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Prediction of the displacement mechanism of the cracked soil using NXFEM and Artificial Neural Networks

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Abstract

The stiffness and strength of the soil foundation govern the seismic safety of the structure. Estimating the influence of the soil crack on the nonlinear displacement of the soil foundation needs to be investigated in detail. In the present study, the cracked soil foundation subjected to the seismic load has been simulated. The nonlinear extended finite element method (NXFEM) was applied for the prediction of the crack path on the soil foundation considering the mechanical properties of the soil as the main parameters. In addition, the impact of the crack morphology on the differential displacement of the soil model was investigated. To examine the validity and prediction of the displacement range of the cracked soil foundation, Artificial Neural Networks (ANNs) were employed by using MATLAB. Considering the results of the numerical simulation and ANNs were observed that there is a direct relationship between the morphology of the soil crack with the soil with displacement mechanism. The morphology of the soil crack has a considerable impact on the vibration mechanism of the soil mass subjecting to the seismic loading. The novelty of the present study is related to the prediction impact of crack morphology on cracked soil foundation differential displacement. The prediction crack morphology of the soil significantly supports geotechnical earthquake engineering design.

Keywords: Soil crack; crack morphology; seismic loading; ANNs; NXFEM; displacement.

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1. Introduction

The crack length, crack initiation mechanism, crack morphology and stress create cracks in different types of concretes (Carpinteri, et al., 2010 Namdar, et al., 2013), sandstone (Zhou, et al., 2009), and steel (Masoudi Nejad, et al., 2021) have different mechanism compared to the soil clay (Namdar, et al., 2022a). The concept of fractural geometry was studied to realize the impact of the strength of the concrete material, which explains the relationship between crack propagation with energy consumption in the crack-developing process (Carpinteri, et al., 2010). The crack due to compressive force on the concrete load with different stages of the loading was investigated (Feng, et al., 2022), and the strength of rail steel subjecting to multiple directional cracks was predicted (Masoudi Nejad, et al., 2021), in addition, the damaging mechanisms in iron associated with the crack were discussed (Iacoviello et al., 2013; Iacoviello et al., 2019), considering previous research works, in the clay, crack is initiated based on the mineralogy and mechanical properties of the soil, and crack initiates even without applying surcharge load only with changing mechanical properties of clay due to climate change causing the clay moisture level. The crack will be extended by applying the loads either in single or multidirectional.

The crack interaction causes the overloading in the soil model and modifies the seismic loadings interaction considerably with the developing deformation transmission condition of the seismic modeled earth structure (Namdar, et al., 2022a). The structural seismic vibration mechanism has an impact on the differential displacement of the soil, and this process gets more complicated when the soil-structure interaction takes place due to the applying seismic loading to the structure. In addition, it was reported that the mechanical properties of the soil are an important factor in developing displacement in soil foundation and structure as well (Namdar, 2020a). The interaction of the crack of the backfill model accelerates the displacement and the impact on the differential displacement mechanism (Namdar, et al., 2022b), also the displacement capacity is related to the crack in recycled aggregate concrete (Feng, et al., 2023).

The extended finite element method was applied for improving the crack trajectory prediction for crack simulation. The procedure method brought benefits for solving engineering problems in all scales (Chen, et al., 2020). The 3D cracks of the specimens subjected to the uniaxial compressive loads were investigated using 3D numerical simulation, for realizing the failure mode of the specimen and crack coalescence procedure (Shou, et al., 2019). Based on the undamaged techniques, the geotechnical structure subjecting to the seismic loading has been simulated to predict the multidirectional displacement with a combination of the finite element and statistical modeling to realize the seismic stability procedure of the model (Namdar, 2021a; Namdar, 2021b)

The mechanical properties of the recycled aggregate were investigated using back propagation neural network for optimal prediction of the results (Feng, et al., 2022). Artificial intelligence was used for predicting the seismic response of the concrete column with a developing algorithm and validation results considering test and train data (Tang, et al., 2021). For solving engineering problems with unknown variables, advanced mathematical concepts and techniques will be supporting tools. (Guo, et al., 2021) were used the artificial neural network (ANN) to predict the displacement of the embankment in the presence of multidirectional seismic loading and the variation of the mechanical properties of the soil during applying seismic loading on the model.

The stress and strain are developing cracks if the materials could not have sufficient flexibility and strength which is leading to the collapse of the soil or structure with a high level of displacement. The concept of crack propagation with respect to the mechanical properties of the soil subjected to seismic loading needs more investigation in detail. In addition, the impact of the morphology of the crack on the displacement mechanism of the soil foundation needs more study in detail. In the present study, to simulate crack propagation and crack morphology, to realize the impact of the soil crack morphology on the displacement mechanism of the soil foundation, and to estimate soil foundation seismic failure patterns NXFEM and ANNs were employed.

Nomenclature

a_i	Unknowns associated with the enrichment
C	Cohesion
C_z	Cracked zone
E	Modulus elasticity
H_t	Model height
S_z	Solid zone
$N_i^*(x)$	Partition of unity
$N_i(x)$	Standard finite element shape functions
$u^h(x)$	Standard equation for XFEM
u_i	Standard finite element unknowns
γ	Unit weight
ν	Poisson's ratio
ϕ	Friction angle
ψ	Dilatancy angle
ψ (x)	Global enrichment function

2. Methodology for predict of the displacement

Due to mechanical properties of the soil and strength and stiffness of the soil, the soil foundation seismic load response is complex compared to the other types of materials are subjecting to the nonlinear excitation. This process is related to the weakness of the soil in sustaining the tensile load and soil mechanical properties as well. Simulation and examination of the soil tensile behavior is not an easy task in the laboratory or field experimental work. For this process, there is a need of using appropriate finite element software and mathematical simulation techniques for testing and validating the results of the numerical simulation to reach appropriate results, which have a higher level of accuracy before applying results to engineering decision-making. Advanced statistical analysis and modeling are powerful tools for predicting engineering problems. In addition, this procedure support minimizing the cost of nonlinear engineering design.

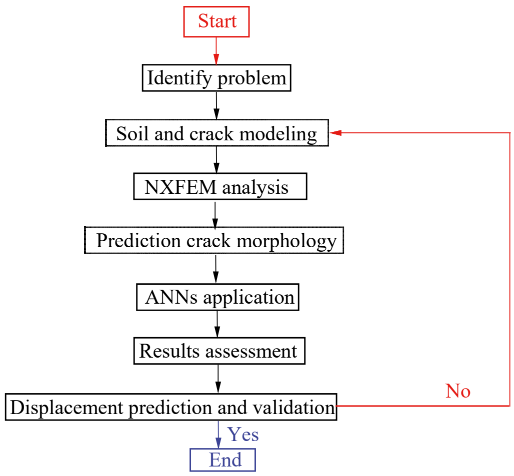

Fig. 1. The flowchart demonstrates the prediction and validation results of the numerical simulation

Figure 1, illustrates the complete procedure of this study. These steps are from the identification of soil foundation problems to the prediction of the soil foundation crack propagation morphology and displacement. The nonlinear extended finite element method (NXFEM) provides the first stage of output from the numerical simulation.

The results of the numerical simulation need to be validate and interpretation for apply in geotechnical earthquake engineering. The testing and validation results of the numerical simulation are done using Artificial Neural Networks (ANNs) with MATLAB programming. In addition, ANNs provide the best results among the huge data are producing from the nonlinear numerical simulation. In fact, the ANNs integrate the results of the numerical simulation, based on the test, train, and validate data in suitable layers for integrating data.

According to the small displacement theory of elasticity, the principle of complementary virtual work could be obtained from strain-displacement relations of a material that is subjected to the loads. The strain-displacement relationship is one of the important material characteristics for the prediction of the volumetric deformation of a model. From the output of the numerical simulation, the strain-displacement relationship needs to be plotted for all models, to predict vibration mechanism and nonlinear deformation of the models during subjecting to the nonlinear seismic acceleration in the multidirectional.

Figure 2, illustrates models 1 and 2. Two models of the soil foundation have the same geometry with two different clay types. At the bottom of the model the igneous rock type, and the bottom of the models are assumed to be rigid. In the modeling, the mechanical properties of the clay govern the crack length. From the seismic design point of the view, the crack length of the model's impact on displacement needs to be analyzed in detail.

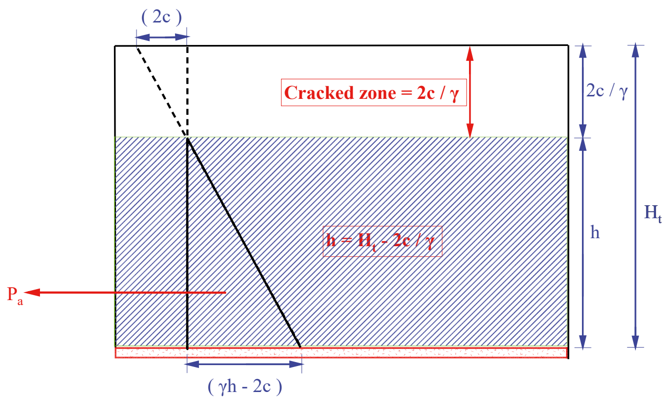

Fig. 2. Soil foundation models 1 and 2, with initial theoretical crack

$$C_z = Cracked\ zone = 2c / \gamma \quad (1)$$

$$S_z = Solid\ zone = h = H_t - 2c / \gamma \quad (2)$$

The equations 1 and 2 were indicated in the literature (Rajapakse, 2016), the analytically the cracked zone and also the solid zone of soil were obtained. The cohesion and unit weight of clay play main function in estimate length of the crack before apply load on the model, these two parameters of soil mechanical properties are the main function in the initiation of the crack and developing crack length. Table 1 illustrates the mechanical properties of two types of clayey soil that have been used in the cracked soil foundation for performing the numerical simulation.

Table 1. The mechanical properties of the soils A and B.

Material	Modulus elasticity, E (MPa)	Friction angle, ϕ (deg)	Dilatancy angle, ψ (deg)	Cohesion, C (kPa)	Unit weight, γ (kN/m^3)	Poisson's ratio, *v*	Ref
Soil - A	24	40	2	17	18.5	0.2	(Valleti, et al., 2018)
Soil - B	35	19.229	-	39.813	19.1	0.37	(Yang, et al., 2020)

Figure 3 shows the seismic acceleration history (m/s^2) of the Norcia, Amatrice Earthquake with 6.2 magnitudes with tolerance excitation in all directions. The critical parts of the acceleration have been used in the numerical simulation and were applied to the soil foundation model in the three directions.

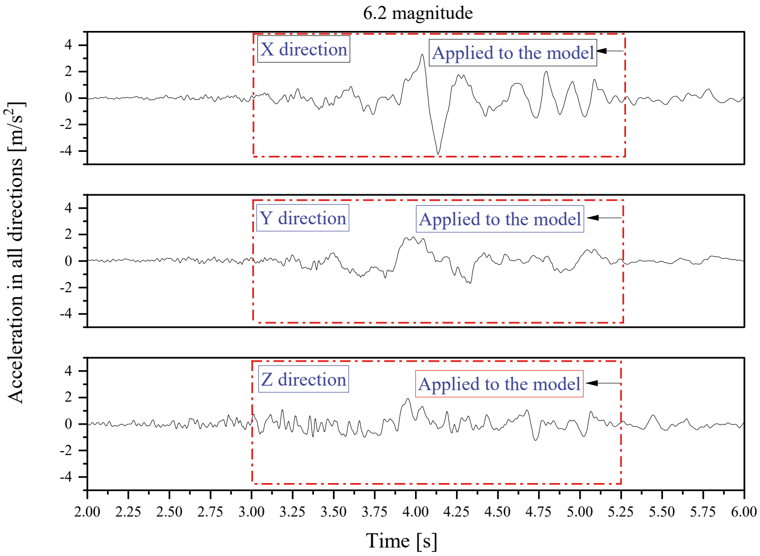

Fig. 3. The seismic acceleration history (m/s^2) of the Norcia, Amatrice Earthquake with 6.2 magnitude [CESMD].

Equation 3 is the standard form of XFEM (Belytschko et al., 1999; Moes et al., 1999). The ABAQUS software has been used for perform the nonlinear numerical simulation for models are subjecting to the seismic loading. Figure 4 shows the model with the dimension used in the numerical simulation. The linear volumetric hexahedral elements has been simulated for mesh modeling of the soil foundation and crack. The mesh for entire model and crack on the soil foundation was created using the ABAQUS software.

$$u^h\,(x) = \sum_{i\in I} N_i\,(x)u_i + \sum_{i=\in I^*} N_i^*\,(x)\,.\,\psi(x).\,a_i \qquad (3)$$

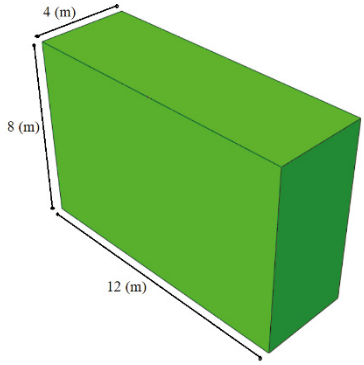

Fig. 4. Models 1 and 2 without any crack used in the numerical simulation.

3. Results and discussion

The mechanical properties of the soil govern the morphology of the crack which is developing in the soil due to the nature of the clay and the crack is extended by applying seismic acceleration in the multidirectional. The direction of the crack extension is a criterion for the prediction of the soil foundation seismic failure. In models 1 and 2, when the morphology of the soil foundation is similar, two types of cracks which are shear crack and flexural crack are developed. The types of crack propagation are dissimilar when the magnitude of seismic acceleration and the geometry of the models are the same and the mechanical properties of the model are different at each model. The types of cracks are associated with the mechanical properties of the soil.

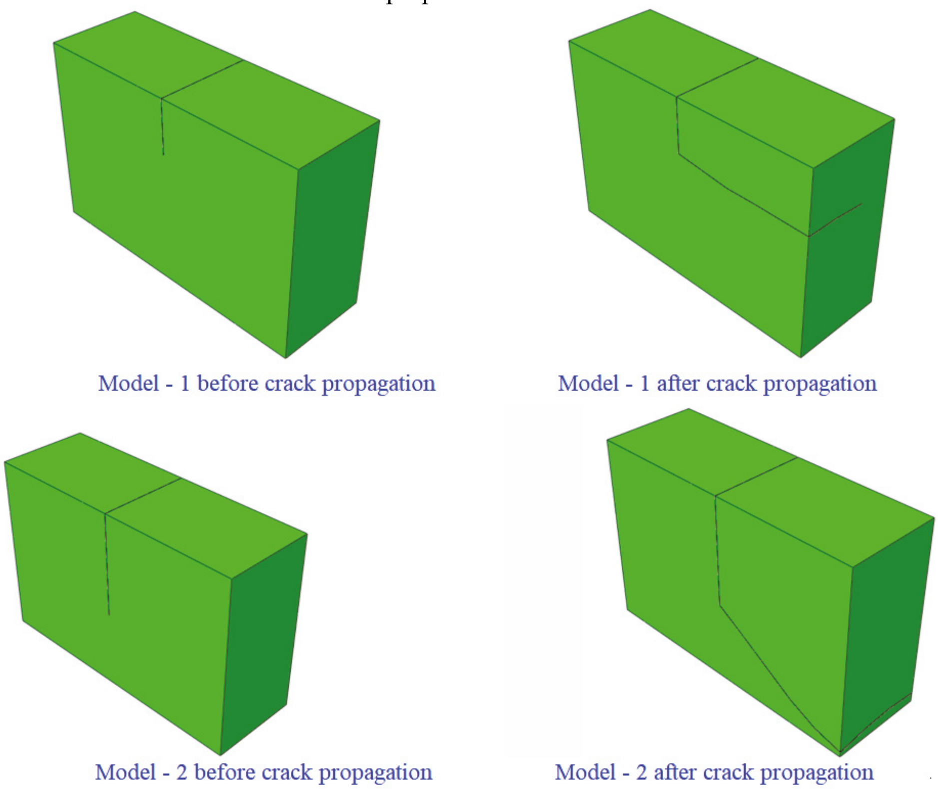

Fig. 5. Crack initiation and propagation in models 1 and 2.

The seismic failure pattern in the two models is not similar, it happened because of the crack morphology and direction of the crack propagation. In addition, the speed of the crack propagation in each model has specific characteristics. Figure 5 shows the crack initiation and propagation in models 1 and 2. According to the mechanical properties of soils 1 and 2, with a reduced friction angle of the soil, more shear failure occurs. The morphology of the soil particles is very effective in the failure patterns of the soil foundation and initiation and propagation of the crack morphology of the soil foundation model. The soil particle interaction is a factor in the seismic stability of the soil foundation.

After the soil cracks fully propagated in model - 2, the failure of the soil foundation occurs along with the sliding, this phenomenon has not been observed in model - 1. In model - 2, the shear stress causes the shear displacement and leads to the failure of the soil foundation. In model-2, the crack is propagated in the shear zone, and with the completion of the shear zone, the shear failure along with the soil sliding occurred. Based on the results of the nonlinear extended finite element method, the ultimate bearing capacity of the soil failure has been divided into shear and flexural failure.

The mechanical properties of the soil were modified by using the mixing soil technique for obtaining the appropriate safe bearing capacity of the soil (Namdar and Pelkoo, 2009). By using mixing soil techniques for designing the mechanical properties of the soil, there is the possibility for controlling the type of crack propagation in the soil foundation, this process controls the failure mode of the soil foundation with an understanding relationship between the crack propagation with soil safe bearing capacity. The mixing soil technique will be a method for controlling the crack propagation of the soil foundation for soil crack propagation research in the future.

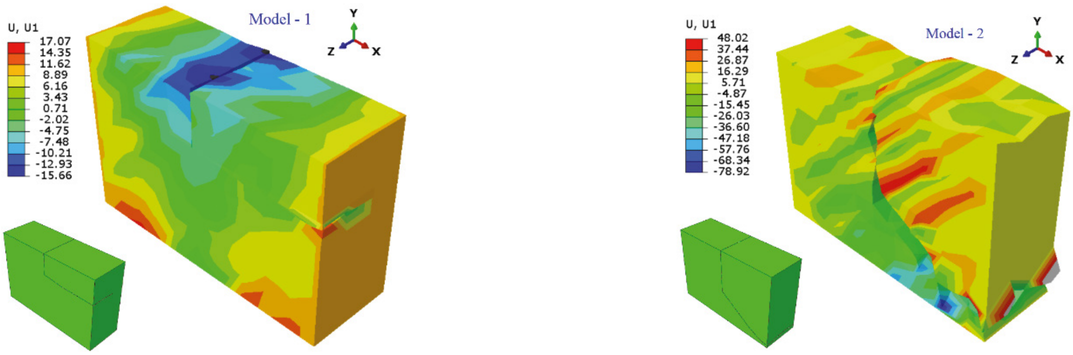

Fig. 6. Displacement in X direction at final stage of simulation.

Figure 6 shows the displacement mechanism of models 1 and 2 in the X direction at the final stage of the numerical simulation, for the tensile and compressive movement of the model. The failure of the soil foundation occurred due to the tensile displacement of the model. This phenomenon occurred due to the very low tensile strength of the soil foundation model. Figure 6 shows higher volumetric deformation in model 2, and also the soil movement is more observed in model 2. The morphology of the soil particles controls the deformation of the soil foundation.

Figure 7 shows the differential displacement mechanism of models 1 and 2 in the X direction, the only tensile displacement of the models is used in ANNs. In this study, the compressive displacement of the model has not been considered. With changing the crack propagation morphology the displacement in models 1 and 2 exhibits two different mechanisms. The morphology of the soil crack has a considerable impact on the differential displacement mechanism and vibration mechanism of the models. The vibration mechanism of the soil foundation is controllable with the application of the mixing soil technique in the soil foundation seismic design.

Figure 7 shows the accuracy of the test, training, and validation of the numerical simulation results. The differential displacement of the models was predicted using ANNs, in addition, the error was obtained. In model - 1, due to high soil tensile resistance, the vibration patterns have a dissimilar frequency compared to model - 2. In addition, the results of ANNs prove the low tensile strength of model - 2, and the weakness of model - 2, cause higher tensile displacement. Table 2 shows the results of the statistical analysis for models 1 and 2.

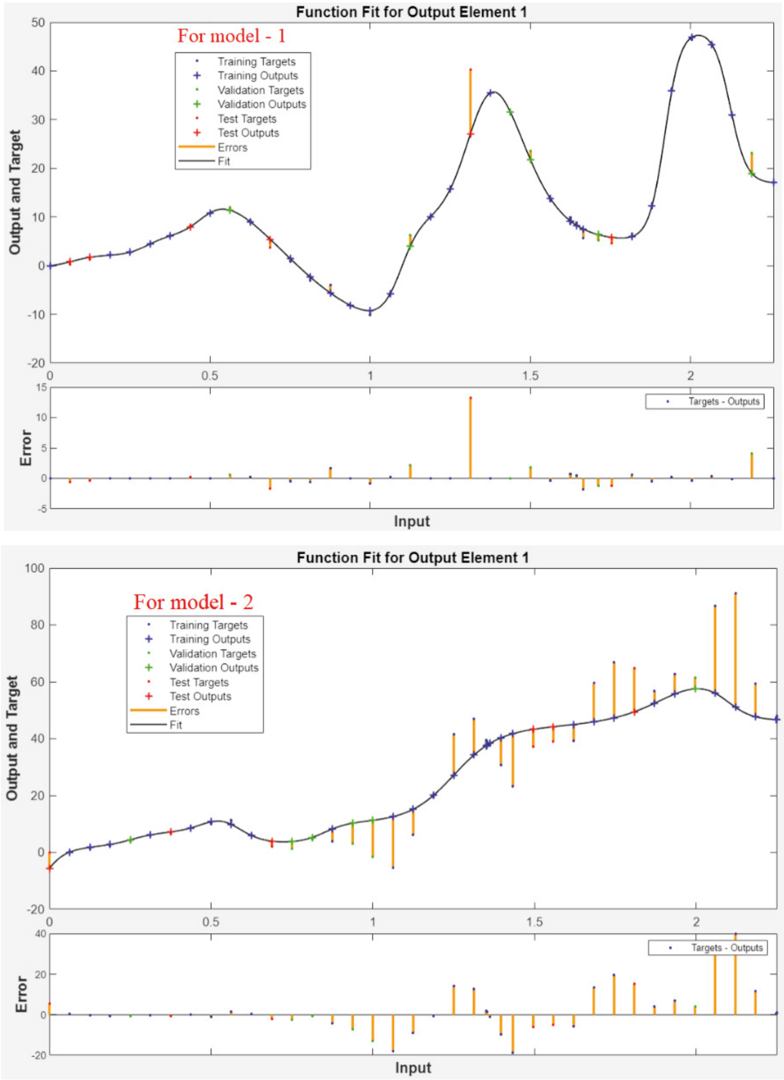

Fig. 7. Differential displacements analysis using ANNs.

Table 2. Results of the statistical analysis.

Model	R Training	R Test	R Validation	MSE Training	MSE Test	MSE Validation
1	0.99	0.99	0.98	0.365	30.18	4.42
2	0.91	0.95	0.98	158.77	55.81	40.17

4. Validation of the results

To validate and improve the results of the numerical simulation Artificial Neural Networks (ANNs) are used with employ MATLAB. The ANNs integrate the results of the numerical simulation, based on the test, train, and validate data in suitable layers for integrating data. The appropriate results of the numerical simulation were categorized for the test and the train. With the comparison of all types of data, the results of the numerical simulation were validated. Finally, the best possibility of displacement value was predicted.

5. Conclusion

The cracked soil foundation subjected to seismic acceleration has been simulated. The crack propagation of the soil foundation was predicted using NXFEM, considering applying seismic acceleration on the model in the multidirectional. Each model has different failure patterns, which are the flexural and shear failure for model-1 and model-2 respectively. The ultimate shear and flexural causes the soil foundation's main deformation and it leads to failure. The differential displacement mechanism of models was predicted using ANNs. The tensile displacement was main factor for soil foundation failure. The vibration mechanism of the model has a direct relationship with the mechanical properties of the soil. In order to reduce the impact of seismic acceleration on a structure, the improving mechanical properties of the soil is a suitable method. In addition, in the soil, the initiation and propagation of the crack are associated with the mechanical properties of the soil. The morphology of the crack governs the failure mechanism of the model, and seismic acceleration transferring in a model. The lowest tensile strength of the model causes tensile displacement. In addition, the speed of the crack propagation in each model has specific characteristics and influences the vibration mechanism of the model.

In geotechnical earthquake engineering, by using mixing soil techniques for designing the mechanical properties of the soil, the type of crack propagation and soil foundation failure could be predicted and support soil foundation design. The prediction of the crack propagation revealed the mixing soil technique is an appropriate soil foundation seismic design. According to the outcome of the present study, the concept of soil crack propagation needs to apply in soil improvement for minimizing soil and earth structure failure.

Acknowledgments

The authors declare that they have no conflicts of interest.

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