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Numerical modeling of slope stability incorporating complex reinforcement solution in high-risk failure area- unusual case study

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ABSTRACT

The rapid economic development of Vietnam triggers a number of challenges in all sectors including infrastructure design and execution. New development plans and lack of space in densely populated and economically valuable areas creates a need for complex engineering solutions to meet the demand. The present research is a case study investigating reengineered vast natural slope to meet all requirements for geotechnical safety such as maximum displacements and factor of safety. Complex ground conditions and significant dimensions of the slope made the entire structure very likely to cause major risk for the future development plan of the site. Due to complex conditions, the slope was divided into 4 main sections. Each section was reinforced using a combination of soil nails, ground anchors, drainage systems and micro piles, of 19m for a single pile. Due to very much limited space available new geometry of the slope was designed for inclination reaching 1:0.3. Based on numerical modelling and computation the results revealed that the maximum lateral displacements felt in a range of 37-50x10^{-3} *m and the factor of safety was 1.56-1.65, depending on a section and analysed scenario. The computations allowed proposing combined geotechnical solutions for very much challenging sites, assuring high safety standards and fitting the entire design within a limited available area.*

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1. Introduction

According to the number of reports, Vietnam's economy has shown strong growth in 2019÷2020. This is the effect of continuous high domestic demand, manufacturing enterprises growth and diversity in developing industries (Dhar, 2021; Nguyen et al., 2020a; 2020b). Despite the impact of recent pandemic circumstances Vietnam is considered to become the fastest growing economy in the South East Asia region (Seah, 2021; Nguyen, 2020b). To be able to follow an ongoing development many challenges will have to be faced. These also concerns geotechnical structures and soil mechanics which are an integrated part of infrastructure development (Berglund et al., 2020). With new development plans in densely populated and economically valuable areas and a shortage of available space, complex engineering solutions will be needed to meet the demand (Tang et al., 2018).

The case study investigated in the present paper is an excellent example of how the combination of sophisticated ground improvement methods could be applied in practice. The case study concerns vast slope stability issues caused by a number of factors like limited space available for earthworks, complex ground condition and large scale investment project, that is planned to be constructed at the study site. Bearing in mind all these issues and to assure the geotechnical safety of the slope a combination of slope reinforcement methods were proposed at the site these included: reengineering the geometry of the slope, installation of soil nails, ground anchors, drainage systems and micro piles (Blanco-Fernandez, 2011; Thyagaraj, 2019; Osinski et al., 2020). The paper aims to present the entire design process for such a complex approach. To meet the highest safety standards numerical computations were considered for most critical scenarios performed to come up with optimal and safe solutions. The geotechnical safety modelling and analyses concerned soil and structure lateral displacements predictions as well as the factor of safety computation, applying shear strength reduction approach using finite element method (Wan et al., 2010; Zetter et al., 2020; Zhang et al., 2021). What makes the case study unusual is the scale and the scope of designing and execution works at the site. The combination of reinforcing approaches including the installation of 19 m long micro piles is found to be an unusual solution in Viet Nam. Complex ground conditions consisting of highly weathered soil, building a 19 m high slope of a valuable urban area, makes the entire analysis even more challenging.

2. Material and methods

2.1. Study site

The study site is located in the southeast part of Viet Nam in Ha Long City, Quang Ninh Province. The site is recognised a highly touristic region, that has been focusing lots of attention on infrastructural development in recent years.

The case study concerns a natural slope surrounding future planned development. The slope is considered vast, of 96 m length in, with its highest elevation point reaching 19 m from the ground level (crest of the slope located at +54.21 and lowest elevation at the toe of the slope is +35). Due to significant changes in the slope's elevations as well as to the complexity of the geometry of the slope, the slope was proposed to be divided into four lateral sections, namely:

- Section No. 1: from the elevation of 45.94 (point 4') to the level of 50.47;
- Section No. 2: from a point of level of 50.47 to 50.80 (point 3');
- Section No. 3: from a point of level of 50.80 to 52.83 (point 2');
- Section No. 4: from a point of level of 52.83 to 54.21 (point H);

The design level of the toe of slope was +35.00. The sections and location are presented in Figure 1.

The site investigation performed at the site allowed identifying five major geotechnical layers. The ground conditions at the site were considered demanding due the presence of highly weathered lime stone layer located beneath the deposits of stiff clay.

4 major geotechnical layers from the top were stiff clay (down to 12 m), weathered limestone (6 m thickness), extensive (14 m thickness) medium sand (dense), finishing with deposits of stiff clay with gravel layer. Details

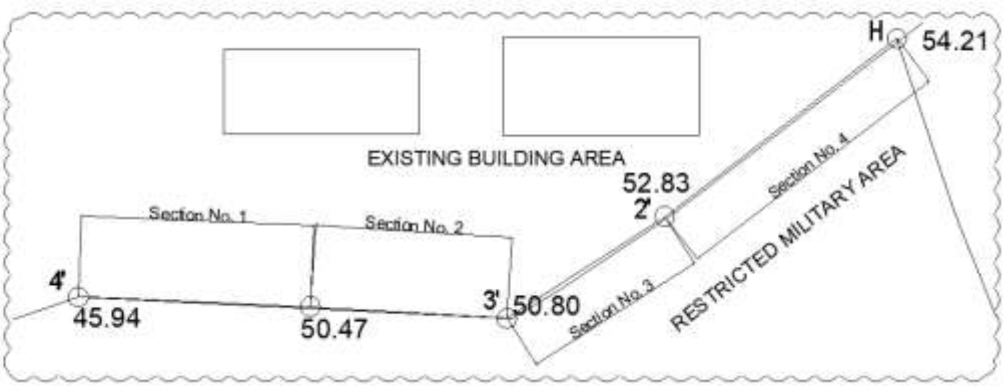

Figure 1. Aerial view of the study site.

including mechanical and physical parameters of soils building only the slope (used for modeling) are presented in Table 1.

Since the moisture content in this particular is changing frequently due to heavy rain frequent events, the content of the small particles could lead to a displacement or even slope failure. Surprisingly, there was no groundwater table found in all boreholes nearby the hill slope. The example of a soil profile for the study area is presented in Figure 2.

2.2. Slope reinforcemnts methods

Because the designed toe level was +35.00, so the height to the crest of the slope, was considered significant compared to typical engineered slopes. Aiming at a long term geotechnical safety performance, in this particular case several reinforcing techniques were employed including soil nailing, ground anchor, micropiles, back wall drainage system (Babu, 2004; Ellis, 2020; Bayesteh et al., 2021).

Table 1. Soil physical, mechanical and hydraulic parameters used for modelling purposes.

Prameter	Unit	Value	
		Soil layer 1	Soil layer 2
γ_unsat	[kN/m³]	19.0	20.0
γ_sat	[kN/m³]	19.5	20.5
E	[kN/m²]	3.0E4	4.0E4
c	[kN/m²]	16.0	18.0
φ	[⁰]	17.0	19.0
K	[m/day]	1.0E-04	1.0E-05
ν	-	0.25	0.25
R_inter	-	0.7	0.7

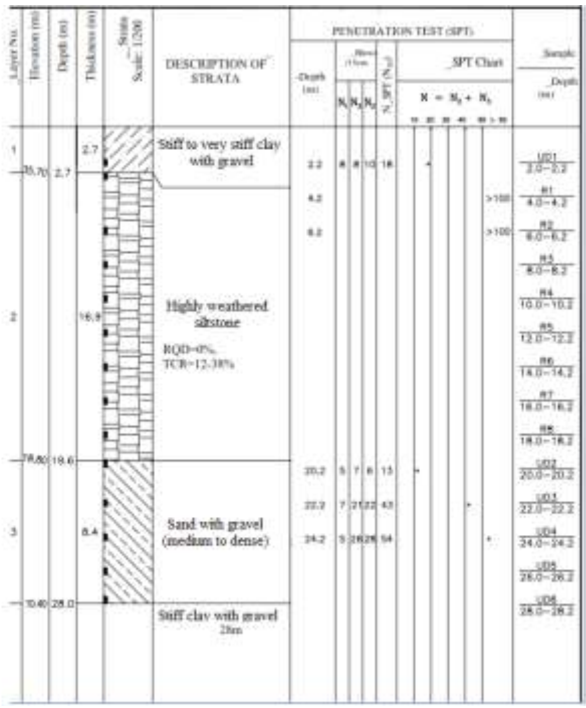

Figure 2. Example of the study site borehole profile.

2.2.1. Reinforcing approaches

Due to confined space with restricted access, the potential impact on surrounding areas, low groundwater table, the techniques of soil nailing, ground anchor were chosen as a readable solution in this case. In addition, in order to prevent potential deep-seated slope failure, three rows of micropiles of 325 mm diameter were suggested in the design proposal. The geometry of a cut slope was reengineered to achieve a slope angle equal to 1:0.3 inclination. The entire height of the slope was divided into subsections 6m high each. The same inclination was proposed to all the sections. all have the same slope angle of 73°, thus the slope is considered extremely steep requiring enough geotechnical safety assurance. To support the structure and improve the ground conditions even more and also to allow more space (by increasing the inclination) as well as to execute the micropile work, two berms with of 1.00 m width were designed at the level of +41.00, and +47.00. Figure 3 presents the entire reinforcing system applied at the slope in sections 3 and 4, a similar approach was used in sections 1 and 2. Each of the sections is described in detail as follows: Slope's face No. 1 from the level of +35.00 to +41.00. This lowest face of the hill slope is stabilized using two soil nail rows (nail diameter of 25 mm, length of the nail is 9.0 m); one ground anchor layer consisting of 8.0 m bond length and 8.0 free length, the designed force of the ground anchor layer is 250 kN. In order to prevent the general slope failure event, a row of micropile was proposed. The diameter and length of the micropile are 325 mm, 7.0 m, respectively. The face slope is consequently protected from infiltration water by using a concrete layer of 400 mm, with drainage layers behind the wall. Slope's face No. 2 (middle face slope) from the level of +41.00 to +47.00: This middle face of the hill slope is stabilized using two soil nail rows (nail diameter of 25 mm, length of nails are 8.0 m and 9.0 m); one ground anchor layer consists of 8.0 m bond length and 8.0 free length, the design force of ground anchor is 260 kN. A row of micropile is proposed of diameter and length of 325 mm, 13.0 m, respectively. The face slope is covered using a

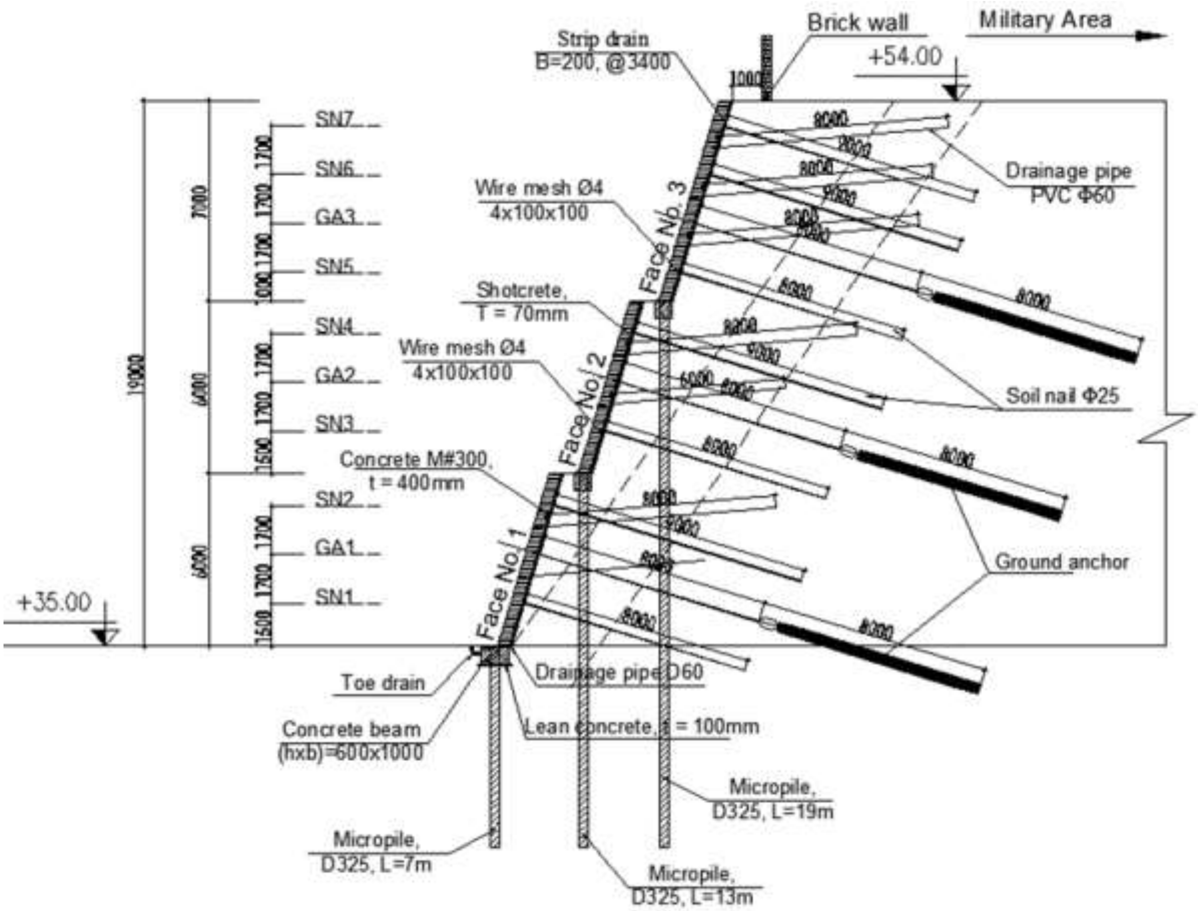

Figure 3. Details of reinforcing approach for slope located in section No.3, and No.4 (acc the locations presented in Figure 1).

concrete layer of 400 mm. Slope's face No. 3, starts from the level of +47.00. This face is stabilized using three soil nail rows, with a nail diameter of 25 mm and length of 8.0 m, 9.0 m and 9.0 m. One ground anchor layer consists of 8.0 m bond length and 8.0 free length, the design force of this ground anchor layer is 250 kN. A row of micropile 325 mm in diameter and 19 m long were proposed. The face slope as in previse sections is protected using a 400 mm concrete layer.

2.2.2. Drainage system

Increasing moisture content in natural slopes has been recognised as one of the most crucial factors triggering severe slope failures and landslides the slope stability (Fredlund et al., 1996; Crosta et al., 2008; Elia et al., 2018). One of the solutions minimising the failure risk, by controlling the groundwater flow is a drainage system without a doubt. For structures as this presented in the study, the drainage is usually installed behind the soil nail wall to collect perched groundwater or infiltrated surface water that is present behind the facing and directs the collected groundwater away from the wall (Dai et al., 2002; Rahardjo et al., 2003). Based on the soil nail reference manual (Lazarte et al., 2015), groundwater condition and the mechanical parameters of soil material (stiff to very stiff silty clay), with the amount of sand occupying 60% of soil samples, the drainage system proposed in the present case study consists of two drainage PVC pipe rows to be installed at each sub-slope with diameter and length of pipes of 60 mm, and 8.0 m, respectively. The inclination angle of a drainage pipe is 5-10^0. To safely manage the infiltration and runoff water, a strip drain having a width of 200 mm and spacing of 3.400 mm was also proposed as a solution for uncontrolled water flow along with the soil profile.

3. Results

3.1. Calculation process and evaluating slope stability

To calculate and evaluate the slope stability, the geotechnical software Plaxis 2D was employed (Brinkgreve, 2010). The geometry of the slope, reinforcing elements, berms, investigation ground conditions data were incorporated into the finite element model. The general view of the model with all its features is presented in Figure 4.

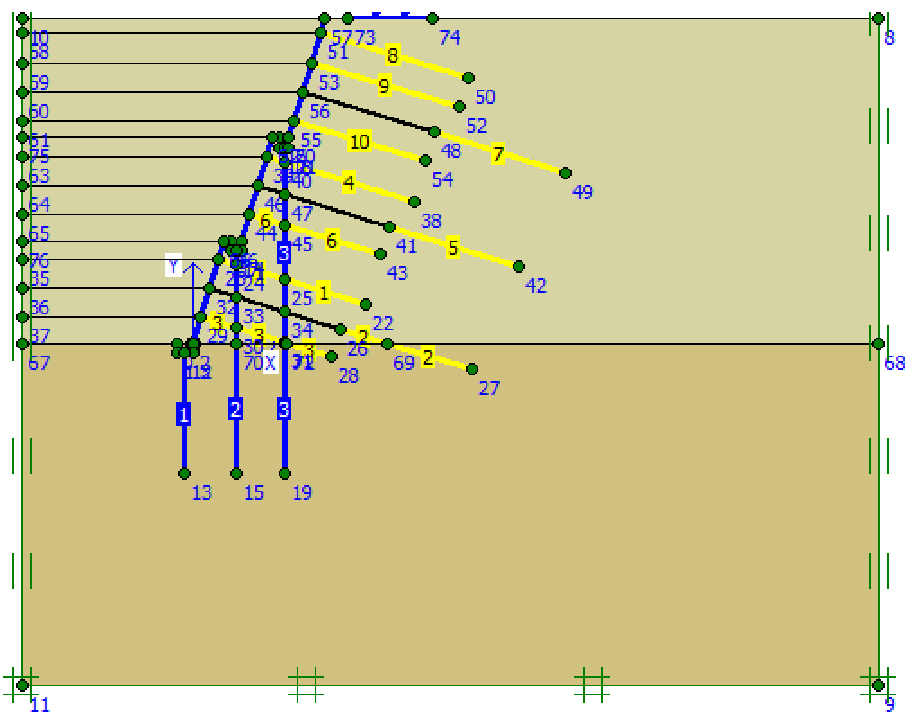

Figure 4. The typical numerical model calculation for the 3rd, 4th sections.

In order to evaluate the long term performance of the slope, a worst-case scenario in which the groundwater table rises to a level of +47.00 was evaluated. The groundwater flow conditions are presented in Figure 5. The size of the model was made large enough in such a way that the boundary condition does not affect the computed results. The computation process took a total number of 22 steps. To make it easy to follow the steps of the procedure are listed in Table 2.

3.2. Geotechnical safety modelling results

The computation of geotechnical safety was performed to evaluate expected lateral displacements and overall Factor of Safety (FS). The approach used for FS computation was shear strength reduction (Farshidfar et al., 2015). The method allows generating out-of-balance forces that are solved using a calculation kernel that results in deformation. These additional displacements that are generated do not have a physical meaning, but the incremental displacements or incremental shear strains in the final calculation step, indicate the likely failure mechanism. The computations were performed for all the sections described (Section No 1-4). According to (Peck, 1969), to restrain the strain level of the backfill and to maintain the stability of the retaining wall the wall displacements should be smaller than the value at the failure. The value at the failure is considered less that H/60 where H is the wall height. For the factor of safety higher than 2 the value becomes H/150-200. The maximum computed lateral displacement for Section No 1 and 2 found to fall in the acceptable range of $U_x = 37x10^{-3}$ m ~ 3.7 cm < [δ]= H/(150-200) = (7.8-10) cm as recommended in (Peck, 1969), where H = 15 is the height of the slope. For section no 3 and 4 the computed displacements where significantly higher (by as much as 35%) but this is simply due to different slope geometry displacements, $U_x = 50x10^{-3}$ m ~ 5.0 cm < [δ] = H/(150-200) = 8.5-11.5) cm, where H= 15 is the height of the slope. The computation results for sections 3 and 4 are presented in Figure 6.

Table 2. Calculation steps applied in modeling.

Step no	Step definition
1	1st layer excavation (ground level) to the depth of soil nail SN.7 row
2	Nail holes drilling and installation for SN7 row, application of shotcrete
3	2nd layer excavation
4	2nd nail row (SN6) installation
5	3rd layer excavation
6	3rd nail row (SN5) installation SN5
7	4th layer excav. down to +47.00
8	Micropile (D325, 19.0m) installation, beam and 400mm concrete facing
9	5th layer excavation
10	4th nail row installation, SN4;
11	6th layer excavation
12	Execute the fifth nail row, SN3;
13	7th layer excavation down to +41.00
14	Micropile (D325, 13.0m) installation, beam and 400mm concrete facing
15	8th layer excavation
16	6th nail row (SN2) installation;
17	9th layer excavation
18	7th nail row (SN1) installation;
19	Excavate the 10th layer down to the level of +35.00
20	Micropile (D325, 13.0m) installation, beam and 400mm concrete facing
21	Micropile (D325, 13.0m) installation, beam and 400mm concrete facing;
22	Anchor stressing, 250 kN, 260 kN, 250 kN.

The geotechnical safety computations also involved numerical analyses of the factor of safety. The results differ for each section but they all proved that the proposed solutions give satisfying FS falling in a range of 1.59 (sections 3 and 4) to 1.67 (sections 1 and 2). Adopting recommended FS value for high risk stricter being 1.45 the case study and the solution proposed could be considered as safe from a geotechnical point of view. The computation captured during the calculation process is presented in Figure 7.

Additional calculations were performed to verify bending moment distributions in each slopes' face (concrete 400mm layers). The example results for each facing (1, 2, 3) of sections 3 and 4 are shown in Figure 8. The extreme bending moments showed acceptable values ranging from 137.37 to 204. 40 kNm/m.

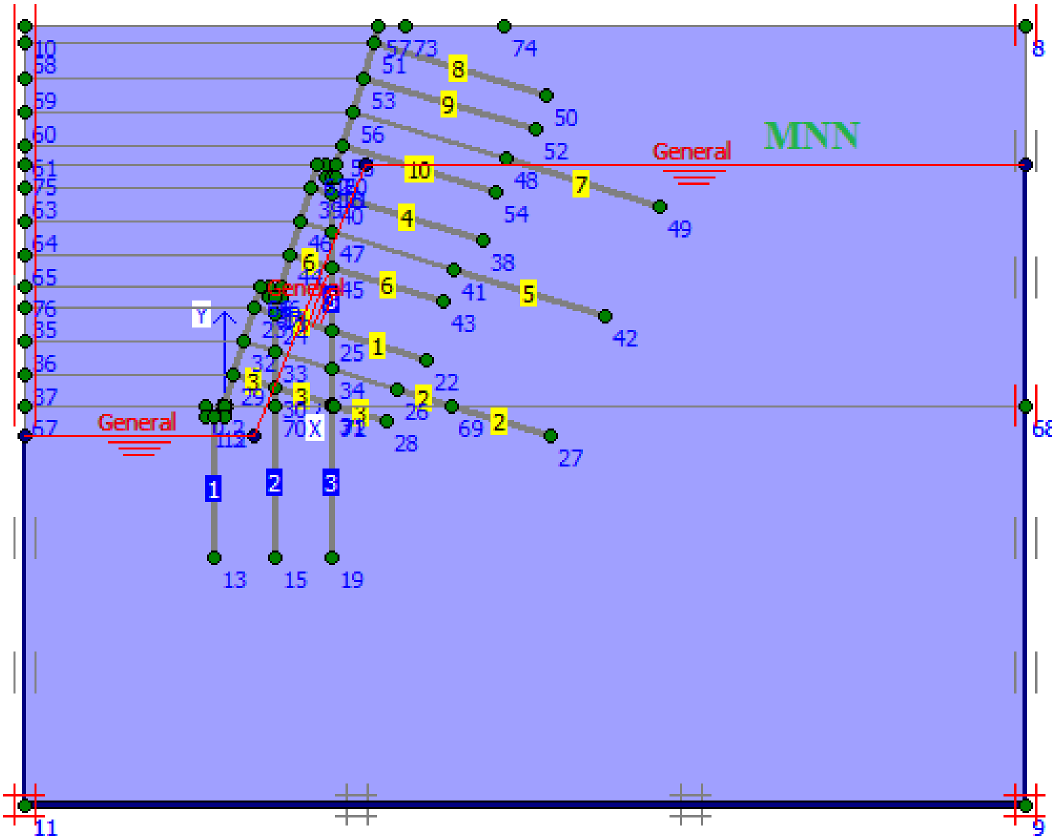

Figure 5. Changed groundwater table conditions.

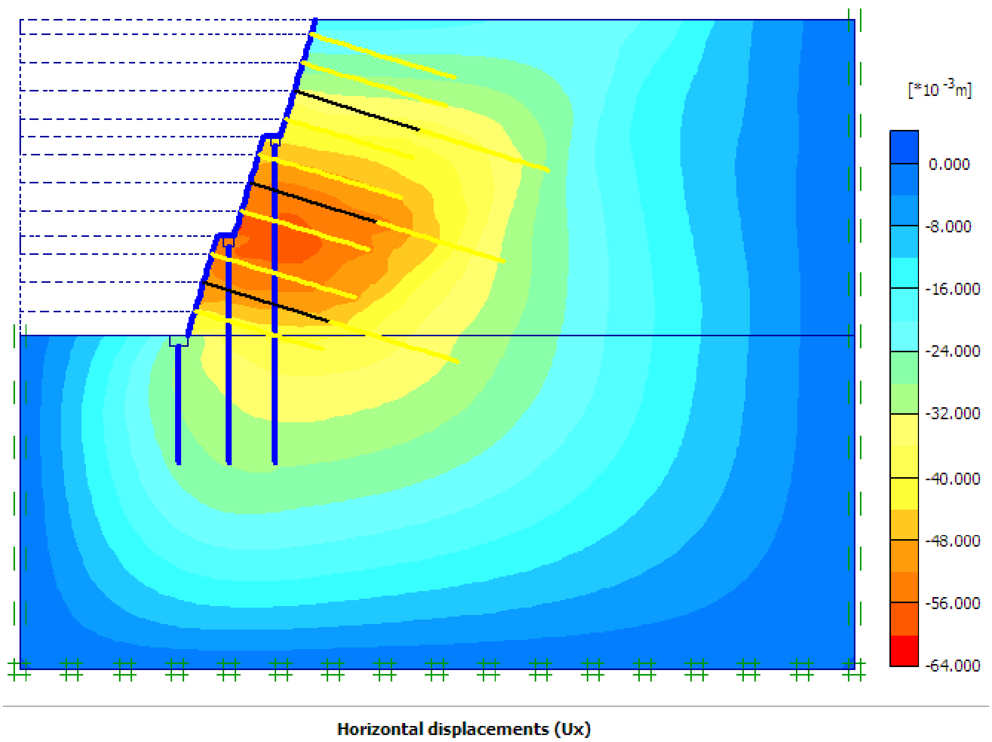

Figure 6. Distribution of lateral displacement of the in sections 3 and 4.

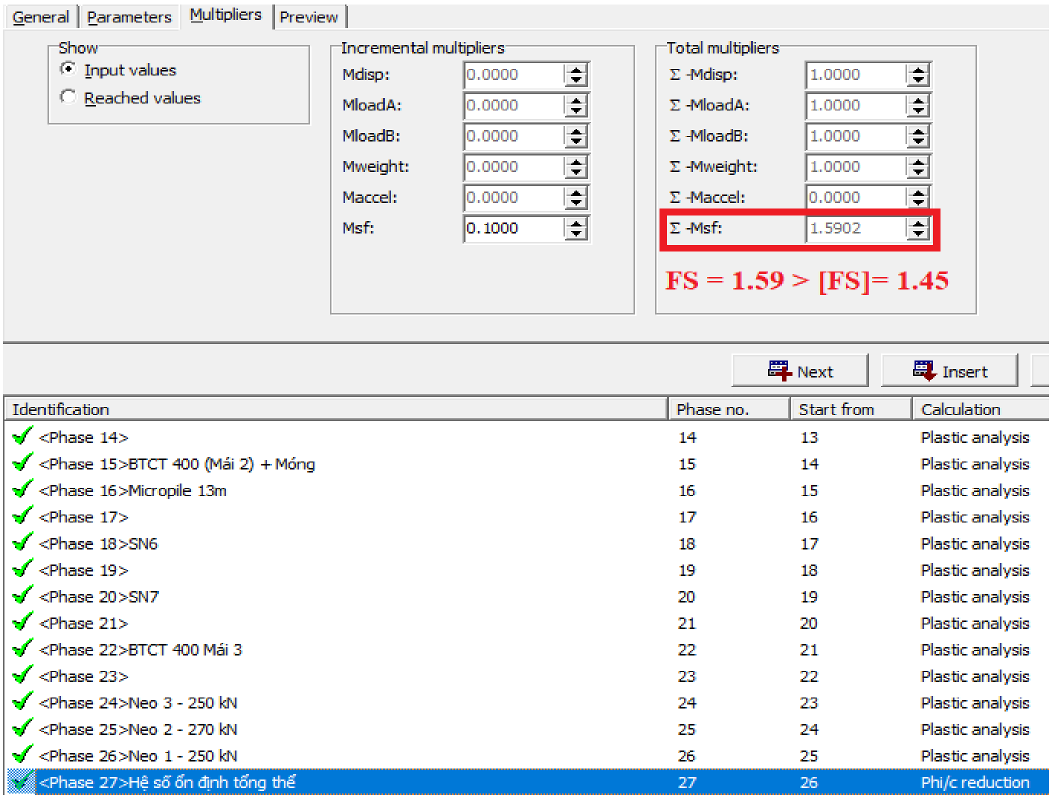

Figure 7. Overall stability analysis result of the proposed approach for sections 3 and 4.

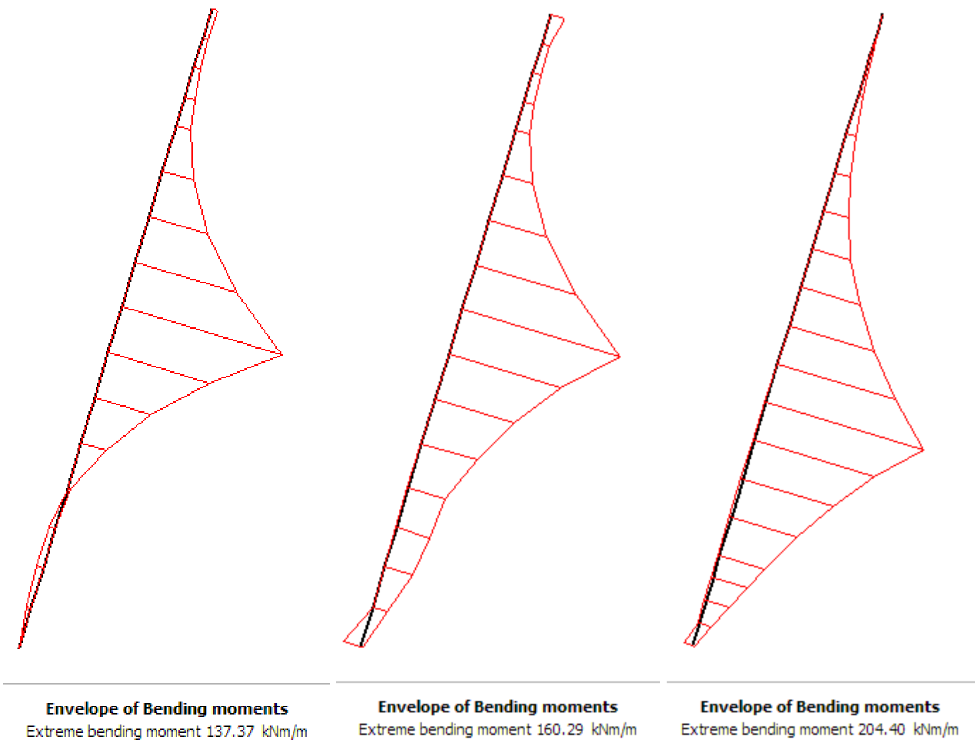

Figure 8. Slope's face bending moment distribution: a – Face No. 1 b – Face No. 2, c – Face No. 3.

4. Conclusion

The rapid economic development of Viet Nam is positively affecting all the national sectors. This includes infrastructures that need safe designing solutions to serve their purpose. New investments often require complex approaches, that would meet the development demand. This concerns the civil engineering sector too, which geotechnical engineering is a crucial part of. The present paper investigates the geotechnical safety of an engineered slope requiring significant and sophisticated reinforcements. Using numerical calculations and models allowing incorporating proposed stability improvement showed the geotechnical safety was met at every phase of the earthworks process. The predicted displacements and computed factors of safety proved the correctness of the proposed complex reinforcing solution, combining soil nails, ground anchors and micro piles. The present case study demonstrated that unusual construction site conditions need to be tackled by a combination of complex approaches.

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Author contributions

NAP contributed 10% during the preparation of the paper by reviewing and editing the content. PO conceived, wrote and edited the paper and contributed 20%. NAD contributed 10% by providing expertise advice during the preparation. EK assisted in the analytical evaluation of the results and contributed 10%. MNV contributed 15% by reviewing and giving critical feedback. DVB conceived the paper and performed the calculation and contributed to editing giving 20% of the contribution. NTV contributed 15% by providing the data for analysis.

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