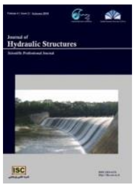
**Journal of Hydraulic Structures**
**J. Hydraul. Struct., 2020; 6(4): 33-46**
**DOI: 10.22055/jhs.2021.36007.1155**



# Liquefaction Behavior of Stabilized Sand using Clay - A Case Study: Dorood Liquefied Sand Investigation

Ahmad Reza Mazaheri [1]
Masoud Nasiri[2]

## Abstract

The phenomenon of liquefaction in loose and saturated sandy soils is one of the most important hazards for engineering structures during an earthquake. In this phenomenon, the sand changes its behavior rapidly from solid to viscous fluid, resulting in the instability of the ground. In this research, at first, sand samples with liquefaction history collected from a site in Dorood, Lorestan, Iran. Samples obtained from depth of 1.8-2.7 and 2.7-3.5 m and in the laboratory, the parameters of maximum density, moisture content, friction angle and cohesion were determined. Then, in order to evaluate the effect of additive on the liquefaction potential, different percentages of clay from Dorood region added to the samples and tested. Finally, three-dimensional finite difference software (FLAC3D) used with inducing Dorood earthquake, to investigate liquefaction potential of stabilized samples by analyzing the u/σ ratio for models. The results showed that adding clay to the soil of this area reduce the friction angle, increase cohesion, and has a favorable effect on the liquefaction potential. Results of this investigation indicated that adding 3% clay to the liquefied Dorood sand, would lead to decrease the liquefaction potential up to 39%.

**Keywords:** Liquefaction, Case Study, Dorood Sand, Clay, FLAC3D.

Received: 17 December 2020; Accepted: 8 February 2021

## 1. Introduction

One of the most important issues in geotechnical engineering is the liquefaction phenomenon. In liquefaction, soil exhibits a special behavior, so that the sand rapidly changes its behavior from solid to viscous fluid. The predisposing factor for liquefaction is the tendency to volume change. Characteristics that play role in this matter are particle size and shape, and grain size distribution [1]. Soil liquefaction is one of the most important hazards for engineering structures

---

[1] Department of Civil Engineering, Engineering Faculty, Ayatollah Borujerdi University, Borujerd, Iran. Email: a.mazaheri@abru.ac.ir **(Corresponding Author)**
[2] Department of Civil Engineering, Engineering Faculty, Ayatollah Borujerdi University, Borujerd, Iran.

constructed on loose sandy fields during an earthquake. Failure of the ground due to liquefaction can cause many structural damages, such as building breakdown, underground facilities breakage, lateral spreading, and even landslide. In general, soil liquefaction can be divided into two types, which include cyclic mobility and flow liquefaction. Cyclic mobility occurs when the static shear stress is less than shear strength of liquefied soil. Flow liquefaction can occur when the shear stress required for static equilibrium of a soil mass is greater than the shear strength of the soil in its liquefied state [2].

In fine sandy soils, there is a stable contact between the soil particles prior to the earthquake. This contact ensures that due to the shear strength of the soil mass, the stability of the structure on the soil is well maintained. When soil is deformed by stresses due to dynamic loads, the contact between the particles disappears. As a result, forces that were previously carried by stable contact between soil particles are transferred to the pore water. In such case, the shear strength of the soil reaches zero and the soil mass behaves similarly to viscous fluid. After liquefaction, when water drained from fine sandy soil, the soil particles settle and the connection between the particles will restored. The amount of soil deformation caused by liquefaction depends on the looseness of the material, depth, thickness, and the width of the liquefied layer, and the distribution of loads applied by other buildings and structures. Liquefaction does not occur by chance, but is limited to environments that are geologically and hydrologically fresh, made up of sand and silt (in areas with high water table level). In general, the sediments, which are fresh and weak with high water table level, are more prone to liquefaction.

So far, several case studies have been conducted on the liquefaction conditions in geotechnical fields [3, 4]. Ishihara and Koseki [5] stated that despite the lack of a clear relationship between the percentage of clay and the potential for liquefaction, increasing the plasticity index increases the resistance to liquefaction. Koester [6] also presented evidence that soil plasticity was not a controlling factor in liquefaction potential for soil with plastic particles, so that if the void ratio keep constant, the type and plasticity condition of fine-grains play the least role in the liquefaction potential. Tianqiang, and Prakash [7] investigated the effect of clay on the cyclic strength and pore water pressure of silt, stating that the nature of pore pressure in non-plastic silt is almost similar to that of sand. Polito and Martin [8] found that up to a certain percentage of fine-grain, liquefaction resistance reduce and with further increase in fine-grains, the liquefaction resistance will enhance.

The results of Arabani and Pirouz [9] study demonstrate that using rough set theory can be helpful for liquefaction prediction and can reduce unnecessary costs in the site investigation process. Lentini and Castelli [1] showed that the cyclic resistance increases with the decrease in the initial confining stress and decreases as the silt content increases and confirmed that the coarsest material has a lower tendency to liquefy. At constant relative density, the liquefaction resistance of fine sand decreases with the addition of non-plastic fines up to 40%. It is also noted that the liquefaction resistance of sand is increased substantially with an increase in cycles of preloading and over-consolidation pressures [10]. The results of sand-tire mixture experiments indicate that the required energy for liquefaction occurrence decreases with the increase in the rubber content. The minimum amount of required energy is determined for mixtures with 10% rubber content. As the result, the inclusion of crumb rubber decreases the liquefaction resistance of sand. However, when the rubber content increases from 10 to 25%, the resistance to liquefaction improves [11].

The settlement and lateral spreading for the liquefied sand are respectively 2.60 and 2.50 times than those of the sand in the dry state. The volumetric strain of the liquefied sand is found to be around 4%, which is significantly higher than that of 1.53% observed in the dry sand [12]. Stone columns, in the case of sand bed reinforcement, behaved in a combined shear and flexure mode and with their high permeability, can dramatically decrease the liquefaction hazard [13]. Reinforcing soil with tire powders and tire shreds reduces the deformations caused by liquefaction [14]. Results of Wang et al. [15] indicated that the liquefaction resistance for undisturbed specimens decreases with an increase in the plasticity index and then increases with a further increase in plasticity index. It is observed that critical silt content to generate maximum pore water pressure, in the case of liquefaction, is varied for different accelerations. Further, effect of silt content is very much dependent on relative density [16]. Other methods, besides using additives, for soil improvement in order to prevent liquefaction are using dynamic compaction [17], stone columns [18, 19], and piles [20]. Liquefaction have been the topic of various researches [21-30].

Sand stabilization methods are among important issues in civil engineering, which has a great impact on the stability of structures and their optimal usage. Previous researches has shown that this is an important topic. In this research, at first, sand samples with liquefaction history collected from a site in Dorood, Lorestan, Iran. Samples obtained from depth of 1.8-2.7 and 2.7-3.5 m and tested in the laboratory. Then, stabilization operations were performed by adding clay to sand and the results were analyzed. Finally, with the help of three-dimensional finite difference software (FLAC3D), the potential of liquefaction for clay-stabilized Dorood sand was investigated.

## 2. Site Characteristics

The investigated area, which contain liquefied sand, is Dorood city in Lorestan province, Iran. The region experienced an earthquake measuring 6.2 on the Richter scale in 2006, which caused great loss of lives and properties, including soil liquefaction. Geographically, as well as in terms of geological zones, with the exception of the eastern margin, most of Lorestan province is located in the Zagros highlands. Dorood city is located in Lorestan province with the center of points with coordinates of 49:03 and 33:28. This region is located in the east of Lorestan province and a wide area called Silakhor plain. The studied site is geologically diverse. Due to the divisions of the western and southern parts, it is located in the folded area of the Zagros. The middle part, which is more extensive, is located in the High Zagros zone. The easternmost areas gradually reach the Sanandaj-Sirjan zone. One of the main reasons for the importance of this region is that it is located on the border of three very important zones of Sanandaj-Sirjan, and the folded and driven parts of the Zagros. The Seismotectonics map of the area is shown in Figure 1.

## 3. Materials and Experimental Procedure

Laboratory tests performed on studied soil are grain size distribution test (ASTM D6913M-17), Hydrometer test (ASTM D442-63), Atterberg Limits test (ASTM D4318-17), and direct shear test (ASTM D3080M-11). Based on the results of the experiments, it can be concluded that the identified layers are categorized SM, according to USCS approach. Table 1 and 2 show sand and clay characteristics used in this paper. It is worth mentioning that the clay used was the local type of clay in studied area. It is noteworthy that the construction of direct shear samples were performed with unit weight equal to 90% compaction.

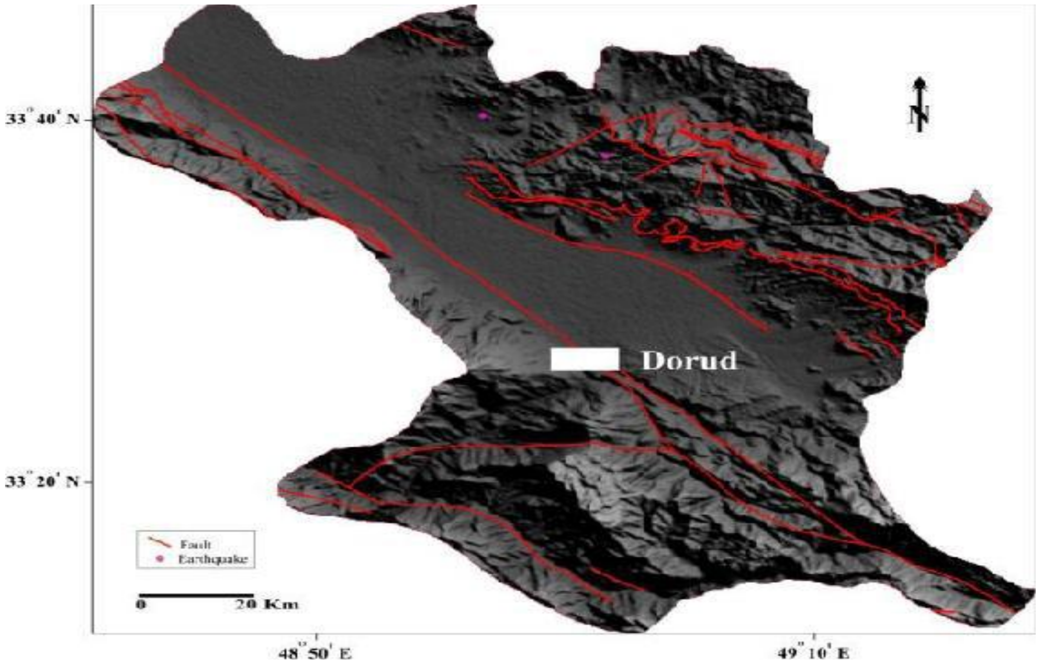


**Figure 1. Dorood Seismotectonics map**

**Table 1. Sand characteristics derived from the site**

| | $G_s$ | $e_{max}$ | $e_{min}$ | $\gamma$ (gr/cm$^3$) | $\gamma_d$ (gr/cm$^3$) | $C$ (kg/cm$^2$) | $\varphi$ (°) | *Soil Type (USCS)* | $\varphi$ (°) |
|---|---|---|---|---|---|---|---|---|---|
| Sand | 2.66 | 0.9 | 0.3 | 1.84 | 1.75 | 0 | 32 | SM | 32 |

**Table 2. Clay characteristics as additive**

| | *Permeability* (cm$^2$/s) | $\omega_{opt}$ (%) | $\gamma_{d\ max}$ (gr/cm$^3$) | *LL* | *PL* | *PI* |
|---|---|---|---|---|---|---|
| Clay | $7.34\times10^{-7}$ | 14.41 | 1.818 | 31.8 | 18 | 13.8 |

### 3.1. Examine the clay effect

In order to investigate the effect of clay addition on the liquefaction properties of the soil in the area, sand was mixed with different percentages of clay and tested using direct shear test in saturated state. Then parameters of density, optimal moisture, friction angle, and cohesion of samples obtained. Investigated specimens include non-additive (pure) sand and sand with 1%, 3%, 6%, and 8% clay. Table 3 shows the results obtained from laboratory experiments.

Figures 2 to 5 show the effect of adding clay on soil density, moisture content, cohesion, and internal friction angle. As can be seen in these figures, the addition of clay reduces the maximum density and internal friction angle, as well as increases the moisture content and cohesion of the soil mass.

Table 3. Sample characteristics and test results in saturated condition

| Material | Optimum Moisture Content (%) | Dry Density (gr/cm$^2$) | | Direct Shear Test (slow) | |
|---|---|---|---|---|---|
| | | 90% Compaction | Maximum | Friction Angle (°) | Cohesion (kg/cm$^2$) |
| *Pure Sand* | 5.2 | 1.56 | 1.73 | 34 | 0.00 |
| *Sand with 1% Clay* | 5.4 | 1.54 | 1.71 | 33 | 0.00 |
| *Sand with 3% Clay* | 5.9 | 1.50 | 1.67 | 32 | 0.03 |
| *Sand with 6% Clay* | 6.6 | 1.44 | 1.60 | 29 | 0.07 |
| *Sand with 8% Clay* | 7.4 | 1.36 | 1.51 | 27 | 0.12 |

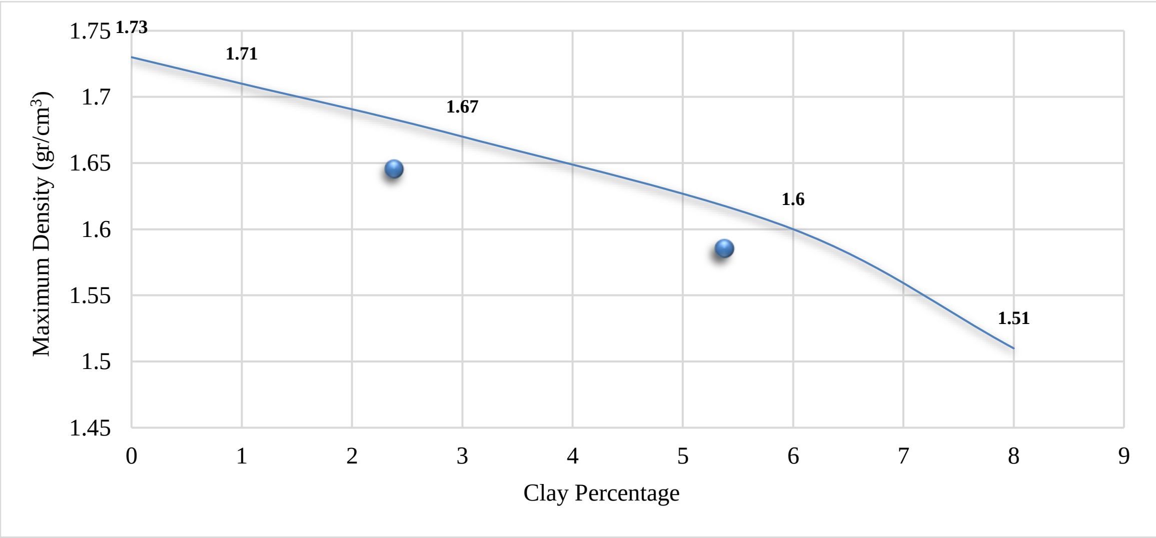


Figure 2. Effect of clay on dry density

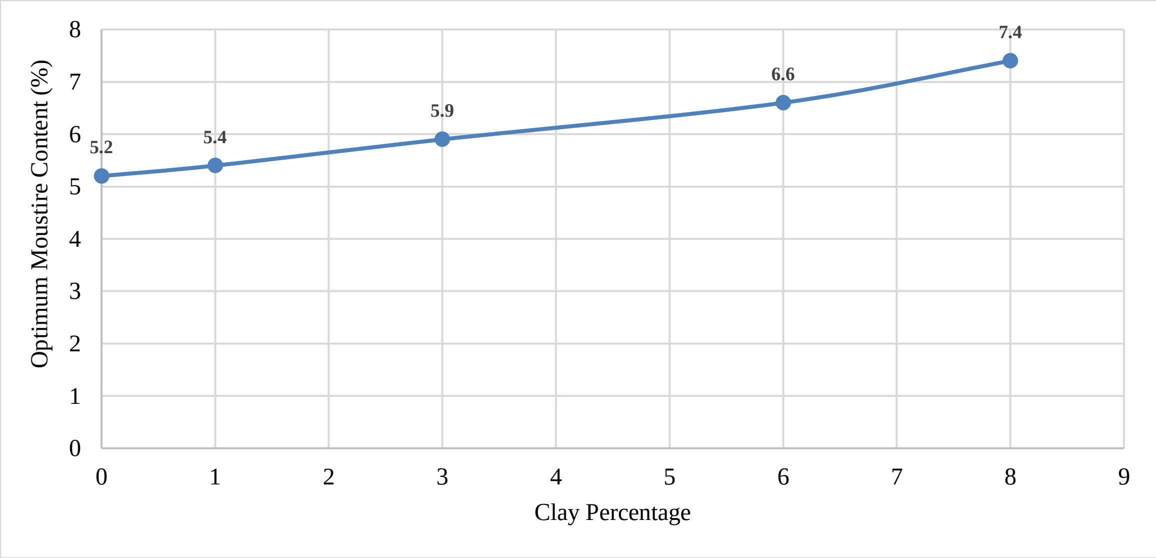


Figure 3. Effect of clay on optimum moisture content

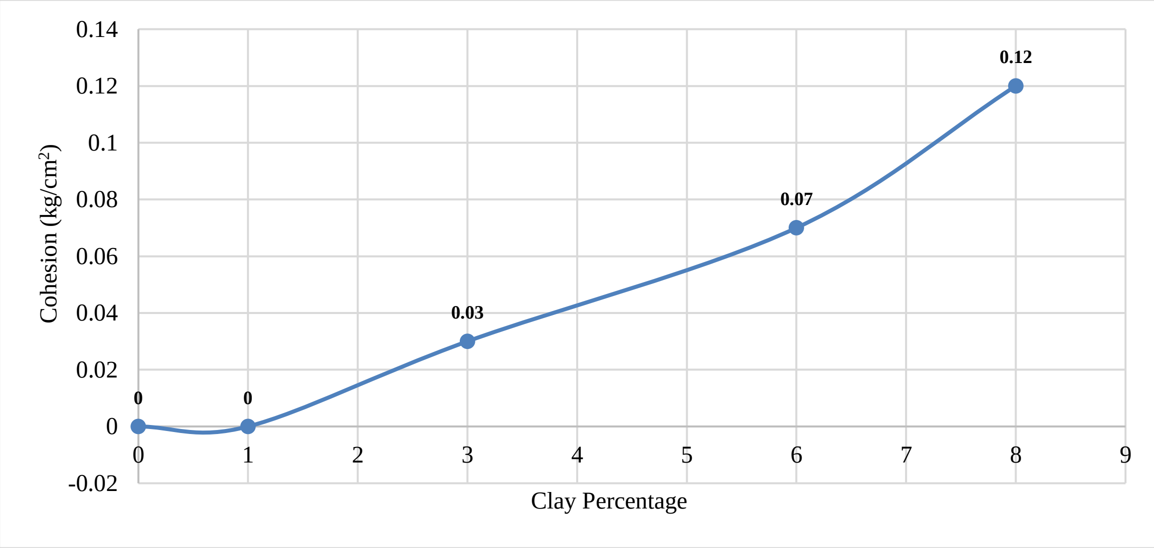


**Figure 4. Effect of clay on cohesion**

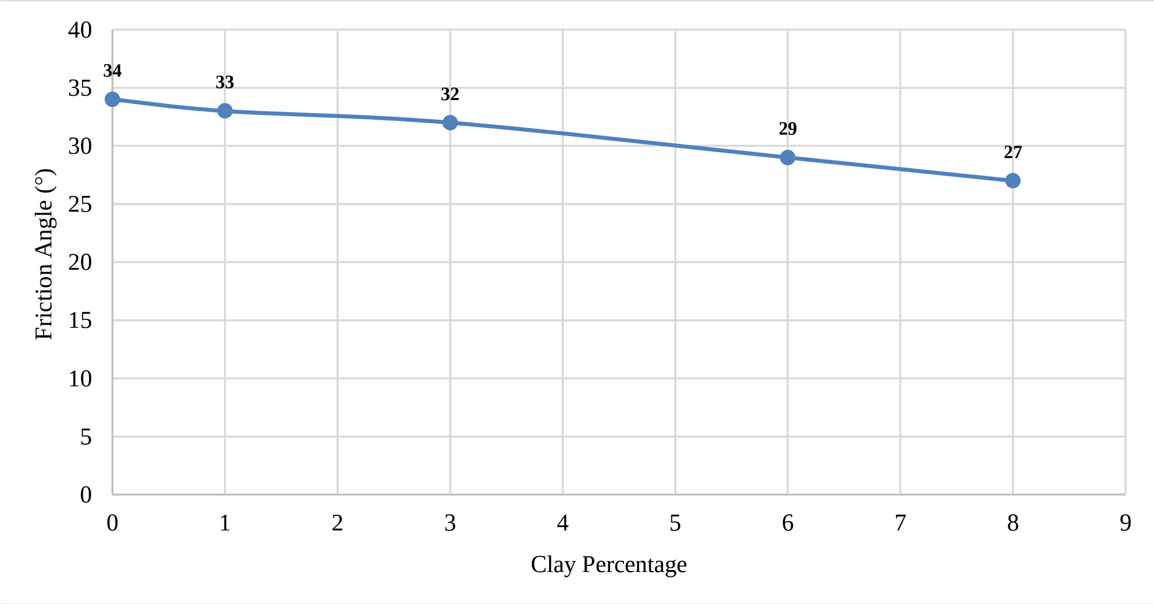


**Figure 5. Effect of clay on friction angle**

## 1. Dynamic Modeling

In this study, dynamic numerical analysis was performed to investigate the dynamic behavior of soil in the studied area (as previously mentioned, investigated site containing regions with potential of liquefaction). In order to investigate liquefaction potential, a model was developed in FLAC3D software, with dimensions of 7×7×10 meters in length, width, and height. It is worth mentioning that, in this 10 meter height (according to the site investigation in the region) there are two layers. The first layer is from the ground surface to the depth of 2.5 meters and is made of silt and clay, and the second one is silty sand layer from 2.5-10 meters. The first layer, i.e. from the surface of the earth to a depth of 2.5 meters, considered without water table, and the rest modeled in saturated state. In order to find the optimal number of meshes, at first, the sensitivity analysis was performed for this model and finally 21296 elements was selected (as optimum mesh numbers). The boundaries used in the models were chosen according to the dynamic condition. Free-field boundaries are used at the vertical sides of the model to prevent wave reflection. Finn's behavioral model, which simulates the increase in pore pressure during dynamic loading, has been used to calculate the potential of soil liquefaction. In the modeled samples, the motion of the sides follow that of the base, and vertical loading is by gravity only (i.e. the motion is that of simple shear). Equilibrium stresses and pore pressures installed in the soil sample, and pore pressure and effective stress monitored in the zone within the soil.

The basic mechanism of liquefaction in saturated and loose sand layers is the gradual increase in pore pressure due to the inducing of cyclic stresses resulting from the propagation of the earthquake shear waves. When applying cyclic stresses to a loose sand mass, there is a tendency for compaction and consequently a decrease in volume. If the loading time is much shorter than the time required for water drainage, it is not possible to reduce the volume in a short time and as a result, changes will be made in the stress state of the soil mass. These changes include reducing the effective stress between the particles and increasing the pore pressure. Therefore, the amount of pore pressure depend on the compression situation, the strength properties of the element due to the load, the intensity, and durability of the applied stresses. If the sand is sufficiently loose and the loading intensity is large enough, the pore pressure may be equivalent to the initial stress between the particles. At this point, the forces between the particles are lost and the particles will be suspended and immersed (i.e., the effective stress becomes zero), which is called the state of liquefaction. In effective stress relation ($\sigma' = \sigma - u$) if $u = \sigma$ then $\sigma'$will be equal to zero. By drawing u/σ ratio versus depth, soil liquefaction can be calculated. If the u/σ ratio reaches 1, complete liquefaction has occurred. Figure 2 shows the pore pressure contours in the model after inducing the Dorood earthquake.

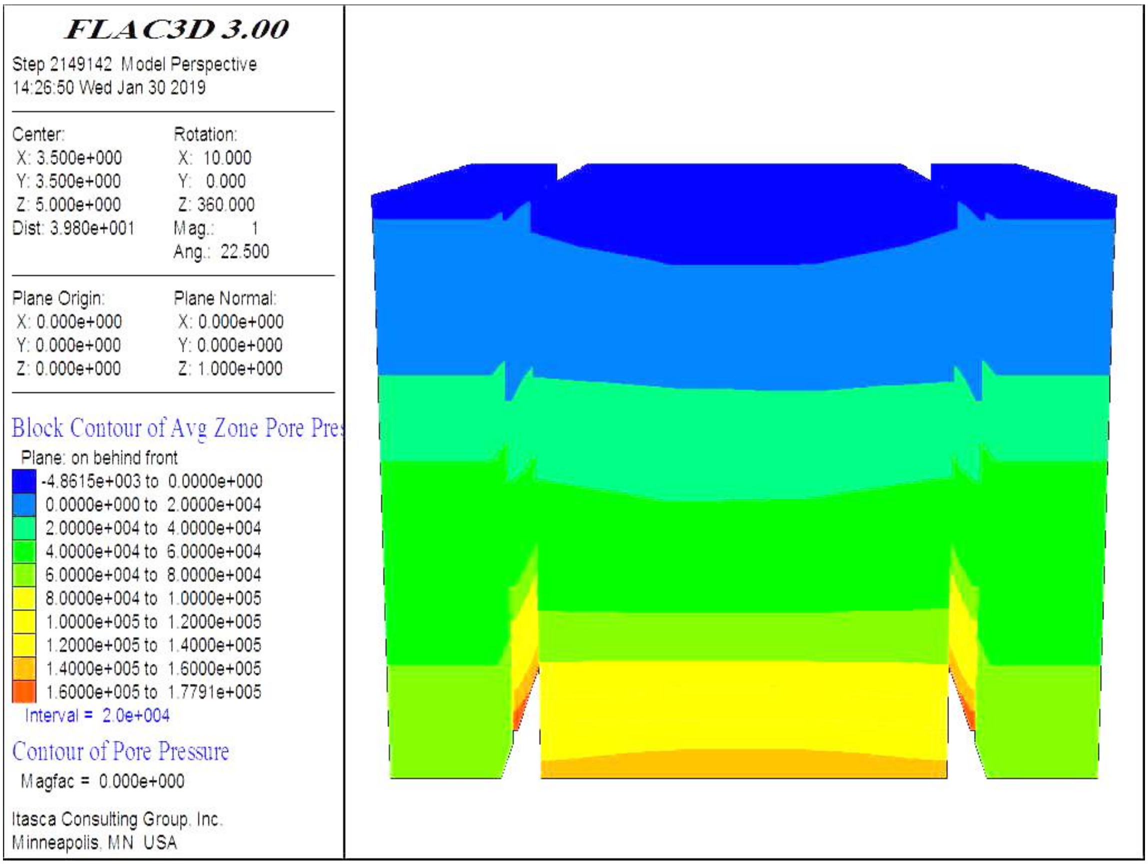


**Figure 6. Pore pressure contour after inducing Dorood earthquake in FLAC3D**

Figures 7 and 8 indicate the process of increasing the pore pressure and reducing the effective stress in the Dorood earthquake at depths of 2, 4, 6, and 8 meters. Black, red, blue, and green lines in these figures are representing the depths of 2, 4, 6, and 8 meters, respectively. At depth of 8 m, the pore pressure has an abrupt increase and the effective stress has a sudden decrease, which indicates the possibility of liquefaction in the soil. As mentioned earlier, liquefaction has been reported in the Dorood earthquake, which confirms the accuracy of the 3D numerical modeling in this study. Given that the behavior of pore pressure and effective stress at a depth of 8 meters has changed abruptly, it can be concluded that increase in the pore pressure at this depth has led to a sudden decrease in effective stress, which consequently resulted in liquefaction.

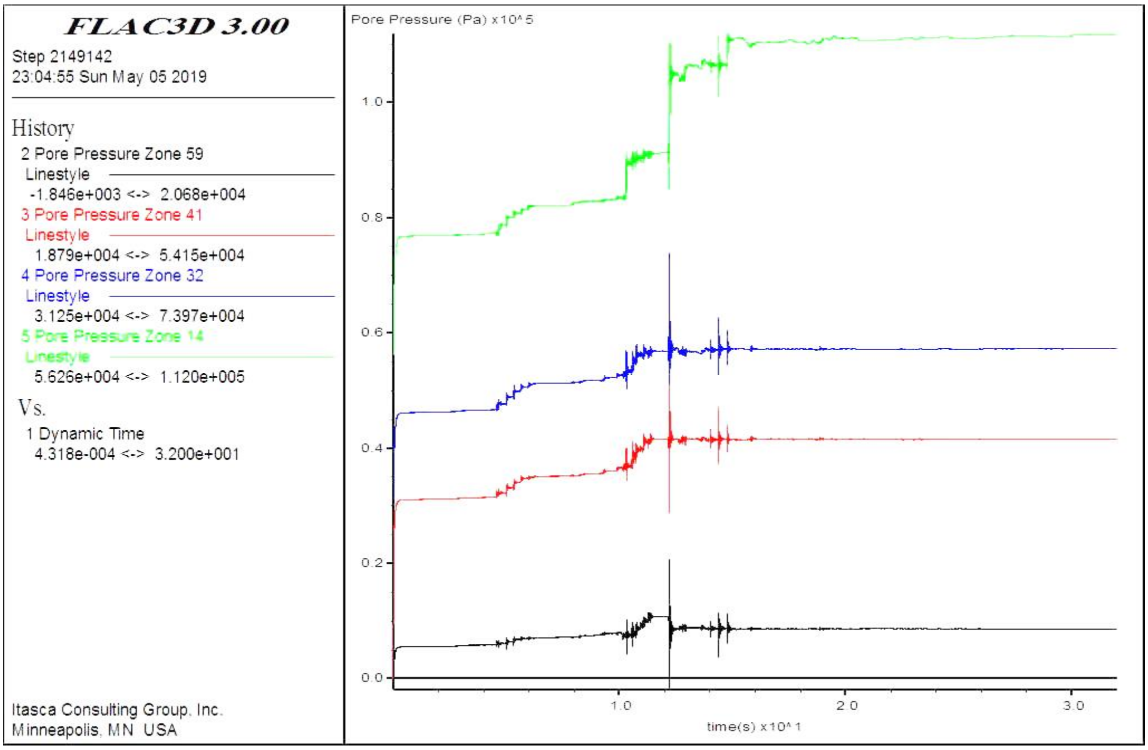


**Figure 7. Pore pressure versus time graph after inducing Dorood earthquake**

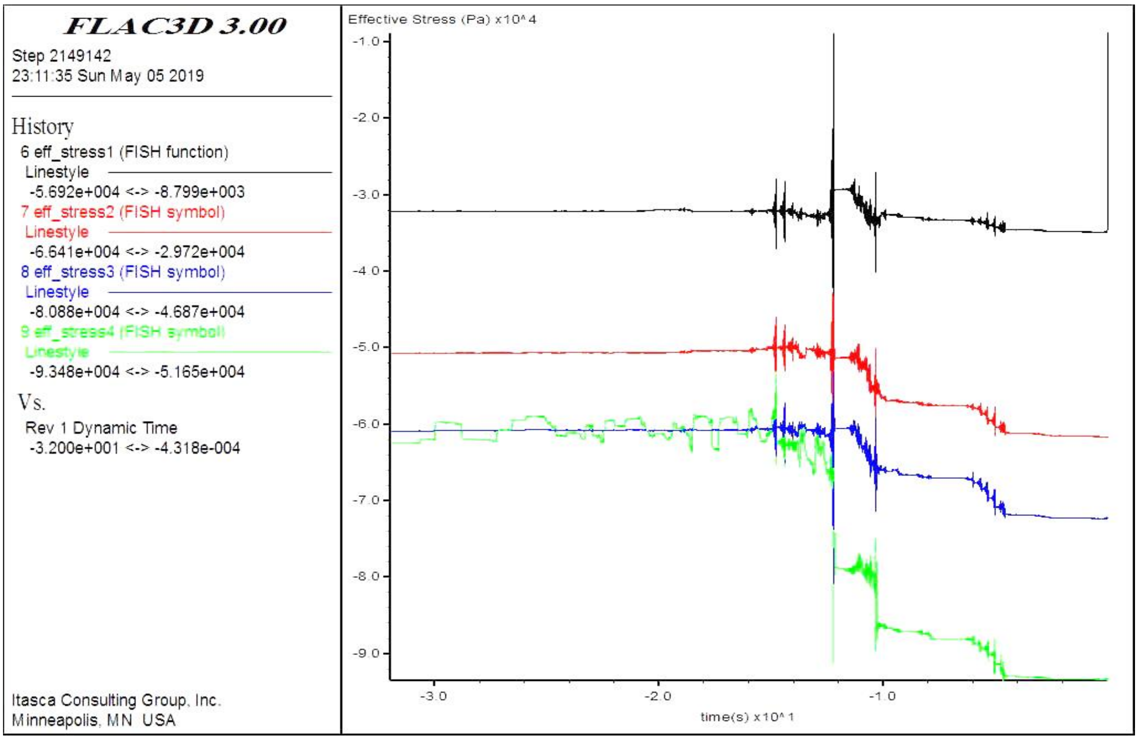


**Figure 8. Effective stress versus time graph after inducing Dorood earthquake**

By drawing u/σ versus depth, soil liquefaction can be examined. Figure 9 shows the changes in u/σ based on depth for sand without additives (i.e. pure sand). The closer the u/σ to 1, the more likely that liquefaction will occur. Based on the above-mentioned relation, at the depth of 8 meters this phenomenon is more probable.

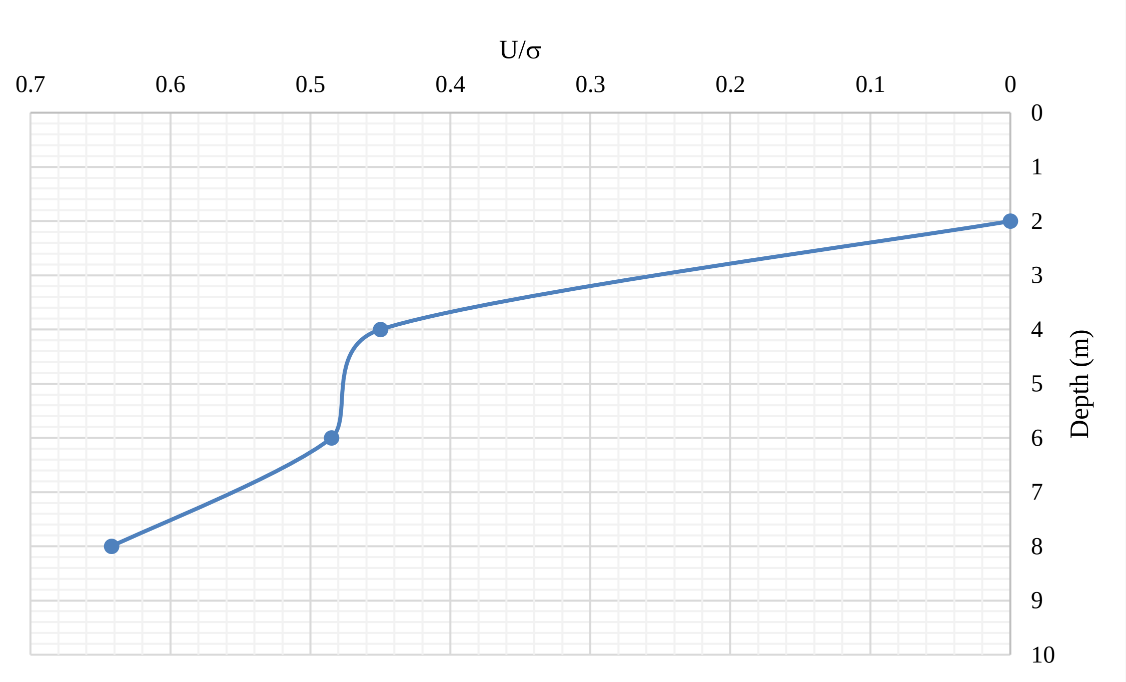


**Figure 9. Variations of u/σ with depth for pure sand sample**

## 4.1. Study the effect of clay additive

In order to investigate the effect of clay addition on the liquefaction properties of Dorood sand, the cohesion and friction angle properties measured in the laboratory (in terms of percentage of clay addition) were applied to the samples and analysis were performed. This means that the characteristics of the layer of sand in the model (i.e. the depth of 2.5 to 10 meters) were replaced by the strength parameters of the sands with additives. Figure 10 shows the changes in u/σ based on depth for soil without additives (pure sand) and sands containing 1, 3, 6, and 8% clay. As can be seen in this figure, the presence of clay reduces the u/σ ratio, which indicates a decrease in the liquefaction potential. Therefore, it can be concluded that using clay, with the mentioned characteristics, since increases the resistance to liquefaction, is very effective approach.

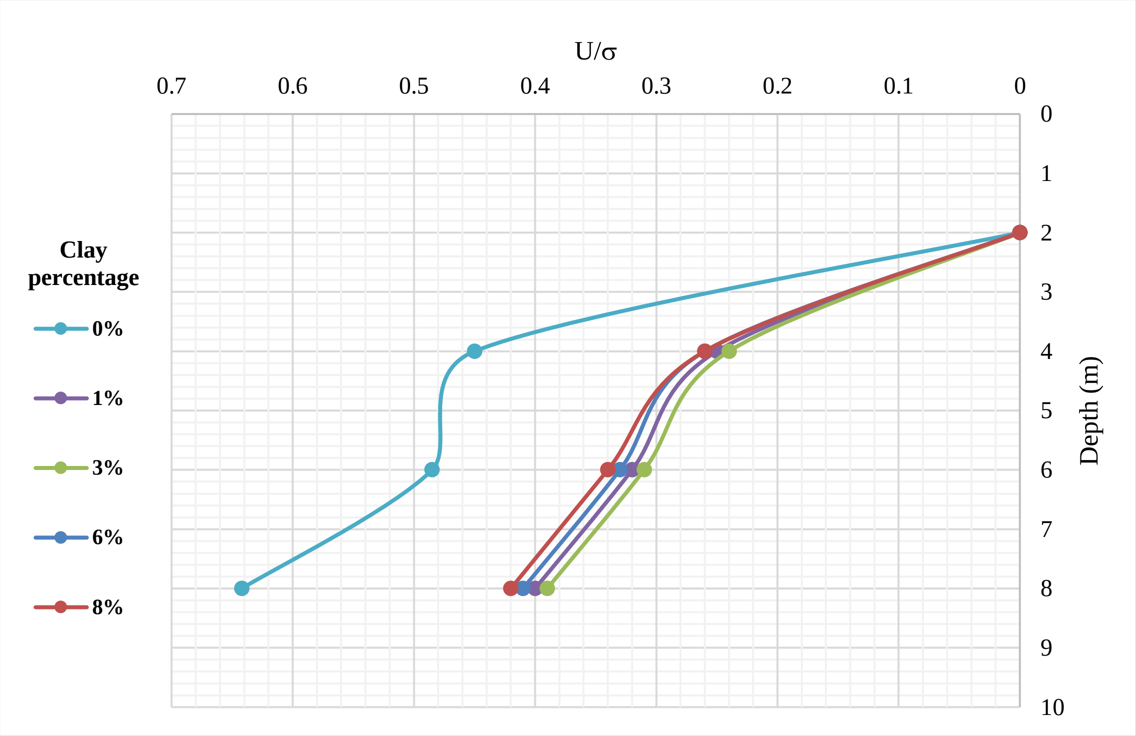


**Figure 10. Variations of u/σ with depth for samples with different percentage of clay additive**

## 5. Results and Discussion

In this section, the laboratory results and numerical analyzes performed on Dorood liquefied sand will discussed. In this study, after determining the strength parameters of Dorood liquefied sand with the help of direct shear experiments, different percentages of clay were added to samples, in order to evaluate the effect of local clay, in different ranges, on the liquefaction potential of studied sand. As shown in Figure 2, adding clay to sand reduces the maximum dry density. By adding 8% clay to the sample, the unit weight is reduced by 13%, while adding 1% clay is almost ineffective (decreased about 1%). Regarding the percentage of optimal moisture content (Figure 3), it can be stated that adding clay will increase the percentage of optimal moisture for the samples (up to 42% increase). As expected, increasing the amount of clay in the samples will reduce the angle of friction and increase soil cohesion. Based on Figures 4 and 5, it can be seen that 8% clay reduces the friction angle by 20% and increases the cohesion by 12%. In the case of adding 3% clay to the samples, a 13% increase in the optimal moisture content achieved, a decrease of 3% in the maximum density, a 3% increase in cohesion and about 6% reduction in the internal friction angle are also confirmed. Briefly, it can stated that the addition of clay to Dorood liquefied sand reduces the density and internal friction angle. While the percentage of optimum moisture content and cohesion will increase.

The results of numerical modeling in the three-dimensional finite difference software (FLAC3D) showed that liquefaction occurred at the depth of 8 m. As can be seen in Figures 7 and 8, at a depth of 8 m, the pore water pressure and the effective stress fluctuate, indicating the occurrence of a liquefaction phenomenon in the soil. Based on figure 7, the depth of 8 m indicates a sudden increase in the pore water pressure, and the same depth in figure 8 shows a sharp decrease in the effective stress. This proves the liquefiable condition of Dorood sand.

Adding clay to the liquefied sand of the studied region reduces the potential for liquefaction. Although the addition of clay to the soil mass generally behaves in the same way, it does not follow a specific incremental pattern. Among all the percentages tested, 3% clay performed the best, reducing the u/σ ratio by 39%. While 1% clay has a weaker function in reducing the potential for liquefaction (37% reduction). In addition, adding more than 3% clay to this sand, i.e. 6% and 8%, will still have weaker performance, in which there were 36% and 34% decrease in the potential for liquefaction, respectively. However, as shown in Figure 10, the addition of clay to Dorood sand at any rate will increase the resistance to liquefaction comparing to pure sand.

## 6. Conclusion

One way to reduce the potential for sand liquefaction is to stabilize it with additives, and clay is among the most successful ones in this regard. In this study, Dorood local clay was used as an additive in different percentages and its optimal percentage was determined to increase the resistance to liquefaction. In this research, Dorood sand, which previously experienced liquefaction, has been used. Initially, different percentages of clay were added to the sand, and the samples were tested with direct shear box. Afterward, the strength parameters results obtained from stabilized samples were used in the analysis of liquefaction potential with the help of three-dimensional finite difference software (FLAC3D). The results of liquefaction analysis (study of the status of pore water pressure and effective stress) and calculation of u/σ ratio for non-additive (pure) sand showed that the depth of 8 m (with u/σ ratio equal to 0.642) was liquefied. In the next step, the parameters of the stabilized sands were used in the modeling, and the results were examined. The results indicated that adding clay to the samples reduced the potential of liquefaction. Same as any additive to the soil mass, the clay used has the optimal percentage to achieve the best results. Three-dimensional analyzes revealed that 3% clay, as the most optimal percentage of additive in this soil, increased the liquefaction resistance well enough and reduced the u/σ ratio by 39%. The results of this research made it clear that clay can be used to protect Dorood sand against liquefaction, to increase its strength, and to achieve the favorable results in this region.

## References

1. Lentini V, and Castelli F, (2019) Liquefaction Resistance of Sandy Soils from Undrained Cyclic Triaxial TestsGeotechnical and Geological Engineering, 37, pp201-216.
2. Kramer S, (1996) Geotechnical Earthquake Engineering1st edition, Pearson Publication
3. Yilmaz D, Babuccu F, Batmaz S, and Kavruk F, (2008) Liquefaction analysis and soil improvement in Beydag damGeotechnical and Geological Engineering, 26, pp211-224
4. Sharma B, and Hazarika PJ, (2013) Assessment of Liquefaction Potential of Guwahati City: A Case StudyGeotechnical and Geological Engineering, 31, pp1437-1452.
5. Ishihara K, and Koseki J, (1989) Discussion on the cyclic shear strength of fines-containing sandsEarthquakes Geotechnical Engineering, Proceedings of the Eleventh International Conference on Soil Mechanics and Foundation Engineering, Rio De Janiero, Brazil, pp101-106.

6. Koester JP, (1994) The influence of fine type and content on cyclic strengthGround Failures under Seismic Conditions, Conditions, Geotechnical Special Publication, ASCE, 44, pp330-345.
7. Tianqiang G, and Prakash S, (1999) Liquefaction of silts and silt-clay mixturesJournal of Geotechnical and Geoenvironmental Engineering, 125(8), pp706-710.
8. Polito CP, and Martin JR, (2001) Effects of non-plastic fines on the liquefaction resistance of sandsJournal of Geotechnical and Geoenvironmental Engineering, ASCE, 127(5), pp408-415.
9. Arabani M, and Pirouz M, (2019) Liquefaction prediction using rough set theoryScientia Iranica, 26(2), pp779-788.
10. Akhila M, Rangaswamy K, and Sankar N, (2018) Undrained Response and Liquefaction Resistance of Sand–Silt MixturesGeotechnical and Geological Engineering, 37, pp2729-2745.
11. Shariatmadari N, Karimpour Fard M, and Shargh A, (2019) Evaluation of Liquefaction Potential in Sand–Tire Crumb Mixtures Using the Energy ApproachInternational Journal of Civil Engineering, 17, pp181-191
12. Banerjee R, Konai S, Sengupta A, and Deb K, (2017) Shake Table Tests and Numerical Modeling of Liquefaction of Kasai River SandGeotechnical and Geological Engineering, 35, pp1327-1340.
13. Tang L, Zhang X, and Ling X, (2016) Numerical Simulation of Centrifuge Experiments on Liquefaction Mitigation of Silty Soils using Stone ColumnsKSCE Journal of Civil Engineering, 20, pp631-638
14. Bahadori H, and Farzalizadeh R, (2018) Dynamic Properties of Saturated Sands Mixed with Tyre Powders and Tyre ShredsInternational Journal of Civil Engineering, 16, pp395-408.
15. Wang S, Luna R, and Yang J, (2016) Reexamination of effect of plasticity on liquefaction resistance of low-plasticity fine-grained soils and its potential applicationActa Geotechnica, 11, pp1209-1216.
16. Maheshwari BK, and Patel AK, (2010) Effects of Non-Plastic Silts on Liquefaction Potential of Solani SandGeotechnical and Geological Engineering, 28, pp559-566.
17. Kumar S, (2001) Reducing liquefaction potential using dynamic compaction and construction of stone columnGeotechnical and Geological Engineering, 19, pp169-182.
18. Al Mahmoud A, and Degen WS, (2006) Marine stone columns to prevent earthquake induced soil liquefactionGeotechnical and Geological Engineering, 24, pp775-790.
19. Hajiazizi M, and Nasiri M, (2019) Experimental and numerical investigation of reinforced sand slope using geogrid encased stone columnCivil Engineering Infrastructures Journal, 52(1), pp85-100.
20. Asadi A, Sharifipour M, and Ghorbani k, (2017) Numerical Simulation of Piles Subjected to Lateral Spreading and Comparison with Shaking Table ResultsCivil Engineering Infrastructures Journal, 50(2), pp277-292.

21. Kumar SS, Dey A, and Krishna AM, (2020) Liquefaction Potential Assessment of Brahmaputra Sand Based on Regular and Irregular Excitations Using Stress-Controlled Cyclic Triaxial TestKSCE J Civ Eng 24, 1070–1082
22. Do J, Heo SB, Yoon YWet al (2017) Evaluating the liquefaction potential of gravel soils with static experiments and steady state approachesKSCE J Civ Eng 21, 642–651.
23. Naik SP, Patra NR (2018) Generation of Liquefaction Potential Map for Kanpur City and Allahabad City of Northern India: An Attempt for Liquefaction Hazard AssessmentGeotech Geol Eng 36, 293–305.
24. Ghani S, Kumari S (2021) Insight into the Effect of Fine Content on Liquefaction Behavior of SoilGeotech Geol Eng 39, 1–12.
25. Liu, J (2020) Influence of Fines Contents on Soil Liquefaction Resistance in Cyclic Triaxial TestGeotech Geol Eng 38, 4735–4751.
26. Jha SK, Karki B & Bhattarai A (2020) Deterministic and Probabilistic Evaluation of Liquefaction Potential: A Case Study from 2015 Gorkha (Nepal) EarthquakeGeotech Geol Eng 38, 4369–4384.
27. Khashila M, Hussien MN, Karray M et al (2020) Liquefaction resistance from cyclic simple and triaxial shearing: a comparative studyActa Geotech.
28. Tsai CC, Hwang YW & Lu CC (2020) Liquefaction, building settlement, and residual strength of two residential areas during the 2016 southern Taiwan earthquakeActa Geotech15, 1363–1379.
29. Yilmaz C, Silva Vand Weatherill (2020) Probabilistic framework for regional loss assessment due to earthquake-induced liquefaction including epistemic uncertaintySoil Dynamic and Earthquake Engineering, 141, 106493.
30. He S, Wang X, Fan, Het al (2020) The study on loess liquefaction in China: a systematic reviewNat Hazards 103, 1639–1669