Journal of Geotechnical Geology

Journal homepage: geotech.iauzah.ac.ir

Zahedan Branch,
Islamic Azad University

Application of micro-pile for excavated trench dynamic stabilization by using three-dimensional finite element numerical method

Leyla Hamedi[1], Ali Sanaeirad*[1]

[1] *Department of Civil Engineering, Faculty of Engineering, Arak University, Arak, Iran*

ARTICLE INFORMATION

Received 10 September 2020
Revised 21 October 2020
Accepted 15 November 2020

KEYWORDS
Numerical modeling; Finite element method; Slope stability; Micro-pile; Plaxis3D.

ABSTRACT

Soil improvement can be expressed as one of the most important applied achievements of geotechnical engineering to improve the resistance conditions and properties of soil mechanics in a wide range of soil materials. The purpose of the improvements is to achieve proper resistance of soils (especially loose soils) to failure, which can cause serious damage and costs to construction projects. The micro-pile is one of most effective stabilization methods, which is used in the materials' limitations and it is more economical than other techniques. The present study is based on investigation on the micro-piles' performance to the improvement of sandy soil's slope under dynamic earthquake loading. Methodologically, the finite element numerical method and Plaxis3D software have been used to implement the loading conditions and evaluate the deformations that have occurred in loose body of slope. The modeling process can be divided into two modeling groups, including slope with and without reinforced by micro-piles which is indicate the improvement process based on deformation reduction by stabilization technique. According to the results of the numerical simulation, it has been found that the use of micro-piles can be very effective on slope stability of the excavated trench in loose soil.

1. Introduction

Generally, the loose soils (low bearing capacity-high settling soils) are considered as problematic conditions in geotechnics which is required to improve on geo-engineering properties like physical-mechanical condition, soil mechanical features, etc. (Han, 2015). For this purpose, different stabilization methods are used by experts that can be classified into two groups as structural and soil condition improvements which are conducted based on site status and aim of stabilizations (Raison and Raison, 2004). One of the structural techniques for soil stabilization were used to modified the soil slopes in excavation operation is micro-plies which cause the least damage to structures and soil especially in urban areas (Nicholson, 2014). The applications of micro-piles to stabilize unstable excavated slopes in urban area or read operations are grow widely in recent years (Howe, 2000). Micro-pile is considered as structural pile or group of plies in different small-diameters from 0.3 m to 0.9 m drilled, and grouted in slope face or excavated trench for provide the required reinforcements (Sun et al., 2014). Figure 1 is present the micro-pile implement procedure. The aim of utilizing the micro-piles are provide the appropriate structures to mainly transferred lateral or axial loads to the deeper layers of the ground behind of the loose soils which is modified the loading condition of slope/trench and reduce the shear stress

*** Corresponding author.**
E-mail address: a-sanaei@araku.ac.ir
Assistant Professor, Academic Staff.

https://doi.org/10.30495/geotech.2020.680485
Available online 20 December 2020

triggered the instabilities on slope or excavation face. In micro-plies, the bearing capacity of the flat is negligible, but on the other hand, the frictional resistance of the wall (lateral strength) is greatly increased by the bearing capacity of the soil-grout bond which is highly depending on the grout type injection technique, and injection quality (Raison and Raison, 2004). As comparative results on micro-piles with ordinary/ conventional stabilization methods like in-situ piles, shields, plates, and so on; it is relatively simple, easily installable, fast, economic and environmental-friendly (Sun et al., 2014) where highly flexible to conducting in different geotechnical improvements as well as illustration on Fig. 2 (Han, 2015).

Lizzi (1978) state that the application of the micro-piles as reticulated network can be creates efficient reinforced soil during the slope cuts which can be considered as natural earth-retaining wall where stabilized by own gravity. This mechanism help to stabilization of trenches by utilizing the modified slope mass agents of lateral movements which is required less equipments then concrete retaining walls (Hokmabadi et al., 2014). Reese et al. (1992) provide the computational methodology to investigate the failure mechanism in embankment and earth-slopes. Loehr et al. (2000) prepared the simplified procedure to estimate the slopes reinforced with micro-plies under circular failures which is lead to understanding the micro-plies efficiency on homogenous slopes. Shin, et al. (2006) suggested the experimental-abased computational method for pile-reinforced slopes' stability analysis were coded by mathematical programming. Sun et al. (2013; 2014) presents the micro-piles behavior on improvements of soil slopes by conducting limit equilibrium and numerical approaches. Esmaeili et al. (2013) performed various experimental works on micro-piles under different loading conditions which is verified by three-dimensional finite element numerical method and Plaxis3D results. Abdelaziz et al. (2017) and Justo et al. (2017) presented the finite element numerical investigations on micro-piles for different type of geotechnical structures which based on their results; it was found that the performance of micro-piles is very effective on ground and slope mass improvements were lead to more soil stability against sliding.

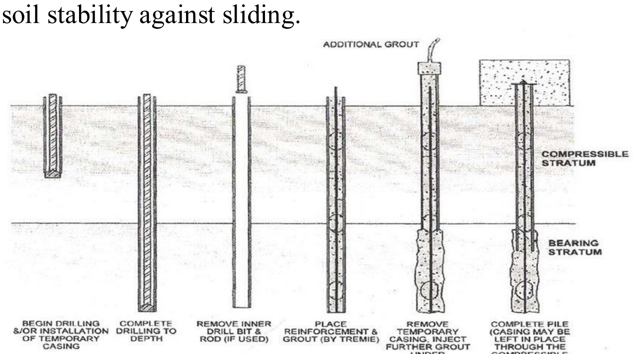

Figure 1. The operation of a micro-pile installation (Nicholson, 2014)

Capatti et al. (2017) on the dynamic behavior of micro-communities under different loading conditions and increasing the level of force, with special attention to the role of different implementation methods and foundation conditions. These experiments were performed on 2 vertical micropiles and an oblique micropile group attached to the concrete cap in silt soil and the results of ambient vibration, lateral impact load test and free vibration test were interpreted. According to the results obtained in the microcosm group, the frequency of the group is higher along the slope of the microcosm and the damping is higher. Zhang et al. (2017) conducted a study on the damping characteristics of the soil-structure interaction system on seismicity. The soil-structure interaction system consists of two parts of soil and structure by physical model, each of which has its own characteristics and behaviors. Based on the obtained results, it is observed that at the beginning of loading, there is a slight difference in the response of the foundation and the soil beneath it, while with increasing loading intensity, the differences in accelerations, frequency and phase decrease and become the same.

El-Sawwaf (2018) presented in an experimental and numerical study of the behavior of a stationary strip foundation with microclimate based on reinforced geosynthesis sand. Special attention was paid to the simulation of foundations made on asymmetric and eccentric geogrid layers in both directions. Different configurations of geogrid layers with number, length, centrifugation of different layers along with the effect of relative density of sand, and off-center load have been investigated. The test results show that by placing layers of geogrids that lead to the basic economic design, the performance of microclimates and foundations can be significantly improved. Cheng et al. (2019) presented in an article that microcosmic foundations were used to evaluate the behavior and deformation of the foundation structure that has been subjected to seismic conditions. He used concrete microspheres to reinforce the structure and simulated the soil-structure microsphere interaction by a numerical approach. Using dynamic response characteristics such as strain history and geometric changes of microenvironment, these researchers modeled the rate of microenvironment strain response. Based on the results, with increasing the diameter and length of the pile in reinforced concrete, its bearing capacity has improved by 40% and 98%, respectively. Pilecka et al. (2020) by using precision instruments and using a numerical model of a separate element, these researchers considered the status of micro-communities and its role in improving embankment stability. The results of his study showed that the use of micro-communities in the stability of soil slopes is very significant and has well limited the plastic area and deformation.

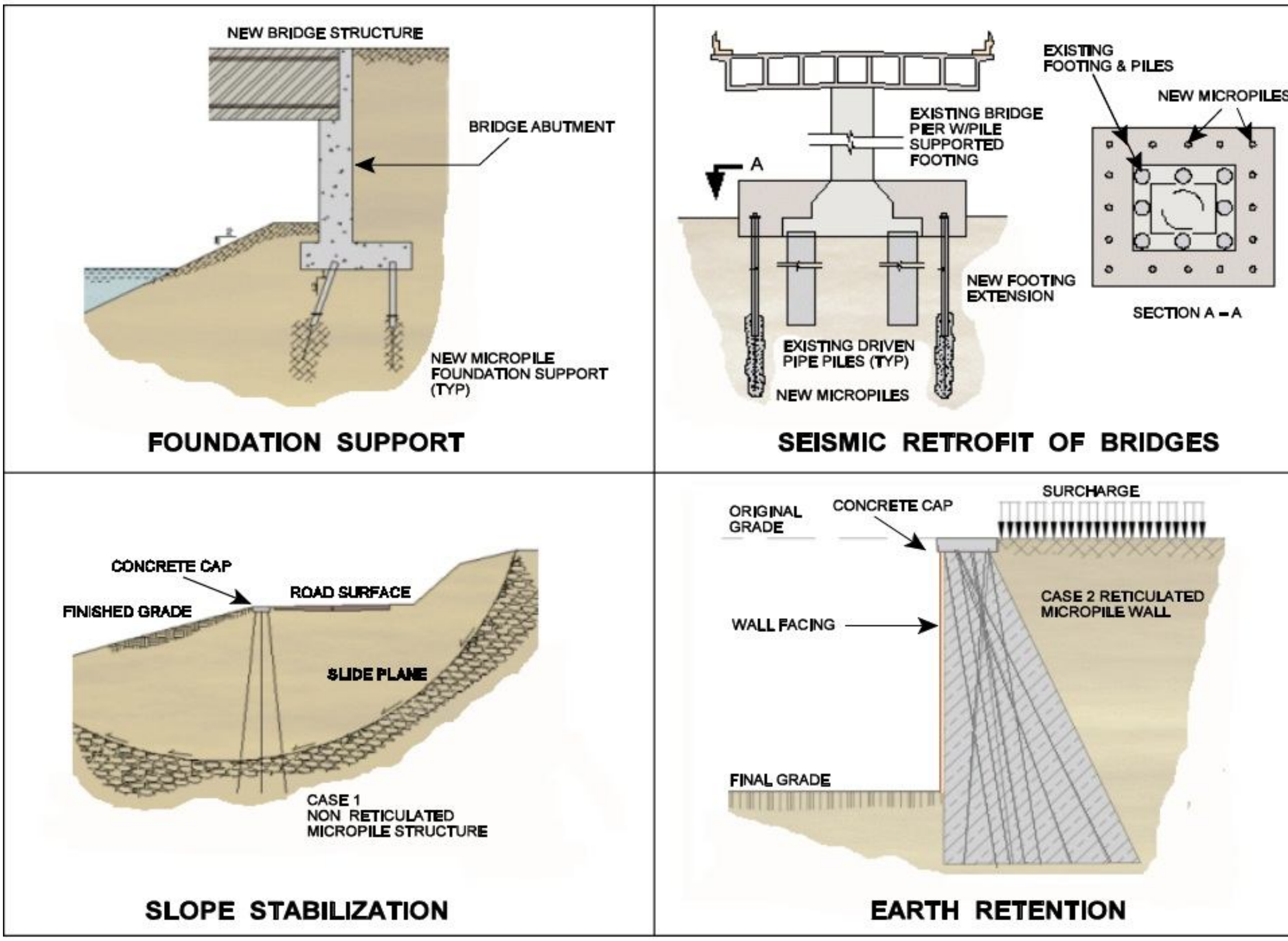

Figure 2. Some applications of micro-piles (Han, 2015)

2. Material and Methods

To investigate the stability performance of trenches in excavation operations by conducting various stabilization techniques, commonly numerical methods was used which provide the clear understanding of stabilization procedures applied on soil slope. In the mean time, application of finite element method (FEM) has received great attention from the geotechnical professionals especially for evaluate the deformability of soil mass under in-situ stress-strain condition (Tong and Tang, 2019). FEM is the most useable numerical procedure for engineering, mechanical and mathematical issues which provide comprehensive interests such as the structural analysis, heat transfer, fluid flow, mass transport, geo-structures, soil mechanics, earth dynamics, and so on. The FEM applied partial differential equations for different variables to estimate the answers of problems by conducting finite elements or meshes. The FEM method approximates the unknown function over the system to provide the simple equations that model meshes then assembled into main system and solving entire problem (Saran, 2010). This application performed in geotechnics to investigate the soil/rock mechanical perspectives as well as structural interactions with soil materials.

Different finite element codes developed by scientific and commercial companies which can be referred to the most important of these softwares as FLAC (Itasca, 2010), GeoStudio (Geoslope, 2019), Geo5 (Finesoftware, 2019), GeoFEAS (FORUM8, 2020), GGU (Civilserve, 2017) and Plaxis (Plaxis, 2019). Among these commercial programs, the Plaxis software due to its high flexibility, user-friendly, high accurate estimation, computational core, and easy accessibly has received high attention from different scholars all around the world. Plaxis2D/3D is developed based on FEM by Plaxis B.V. (American Bentley Systems, Inc.) for geotechnical evaluations on soil/rock media with various behavioral criterions which capable to accurately model the geotechnical environment’s conditions (Plaxis, 2019).

The presented research uses the Plaxis3D to investigate and three-dimensional modeling of the soil’s failure’s development on slope mass step by step before and after of conducting reinforcement by micro-piles in soil slope. In this regard, the dynamic simulation of soil-micropile interaction was conducted. For this purpose, firstly the excavated slope was implemented as with/without micro-piles and then dynamic analysis was performed for the free and reinforced models. The results of these two simulation groups have been analyzed comparatively and the role of micro-piles implementation in improving of slope deformability was investigated.

In this regard, a set of modeling including geometric modeling, determination of boundary conditions and behavioral models, assignment of material properties and also a dynamic modeling was performed to evaluate deformation and displacement conditions on slope under in-situ stress fields for both armed and unarmed states. Figs. 3 and 4 shows the geometrical models prepared for the different status of the studied slope. As behavioral model of soil materials, the Mohr–Coulomb (MC) failure criterion was used as well as geo-materials properties which are obtained from geotechnical tests based on ASTM international standard guidelines. Table 1 illustrates the geo-materials properties used in the simulation operation.

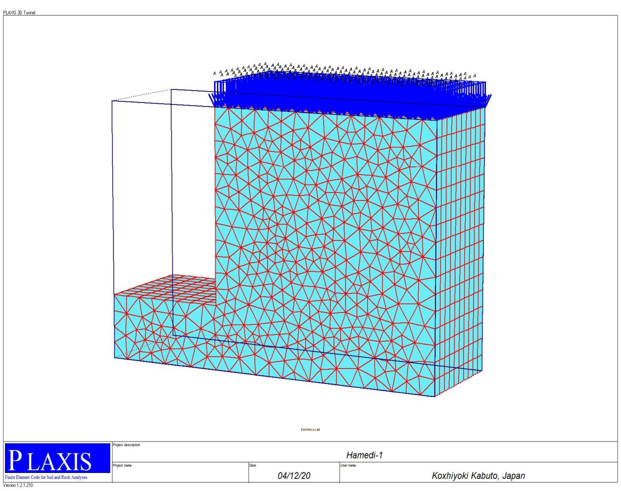

Figure 3. Geometrical model prepared for excavated slope without micro-piles reinforcement

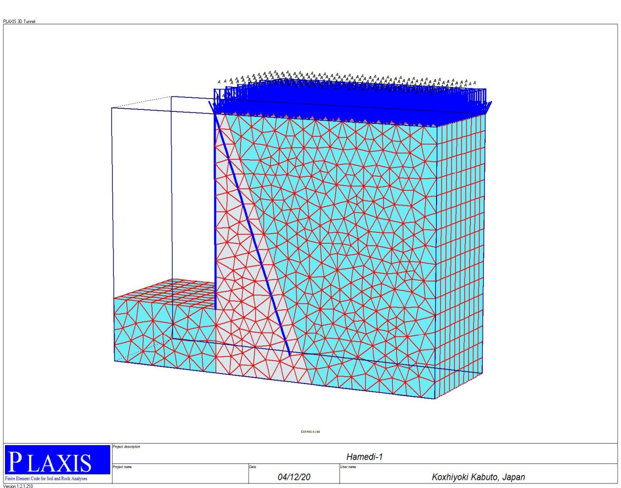

Figure 4. Geometrical model prepared for excavated slope with micro-piles reinforcement

Table 1. Geotechnical properties used in modeling as geo-materials features

Material	Parameter	Unit	Value
Loose sand	γ_{unsat}	kN/m^3	18.00
	γ_{sat}	kN/m^3	20.00
	E_{ref}	kN/m^2	5.0×10^7
	υ	-	0.33
	Cr_{ef}	kN/m^2	10.00
	ϕ	Degree	35.00
	ψ	Degree	00.00
Concrete	γ_{unsat}	kN/m^3	23.00
	γ_{sat}	kN/m^3	23.00
	E_{ref}	kN/m^2	2.8×10^{10}
	υ	-	0.18
	Cr_{ef}	kN/m^2	500
	ϕ	Degree	28.00
	ψ	Degree	00.00
Grout	γ_{unsat}	kN/m^3	19.00
	γ_{sat}	kN/m^3	21.00
	E_{ref}	kN/m^2	2.3×10^9
	υ	-	0.30
	Cr_{ef}	kN/m^2	100.0
	ϕ	Degree	20.00
	ψ	Degree	00.00
Micro-pile	EA	kN/m	7.6×10^6
	EI	kNm^2/m	1.0×10^6
	d	m	1.257
	w	kN/m/m	10.00

3. Results and Discussions

After preparing model for mechanical modeling such as assigning geo-materials features and behavioral criteria to the model, the model is analyzed for dynamic conditions. The results of the evaluation for the domain state without the implementation of inhibitory microenvironment are shown in Figs. 5 to 9. Due to these results, it can be stated that the occurrence of failures in loose sand's slopes during an earthquake/dynamic loading is a definite matter and requires comprehensive improvements, especially during drilling or excavation operations. As can be seen in Fig. 5, the slope instability is slope-toe type that is well visible in loose sandy soils. Also, as illustration of Fig. 6 which shows the lateral displacement in the slope, it can be stated that this slope sliding generally has the aspect of lateral movement to the studied slope. In this figure, it can be seen that the slip is occurred as progressive process and cause local uplift in the slope toe. Figs. 7 to 9 shows the in-situ stress-strain fields in the slope during final stage of excavations which indicated the nature of the probable slip surface in slope mass. This surface could consider as the initial slip surface in the slope that can be progressively becomes as slope's sliding surface.

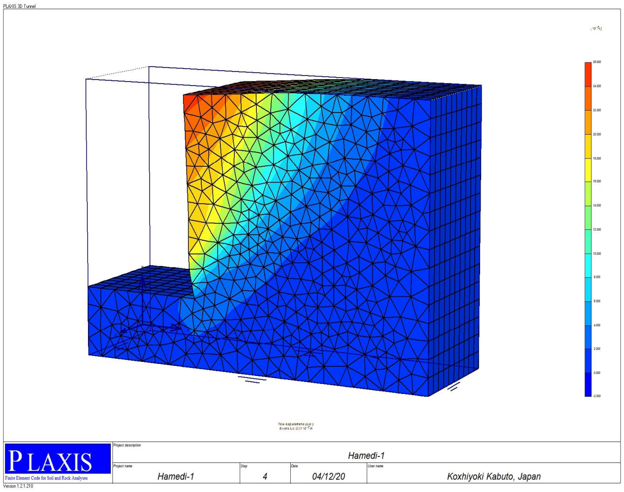

Figure 5. The displacement model prepared for excavated slope without micro-piles reinforcement

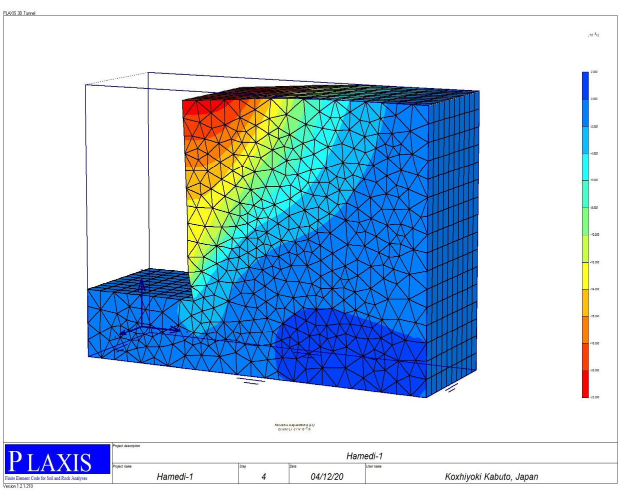

Figure 6. The lateral displacement model prepared for excavated slope without micro-piles reinforcement

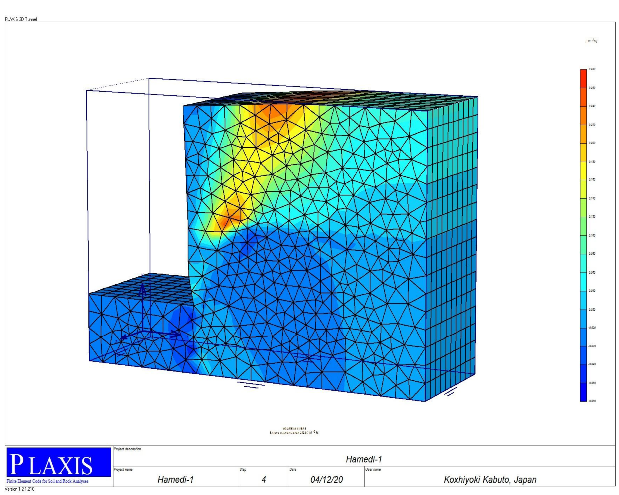

Figure 7. The main strain field model prepared for excavated slope without micro-piles reinforcement

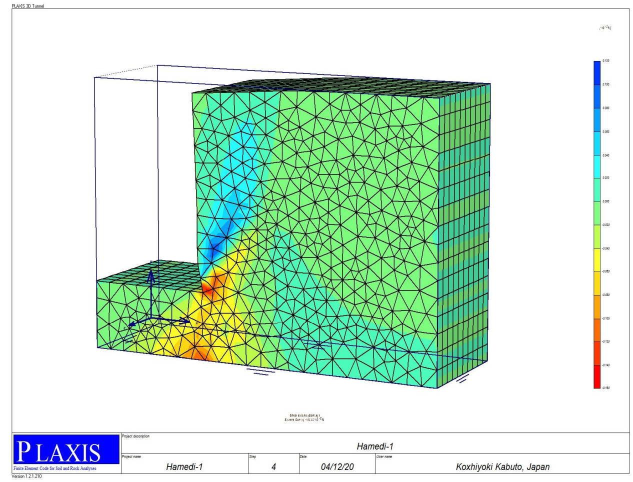

Figure 8. The shear strain field model prepared for excavated slope without micro-piles reinforcement

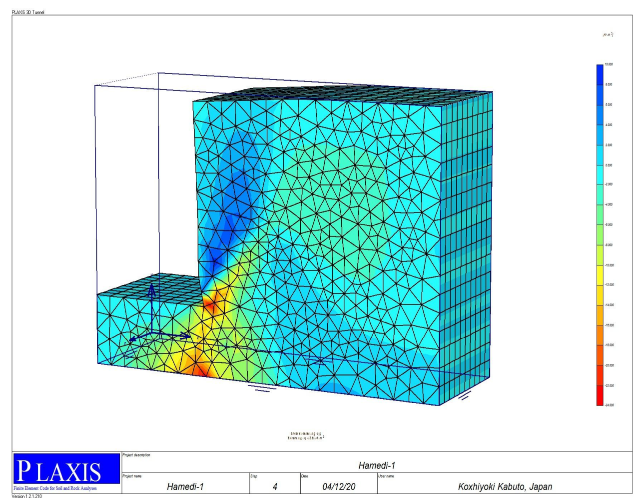

Figure 9. The shear stress field model prepared for excavated slope without micro-piles reinforcement

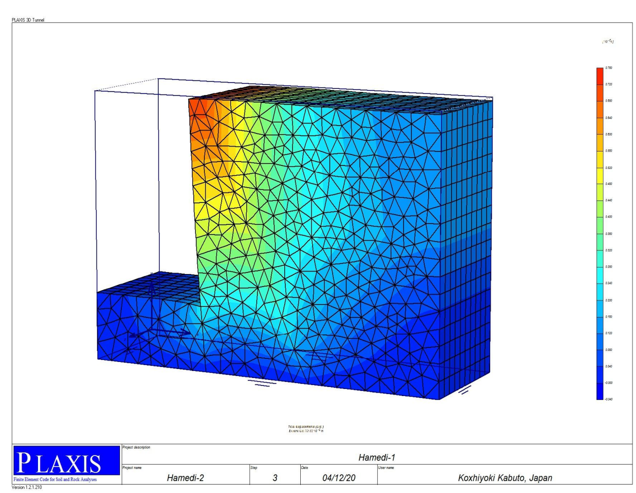

Figure 10. The displacement model prepared for excavated slope with micro-piles reinforcement

After performing the modeling for the slope under dynamic condition, the slope is improved by using micro-plies as reinforcement to slope to be retrofitted. In this regard, the geometrical model of the mass was reinforced by installation of micro-plies as presents as Fig. 4 is utilized. Figs. 10 to 14 show the stability analysis results of the reinforced slope. As can be seen from these results, the application of micro-piles has been able to significantly reduce shear displacements and restrained deformations in the slope. Fig. 10 illustrated the main displacement model that obtained in the slope mass after the micro-piles' installation. As shown in this figure, the highest concentration of displacement is in the top of the micro-piles (top of excavated slope) which indicates the restraint of mass movements.

Figure 11 is presents the lateral displacement measured by model were expressing the lateral deformation and sliding status of the excavated face. As can be seen in this figure, the deformation pressure due to soil displacement has shifted from the entire slope to specific slope-top which indicates the capability of micro-piles to restraint the deformable mass. On the other hand, referring to Figs. 12 to 14 where presented the in-situ stress and strain fields on slope body, it can be well seen that the loading repercussion on slope body is reduced by reinforcement strategy properly. These results show the spatial explanation of shear stress and shear strain in the slope which was indicate the micro-piles have well controlling capability to restrained deformations.

4. Conclusion

Soil stabilization has always been one of the most important procedures in the geotechnical stabilization for civil engineering projects, which is implemented with the aim of soil conditions' improvements where classified as structure or soil mass modifications. The purpose of using these stabilization procedures is to improve the geo-engineering properties or restrained deformations in the soils. Practically, various methods for soil improvement are used by geotechnical engineers to stabilize the soil. One of these methods is the use and implementation of microcontrollers. Micro-piles have a structure similar to the executive structure of micro-piles, but are used on a smaller scale and with a superficial improvement. On the other hand, the use of executive materials for micro-piles is much more limited and economically appropriate than the implementation of micro-piles.

The present study attempted to investigate the micro-piles performance for providing the stability in loose sand slopes faced with excavation operations. In this regard, the three-dimensional finite element numerical method by and Plaxis3D software have been used to implement the loading conditions, evaluate the deformations and stability analysis of the slope mass. Methodologically, a set of modeling including geometric modeling, determination of

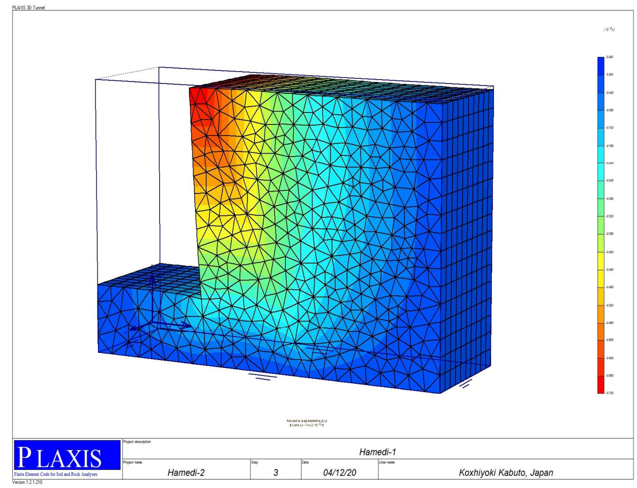

Figure 11. The lateral displacement model prepared for excavated slope with micro-piles reinforcement

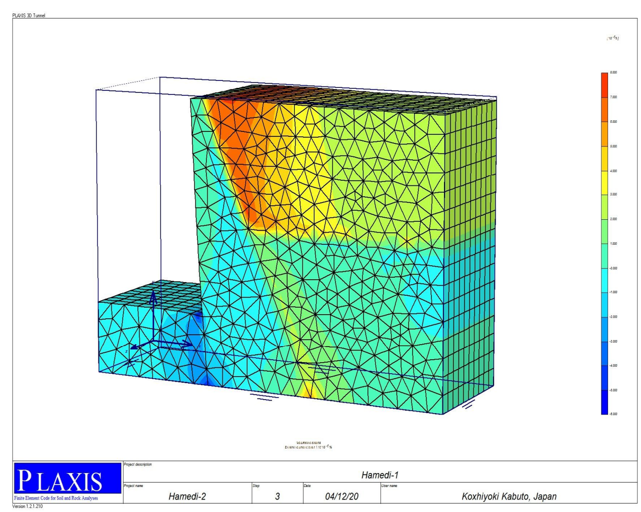

Figure 12. The main strain field model prepared for excavated slope with micro-piles reinforcement

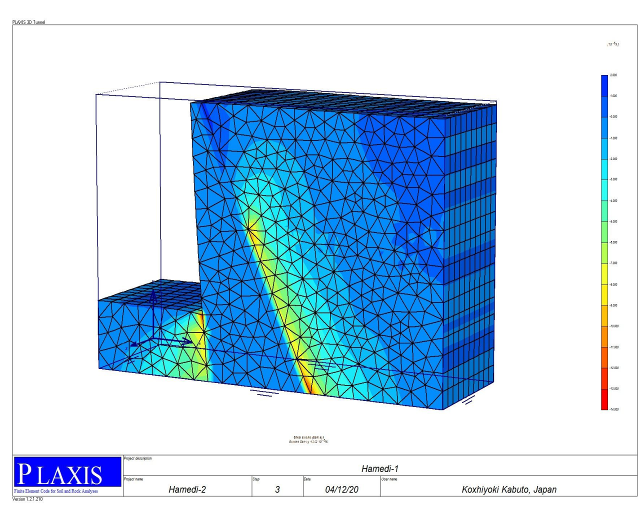

Figure 13. The shear strain field model prepared for excavated slope with micro-piles reinforcement

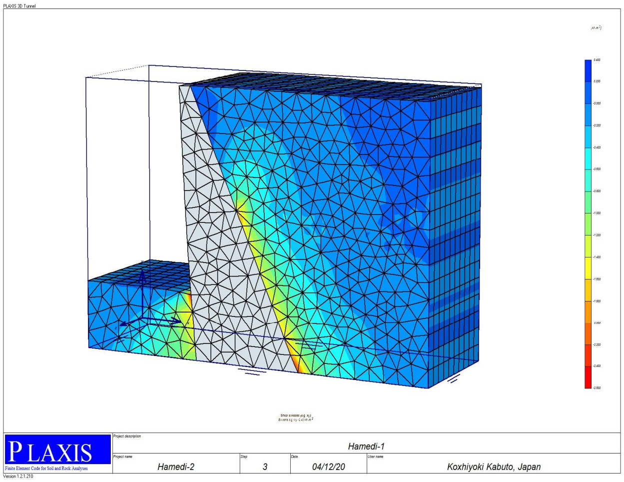

Figure 14. The shear stress field model prepared for excavated slope with micro-piles reinforcement

boundary conditions and behavioral models, assignment of material properties and also a dynamic modeling was conducted to investigate the stability assessment and obtain the micro-piles performance for restraint of mass movements. According to the results of numerical modeling, it has indicated the application of reinforcements has been able to significantly reduce shear displacements and restrained deformations in the slope.

Acknowledgements

The authors wish to thank the Department of Civil Engineering for giving the permission of the studies.

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