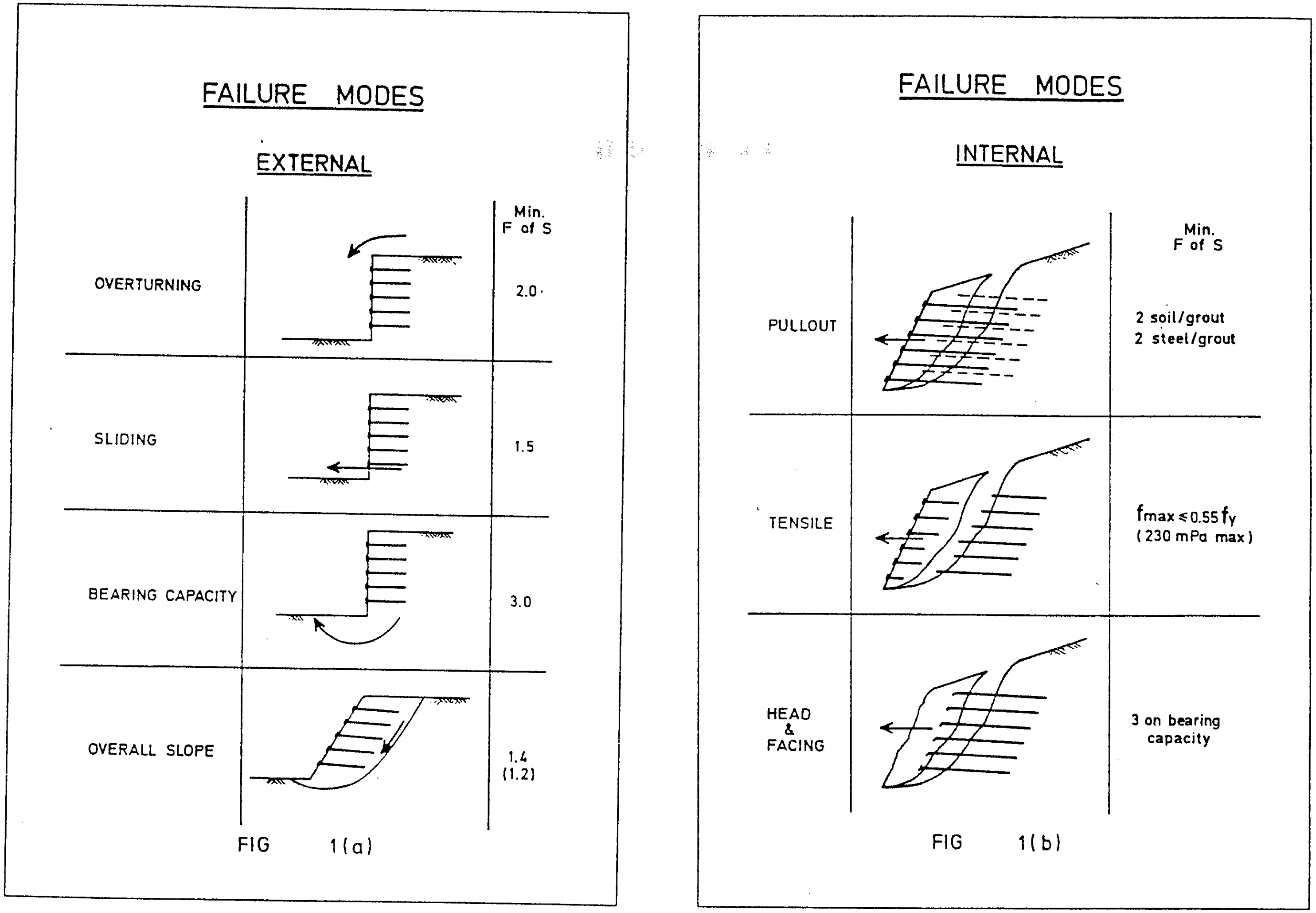


Figure 1. Failure modes for soil nailed slope. (From Watkins and Powell 1992).

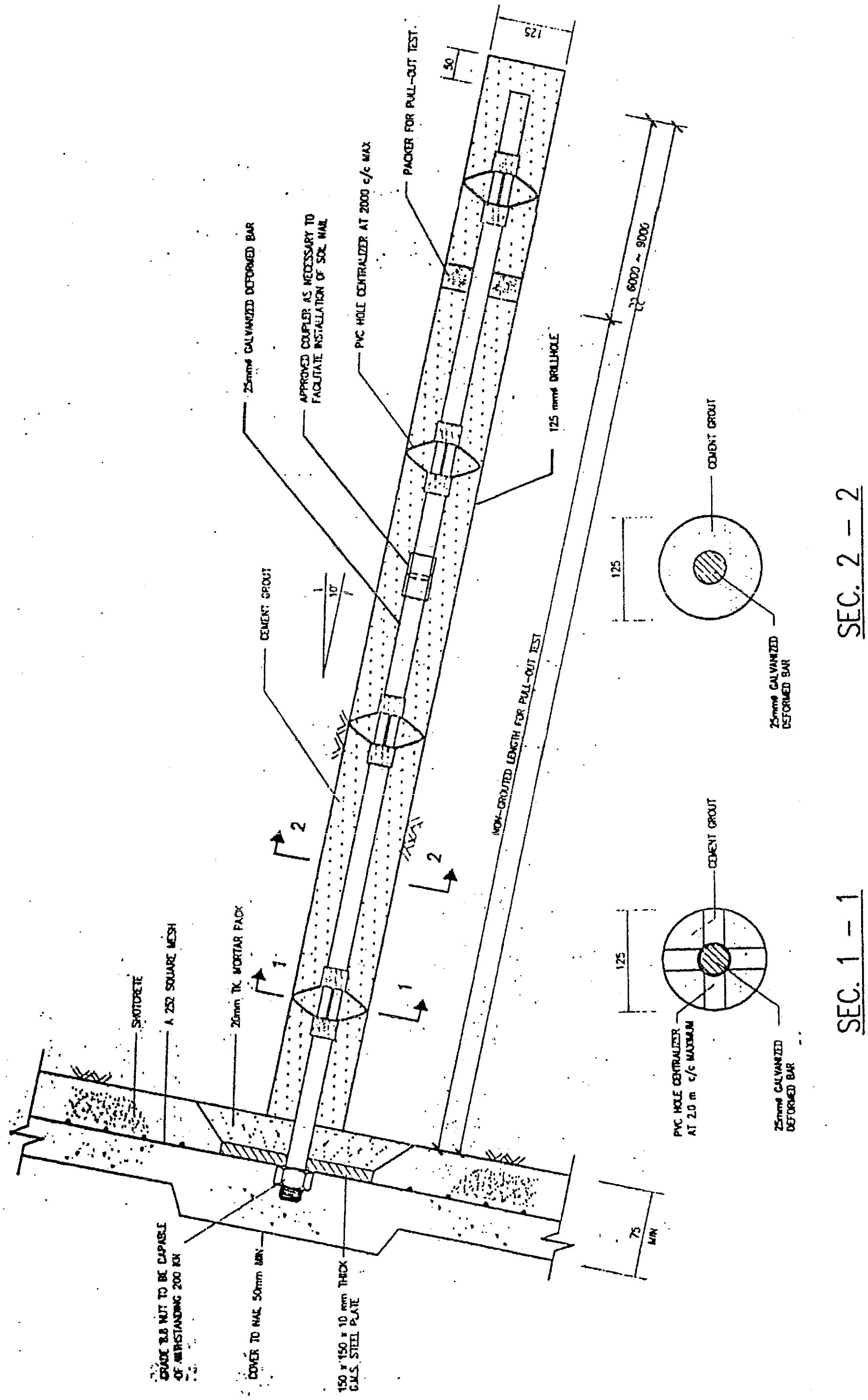


Figure 2. Typical soil nail details.

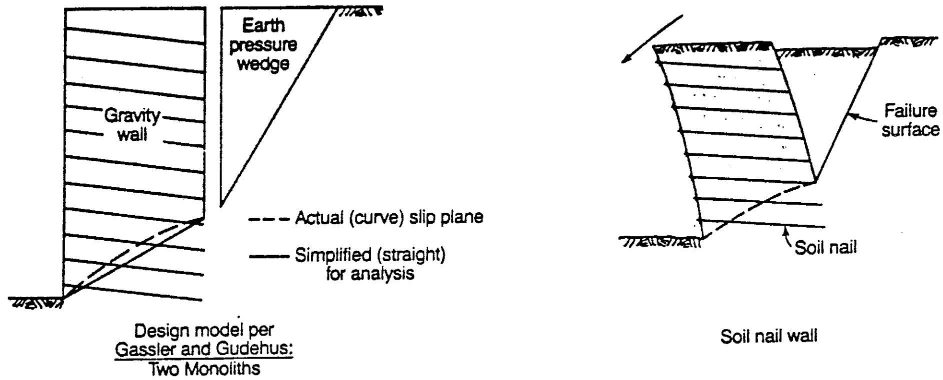


Figure 3. Alternative failure mode. (From Gnilsen 1988)

CASE 1 - LAI TAK TSUEN ESTATE

Site Conditions and Soil Profile

The slope is horse-shoe shaped in plan, surrounding a playground on three sides, with length of about 62 m and height ranges from 6 to 35 m. The two sides of the slope are covered by chunam (Hong Kong's name for a soil-cement mixture) and rock outcrops at a slope angle of 70° to 80°. The middle section of the slope consists of a 9 m high 80° chunam batter and a densely vegetated 26 m high 40° to 50° cut slope. The nearest building is about 30 m west of the slope, but the playground at the toe of the slope is a major recreation playground for the estate.

In a 1990 subsurface exploration for a nearby slope, one borehole was advanced with a piezometer installed and one chunam stripping was excavated. A subsurface exploration for the slope, comprised of two boreholes (one vertical and one horizontal) and four trial pits was carried out in November 1993. The locations of borehole and chunam strip are shown on Figure 4. Undisturbed soil samples were taken using Mazier triple tube core barrels and Standard Penetration tests were preformed. Soil index properties tests and multi-stage consolidated undrained triaxial tests with pore pressure measurements were performed on the samples.

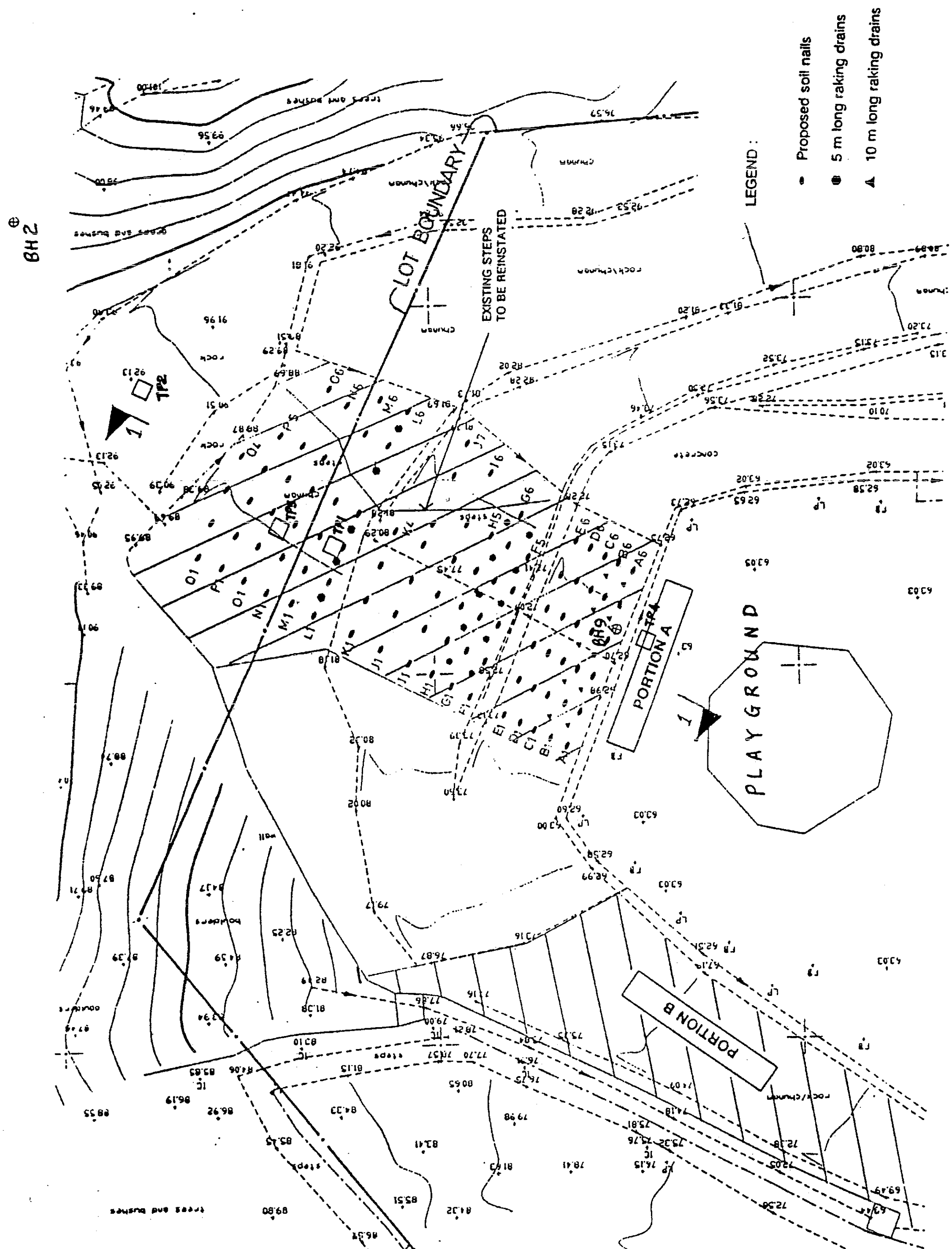


Figure 4. Site plan of slope 11SE-A/C135 at Lai Tak Tsuen Estate.

The two sides of the slope is consisted of slightly weathered granite while the middle section is consisted of completely to highly weathered rock. The subsurface profile of the middle section is consisted of 2 m of loose, greyish brown clayey silty fine to coarse sand with many large boulders (Colluvium); overlying dense to very dense, light yellowish brown pink, fine to coarse sand, Completely Decomposed Granite (CDG); overlying weak to moderately strong, pinkish grey mottled black, medium grained, medium to closely spaced joints, Highly to Slightly Decomposed Granite. The inferred subsurface stratigraphy of the site is shown on Figure 5. The following soil parameters derived from the laboratory test results were adopted in stability analyses and soil nail design:

Soil Description	Unit Weight (kN/m^3)	C' (kPa)	ϕ' (degree)
Colluvium	19	4	32
Medium dense to dense CDG	19	6	39
Very dense CDG	19	9	41

No seepage was observed apart from minor seepage noted at a few weepholes at the lowest batter and slope surface was noted to be dry. Records of the piezometer indicated that ground water is about 10 m above the bedrock at the upper part of the slope. The groundwater monitoring records indicate that the groundwater was generally 5 to 7 m below ground level.

Design and Proposed Improvement Works

The minimum factor of safety against slope failure depends on the level of risk to life and economic losses. Current Hong Kong Government standards require that the minimum factor of safety for existing high risk slopes be 1.2 for groundwater levels associated with rainstorms of 1 in 10 years return periods. A minimum safety factor of 1.4 was adopted for this slope because of the presence of an open playground at the toe of the slope. The analysis revealed that the calculated factors of safety are marginally above unity. Soil nailing with shotcreting cover was therefore recommended to improve the stability of the slope.

The proposed soil nails were spaced at 2 m horizontally and 2 m vertically. Nails of 32 mm diameter and 20 m maximum length were required for the critical section. Soil nails were to be installed directly into 125 mm diameter drilled holes inclined at 10° below horizontal. A total of about 96 nails was required. The slope surface was to be protected with 75 mm

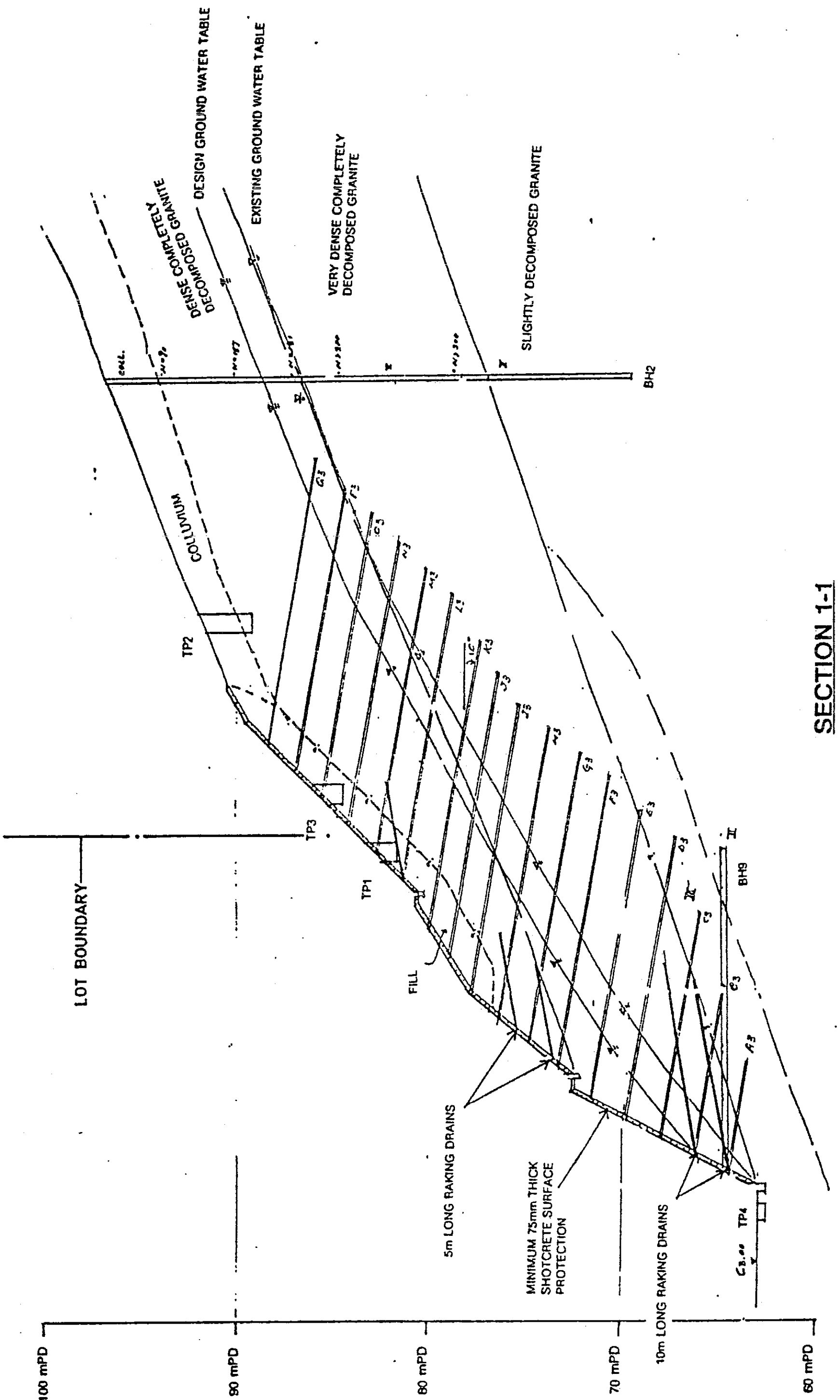


Figure 5. Section 1-1 of slope 11SE-A/C135 at Lai Tak Tsuen Estate.

thick shotcrete applied in at least 2 layers.

To minimize the effect of the possible perched water table, twenty five horizontal drains were recommended to be installed in the central section of the slope.

Construction

A typical cross-section of the slope reinforced by soil nailing is illustrated in Figure 5. Rotary percussion drilling rigs were used for nail installation were. They are relatively small and mobile and were suitable for this slope with access constraints. Working platforms were provided for nail installation. Drilled holes of diameter 125 mm were formed at spacing of 2 m horizontally and 2 m maximum vertically. The holes were drilled at 10° below horizontal. Casing was not required as groundwater was not encountered and collapse of holes did not occur. All the nails were installed with a minimum of 2 m embedment length within the Slightly Decomposed Granite.

High yield steel with diameter 32 mm were used as nails and grouted into predrilled holes with cement grout (water cement ratio <0.45) under gravity or very low excess pressure. Couplers were used to join the bars together. Centralizers were placed at regular intervals (1.5 m) along the reinforcement to ensure concentricity with the drillhole. The faces of the nails were then formed with 350 mm square concrete pads to locally stabilize the slope face. Twenty five horizontal drains were installed row by row in the central section of the slope. The construction was completed in about 3 months near the end of October 1995.

Pull-out tests were performed on trial soil nails to verify the design parameters and assumptions so that modifications could be made to account for any deviation and change of the existing site condition. A total of 10 pull-out tests, which was approximately 10.4 % of the total number of nails installed, were carried out. The data of test results are summarized in Table 1. A typical graphical presentation of pull-out test results is shown in Figure 6.

None of the tests failed to reach the test load 1.5 times the working load. The soil nail extensions under the test load (T_p) were well below the specified acceptance limit (0.3% of the grouted length of the nail). These test results indicate that the bond stress design approach adopted was adequate.

Table 1. Summary of pull-out test results

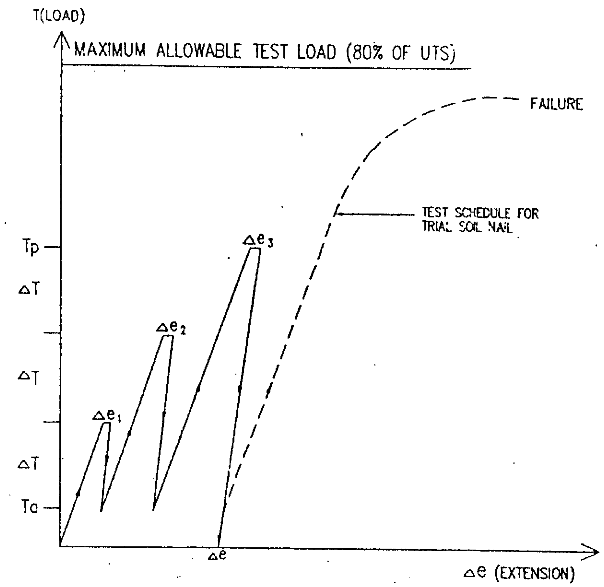
Test No.	Bar Dia. (mm)	Depth of Nail below crest (m)	Working Load (kN)	Ultimate Test Load, T_p (kN)	Total Length (m)	Grout Length (m)	Extension under T_p (mm)
PO1	32	26	160	240	4	4	1.39
PO2	32	20	160	240	8	6	6.52
PO3	32	22	160	240	10	6	6.50
PO4	32	22	160	240	17	6	14.57
PO5	32	20	160	240	9	6	8.85
PO6	32	13	160	240	6	6	1.83
PO7	32	12	160	240	8	6	9.02
PO8	32	11	160	240	12	6	6.42
PO9	32	10.5	160	240	13	6	8.26
PO10	32	7	160	240	10	7	7.08

CASE 2 - TANNER HILL ESTATE

Site Conditions and Soil Profile

The site is located on Tanner Hill, North Point, Hong Kong. Tanner Hill Estate is comprised of two residential blocks constructed on a series of terraces cutting into the natural hillside. The concerned slope is located adjacent to the two residential blocks as shown on Figure 7. It was covered with chunam (a soil-cement mixture) with some rock outcrops at the middle section. The slope is about 7 to 17 m high and 40 m long with an average slope angle of 50°. Weepholes of 75 mm diameter were installed at 1.5 m spacing. Stepped channels and U-channels were provided on the slope and at the crest. Bulging and cracking of chunam cover were noted.

A subsurface exploration, comprising three vertical boreholes and two chunam strips, was carried out between 9 June and 5 July 1993. The locations of boreholes and chunam strips are shown on Figure 7. Undisturbed soil samples were taken using Mazier triple tube core barrels and Standard Penetration tests were performed. Observation wells were installed



NOTES:

Tp – SPECIFIED TEST LOAD (1.5 x Tw)

Ta – INITIAL SEATING LOAD = 0.2 Tp

Δe_i – THE INCREASE IN EXTENSION UNDER CONSTANT LOAD IN THE i[th] LOADING CYCLE.

Δe – TOTAL INCREASE IN EXTENSION AFTER TESTING THE PROPOSED SOIL NAIL

ΔT – LOAD INCREMENT FOR EACH CYCLE = (Tp – Ta)/3

UTS – ULTIMATE TENSILE STRENGTH OF STEEL BAR

Project : Slope Stability Improvements For Slope 11SE-A/C135 Lai Tak Tsuen

SOIL NAIL PULL OUT TEST - DATA PLOTTING SHEET

Soil Nail Ref. No : PO 10 Date of Test : 7-Aug-95

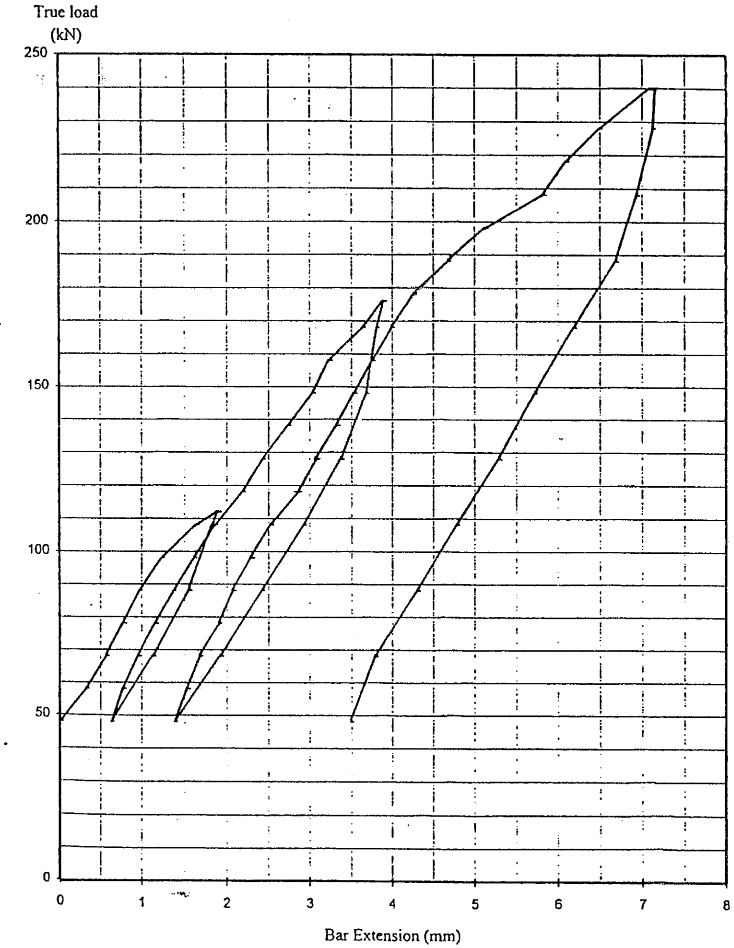


Figure 6. Load test path and typical results of pull-out test.

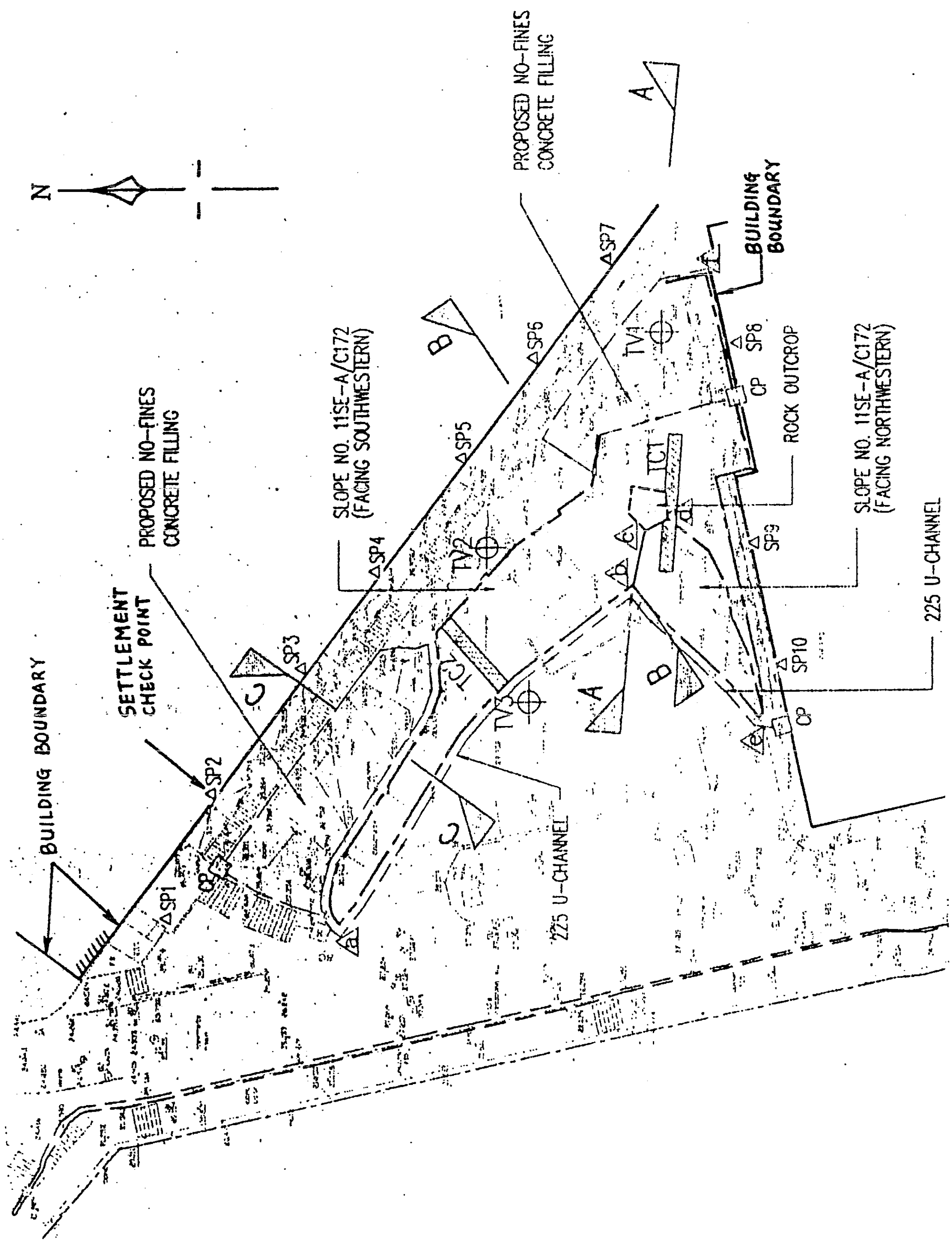


Figure 7. Site plan of slope 11SE-A/C172 at Tanner Hill Estate.

in all boreholes to monitor the groundwater level. Soil index properties tests and multi-stage consolidated undrained triaxial tests with pore pressure measurements were performed on the samples.

The subsurface profile consisted of loose to medium dense, yellowish brown silty sand with gravel (FILL); overlying medium to very dense, yellowish brown silty gravelly sand (Completely Decomposed Granite); overlying moderately strong to strong, pinkish grey mottled black, medium grained, medium to closely spaced joints, Moderately to Slightly Decomposed Granite. The groundwater monitoring records indicate that the groundwater was generally 5 to 7 m below ground level. The subsurface profile is inferred as shown on Figure 8. Soil strength parameters of $c' = 0$ kPa and $\phi' = 36°$ for fill; $c' = 9$ kPa and $\phi' = 36°$ for completely decomposed granite were obtained. The unit weights for fill and completely decomposed granite are 19 kN/m^3.

Design and Proposed Improvement Works

A minimum safety factor of 1.2 against slope failure with a surcharge of 5 kPa at slope crest were adopted for this slope. Slope stability analysis using the simplified Janbu's method revealed that the safety factor is below unity. Using Janbu's simplified method, the horizontal force necessary to bring the minimum safety factor to 1.20 was calculated and a soil nailing system was designed to provide this resistance.

The proposed soil nails were spaced at 1.5 m horizontally and 2 m vertically. Nails of 25 mm diameter and 6 to 9 m lengths were proposed. Drilled holes of 125 mm diameter inclined at 10° below horizontal were required to accommodate the nails. A total of 77 nails was required. The slope surface was to be protected with 75 mm thick shotcrete applied in at least 2 layers. In two areas, the upper 2 m of the loose fill was required to be replaced by no-fines concrete.

Construction

A total of 77 nails were installed for this slope. Soil nails were installed row by row in the proposed slope in panels from top to the base of the slope. High yield steel with diameter 25 mm were used as nails and installed following the same procedure as in Case 1. The faces of the nails were also formed with 350 mm square concrete pads to locally stabilize the slope face.

In the two areas where the loose fill was excessively thick, up to 2 m of the fill was replaced by no-fines concrete. The construction was completed in about 3.5 months near mid-January 1996.

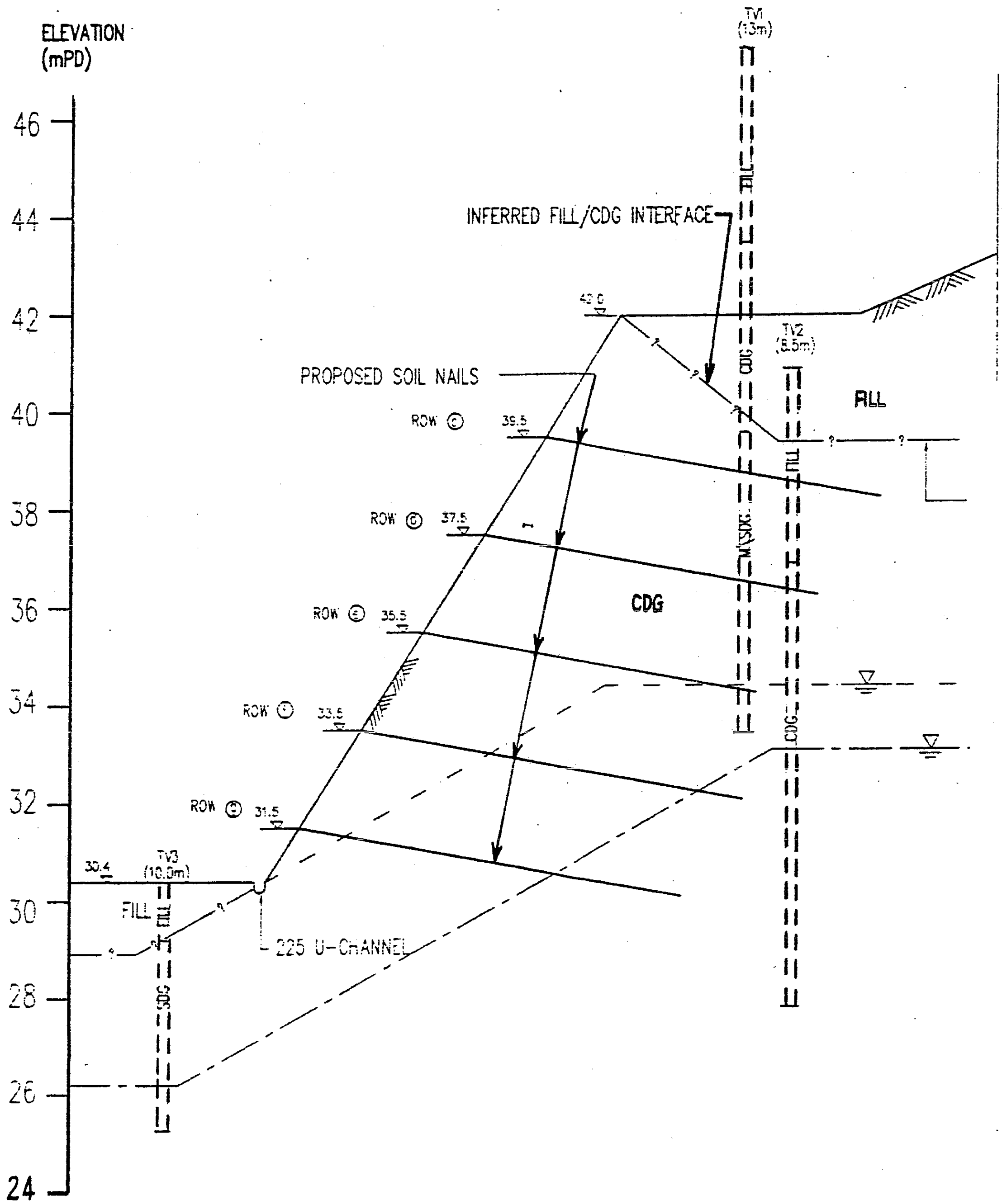


Figure 8. Section B-B of slope 11SE-A/C172 at Tanner Hill Estate.

Five pull-out tests on trial soil nails (about 6.5 % of the total number of nails installed) were conducted on site. The nail lengths varied from 7 to 8 m with 2 m grout lengths. The working loads varied from 20 to 66 kN and the testing loads (1.5 times the working load) varied from 30 to 100 kN. All the tests were successful in reaching the test load without failure. The soil nail extensions under the test load (T_p) were again found to be well below the specified acceptance limit (0.3% of the grouted length of the nail).

Because of the presence of residential buildings along the slope crest, ten settlement check points were installed along the slope crest prior to construction. These settlement points were monitored daily during the construction and weekly after the construction for 2 months. Maximum settlements of 0 to 3 mm were observed during the construction. No further settlement was observed after the completion of the construction. The three piezometers located at TV1, TV2 and TV3 were also monitored daily during the construction. No significant variation of groundwater table was observed during the construction.

CASE 3 - YUE KWONG CHUEN

Site Conditions and Soil Profile

The site is located at the northern portion of the estate. Along the slope crest is a main road. A residential building is located about 5 m from the toe of the slope. The slope consists mainly of completely decomposed tuff comprising sandy silt material. The slope face is covered by chunam with rock outcrops at various locations. The slope is about 2 to 7 m in height and is about 30 m in length with an average slope angle of about 65°. No weepholes were provided on the slope face. Surface drainage channels have been provided along the crest and the toe of the slope.

A subsurface exploration, comprising two vertical boreholes and one chunam strip, was conducted between 4 and 26 June 1993. Similar to Cases 1 and 2, Mazier samples were obtained with Standard Penetration tests preformed between the Mazier samples. Observation wells were installed in the boreholes to monitor the groundwater level. Soil index properties tests and multi-stage consolidated undrained triaxial tests with pore pressure measurements were performed on the undisturbed samples.

The subsurface profile consisted of medium dense, reddish yellow, clayey silty sand with gravel (FILL); overlying firm, reddish yellow, very clayey sandy, dandy silt with rock fragments (Completely Decomposed Tuff); overlying moderately strong to strong, light yellowish grey with spotted white coarse grained closely to medium spaced joints, Moderately to Slightly Decomposed Tuff. The groundwater monitoring records indicate that the groundwater was generally about 6 m below the toe of the slope. Soil strength parameters of $c' = 4$ kPa and $\phi' = 33°$ for completely decomposed Tuff (CDT) were obtained. The unit weight of CDT was found to be 19 kN/m^3.

Design and Proposed Improvement Works

A minimum safety factor of 1.2 against slope failure with a surcharge of 10 kPa at slope crest were adopted for this slope. Dry condition was assumed in the slope stability analysis. The analyses show that the minimum factor of safety of the slope was below unity and therefore slope stabilization works was required. Using Janbu's simplified method, the horizontal force necessary to bring the minimum safety factor to 1.20 was calculated and a soil nailing system was designed to provide this resistance.

The proposed soil nails were spaced at 2.0 m horizontally and 1.2 m vertically. Nails of 25 mm diameter and 7 to 9.5 m lengths were required to be installed into the 125 mm diameter drilled hole inclined at 10°. A total of 70 nails was required. The slope surface was to be protected with 75 mm thick shotcrete applied in at least 2 layers.

Construction

A total of 70 nails were installed. Soil nails were installed in panels from top to the base of the slope following the same procedure as in Cases 1 and 2. The construction was completed in about 3 months near the end of December 1995.

Five pull-out tests were performed. The nail lengths varied from 5 to 9.5 m with 2 m grout lengths. The working loads varied from 17 to 37 kN and the testing loads (1.5 times the working load) varied from 26 to 56 kN. The pull-out tests were all found to be successful with the soil nail extensions under the test load well below the specified acceptance limit.

Adjacent structures and roadways were observed daily for any signs of distress during the construction. No significant settlement and no signs of distress on the adjacent structures or ground were observed during the construction. The two piezometers located at YV1 and YV2 were also monitored daily during the construction. No significant variation of groundwater table was observed during the construction.

COST COMPARISON

The costs for soil nail installation of the three presented cases is averaged to be approximately HK$3,000 (C$550) per m^2 of slope surface repaired. Costs for other alternatives, e.g. hand-dug caissons, are estimated to be at least 2 to 3 times as high.

CONCLUSION

The three case histories described indicate that soil nailing can be used for the support of major cuttings up to 18 m. Soil nailing can be used to improve the safety standard of steep slopes in sites with access constraint without changing the slope geometry.

All the test results indicate that the assumed soil/grout bond is adequate. In fact in most cases, much higher bond stress was measured.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the permission of the Hong Kong Housing Society to publish the information in relation to the case histories. The contents do not necessarily reflect the views and policies of the Hong Kong Housing Society and are solely the views of the authors.

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