# Design, construction and performance of a soil nailed excavation in Hong Kong
## Dessin, construction et accomplissement d'une excavation cloutée au sol, à Hong Kong

Y. K. Shiu, P. C. Y. Yung & C. K. Wong – *Geotechnical Engineering Office, Hong Kong*

ABSTRACT: Soil Nailing is an insitu ground improvement technique. For the last decade, this technique has been widely used in Hong Kong as an economic, effective and simple means for stabilizing cut slopes and retaining excavations. This paper describes the design, construction and performance of an instrumented soil nailed excavation in Hong Kong. Interpretation and analysis of field monitoring results are also presented. The behaviour of the nailed excavation derived from numerical modelling is compared to the field measurements.

RESUME: Le cloutage du terrain est une technique d'amélioration du sol sur le site. Durant la dernière, décennie, cette technique a été amplement utilisée à Hong Kong, comme étant les moyens économique, efficace et simple de stabilisation des pentes coupées et de retention des excavations. Ce papier décrit le dessin, la construction et l'exécution d'une excavation de sol clouté, au truchement d'équipement; à Hong Kong. Les résultats d'interprétation et d'analyses de control du terrain sont aussi présentés. La conduite de l'excavation cloutée dérivée du modelage numérique est comparée aux mesurages du champ.

## 1 INTRODUCTION

An excavation into the toe of a natural hillside was necessary for the purpose of constructing a large pumping station. This involved forming steep cut slopes up to 13.5m in height. The technique of soil nailing was used to provide permanent lateral support to the deep excavation.

Instrumentation was installed for monitoring the performance of the nailed excavation both during and after construction. The field monitoring was carried out during the period between April 1993 and July 1994. In order to gain understanding of the basic mechanics of the behaviour of the nailed slope, numerical modelling was also performed using the explicit finite difference code called FLAC (Fast Langrangian Analysis Continua). This modelling method was developed by Cundall (1976).

This paper summarises the design and construction of the nailed excavation, and discusses the results of the field monitoring. The results of the numerical modelling are compared with the field monitoring data.

## 2 DESCRIPTION OF THE SITE AND GEOLOGY

The site is located at the toe of a natural slope at the northern part of Hong Kong Island. The natural slope stands at an average angle of 33°. Based on information obtained from a detailed site investigation, the geology of the site comprises up to 15m of completely decomposed granite (CDG) overlying a thin layer of highly decomposed granite (HDG) which in turn grades into moderately to slightly decomposed granite (M/SDG) at depths of about 12m to 20m. The ground water table was below the base of the excavation.

The excavation was mainly carried out in CDG. The effective shearing strength parameters of this material are $c'$ = 16 kPa and $\varphi'$ = 37°.

## 3 DETAILS OF THE SOIL NAILED CUT SLOPE

The soil nailed cut slope was formed at angles up to 80°. The nails were generally installed at a horizontal spacing ($S_h$) of 1m and a vertical spacing ($S_v$) of 1.5m. The lengths of the soil nails vary between 6m and 11m. The most critical section of the nailed slope is shown on Figure 1. In this section, the nails on rows 1 to 4 are 10m long and the others are 11m long.

Each nail consists of a high yield steel bar grouted over its full length into a 100mm diameter pre-drilled hole. The holes were formed by percussive dry drilling without steel casing. The nails were placed at an inclination of 10° to the horizontal. The diameters of the steel bars are either 32mm or 40mm. For corrosion protection purpose, all the steel bars were hot-dip galvanized. Also, a sacrificial thickness of 2mm on the bar radius was allowed for in the design to account for probable loss of steel with time. The final excavation face was protected by a 100mm thick shotcrete facing reinforced with a layer of steel mesh. The typical details of the soil nails are shown on Figure 2.

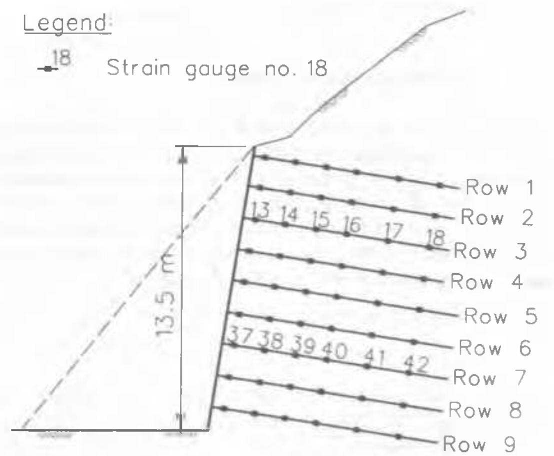


Figure 1. Critical section of the soil nailed slope.

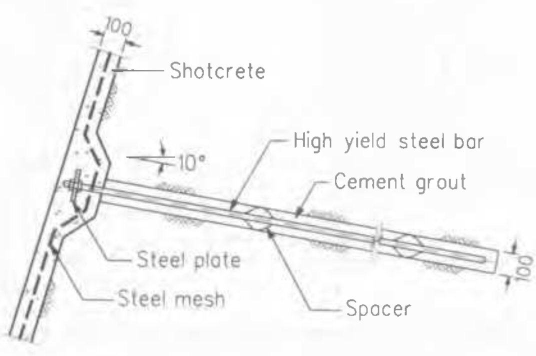


Figure 2. Typical details of soil nail.

## 4 DESIGN METHOD OF SOIL NAILS

In Hong Kong, a force limit equilibrium approach is commonly used for soil nail design. Full details of this design approach are described by Powell and Watkins (1990). Both external and internal stability must be considered in the soil nail design. The external stability checks consider the bearing failure, and slip failures both within and outside the nailed soil mass.

The internal stability checks consider the pull-out and tensile failures of the soil nails. This requires the knowledge of the soil/nail interaction mechanism which at present is still poorly understood. In Hong Kong, Janbu's Simplified or Rigorous Method is normally used to calculate the total horizontal force that will be required to increase the factors of safety of the potential slip surfaces to the required value. The soil nails are then designed to provide this force. The distribution of this horizontal force along the sliding plane has been a matter of some debate. It is often assumed that the force is distributed evenly among the nails.

In this project, the design of the nailed slope was more or less based on the force limit equilibrium approach but the sequence of excavation was also taken into consideration in the design of nail loads. Particular regards were given to the spacings of the nails. Close vertical and horizontal spacings were provided to ensure that the nailed soil body would behave as a monolithic body.

## 5 FIELD INSTRUMENTATION SYSTEMS

Several field instrumentation systems were used for monitoring slope deflections, nail loads, groundwater tables and ground settlements. In this paper, only the systems relating to slope deflection and nail load monitoring are discussed.

### 5.1 *Slope deflection monitoring system*

An inclinometer casing was installed at the most critical section of the nailed slope for monitoring lateral displacements of the nailed slope during and after construction. The inclinometer casing was located at about 1m from the crest of the slope. Readings were taken at weekly intervals during and after construction.

### 5.2 *Soil nail load monitoring systems*

Nine soil nails in the most critical section of the slope were instrumented to measure the distribution of nail forces. Along the length of each nail, six vibrating wire strain gauges were installed to the steel bar. The arrangements of the strain gauges are shown on Figure 1. As only single gauge was used at each location, bending moment of the bars could not be measured. The strain gauges were generally read weekly throughout the monitoring period.

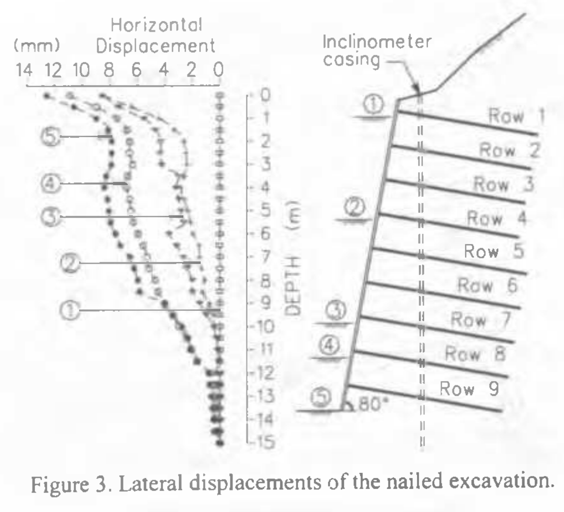


Figure 3. Lateral displacements of the nailed excavation.

## 6 INCLINOMETER MONITORING RESULTS

Lateral displacements of the inclinometer recorded during and after the excavation are shown on Figure 3. The following observations can be made from this displacement plot:

1. The lateral displacement increased as the excavation depth increased.
2. At each lift of excavation, the maximum lateral displacement was at the top of the nailed slope.
3. The displacement pattern was similar at each lift of excavation.

The maximum displacement at the top of the nailed slope at the end of construction was 13mm which is equal to 0.1 % of the height of excavation. This is comparable to the range of typical values (0.1% - 0.3%) reported by different researchers in connection with nailed excavations. Figure 4 shows the monitoring result of the subject slope and other published data on horizontal displacements.

No appreciable further movements were measured after the completion of construction.

## 7 STRAIN GAUGE MONITORING RESULTS

The strain gauge monitoring data provided valuable information on the behaviour of the nailed excavation. This included the development and distribution of load along nail length, and responses of the soil nails to each excavation lift. Such behaviour cannot be predicted by the force limit equilibrium analysis.

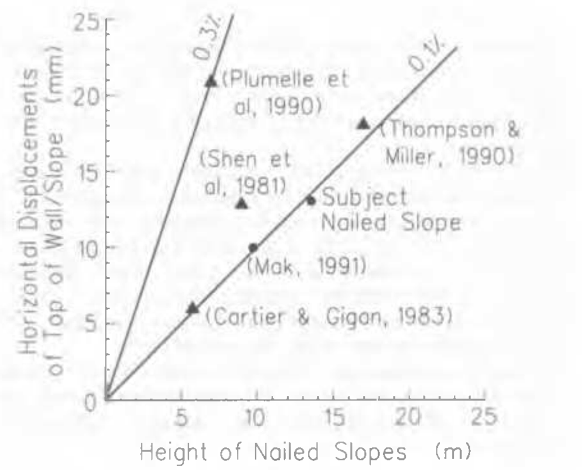


Figure 4. Published data on horizontal displacements of soil nailed slopes/walls.

### 7.1 *Responses of soil nails to excavation*

Figure 5 shows the strain measurements (expressed as forces) from the nail on row 7 over the monitoring period. The responses of the strain gauges to the two subsequent lifts of excavation are indicated clearly as rapid increases in forces. Following the completion of construction, there was a slow increase in force for a short period of time and no further noticeable changes thereafter. This was probably related to the construction of the shotcrete facing.

The distribution of nail forces along the nails on rows 3 and 7 and their responses to excavation lifts are shown on Figure 6. The effect of advancing excavation was significant on row 7 but was much less noticeable on row 3. The stress distribution in row 3 was rather uniform and did not increase appreciably with depth of excavation. Similar observations can be made on other nails at the upper part of the slope, indicating that the upper nails (rows 1 to 4) did not have substantial contribution to the retaining force of the nailed slope. Unlike the upper nails, row 7 carried a distinct peak force. The forces developed in this nail were small initially but they increased substantially with subsequent lifts of excavation. Other nails in the lower part of the slope also showed the same pattern of changes in forces. This illustrates that they contributed significantly to the stability of the nailed slope.

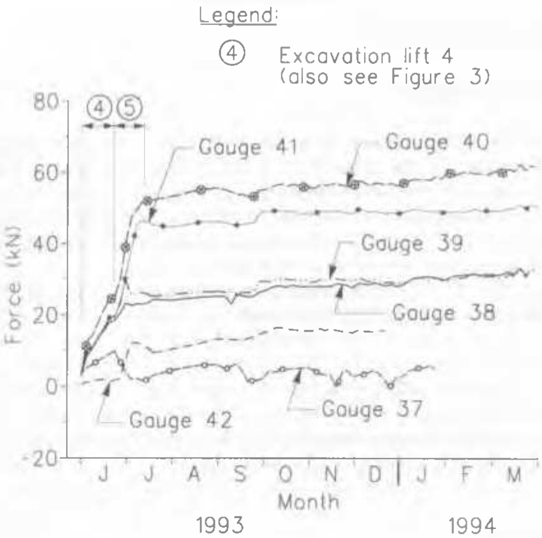


Figure 5. Nail forces against time for row 7.

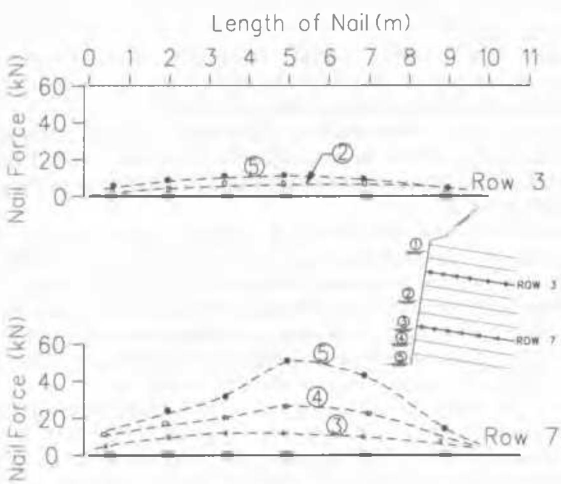


Figure 6. Responses of soil nails (rows 3 & 7) to excavation.

## 7.2 *Distribution of nail forces*

Figure 7 presents the distribution of axial forces along each soil nail at the end of construction. The tensile forces mobilised were different in different nails. The highest force was recorded by the nail on row 7. The top two rows of nails show compressive forces at the front of the bars. They may be related to bending forces caused by the weight of the shotcrete facing hanging from the nails during excavation of the underlying lifts.

The maximum tensile forces on the nails are located at some distance from the shotcrete facing. They form the locus of maximum strain in the soil mass. This should coincide with the critical failure surface predicted by the force limit equilibrium analysis.

## 7.3 *Maximum nail forces in vertical profile*

In order to analyse the distribution of maximum nail forces in vertical profile, the maximum force at each nail level is represented as a non-dimensional parameter ($F_N = T_{max}/(\gamma \cdot H \cdot S_v \cdot S_h)$) at relative depth $z/H$. The variation of the normalized maximum forces with the relative depth is plotted on Figure 8. The maximum forces

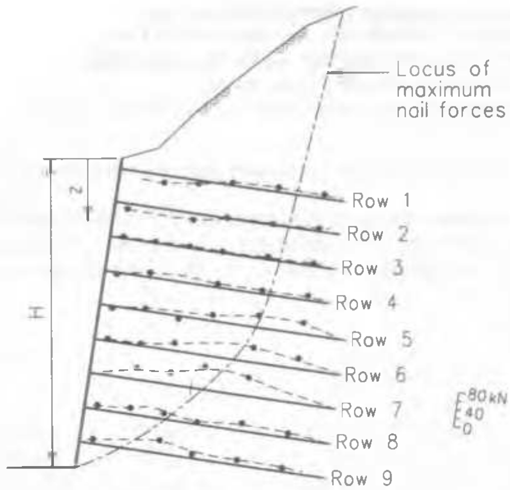


Figure 7. Distribution of nail forces at the end of construction.

mobilised in the nails were not constant but they varied with depth. The maximum forces increased more or less linearly with depth down to row 7 below which they started to decrease with depth. The nails in the upper rows corresponded to a lateral pressure above the active ($K_A$) state of stress. The measured maximum nail forces for the lower part of the slope compare well with the empirical stress envelope for braced excavations, as shown in Figure 8.

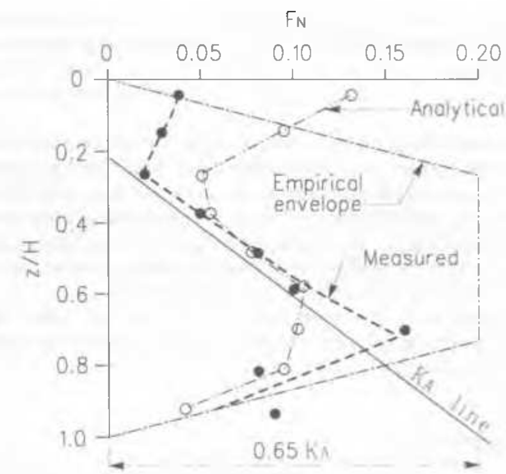


Figure 8. Distribution of normalized maximum nailed forces.

The monitoring results illustrate that the development and distribution of nail forces are different from those assumed in the force limit equilibrium method described in Section 4. This is a shortcoming of the force limit equilibrium method in respect of simulating the soil/nail interaction.

# 8 NUMERICAL MODELLING

## 8.1 *Approach used in the numerical modelling*

Numerical modelling was performed on the nailed excavation using FLAC. The approach adopted in the modelling was to simulate the excavation sequence to obtain a reasonable fit between the computed and the field measured profiles of lateral displacement. The computed nail loads were then compared with the field measurements.

The soil mass was modelled as a linear elastic-plastic material with a Mohr-Coulomb failure criterion. The soil stiffness was found to be a parameter that significantly affects the outcome of the numerical analysis. Based on the site investigation result and the construction sequence, the values of the Young's modulus of the soil mass were adjusted within the range from 3N to 5.5N (MPa) where N is the SPT blow count.

### 8.2 *Comparison of the analytical results and monitoring data*

Figure 9 shows the analytical lateral displacements of the nailed slope at the end of construction. It can be seen that this displacement pattern matches fairly well with the monitoring results.

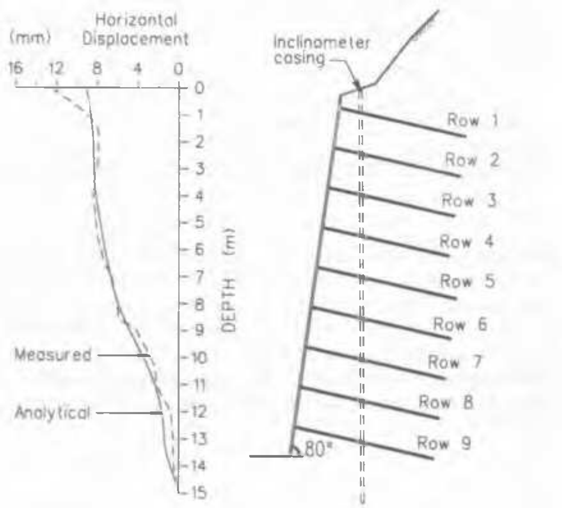


Figure 9. Comparison of the analytical and measured horizontal displacements.

Both the analytical and the measured axial forces along the nails are shown on Figure 10. The analytical nail forces on the upper nails are generally larger than those obtained from the field measurements. The pattern of force distribution derived from the numerical modelling is similar to that obtained from the instrumentation. The shape of the locus of maximum nail forces generally compares well with the measured data.

The normalized maximum nail forces derived from the numerical modelling are shown on Figure 8. They follow the same trend of the monitoring results.

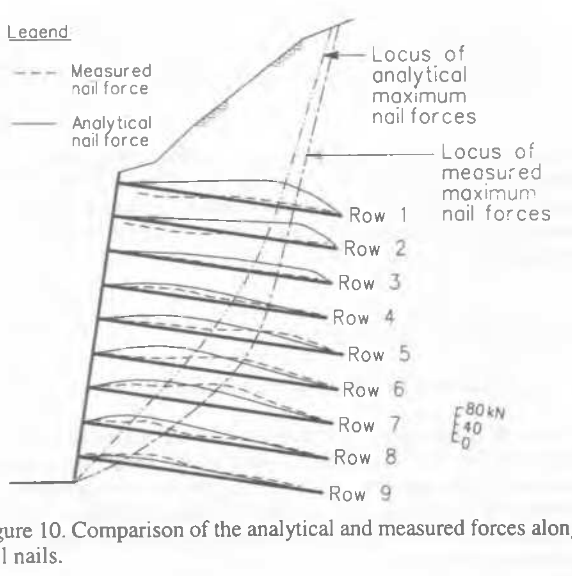


Figure 10. Comparison of the analytical and measured forces along soil nails.

There are a number of uncertainties such as the assumed geological model, soil behaviour, soil/nail bond and excavation sequence which should be borne in mind when considering the results of the numerical modelling. The uniqueness of the combination of variables that produce a good fit to the field data is therefore difficult to verify.

## 9 CONCLUSIONS

The field monitoring results have provided a fundamental understanding of the behaviour of the nailed excavation. The forces observed in the instrumented nails and those obtained from the force limit equilibrium were quite different. This points to the need for a more comprehensive design method that can simulate the actual behaviour of nailed excavation.

Results of the numerical modelling of soil nail forces generally compare well with field measurements.

## 10 ACKNOWLEDGEMENT

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