Study on the influence of sand liquefaction caused by earthquake on the floating of underground structures

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Abstract. The effective stress of the soil decreases and the pore water stress increases under the earthquake, which causes the sand to liquefy. The vertical deformation of the ground caused by the liquefaction of sand causes serious damage to the ground and the buried structure, which seriously threatens the safety of underground lifeline engineering. In order to study the impacts of sand liquefaction, the language FORTRAN was used to establish a finite element model under the earthquakes. The floating of various locations of the underground structure under different earthquakes was studied, and the factors affecting the floating were discussed. The results show that during the earthquake, the liquefaction of sand occurs, which causes the underground structure moves up due to buoyancy, and the soil mass from the structure collapses. The liquefied sand diffuses to the surrounding area after the earthquake, causing the sand beneath the underground structure to be lost, and the building will return to its original position or even collapse. The results provide references for the anti-floating research of underground structures.

1. Introduction
There are frequent earthquakes in China, when a violent earthquake occurs, there will be a phenomenon of sand blasting on the surface. This is the liquefaction of sand. The liquefaction of sand is actually the reduction of the effective stress of the soil, and the increase of the pore water pressure, which eventually leads to the soil liquefaction which resulting in the shear strength of the soil is insufficient[1-2]. The buoyancy generated by the liquefaction of sand will cause the lateral deformation and tilt of buildings, which will eventually cause the buildings to lose their own functions and cause a lot of economic losses. Understanding the liquefaction of saturated sand under earthquakes can help us decrease the damage of sand liquefaction to buildings and reduce the influence caused by floating under structure.

In recent years, the research on floating of underground structure caused by liquefaction of sand in China is continuing. Chen Guoxing et al. conducted a shaking table test on the subway station in the liquefaction site. The test shows that not only the surface will appear sandblasting water phenomenon, but also the soil around the station is liable to liquefy. The subway station has obvious floating displacement and large residual deformation [3]. Based on the finite element model of underground structure under the sand liquefaction, the corresponding displacement cloud diagram of subway station and the displacement curve diagram of node are obtained in this dissertation. The influence rule of sand liquefaction of underground structure is revealed. This analysis provides conditions for the development of underground structures in the future, and provides references for the construction and protection analysis of underground structures.
2. Principle of sand liquefaction

The basic expression of the effective stress of Terzaghi is:

$$\sigma_{ij} = \sigma_{ij}^e + p^w \delta_{ij}$$

(1)

Where $\sigma_{ij}$ is the total stress tensor of the mixture; $p^w$ is the pore water pressure assumed by the pore water; $\delta_{ij}$ is the symbol of Kronecker; $\sigma_{ij}^e$ is the effective stress tensor assumed for the soil skeleton.

The relationship between the effective stress increment of the solid phase and the solid stain increment can be represented by the corresponding constitutive relationship.

$$d\sigma_{ij} = D_{ijkl} d\varepsilon_{ij}$$

(2)

Where $D_{ijkl}$ is the solid phase stiffness tensor. If the elastoplastic constitutive relationship is used, $D_{ijkl}$ can use an elastic-plastic stiffness matrix to represent as $D_{ijkl}^{ep}$. The pore pressure of liquid phase and strain of the liquid phase can be expressed by a relatively simple relationship as follows:

$$p^w = K^w \varepsilon_{ii}$$

(3)

Where $K^w$ is volumetric elastic coefficient of liquid phase. The strain of the solid and liquid phases can be established by the geometric equation and the relationship between its displacement vector.

$$\varepsilon_{ii} = \frac{1}{2} \left( \frac{\partial u_i^s}{\partial x_i} + \frac{\partial u_i^w}{\partial x_i} \right)$$

(4)

$$\varepsilon_{ii}^w = \frac{1}{2} \left( \frac{\partial u_i^w}{\partial x_i} + \frac{\partial u_i^w}{\partial x_i} \right)$$

(5)

Where $u^s$ and $u^w$ are the displacement vectors of the soil skeleton and pore water.

3. Displacement analysis of underground structures

3.1. Calculation profile

Taking the subway station as an example, this dissertation sets up a double-layer box-type subway station structure with a central column. The buried depth of the subway station is 5 m. The size of the subway station is shown in Figure 1. The soil 1 is a liquefiable saturated sand layer with a depth of 50 m. The soil 2 is a non-liquefiable soil with a depth of 50 m. The nodes on both sides are fixed in the horizontal direction and fixed in the vertical direction; the nodes on the lower surface are horizontally free, and the vertical direction is fixed; nodes N1, N2 and N3 are output nodes of displacement variable, the soil Unit E1, E2, E3, and E4 in soil 1 serve as output units of the pore pressure variable. E4 is used as a comparison unit. Unit E1, E2 and E3 are output units of the liquefiable soil. The ordinates of the points at different depths of the four elements are -48.543m, -35.084m, -19.191m and -6.3m, as shown in Figure 2. A Goodman unit is used as a contact unit between the subway station and the soil. The model has a total of 8106 nodes and 7876 units.

![Figure 1. Geometric model of the subway station](image-url)
3.2. Displacement response analysis of underground structures during earthquakes

3.2.1. Calculation process. In addition to applying conventional loads to the subway station, seismic loads are applied to the underground structure model, seismic waves in the horizontal and vertical directions were applied to the underground structure model. Seismic waves were 0.05g, 0.1g, 0.2g and 0.3g, as shown in Figure 3.

![Horizontal seismic waves](image)

(a) Horizontal seismic waves

![Vertical seismic waves](image)

(b) Vertical seismic waves

Figure 3. Seismic acceleration time history curve

Firstly, the excess pore water pressure ratio of E2 and E4 units was recorded and a time history curve was drawn, as shown in Figure 4-5. Secondly, the displacement of the upside soil at the center of the underground structure and the displacement at the center of the subway are documented and the corresponding displacement curves are plotted, as shown in Figure 6-7. Thirdly, the floating displacement of the station under different seismic loads was recorded and the displacement cloud map was drawn, as shown in figure 8. Finally, the central displacement curve is drawn according to the displacement at the center of the underground structure under different seismic waves at the same time, as shown in Figure 9.

3.2.2. The results of the analysis. Table 1 shows the displacement caused by the liquefaction of three different nodes of the surface of the subway station under the seismic load of 0.05g and 0.3g at 40s. When the seismic wave is 0.05g, the final displacement of different nodes in the center of the subway station is roughly the same, which indicates that the phenomenon of floating is inevitable. When the local seismic wave is 0.3g, the displacement of each node is very obvious, and the displacement of
each node is approximately the same.

| name | displacement /m(0.05g) | displacement /m(0.3g) |
|------|------------------------|-----------------------|
| N1   | 0.00389                | 0.90444               |
| N2   | 0.00388                | 0.90446               |
| N3   | 0.00391                | 0.90444               |

As shown in Figure 6, there is vertical vibration deformation in the first 7s but no obvious vertical displacement, and the floating displacement is obvious after 7s. The epwpr time-history curves of elements E2 and E4 in Figures 4 and 5 show that the initial liquefaction of the soil 1 occurs at t = 7 s, at which time the structure begins to have a significant upward floating displacement.

As shown in Figure 7, the vertical displacement is the largest directly above the surface of the subway station center, and decreases gradually when it is away from the subway center. Under the different seismic waves, the curve is similar to a normal distribution. The trend of each situation is roughly the same, and the larger the earthquake wave is, the more obvious the trend is.

Figure 8 is a vertical displacement cloud diagram of the soil around the subway station. The structural displacement increases as the load increases. The top of the station and the surrounding soil have corresponding upward displacements, and vertical subsidence deformation occurs at a distance from the subway station. It can be seen from Figure 8 that the floating of the structure is related to the thickness of the soil, and reaches a certain depth, the floating displacement is small.
It can be seen from Figure 9 that under the seismic load, the displacement of the central node increases with the increase of seismic load, and the displacement gets larger and larger. When the seismic load is 0.3g, the floating displacement reaches the maximum at 40s. The magnitude of the seismic load has a direct impact on the floating displacement.

4. Conclusion
(1) The displacement of the structural center is the largest, and the displacement from the center to the periphery decrease gradually, under different earthquakes. The larger the earthquake is, the larger the increase of displacement is. The floating of the structure is also related to the thickness of the soil. When the soil reaches a certain depth, the floating displacement is very small. Since pore water pressure takes some time to rise, the structure will be lifted up by the buoyancy generated by the
liquefied sand after the earthquake starts for a while.

(2) Liquefaction of sand during the earthquake causes the sand beneath the building to flow and to be lost. The pore water pressure gradually dissipates, and the displacement of the underground structure recovers or even sinks after the earthquake. Since the element of the finite element software is continuous and mass conservation is always assumed in the analysis process, the flow of sand cannot be accurately simulated, so the displacement after the earthquake needs to be analyzed separately.

(3) In addition, the displacement response of underground structures subjected to earthquakes under different buried depths should be studied in the specific research. In order to provide a scientific basis for the development of anti-floating measures, this dissertation summarizes the factors influencing the floating of underground structures by comparative analysis.

References
[1] Chen, G.X., Zhuang, H.Y., Du, X.L. (2007) Study on large-scale shaking table model test of liquefaction site soil-metro station structure. Earthquake Engineering and Engineering Vibration, 27(03):163-170.
[2] MUNENORI H, AKIHIKO U, JUNRYO O. (1997) Liquefaction characteristics of a gravelly fill liquefied during the 1995 Hyogo-Ken Nanbu Earthquake. Soils and Foundations, 37(3):107-115.
[3] Zhuang, H.Y., Chen G.X., Du X.L. (2007) Study on large-scale shaking table test of dynamic response of metro station structure under liquefaction large deformation conditions. Earthquake Engineering and Engineering Vibration, 27(04):94-97.