Soil nailing behaviour for slope stabilization: A case study

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Abstract. In terms of sustainable solutions of talus slopes with the soil nailing solutions, the input design parameters such as the inclination angle of anchor and the length of anchor are mainly based on the recommendation of British Standard or American Standard and the experience of the contractor. The purpose of this study is to provide more options to the designer to make a reasonable choice of the design parameters described above. Taking one of the improvement works of the La Son – Tuy Loan Highway in Vietnam as an example, a series of numerical analysis has been conducted to examine the factors mentioned above. Hopefully, the results from this study would assist in deriving a more economical construction method in improving the efficiency of reinforcing the slope by soil nailing.

1. Introduction
In Vietnam, soil nailing has been used extensively in many different areas of construction such as slope stabilization, earth retaining structure and deep excavation. The purpose of using soil nailing is thus to strengthen or stabilized the existing steep slopes and excavations as construction proceeds from the top to bottom [1–4]. In December 2013, Vietnam Government kicked off the La Son–Tuy Loan Highway project with an investment totalling about VND 11.5 trillion (US$ 515.66 million). Construction work stretches 77 km, beginning in La Son Town in the Phu Loc District and ending at the intersection of the Da Nang–Quang Ngai Highway in Tuy Loan Town of Da Nang City. The highway can be characterized as a continuous winding mountainous route that passes through hilly terrains and founding on the talus of many large slopes. In 2016, Typhoon No. 9 inflicted severe damages to the entire route. As reported by the Da Nang Department of Transport [5–7], there were 20 landslides along the highway, with the worst locations being found between KM41+000 and KM43+400. This study will present the method used to repaired and strengthen one of the collapsed section along the highway. A series of parametric study via numerical analysis has been conducted to examine some of the factors that could affect the analysis and the design of the improvement method. It is hope that the result can contribute to the analysis and design of such improvement method in the future in the domestic construction industry.

2. Background of Soil Nailing
Soil nails develops their reinforcing action through soil/nail interaction due to ground deformation, which results in the development of tensile forces in soil nail. The major part of resistances comes from this developed tension force. Conventionally, shear and bending have been assumed to provide little contribution to its resistance [8]. The effect of soil nailing is to improve the stability of slope through:
(i) increasing the normal force on shear plane and hence increase the shear resistance along slip plane in friction soil; and (ii) reducing the driving force along slip plane both in friction and cohesive soil.

The reinforcement of soil nail is installed horizontally or gently inclined parallel to the direction of tensile strain so that it develops maximum tensile force develops. Soil nails are passive inclusions, which improve shearing resistance of soil. The soil nail system can be divided into active and passive region (Figure 1). During the process of slope failure, the active region tends to deform and result in axial displacement along the nails which are placed across the slip plane. This results in the development of tensile forces in soil nails in the passive zone which resists the deformation of active zone. This tension force results in increment of the normal force coming on slip plane and reduces the driving shear force. The soil nails embedded in passive region through which it resists the pull-out of nail from slope through friction between nails and soil. Based on the above two mechanisms, the required amount of nail length should be placed in resistive zone. In addition, the combined effect of nail head strength and tension force generated in active zone must be adequate to provide the required nail tension at the slip surface [9].

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British Standard [10] suggests the following stages when performing a soil nailed structures design:

- Determine the position of the critical slip surface and the resisting force or moment to maintain equilibrium of the active zone.
- Determine the tensile and shear loads for an initial constant spacing and inclination of nails of constant stiffness and length.
- Check for each level, allowing for stages of construction, against failure due to tension in the nail at the slip surface, pull-out of the length of nail in the resistant zone, bending and shear in the nail near the slip surface, and bearing failure of soil against the nail.

3. Method of Study
The collapsed section at KM42+861.05 of the La Son–Tuy Loan Highway has been the subject of this study. The method of study is via a series of numerical analysis using the computer program PLAXIS 2D.

3.1. Geological Conditions
This study focuses the cross-section at KM42+861.05 (Figure 2). Three boreholes were drilled to an average depth of 20 m; the corresponding soil properties for the first and the second layers were obtained from laboratory tests, and they are tabulated in Table 1. The first layer (8a) is silty clay (CL), grey gold with semi-solid state; this is a layer which have the average values of load bearing capacity. The second layer (7) is silty clay (CL), grey brown in semi-solid state, and having the average values of load bearing capacity. The third layer (9a) is shale rock, grey gold and grey brown. This layer is a weathering product from the original stones and having the good values of load bearing capacity. The fourth layer (9b) is...
shale rock, grey blue, grey brown. This layer is a weathering product from the original stones and having the good values of load bearing capacity. Layers (8a) and (7) are the layers of soil weathering grades that located near the surface; they are saturated under rainfall infiltration and could cause slope sliding. Layers (9a) and (9b) are weathering of rock, which are susceptible to water saturation by rainfall.

Figure 2. Cross-section at KM42+861.05 of La Son – Tuy Loan Highway.

Table 1. Soils and Foundation Data Parameters

| Parameters       | Layer 1 (Silty clay) | Layer 2 (Silty clay) | Layer 3*[11] (Shale rock) |
|------------------|----------------------|----------------------|---------------------------|
| $\gamma_{unsat}$ | 16.50                | 15.00                | 26.00                     |
| $\gamma_{sat}$   | 19.50                | 18.00                | 26.00                     |
| $k_x, k_y$       | 8.64E-2              | 8.64E-2              | 2.5E-5                    |
| $E_{ref}$        | 12700                | 12400                | 100000                    |
| $v$              | 0.35                 | 0.35                 | 0.1                       |
| $c_{ref}$        | 25                   | 24.25                |                           |
| $\phi$           | 16°20’               | 17°25’               | 35                        |
| $\psi$           | 0                    | 0                    | 5                         |
| $R_{inter}$      | 0.67                 | 0.67                 | 0.67                      |

3.2. Geometric Modelling

Figure 3 shows the geometry of the section at location KM42+861.05. The numerical model simulates the facing of slope and the gravity wall with beam elements, node to node elements for anchor and geo grid elements for grout anchor and the soil-structure contact area with interface element. Mohr-Coulomb model is used to represent the behaviour of the soil, while linear elastic model is used to simulate the facing of slope and the gravity wall. The soil nailing construction is modelled in stages as happened on site. The inputs parameters used in the numerical analysis are presented in Table 1 to 3.
Figure 3. Geometry of soil nailing wall modelled in PLAXIS 2D

Table 2. Parameters of soil nailing facing and gravity wall.

| Name                  | Unit | Gravity Wall | Facing of slope |
|-----------------------|------|--------------|-----------------|
| Axial stiffness, EA   | kN/m | 1.75E7       | 6.3E6           |
| Flexural rigidity, EI | kNm²/m | 2.1E7       | 4.7E5           |
| Diameter, d           | m    | 1.0          | 0.53            |
| Weight, w             | kN/m/m | 7           | 2.1             |
| Poisson’s ratio, ν    | –    | 0.17         | 0.17            |

Table 3. Parameters of anchor and anchor grout.

| Name                  | Unit | Anchor OVM 15 | Anchor Grout |
|-----------------------|------|---------------|--------------|
| Axial stiffness, EA   | kN/m | 2.0E9         | 2.0E9        |
| Pre-stressed force, Nc| kN   | 600           | –            |
| Anchor length, L      | m    | –             | 4            |

4. Results and discussion

Figure 4 shows the slip circle of the natural slope obtained from the PLAXIS analysis, the corresponding factor of safety is 0.84, which is less than the required 1.3, as recommended by the British Standard. The slope is unstable and slide with a circular arc at the interface between Layer 1 (8a) and Layer 2 (7), the deepest slip circle, having the largest distance from the sloping surface to the failure arc, is found to be around 8.19 m (Figure 5).

4.1. Effect of normal and pre-stressed anchors

The effect of the normal and pre-stressed anchors has been studied. Using the geometrical configuration for the stability analysis of natural slope (Figure 4), which has a sliding depth of about 8.19 m (Figure 5), anchors with a total length of 13 m and grout length of 4 m has been selected in this study. There were nine layers of anchors required, with a horizontal spacing and a vertical spacing of 3 m. The inclination angles to be examined are 5°, 15°, 25°, 35°, and 45°. The results are shown in Figure 6.
Figure 4. Slip circle obtained from the PLAXIS analysis

Figure 5. Sliding arc at KM42+861.05

Figure 6 shows that the factor of safety increases with the increased of inclination angle between 5° and 30° and trying to remain constant or decreases slightly between 30° and 45°. Thus the optimum inclination angle is 30°. The results are comparable to other studies such as the British Standard BS 8081:1989 [3]. The British Standard recommended that the inclination angle should be between 5o and 40°, which would lead to an improved stability of slope, the anchor system and the slope will be more durable links, reducing the shear stress in the soil.

Figure 6. Effect of inclination angle of anchor (L=13 m) on factor of safety

The effect of the use of either the normal or pre-stressed anchors is not obvious in the current study. To view the effect, the horizontal displacement contour generated in the slope has been plotted in Figures 7 and 8, and tabulated in Table 4. Table 4 shows that the slopes reinforced with normal and pre-stressed anchors have factor of safety of 1.650 and 1.662, respectively; their maximum horizontal displacement is 0.120 m and 0.123 m. However, the slope reinforced with pre-stressed anchors generated more
displacement compared to that in the slope with normal anchors, thus slope with pre-stressed anchors is under more straining, which is plausible.

![Figure 7. Contour of displacement $U_x$ generated by normal anchors inclined at 30°](image)

![Figure 8. Contour of displacement $U_x$ generated by pre-stressed anchors inclined at 30°](image)

**Table 4.** Factor of Safety (FoS), maximum displacement $U_x$ of studied slope.

| Parameter | Slope reinforcement method | Natural slope | Normal anchors | Pre-stressed anchors |
|-----------|----------------------------|---------------|----------------|----------------------|
| FoS       |                            | 0.845         | 1.650          | 1.662                |
| $U_x$ (m) |                            | 0.211         | 0.120          | 0.123                |

![Figure 9. Relation between factor of safety and types and lengths of anchor](image)
4.2 Effect of anchor lengths

The effect anchor length \( L \) on the stability of slope and the maximum displacement horizontal slope is examined here. Anchor lengths of 9, 10, 11, 12, and 13 m have been used on two types of anchor: normal and pre-stressed anchors. The results are shown in Figures 9 and 10; while the force distributed in the anchor is presented in Figures 11 and 12.

Figures 9 and 10 show that for length of 10 m to 12 m the factor of safety increases almost linearly while the maximum horizontal displacement decreases. Further length increase would be uneconomical as it does not contribute significantly. The results are reasonable because the longer the length the larger the resistant zone it is. The shear stress developed in the soil mass is much smaller than that in the natural slope, so the slope tends to be more stable.

![Figure 10. Relation between slope maximum displacement and types and lengths of anchor](image)

![Figure 11. Relation between anchor length and anchor force distribution (pre-stressed anchors)](image)
Figures 11 and 12 show that the force in the anchors varied along the length of the anchors, for both the normal and pre-stressed anchors. For the pre-stressed anchors (Figure 11), a constant pre-stressed force of 600 kN had been applied to these anchors, this pre-stressed force remained reasonably locked in if the anchor length is less than 11 m, if the length exceeds 11 m, the force in the anchor fluctuated, in particular those in Layers 1, 7 and 8, which increased dramatically. The anchor length has affected the pre-stressed force. For the normal anchor the force in the anchors fluctuated with anchor length, in general the longer the anchor, the higher the force it is. In addition, the force varied from layer to layer; Layer 1 (the most bottom layer) attracted the highest force while Layer 9 attracted the lowest force, indicating that the bottom half of the slope is undergoing more movement than the top half of the slope. These analyses were performed under plane strain condition, however, according to Gui and Ng [12] the effect of 3D must also be accounted for. More study in this direction will be conducted in the future to verify the above factors on the effective use of anchors.

5. Conclusions
There are many factors that could affect the performance of soil nailing or anchor. Factors such as normal (soil nails without pre-stressing), pre-stressing, length, inclination (installation angle) of anchor have been examined in this study. The method of study in via a series of numerical analysis. The following conclusions have been made:

i. It seemed from this study that there was no different in adopting either the normal or pre-stressed anchor in achieving the stability of the studied slope.

ii. Increasing the length of the anchor into the resistant zone of the slope contributed to the stability of the slope, and it reduced the displacement of the slope.

iii. For pre-stressed anchor, if the length is less than 11 m, the pre-stressed force remained reasonably locked-in in the anchor; for anchors with length longer than 11 m, the bottom 4 layers of the anchor seemed to have developed extra forces in the anchor while the pre-stressed force in the top 5 layers of the anchor fluctuated gently, indicating that the bottom half of the slope is undergoing more movement than the top half of the slope.

iv. For normal anchor, the forces developed in the anchors varied along its length; anchors in the bottom 5 layers have a larger anchor force than the top 4 layers of the anchor. Again, it indicates that the bottom half of the slope is undergoing more movement than the top half of the slope.
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