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Mechanism Analysis and Mitigation Measures for the Seismic Performance of Foundations During Sand Liquefaction

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Abstract. A typical problem of geotechnical earthquake engineering is liquefaction-induced foundation instability in sand. Many available review papers focus on only one specific ground improvement method or separate liquefaction-control solutions, and few provide all-encompassing comparisons of various mitigation technologies. First, this paper will introduce the process of sand liquefaction and the resulting secondary damage, such as differential settlement and lateral spreading of the ground. Based on the core theoretical formulas and basic physical laws, some typical anti-liquefaction countermeasures are introduced here and their comparative analysis is conducted. The two groups of conventional ground-improvement methods are based on whether the native soil properties are altered. Based on the theoretical model and empirical formulas of previous studies, this paper will introduce the locations and favourable conditions for applying each anti-liquefaction measure. Shake-table experiments are often used to test the liquefaction-mitigation performance, and their drawbacks have also been mentioned. This study will offer theoretical support for interpreting liquefaction-induced seismic damage and selecting suitable ground-treatment measures in practice.

Keywords: sand liquefaction, foundation, seismic performance

1. Introduction

For a long time, there have been serious earthquakes that have harmed people and property. Since 1900, earthquakes worldwide have caused 8 million direct deaths and property losses totaling $1.95 trillion [1]. Therefore, how to carry out a scientific and reasonable optimisation design for foundation stability has become an important issue in earthquake resistance. At present, the main research focus in the field of foundation seismic resistance is on preventing and controlling sand liquefaction. At present, some researchers have conducted small-scale physical shake-table experiments to simulate the distribution of sand particles under the influence of seismic waves [2].

A large number of studies have been conducted by scholars at home and abroad on the reasons for sand liquefaction and foundation reinforcement measures to provide a solid theoretical basis for this paper. However, most of the existing research focuses on a specific foundation treatment

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method, techniques suitable for a certain set of seismic conditions, or the prevention and control of sand liquefaction in isolation; few studies have compared different treatment methods side by side and systematically summarized the applicable conditions and actual effectiveness of various methods.

Therefore, this paper will first introduce the reasons for liquefaction and the secondary disasters that occur as a result, as well as typical ground improvement technologies, and then compare the conditions under which they can be applied. Based on the deficiencies of the current studies, future research directions will be proposed.

2. Characteristics and mechanisms of seismic damage to foundations

2.1. Soil characteristics in typical liquefaction-induced earthquake damage

Sand liquefaction is a representative disaster caused by a large-scale earthquake. When the ground shakes violently, water and sand are ejected from the ground, and high-pressure water rapidly carries dense sand up through the liquefied soil layer in a fountain-like manner. The sand-ejection holes are not uniformly distributed; thus, the surface level of the soil is uneven, and the compacted, saturated loose sand instantly turns into a slurry-like fluid that has lost its original bearing capacity and caused foundation settlement [3].

For example, the 2025 Ms 6.8 (Mw 7.1) earthquake in Dingri, Tibet, resulted in the formation of a large-scale pull-down trough zone east of Lake Dingmu Co, which was mainly caused by sandy soil liquefaction-induced deformation. A large-scale fault zone appeared at a certain distance east of the main fault east of Lake Dingmu Co. These fault zones have strong features of landslides caused by sandy soil liquefaction, and the fault-subsidence zone generally extends along the shore of Lake Dingmu Co, with subsidence areas forming a step-like pattern [4].

2.2. Mechanisms of earthquake damage caused by soil liquefaction

The necessary condition for sand liquefaction is a decrease in the effective stress of the soil; this effective stress can be expressed as follows: (1) [5]

$$\sigma = \sigma' + u \tag{1}$$

σ is the total stress, σ' is the effective stress, u is the pore water pressure.In this context, σ can be considered to remain.

Relatively constant under seismic loading. When pore water pressure rises rapidly due to seismic loading, the effective stress decreases accordingly. This rise and fall can be used to derive the formula for the excess pore-water pressure ratio, as shown in Equation (2) [5]:

$$r_u = \frac{\Delta u}{\sigma_0'} \tag{2}$$

r_u is the excess pore water pressure ratio, Δu is the change in pore water pressure, and σ' is the effective stress. When the effective stress is low enough, the ratio will reach 1, and thus sand liquefaction occurs. At this time, the original stress equilibrium of the soil is altered abruptly. In its original state, the hydrostatic pressure is carried only by the pore water in the soil, and the soil skeleton bears most of the external load; at this time, the level of effective stress in the soil provides stable shear strength and bearing capacity. When cyclic dynamic loads from a strong earthquake are continuously applied to a saturated sand layer, the original stable skeletal structure of the sand

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particles is damaged, and the pore volume of the soil is continuously reduced. Under undrained conditions, the stress expression for cyclic dynamic loads can be simplified to a harmonic motion form, as shown in Equation (3), for ease of theoretical analysis [5]:

$$\sigma(t) = \sigma_0 + \sigma_c yc \cdot sin(\omega t) \tag{3}$$

σ(t) is the instantaneous total stress, σ_0 is the initial stress amplitude, and $\sigma_c yc$ is the cyclic dynamic stress amplitude at this time. Under a static load, the amplitude and direction are 0; only a downward stress on the soil is applied. Under dynamic loading, the sine value ranges from -1 to 1; thus, there are alternating compressions and extensions of the soil. The skeleton of the soil is repeatedly disturbed in a cycle and thus deforms.

Another reason for differential settlement in the ground after an earthquake is soil liquefaction. When the effective stress of the soil is reduced and its structural strength is weakened, suspended particles rapidly settle under the weight of the soil, causing significant compression of the liquefied layer and thus large-scale settlement. In addition, the liquefied zone of the soil will settle rapidly and significantly, while the adjacent soil layers will not show any such settlement. A separate settlement pressure difference will be formed between the liquefaction zone and the main body; the difference in vertical settlement in the liquefaction zone and that in the non-liquefaction zone indicates the extent of differential settlement.

In addition to uneven settlement, liquefaction of sandy soil can also cause a lateral spread of liquefaction. A decrease in soil strength due to liquefaction is required for lateral spreading to occur. As shown in the model by Hamada et al., a slope of only 0.3° to 3° is sufficient to cause lateral spreading due to liquefaction. For example, in Hamada's seismic damage survey, the lateral horizontal displacement of the porous soil layer beneath a four-story building was almost 1.1 m, and the maximum lateral displacement of a pile with a diameter of 35 cm and a length of 6 m reached 70 cm; the lateral propagation of the liquefied layer caused serious damage to the pile foundation [6]. Cyclic seismic loading will cause liquefaction of the sand and a continuous decrease in shear strength. The soil becomes a fluid and undergoes continuous lateral deformation. When liquefied soil is subjected to the pressure of the structure above, it continuously pushes the underlying fluid towards a low-lying area. After the seismic load ceases, the horizontal lateral spread stops, and the soil particles in the liquefied layer settle under the force of gravity, resulting in dual damage of lateral spread and settlement [7]. Hamada et al. proposed an empirical formula in 1986 to determine the size of the lateral displacement based on a comparative analysis of various data obtained from aerial photographs of the three sites where liquefaction occurred and on-site field surveys [6]; see Equation (4):

$$D = 0.75\sqrt{H} \cdot \sqrt[3]{\theta} \tag{4}$$

Based on the empirical formula, the degree of lateral displacement and the thickness of the liquefaction layer are positively correlated with the slope; at the same time, the slope has a smaller effect on displacement than thickness [6].

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3. Measures to prevent and control sand liquefaction

3.1. Improving the properties of the soil itself

3.1.1. Dynamic Compaction method

Dynamic Compaction is a typical kind of soil densification. First developed by the French engineer Menard, it is known in China as the dynamic compaction method [8]. Different ways are used to apply the dynamic compaction method for clay and sandy soils; generally, a crane is employed to raise a 10-60 metric-ton compaction hammer to a height of 10-40 metres [9]. The potential energy of a rammer is used to repeatedly strike the ground. In clay, the impact load causes a rapid increase in pore water pressure and a corresponding drop in effective stress; thus, instantaneous localised liquefaction of the soil occurs as the effective stress approaches zero. At this time, radial vertical cracks form around the impact site in the clay and extend to the surface. A low-pressure zone is created inside the pores of the soil relative to the outside air, and thus water is drawn out. Meng Xiangyue and others have conducted experiments to study the effect of changes in pore water pressure on compaction-induced liquefaction, and sensors have been used to measure these pressure changes in sand samples. The results showed that when the soil was subjected to a certain load, pore pressure increased and localised liquefaction occurred; the effective load corresponded to the maximum value of the excess pore water pressure [10], and the bearing capacity of the compacted foundation was significantly improved. Since clay has a certain tensile strength and sandy soil has extremely low tensile strength, the cracks that form around clay particles after localised liquefaction at compaction points do not occur in sandy soil. After drainage through the natural intergranular voids in the sandy soil, the soil particles will rearrange, reduce pore water pressure, prevent an increase in excess pore water pressure, and thus avoid liquefaction of the sandy soil. The actual consolidation depth of the dynamic compaction method can be shown in Equation (5) [8]:

$$D = \alpha \cdot \sqrt{M \cdot h} \tag{5}$$

D is the effective consolidation depth, α is the correction factor, M is the product of mass and gravitational acceleration, and h is the lifting height; the product of the two is the compaction energy.

Based on the effective consolidation depth, we can see that the relationship between compaction energy and effective consolidation depth is not linear; instead, it follows a power-law relationship with an exponent less than 1, and the increase in compaction energy achieved by increasing the effective consolidation depth gradually diminishes [8].

3.1.2. Vibro-penetration method

The two kinds of vibroflotation methods are the vibroflotation method with fill material and the vibroflotation method without fill material; these are the two general categories of the vibroflotation method. The basic idea of both is a compaction effect. Both methods use high-frequency vibrations of a vibroflotation device to generate elastic waves in the surrounding soil and thus increase the density of the soil. A vibro-compactor is placed in the ground, and then it starts to vibrate at a high frequency. Vibrate to raise the vibro-compactor slowly; at this time, the liquefied fine particles will be carried by the vibration wave into the voids between the larger particles and compacted. Zhou Jian and others have carried out field tests of a vibro-penetrator with an integrated pore-pressure

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sensor. They have studied how soil consolidation changes under the three vibro-compaction methods (single-vibration, double-vibration and triple-vibration) in vibration-table experiments. As shown in the three standard penetration test (SPT) curves, it has been determined that this method is simple and low-cost, and can improve the uniformity of the foundation to a certain extent to prevent differential settlement. Furthermore, the reinforced fine- to very fine sand layer can achieve a medium-dense to dense state. At present, the filled vibrocompaction method is only applicable to loose foundations, and the unfilled vibrocompaction method is currently only suitable for treating medium- to coarse sand and coarse-grained soils with a clay and silt content of less than 10% [11]. Due to the high content of impurities, these two materials are converted into a slurry when water is added by the vibroflotation device and cannot be compacted. Another name for the vibro-compaction method is the gravel pile method, and it is a general-purpose anti-liquefaction measure in engineering practice. In the crushed stone pile method, crushed stone is added to each layer of the vertical borehole drilled by a vibro-compactor, and then cyclic vibration is used to compact the material. Vibration will increase the density of the soil and, at the same time, replace some of the original soil with crushed stone to form a crushed-stone pile. Voids in the crushed stone serve as drainage paths and enhance the earthquake-resistant drainage capacity. This addresses the problem of a weak drainage capacity in the unfilled vibro-compaction method. Since the strength of the gravel piles is higher than that of the surrounding soil, most of the stress under seismic load will be borne by the gravel piles, and they will constrain the surrounding soil. In short, although the vibro-compaction method is more expensive, it can achieve better compaction, drainage and constraint effects to improve the liquefaction resistance of the soil under earthquake loading significantly. Cao Zi'ang and his group conducted shake-table experiments in several sandy soil environments to study the effect of an excess pore-pressure ratio and time at various operating conditions. Based on the above results, the crushed-stone pile method is more effective at reducing excess pore water pressure in coarse-grained soils, and its effect on fine-grained soils is relatively small [2]. Therefore, the clay content should not be too high during vibro-compaction reinforcement; crushed-stone piles can also be used to provide additional drainage paths and increase the density of the soil.

3.2. Does not alter the inherent properties of the soil

Liquefaction-mitigation measures that do not alter the inherent properties of the soil are generally reinforcement types. The two kinds of reinforcement methods for the foundation construction are horizontal reinforcement and vertical pile reinforcement. Horizontal reinforcement is generally only suitable for low-rise buildings, usually no more than three stories high. Geosynthetics are currently used for lateral reinforcement and mainly fall into two categories: geogrids and geotextiles. Geogrids are generally arranged in layers, and the first layer is placed at a depth of about 0.3-0.6 metres below the base of the structure; subsequent layers are added one after another downwards, and the distance between the layers is generally not more than 0.6 metres. Mittal and others have conducted shake-table tests to show that with an increase in the number of layers, the maximum pore-water pressure ratio decreases; thus, the development of excess pore-water pressure is effectively suppressed, and a significant reduction in soil effective stress can be avoided [12]. Friction at the interface of the geogrid and the soil limits the horizontal displacement of the soil during an earthquake. Soil particles are also lodged in the mesh openings and thus mechanically interlocked. Under seismic load, lateral displacement of the soil pulls on the geogrid, and the restraining force of the geogrid limits the lateral displacement of the soil under load by working with frictional force to create an interlocking force in the soil itself.

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The main kind of vertical reinforcement in construction is the reinforced gravel pile method. The general idea of a reinforced gravel pile is to place a vertical geogrid at the top of a fill gravel pile and fix it at a certain depth. As ordinary gravel piles do not have internal cohesion, they are supported by lateral confinement forces from the surrounding soil. The constraint is relatively weak, and the main type of seismic damage to gravel piles is lateral swelling; that is to say, the gravel particles are pushed into the surrounding soil, leading to a general foundation failure. Therefore, geogrids with a diameter equal to that of the gravel piles are used in the project to add confinement, prevent serious damage to the friction bearing capacity and drainage channels of the gravel piles, and ensure that the anti-liquefaction function of the gravel piles remains stable during an earthquake.

3.3. Comparative analysis of measures

Most of the existing liquefaction simulations are shake-table tests; in the previous section on methods to prevent soil liquefaction, we also mentioned researchers who have used shake-table tests to determine the effectiveness of reinforcement measures. Shake table tests are conducted in an equivalent manner by matching similarity coefficients and placing sensors under the test setup to record soil pore pressure and lateral displacement during an earthquake induced by computer-generated seismic waves. It is a simple index of changes in soil behaviour, but it also has some deficiencies. First, shake-table tests can only generate one-way or two-way seismic waves; as real seismic waves are generally irregular, such tests cannot accurately reproduce the actual data. Future work will focus on building shake-table models with multiple input points. Although shake-table tests can simulate the triggering conditions for sand liquefaction, such as the buildup of pore water pressure and a drop in effective stress to zero, once the sand has fully liquefied and turned into a non-Newtonian fluid, the existing two-phase medium governing equations are no longer suitable for describing the entire liquefaction process [13]. Therefore, the accuracy of the simulation for the expansion and settlement phenomenon mentioned above is relatively low and thus not suitable for research by scholars of liquefaction. Secondly, as the original area is too large for direct experimental investigation, it must be reduced in scale; however, this leads to considerable scale effects that affect the accuracy of the experimental results [14]. It also fails to replicate the in-situ soil conditions accurately; sand particles and pore sizes cannot be scaled down proportionally, and thus the permeability will be significantly different from that of real soil.

As shown in Equation (2), an increase in the pore-water pressure ratio is directly related to drainage conditions; when the clay content exceeds a certain limit, the drainage capacity of the soil is greatly reduced, and scaled models cannot reflect this physical phenomenon. Given that the foundation of selecting a liquefaction mitigation method is stratigraphy, the vibrocompaction method is only suitable for clays with a clay content of 10% or less; the reinforced method is limited to shallow foundations no deeper than five metres, and only sandy soil, gravelly soil and low-saturation clay can be treated by dynamic compaction [9]. The model cannot accurately simulate the above-mentioned applicable conditions, so it is not feasible; thus, research on the combined application of multiple construction methods cannot be carried out. This is because the interaction among the above methods needs to consider the deep compaction and drainage paths of the vibroflotation method, the shallow confinement forces of the reinforcement method, and the clay conditions and effective reinforcement depth of the dynamic compaction method. Scale models are already unable to accurately simulate the variables in the prediction of a single method's performance, let alone the combined effect of multiple methods working together.

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4. Conclusion

Soil liquefaction is a typical type of seismic damage to foundations; it reduces the effective stress of the soil to zero and can cause other problems such as lateral spreading and differential settlement. The two types of the main anti-liquefaction methods are classified according to whether they alter the intrinsic characteristics of the soil: those that modify soil properties, such as dynamic compaction and vibroflotation; and those that do not change soil properties, such as reinforcement and stabilisation measures. Before the implementation of the above anti-liquefaction measures, shake-table tests were often carried out to evaluate their effectiveness. It is a good index, but it also has many defects. For example, it cannot simulate the complex seismic waves that occur during an actual earthquake; there is a distortion in the particle size distribution of sandy soil during model construction; and it lacks the ability to accurately simulate the non-Newtonian flow behavior of liquefied sandy soil. Due to the above reasons, the connection links among the various construction methods for this project have not been identified. Shake tables that can be connected to multiple points and have better performance for simulating and predicting the effects of synergy among various construction methods need to be developed further.

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