Journal of Geotechnical Geology

Journal homepage: geotech.iauzah.ac.ir

Zahedan Branch,
Islamic Azad University

Three-dimensional Finite Elements Numerical Modeling for Strip Foundations on Granular Soils Reinforced with Micro-piles

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ARTICLE INFORMATION

Received 01 September 2021
Revised 17 October 2021
Accepted 22 October 2021

KEYWORDS
Numerical modeling; Strip foundation; Granular soils; Finite element method; Plaxis3D.

ABSTRACT

In the present study, the performance of micro-piles for the improvement of loose sandy soils under dynamic loading on strip foundations was investigated. For this purpose, finite element numerical method (FEM) by Plaxis3D software has been used to implement loading conditions and evaluate deformations in loose sandy soils below the strip. The modeling process includes geometrical, behavioral models, boundary condition, material properties and dynamic modeling which that implemented on both unreinforced and reinforced strip foundation by micro-pile. Based on the results of the study, it can be well stated that the implementation of micro-piles has been able to improve loose sandy soils in strip foundations under dynamic loading conditions. So, the use of micro-communities in improving soil conditions against similar soils can be suggested.

1. Introduction

The term reinforced soil refers to soil that is reinforced by geotechnical elements such as rebar, steel belts, fibers or geosynthetics, geotextiles and geogrids, and that are compatible with internal friction and soil adhesion (Moin et al., 2020). The original idea of reinforced soil is not new and dates back to antiquity, but the current concept of this idea and the method of its analysis and design have been developed by a French engineer named Vidal (Nicholson, 2014). The main purpose of soil reinforcement is to improve its stability, increase bearing capacity and reduce deformations of loose soils (Raison and Raison, 2004). Loose (and usually saturated) soils due to low permeability and low bearing capacity, became highly compactable which pose a high risk to structures and lead to failures and subsidence. To solve this problem, the soil reinforcement is considered which depended on the executive and operational goals. The soil reinforcements can be classified into groups of soil and structural improvements (Azarafza and Asghari-Kaljahi, 2016). In soil-based improvements, soil materials are improved regarding to the strength parameters and mechanical properties. In structural improvements, the geotechnical properties of soils are improved by implementing engineering structures (Nicholson, 2014). Among these, structural improvements have higher priorities than soil improvements in urban areas due to the implementation of continuous structures without the need to change the nature of the soil (Raison and Raison, 2004). Existence of spatial constraints, impossibility of transportation and proper earthworks, continuous excavations and the existence of ancillary structures are among the most important reasons for this prioritization (Nicholson, 2014).

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https://doi.org/ 10.30495/geotech.2021.686314
Available online 07 November 2021

Micro-piles are piles less than 300 mm in diameter, often operated by light steel reinforcement and high-pressure cement slurry injection. The loads applied to the micro-piles are mainly transferred to the ground and deeper layers in the form of tip resistance and frictional resistance created between the pile element and the adjacent soil (Han, 2015). In micro-piles, bearing capacity of the floor is insignificant, but the frictional resistance of the wall is greatly increased by the resistance capacity of the bond between the slurry and the surrounding soil regarding on the grouting injection quality (Azarafza and Asghari-Kaljahi, 2016). In addition to increasing the bearing capacity of micro-piles; they improve the mechanical properties of the surrounding soil by injecting grout. Micro-piles can be considered as a combination of two structural-environmental improvement techniques in geotechnical projects (Atarchian and Niazi, 2017) which are operationally divided into two groups: prefabricated and in-situ microfluidics. Prefabricated microcontrollers are elements that are pushed into the ground by impact or vibration, so during installation, they move the surrounding soils and push them forward. On-site micro-piles are placed in pre-drilled boreholes and wells or built and executed on site. So they are placed in the excavated ground (Han, 2015).

Micro-piles can be subjected to axial or lateral loads. They can also be used instead of ordinary piles or as part of a composite pile-soil system, depending on the design method in the body of loose soils (Han, 2015). The structures are also applicable in environments with limited access, different types of soils and different land conditions. Micro-piles with equipment similar to that used in injection and inhibition projects. On the ground, they can be installed at any angle. Due to the minimal noise and vibration during installation and the lack of need for much space to run, micro-piles are often used to improve the foundations of existing structures (Azarafza and Asghari-Kaljahi, 2016). In order to implement these geotechnical structures in the existing foundations and in operation, most of the special drilling equipment is required (Niazi et al., 2014). Most of the loads applied to conventional reinforced concrete piles are borne by the concrete. So that increasing the capacity of the instruments requires increasing the cross-sectional area and its lateral surface. In comparison, the load-bearing capacity of micro-piles structures depends on the high capacity of metal elements that withstand most of the applied loads. These steel elements occupy about half the volume of the micro-pile cavity (Han, 2015).

In this study attempt to investigate the bearing behavior of strip foundations on granular soils reinforced with micro-piles. For this purpose, the 3D finite element numerical approach (FEM) and Plaxis3D software have been used. The aim of application was estimate the performance of micro-piles to reduce the strip foundation's deformation on loose soils and control the capability of the micro-piles to improve the soil geotechnical condition.

2. Background

The history of the micro-piles is back to the early 1950s, when Europe was plagued by massive buildings that had been damaged by World War II. During this time, it was necessary to invent a method of improving the bed rock and foundation soils with applicability the demolished buildings, and also fast and economical. In the beginning, the use of micro-piles was considered only in improving the poor-bed buildings. After time with implementation of this method in different countries, the scope of usage of micro-piles has been extended to other geotechnical engineering structures (Han, 2015). By passing a time, micro-piles application in the structural improvement of loose soils has included significant changes. Depending on the implementation goals, it can be applied continuously or with slurry/grouting. In the first scenario (without grouting), the goal of improving is only modified the lateral bearing, and in the second scenario (with grouting), soil improvement with increasing general soil fertility is considered for all type of foundations. The presented article is fallowed the second scenario. However, a look at the history of studies has shown that the flexibility of using micro-piles in loose soil remediation is very high compared to other remediation methods and has had significant performance.

Capatti et al. (2017) provide an article on the dynamic behavior of micro-piles under different loading conditions. The experiments were performed on 2 vertical and inclined micro-piles where attached to the concrete cap in silt soil. El-Sawwaf (2018) presented an experimental and numerical study to investigate of the stationary strip foundation's behavior with micro-piles based on reinforced geosynthtics. The results of studies show that the placing of geogrids layers lead to economical design and the micro-piles' performance on foundations can be significantly improved. Cheng et al. (2019) presented in an article on strip foundations were modified by using micropiles and concrete grouting subjected to seismic conditions. The authors investigate the micropile-soil-structure interaction by a numerical approach and simulated the condition by finite element. Based on the results, by increasing the diameter and length of the micro-pile in reinforced concrete, its bearing capacity has improved by 40% and 98%, respectively. Pilecka et al. (2020) have used micro-piles to improve the slope's stability on an embankment. The results of the study showed that the application of micro-piles in the stability of soil slope is very significant and has well limited the deformation. Carroll et al. (2020) examined the effects of steel type, soil properties, and water level depth and micro-pile diameter on sand-soil regarding tensile test for 51 open-end micro-piles. The micro-piles varied of 48 to 60 mm outside diameter which done to better understand about axial loading processes. By integrating fatigue under cyclic loading in micro-piles for diameters of 340 to 508 mm, the authors showed that the parameters studied had a significant effect on the bearing capacity of the piles.

3. Material and Methods

The finite element method (FEM) is for the approximate solution of the differential equations governing continuous environments. This method is a numerical solution method to obtain answers to a wide range of geotechnical engineering problems, especially soil mechanics and foundation design. FEM method is a process in which a specific domain is expressed as a combination of fixed domains called finite elements, so that it is possible to form the approximation functions required in the residual weight approximation to solve a problem on each component. Therefore, the finite element method differs from traditional least squares, and other residual weight methods in terms of how approximate functions are formed. An important part of FEM modeling is networking, which involves numbering nodes and components and creating node coordinates and connection matrices. While creating such information is quite simple and the type of information affects the efficiency of calculations and their accuracy. The accuracy of FEM resolution also depends on the choice of finite element network. If the responses converge to a certain value by subtracting the lattice, the solution is said to have convergence. The selection of test answers as well as weighting functions is effective in the convergence of finite element solution. Weight functions as well as test responses should be sufficiently soft. This softness depends on the degree of the derivatives appearing in the weak form of the governing equation. In finite elements, weight functions as well as test responses and their derivatives must be able to accept constant values to the extent that they exist in the weak form of the governing equation (Brinkgreve et al., 2011).

Plaxis software is one of the most widely used geotechnical engineering software and has been used by engineers and consultants in the field of soil-foundation and geotechnics for many years around the world and in Iran. This software is a finite element advanced numerical software for deformation and stability analysis and is used to simulate an advanced behavioral model of nonlinear soil behavior depending on the intended purpose. With this software, it is possible to model excavation and stage excavation with different loading conditions and boundary conditions using 6-node and 15-node triangular elements. In this software, Mohr-Coulomb behavioral models, hyperbolic hardening model, softening model (Cam-Clay model), creep softening model and dynamic model can be used. Also with this software, the process can be made and Modeling drilling by activating and deactivating the elements in the calculation stage (Niazi et al., 2014). Plaxis, due to its capabilities and flexibility, can be dynamically evaluated based on the damping model and duration of the earthquake. In the present study, this capability has been used to simulate the dynamic soil-micropile-structure interaction. For this purpose, first dynamic analysis was implemented for the foundation without performing micro-pile and then dynamic analysis was performed for the model reinforced with micro-pile. The results of these two simulation groups have been analyzed comparatively and the role of microclimate implementation in improving soil-micropile-structure interaction has been investigated. It should be noted that in numerical studies, before dynamic analysis, dynamic parameters including damping, dynamic boundary conditions and dynamic networking dimensions should be implemented (Azarafza et al., 2015) which in this study is as follows:

- *Damping*: Since the dynamic waves in nature are damped with progress in the environment and its energy is reduced, so this phenomenon should also be considered in the software for dynamic analysis. In Plaxis software, in order to determine the damping automatically and based on Riley damping, the kinetic energy of the system is depleted, which is under seismic loading. For Riley damping, it is necessary to first define the Riley value in the natural frequency range by determining the natural frequency value of the prepared model. Determining the damping of the environment by computational methods is not easily possible and experimental achievements are generally used for this purpose. Based on experimental approaches, damping of 2 to 5% can be defined for dynamic critical conditions for soil and rock range (Brinkgreve et al., 2011). It is worth noting that if you use models that use viscous models (such as Mohr-Coulomb) due to the flow of plastic in the early stages, some energy load will be reduced. This energy loss requires that the attenuation in numerical studies reach about 0.5% (Niazi et al., 2014).
- *Dynamic boundary conditions*: In applying seismic acceleration to the model to prevent the reflection of seismic waves from the surface or boundaries of the model and its return into the model, it is necessary to change the type of boundaries from static to energy absorbing boundaries. In this regard, dynamic dampers are used vertically and shear. So, in the numerical model, free boundaries and viscous boundaries are replaced by static boundaries. This process is done automatically in numerical software such as Plaxis (Niazi et al., 2014).
- *Dimensions of networking*: Dimensions of networking or dynamic networking plays an important role in dynamic analysis. This is because increasing the size of the nets reduces the analysis nodes and also reduces the evaluation range and thus reduces the accuracy of the evaluation. Although reducing the size of the networking will increase the accuracy of the analysis, it will increase the computation time and will require hardware for more detailed models. In the present study, the mesh size of the nets is considered as follows so that it can evaluate the

models with good accuracy during dynamic analysis (Niazi et al., 2014).

4. Results and Discussions

In order to evaluate the performance and behavioral analysis of strip foundations improved by micro-piles located on loose soil; A set of modeling including geometric simulation, determination of boundary conditions and behavioral models, assignment of material properties as well as dynamic modeling has been done by Plaxis software. In the geometric modeling stage, all geometric structures, including the initial conditions, the location of the foundation, the condition of the slope and the soil layering conditions are determined. After specifying the geometric model, the boundary conditions of the model are assigned to the model. These boundary conditions are automatically taken into account by Plaxis software considering the dynamic conditions, and the free and closed boundaries are also marked in this way. In this study, the Mohr-Coulomb criterion is used as a behavioral model and the model is analyzed under dynamic conditions within 4 seconds of dynamic load. Table 1 presents the characteristics of the materials used during the simulation operation. Material properties are usually estimated using in situ and geotechnical laboratory tests that will be applicable in accordance with ASTM International Standard Guidelines. For this purpose, common soil mechanics tests such as uniaxial compression test, direct laboratory cutting test, triaxial compression test, box cutting and in situ plate loading are used. The simulation results are presented in Figs. 1 to 8.

Table 1. Geotechnical properties used in simulation

Materials	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
	C_{ref}	kN/m^2	10
	ϕ	Degree	35
	ψ	Degree	0
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
	C_{ref}	kN/m^2	500
	ϕ	Degree	28
	ψ	Degree	0
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
	C_{ref}	kN/m^2	100
	ϕ	Degree	20
	ψ	Degree	0
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

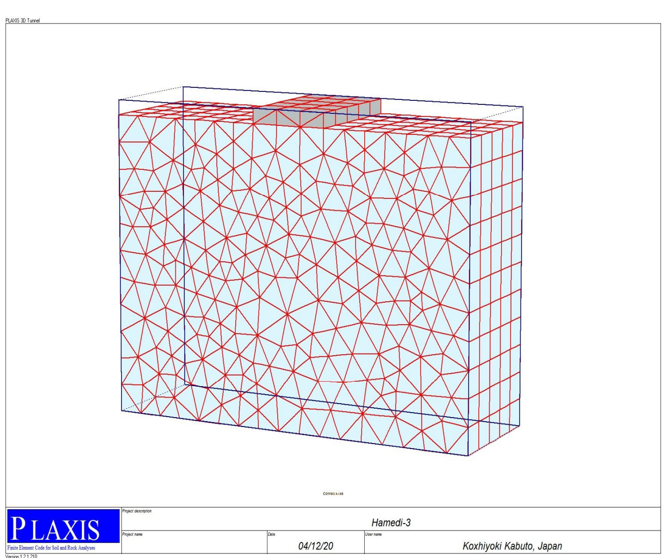

Figure 1. Geometric model prepared for strip foundation without micro-pile reinforcement

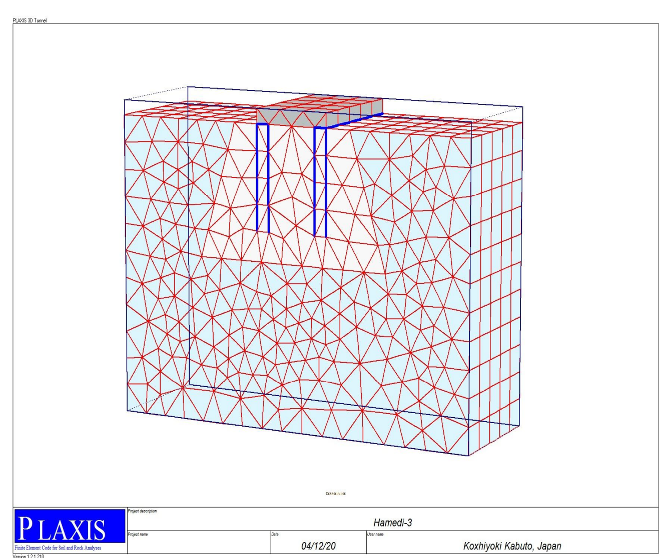

Figure 2. Geometric model prepared for strip foundation with micro-pile reinforcement

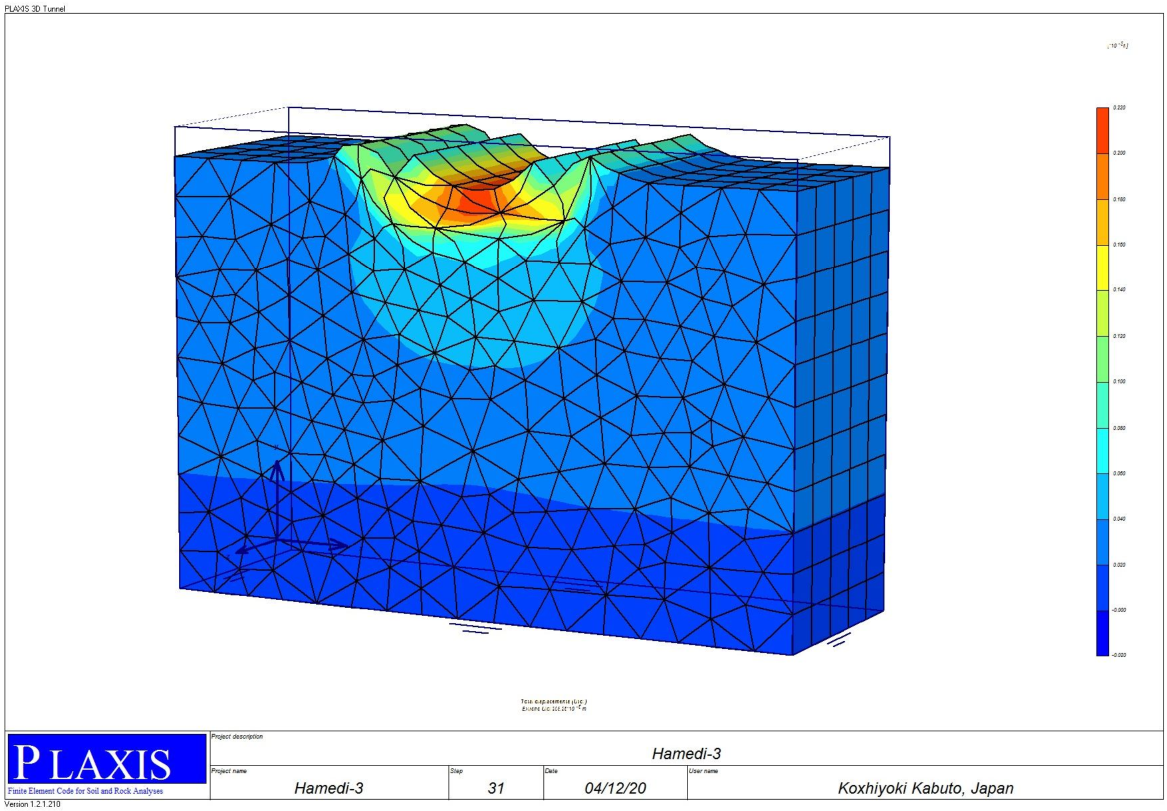

Figure 3. Displacement model for strip foundation without micro-pile reinforcement

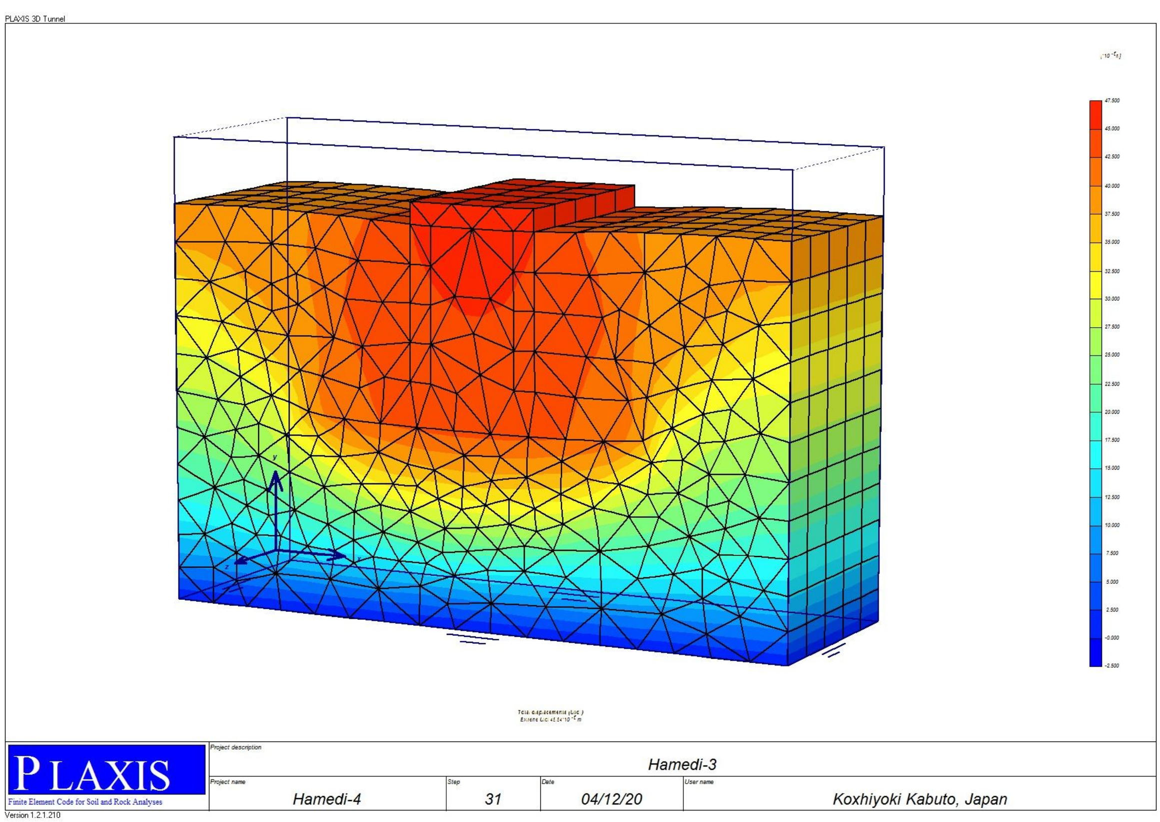

Figure 4. Displacement model for strip foundation with micro-pile reinforcement

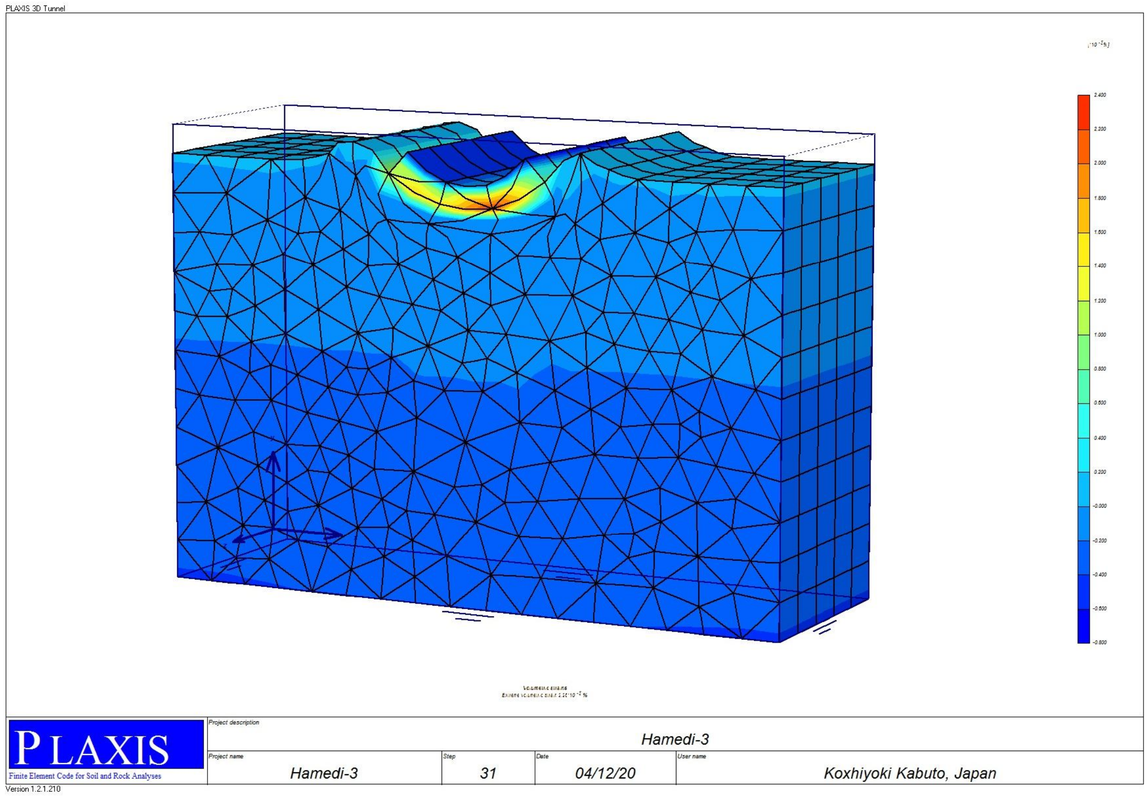

Figure 5. Strain model for strip foundation without micro-pile reinforcement

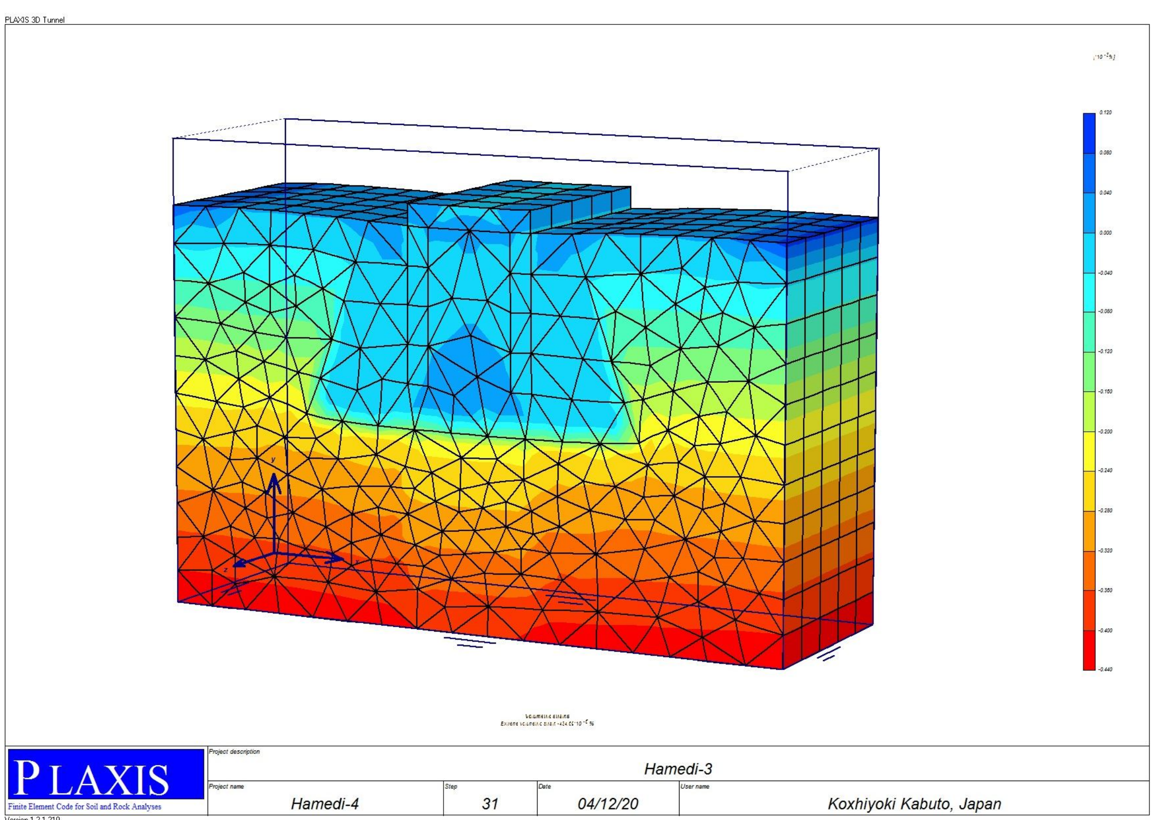

Figure 6. Strain model for strip foundation with micro-pile reinforcement

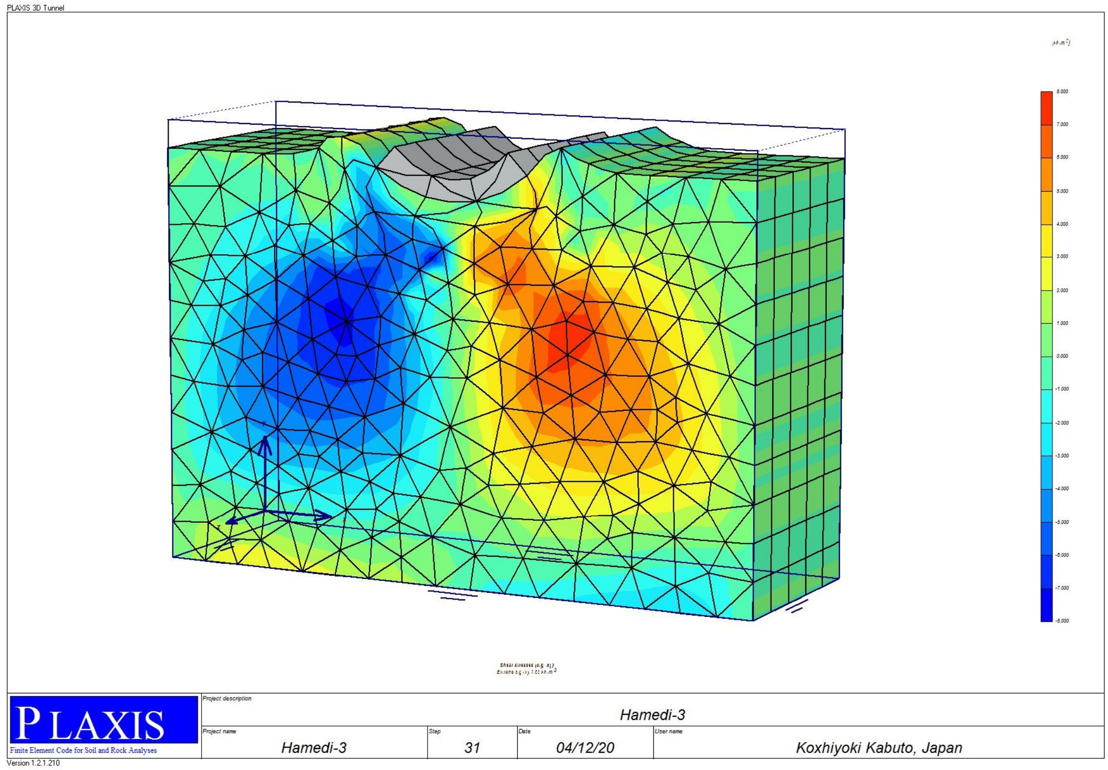

Figure 7. Shear strain model for strip foundation without micro-pile reinforcement

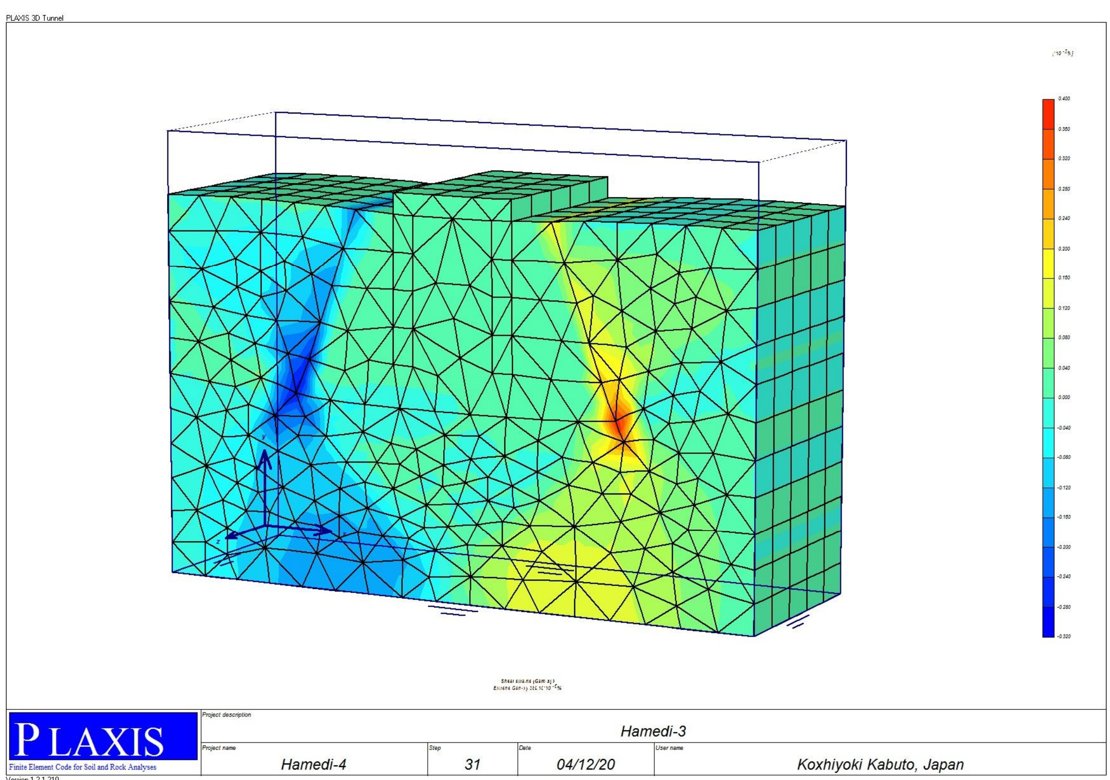

Figure 8. Shear strain model for strip foundation with micro-pile reinforcement

According to the dynamic modeling done in this study, it can be well stated that the implementation of micro-piles has been able to improve loose sandy soils in both sloping and surface foundations in dynamic loading conditions. Therefore, the use of micro-piles in improving soil conditions against similar soils can be suggested.

5. Conclusion

In the present study, micro-piles have been used to evaluate and analyze the structural improvement performance of strip foundations under dynamic loading. For this purpose, an attempt has been made to evaluate the performance of micro-communities in loose sandy soils in two ways, without reinforcement and with reinforcement. In this regard, using FEM method and Plaxis3D software, the conditions for improving structures under static and dynamic loading have been implemented. The purpose of dynamic foundation analysis in this study was to measure the performance of micro-piles in improving loose soil against rupture, based on which numerical modeling has been designed. Geometric modelings, determining the boundary conditions of the model, behavioral model, assigning material properties and solving the dynamic model have been the steps of model implementation, which has been done in both cases (without and with reinforcement). According to the dynamic modeling done in this study, it can be well stated that the implementation of micro-piles has been able to justify loose sandy soils in the improvement of strip foundations. Therefore, the use of micro-piles in improving soil conditions against similar soils can be suggested.

Acknowledgements

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

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