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The displacement simulation for cracked earth structure with different geometry

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Abstract

The strength of the material and safe economical design are important from the design point of the view in all branches of engineering. In many regions, the geographical characteristics of territory play important role in the design geometry of the backfill. In addition, using clayey soil to construct backfill results to have a crack in the cracked zone of the backfill. In the present study, the geometry of two different clayey soil backfill was investigated. The main aim of this study is for understanding the impact of the geometry of the model on the nonlinear displacement of the clayey soil backfill when the seismic load with equal magnitude is applied on the modelled clayey soil backfill. The results illustrate the seismic response and nonlinear displacement of the clayey soil backfill were modified by changing the geometry of the model. In point of view, to construct clayey soil backfill in a site needs to use different soil in constructing each clayey soil backfill concerning the geometry of the model. The novelty of this work introduces the concept of strength of the material association with the crack and geometry of the model in seismic design of the clayey soil backfill, considering the nonlinear displacement of the model in loading and reloading stages. Moreover, illustration of the nonlinear strain and nonlinear displacement of the model. The outcome of this investigation importantly explains the impact of model geometry in the cracks interaction, distribution of the displacement of the model, and displacement magnitude.

Keywords: Geometry; Clayey soil; Crack; Nonlinear displacement; Mechanical properties.

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Highlights

- The nonlinear displacement of the clayey soil backfill model is studied.
- The cracks interaction is associated with the geometry of the model.
- The distribution of the displacement of the model is associated with the geometry of the model.
- The distribution of the high and low peaks of the displacement governs the crack's interactions.

1. Introduction

The microstructural crack relates to the mechanical properties of the materials, also propagation, and initiation of the crack on the material investigated, and loading conditions, cracks interaction, and damaging mechanisms were discussed in detail (Iacoviello et al., 2014; Iacoviello et al., 2013; Iacoviello et al., 2019).

Nomenclature

C_z	Cracked zone
S_z	Solid zone
E_b	Earth pressure at beneath
E_t	Earth pressure at the top
E	Modulus elasticity
ϕ	Friction angle
ψ	Dilatancy angle
C	Cohesion
γ	Unit weight
ν	Poisson’s ratio

In addition, the macrostructural crack model on construction materials was reported in the literature to improve the quality of the construction design and analysis (Zhou et al., 2009; Masoudi Nejad et al., 2021; Namdar et al., 2016; Carpinteri et al., 2010). The impact of the mechanical properties of the materials on the macrostructural crack of the sandstone shows the mechanism of the crack significantly changes with association to the mechanical properties of the materials (Zhou et al., 2009). The possibility of macrostructural crack occurrence was analyzed for estimation of the stress intensity factors owing to applying cyclic loading on the rail steel, and geometry of the crack obtained using advanced statistical techniques (Masoudi Nejad et al., 2021). The cracking moment and forcing frequency became the applied forces for analyzing the impact of the load interaction and crack growing for displacement monitoring and failure of the structural element (Namdar et al., 2016). Using concepts of fractal geometry the fracture energy and stress intensity factor was investigated (Carpinteri et al., 2010). Concerning the crack mechanism in each construction material, the cracked clayey soil backfill needs to investigate for realizing the seismic response soil when the applying seismic loading is equal at each model. Furthermore, the nonlinear displacement of the soil model in earth structure is complicated when the crack is developing on the model.

The seismic response of the subsoil-embankment model revealed the geometry of the model relates to the nonlinear displacement mechanism of the model (Namdar, 2020a), and the function of the mechanical properties of the soil control the lateral and vertical displacement of the embankment-subsoil model (Namdar and Dong, 2020). The multilayered soil was subjected to the seismic loading simulated and it considered the change of the nonlinear displacement to linear displacement by application of appropriate multilayered soil design (Namdar and Satyam, 2021). The geometry of the model, mechanical properties of the construction material, and soil layer arrangement govern the displacement. The displacement mechanism of subsoil and infrastructure without crack reports in the literature. In addition, the displacement on the cracked soil infrastructure needs to investigate more in detail.

For investigation on mechanical properties and boundary condition of the model influences on the seismic stability, the embankment-subsoil has been modeled (Guo et al., 2021; Namdar, 2021). The finite element method simulated crack propagation (Chen et al., 2020; Shou et al., 2019), in addition, the finite element method along with statistical techniques needs to use for illustrating the displacement mechanism at each moment of applying seismic load on the model. Accumulating displacement in several stages of the numerical simulation creates the nonlinear displacement of the infrastructure model. The nonlinear displacement of the model in both loading and reloading stages has to investigate by applying appropriate techniques.

Artificial neural networking recommends the prediction of the bearing capacity of the soil concerning the mechanical properties of the soil (Namdar, 2020b). Moreover, the mixed-mode fracture (Marsavina et al., 2017), fatigue strength (Marsavina et al., 2019), damage development (Albinmousa et al., 2020), welded joint (Song et al., 2018), and hot rolling process (Bordonaro et al., 2018), have been predicted. The investigation on the impact of the structural geometry of the clayey soil backfill on load interaction and developing the nonlinear displacement of the model needs to predict concerning seismic resistance of the clayey soil backfill. In the present study, an attempt was made to realize the influence of the geometry of clayey soil backfill on the nonlinear displacement of the model, when the model is subjected to the seismic acceleration in three directions simultaneously and the model has five cracks in the crack zone. The nonlinear displacement of the model in both loading and reloading stages are investigated by applying the appropriate technique.

2. Method for simulation

The cracks interactions influence the soil seismic resistance of the infrastructure and it is a new and interesting topic in geotechnical earthquake engineering for estimating the safety of the infrastructure. The cracks interactions concept needs to apply in analysis and design for better understanding the earth structure seismic response, improving construction quality, and minimizing damage and collapse of the infrastructure. In the present study, the geometry of two different clayey soil backfill with five cracks in the crack zone was proposed, and with changed geometry of the clayey soil backfill, the lengths of the cracks are not changed, because the length of the cracks is associated with the mechanical properties of the soil. The finite element method was employed for analyzing the influence of the cracks interaction and impact of that on the nonlinear displacement of the clayey soil backfill model in loading and reloading stages of the applying acceleration.

Figure 1 illustrates the clayey soil backfill model in two dissimilar sizes. The occurrence of the changing geomorphology at each region causes to have clayey soil backfill with several sizes in the construction site. Owing to this reason, we did not consider the specific case study of the clayey soil backfill and it was assumed two different sizes for the clayey soil backfill. The seismic acceleration characteristics of the earthquake were applied on the clayey soil backfill using the nonlinear numerical simulation which is shown in figure 2.

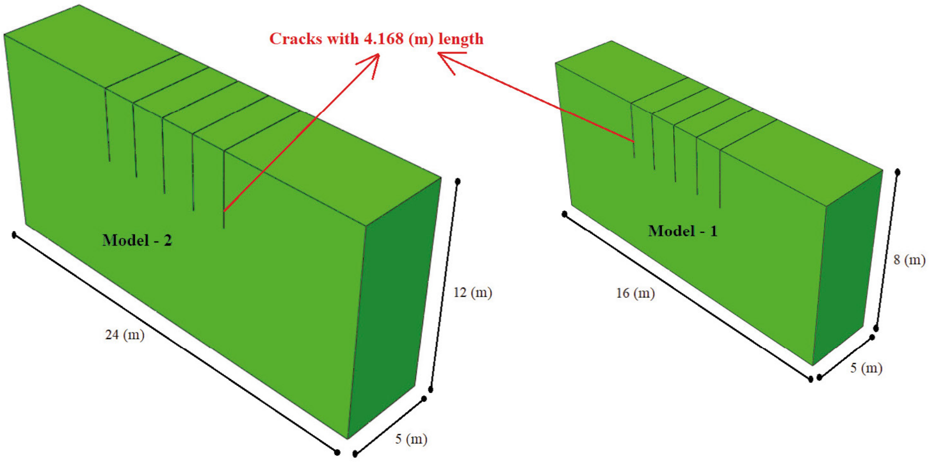

Fig. 1. Clayey soil backfill model in two different sizes.

The nonlinear seismic acceleration collected from those were reported in available literature (CESMD). To precisely simulate clayey soil backfill is subjecting to the acceleration loading, with referring to literature, the seismic acceleration in three directions was applied on the clayey soil backfill (Namdar, 2021). Applying seismic acceleration at the three directions of the model is an accurate boundary condition in geotechnical earthquake engineering for analysis and designing the seismic response earth structure. In the present work, the seismic acceleration was applied to models 1 and 2, in three directions simultaneously. The present method can accurately simulate the earth structure behavior when is subjecting to seismic acceleration. According to the literature report (Namdar, 2021), if only horizontal seismic loading is applied to the model, the results of the nonlinear displacement will be underestimated and it is difficult to make a judgment based on the research outcomes. In addition, to estimate nonlinear displacement with acceptable accuracy needs to apply seismic loading on the model in three directions simultaneously and interpret the results using appropriate statistical techniques. The reliability of the research outcome requires support using statistical techniques.

The equation 1-4 were reported in the literature and from using these equations (Rajapakse, 2016), the cracked zone and the solid zone of the clayey soil backfill were estimated. The cohesion and unit weight of soil are important factors for the creation of the cracked zone and the solid zone of the clayey soil backfill. The results of the analytical method integrate the modeling for performing the numerical simulation process.

$$C_z = Cracked\ zone = 2c\,/\,\gamma \tag{1}$$

$$S_z = Solid\ zone = h = H_t - 2c\,/\,\gamma \tag{2}$$

$$E_b = Earth\ pressure\ at\ beneath = (\gamma h - 2c) \tag{3}$$

$$E_t = Earth\ pressure\ at\ top = (\,2c\,) \tag{4}$$

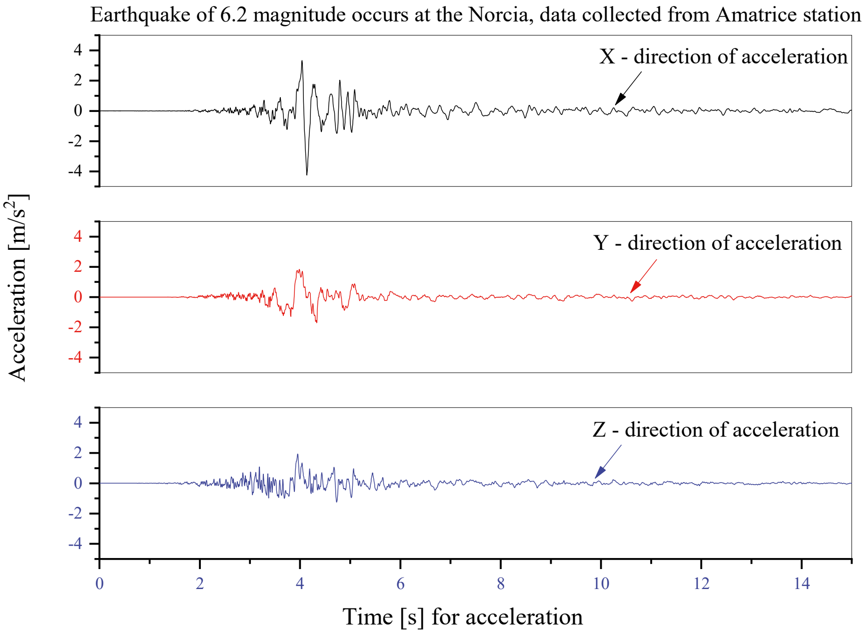

Fig. 2. Seismic acceleration characteristics applied on the clayey soil backfill [CESMD].

Table 1 presents the mechanical properties of the clayey soil was used in modeling the clayey soil backfill for models 1 and 2 (Yang et al., 2020). The cracked zone was calculated for models 1 and 2 according to the mechanical properties of the clayey soil. The numerical simulation was performed considering the results of the analytical method, mechanical properties of the soil, and geometry of each model. According to table 1, the mechanical properties of the soil has the following characteristics, the modulus elasticity of 35 (MPa), friction angle of 19.229 (deg), dilatancy angle of zero (deg), the cohesion of 39.813 (kPa), unit weight of 19.1 (kN/m^3), and Poisson's ratio of 0.37. Concerning the mechanical properties of the soil, the soil is clayey and will have a cracked zone when it is used for constructing the backfill model, and the crack in the cracked zone is the main parameter for assessing the nonlinear displacement of the model when is subjecting to the seismic acceleration. Figure 1 shows the crack is developed in the crack zone and, the remaining part of the backfill is a solid zone at each model. Models 1 and 2 have two different geometry with the same number of cracks. Figure 3 shows a flowchart that explains the structure of the research.

Table 1. Mechanical properties of the clayey soil (Yang et al., 2020).

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
Soil	35	19.229	-	39.813	19.1	0.37

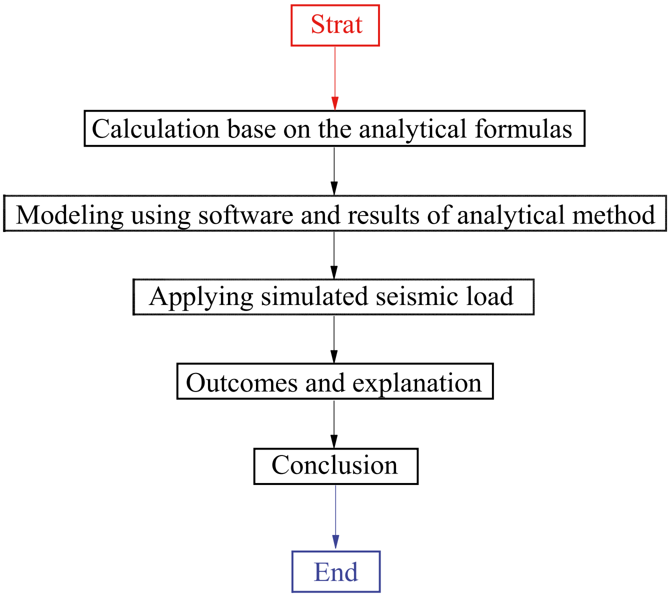

Fig. 3. The flowchart explains the structure of the research.

3. Outcomes and explanation

The results of the numerical simulation in the present study is considering the geometry of two different clayey soil backfill. The nonlinear displacement of the clayey soil backfill compared in single and all stages of the numerical simulation. According to figure 4, with increasing the dimension of the clayey soil backfill, the magnitude of the differential displacement at the final stage of the numerical simulation reduces and the model is facing the lower range of the nonlinear displacement.

With changing the geometry of the clayey soil backfill, the crack zone of the model is calculated, but the length of the crack is not changing. Because the length of the cracks is using equations of 1-4. Considering figure 4, the cracks interaction is associated with the geometry of the model. The internal compression and expansion of the clayey soil backfill were demonstrated by comparing cracks interaction in models 1 and 2. The load transmission and cracks interaction mechanism are changing related to the model geometry. The geometry of the clayey soil backfill influences the strength and stiffness of the soil and loads interactions as well. The distribution of the high and low peaks of the displacement of the clayey soil backfill model is changing with the geometry of the model at each stage of the numerical simulation, and subsequently, the nonlinear vibration in each model is different for each model. The distribution of the high and low peaks of the displacement governs the crack's interactions. The cracks interactions of the model for each model are different. In addition, the expansion and compression of each crack is following different configurations. For example, the central cracks are habiting with lower expansion and compression, while the cracks in the corner of each model exhibit more expansion and compression. The cracks interaction is playing the main role in the vibration of the model.

The equivalent value of mechanical properties for both models and differential geometry of model leads to display different cracks interaction in the displacement mechanism of each model. The stiffness and strength of the clayey soil backfill model are associated with the cracks interaction of the model. The one type of mechanical properties in the present work is used while in the future research could use several mechanical properties for predicting the seismic resistance of the clayey soil backfill with considering the more than five cracks interactions.

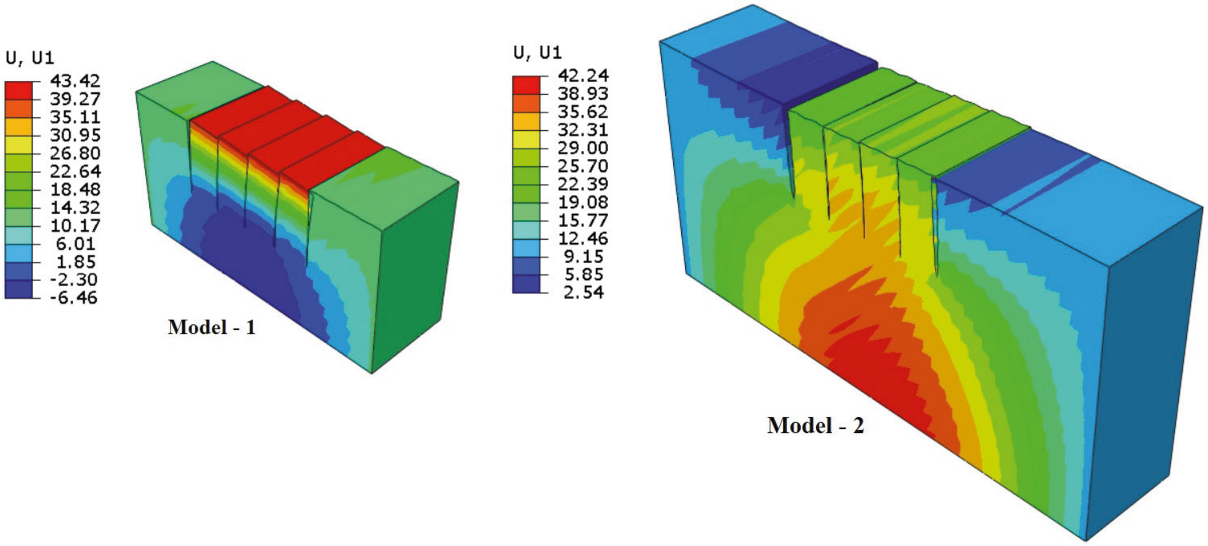

Fig. 4. The nonlinear displacement and cracks interaction at the final stage of the simulation.

Referring to figure 5, at the final stage of the numerical simulation, the strain energy in model 1 and model 2 are not similar. The higher strain variation is observed in model 2 of the clayey soil backfill. The compressive strain and tensile strain distributing around the cracks in model 1 are observed. Moreover, for model 1, higher tensile strain occurs around some cracks. The higher compression in the soil causes more displacement. In the final stage of the numerical simulation, the more compressive strain is developing in model 1, owing to the cracks interactions and this phenomenon causes the displacement in the final stage of the numerical simulation. The cracks interaction also has the main function in the nonlinear deformation of the clayey soil backfill. In the interpretation of the seismic response of the model, considering data from all stages of the numerical simulation is needed. For this reason, figure 6 describes the maximum magnitude of the displacement for all stages of the numerical simulation.

The geometry of the clayey soil backfill is significantly important in the seismic response and magnitude of damage at each earthquake. Considering figure 6, the maximum magnitude of displacement for model 1 and model 2, at all stages of the nonlinear numerical simulation are depicted for both loading and reloading stages. This figure shows that applying a statistical model for the engineering design is very important and will support in minimaxing error in conclusion making for all the engineering problems. Concerning figure 6, in most of the cases, the maximum range of the displacement for model 2 has a higher magnitude compared to model 1. It means model 2 has a higher frequency in the vibration compared to model 1. Additionally, a higher magnitude is observed in model 2, but it is not in the final stage of the numerical simulation.

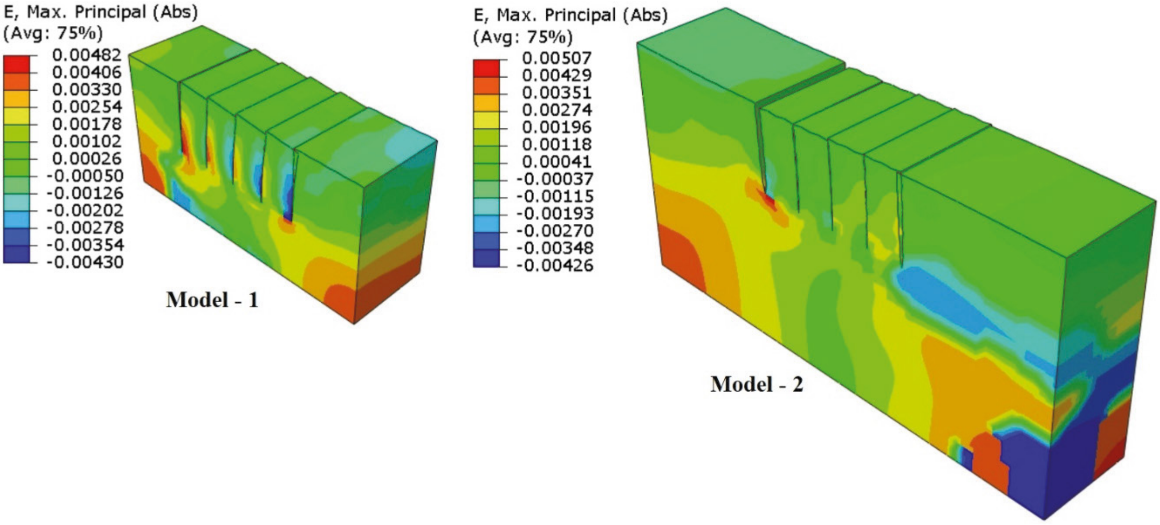

Fig. 5. The strain at the final stage of the simulation.

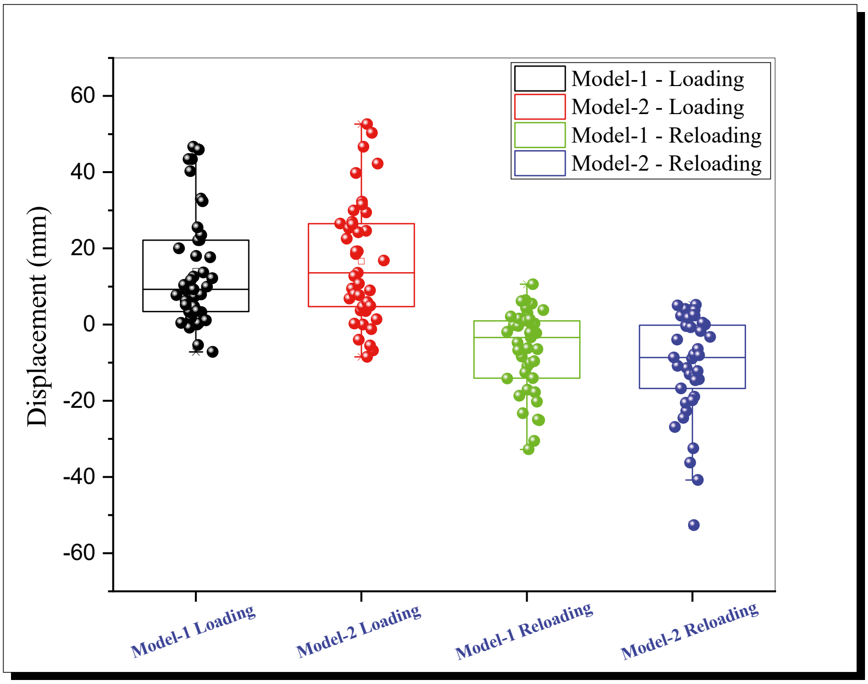

Fig. 6. The statistical model for nonlinear displacement from the simulation at all stages of the simulation.

In literature was indicated that the higher fit in R^2 in the statistical modeling for geotechnical engineering is evidence for the reduction of differential displacement of multilayered soils when the model is subjected to seismic excitation in the horizontal direction (Namdar and Satyam, 2021). According to the statistical model of the present study, both of the models are following a nonlinear vibration mechanism, but the geometry of the model changes the cracks interactions and the nonlinear displacement magnitude. Based on the finding of the high magnitude of the displacement of models 1 and 2, the maximum displacement of model 2 did not occur in the final stage of the numerical simulation. This phenomenon guides to using of suitable technics in interpreting results of the numerical simulation in solving engineering problems.

4. Conclusion

In the construction site, the size of the clayey soil backfill changes concerning the geography of a region. The clayey soil backfill with two types of geometry numerically simulated, considering the nonlinear displacement of the model in application equal seismic acceleration on both models in the three directions simultaneously. The analytical results demonstrate the length of the crack did not change with the geometry of the model because the length of the cracks depends on the mechanical properties of the clayey soil is using in the modeling. The numerical simulation results show the nonlinear displacement and acceleration seismic response at each model, which has specific stiffness, and strength characteristics that are developing based on the cracks interaction. The load transmission and cracks interaction have a meaningful relationship. The numerical simulation is explaining that cracks interactions play an important role in using soil materials for the design of a clayey soil backfill to improve model seismic stability during an earthquake. For technical application in geotechnical earthquake engineering, we can suggest minimizing nonlinear displacement of a model is possible, by considering the technical and economical concept through selecting a suitable geometry for clayey soil backfill with appropriate mechanical properties. This work introduces the concept of crack interactions for minimizing nonlinear displacement of the clayey soil backfill subjecting to the cracks and nonlinear acceleration. The concept of nonlinear displacement of the model in both loading and reloading stages was supportive of earth soil design.

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The authors declare that they have no conflicts of interest.

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