Soil Desaturation Methods for the Improvement of Liquefiable Ground

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Abstract. Soil liquefaction is a phenomenon where soil loses its shear strength and behaves like a fluid because of the increase in excess pore water pressure subject to dynamic loads such as earthquakes. Soil liquefaction can cause disastrous consequences to buildings and structures, and it is one of the main problems in geotechnical seismic engineering. At present, the traditional measures for the treatment of soil liquefaction include soil densification methods and soil cementation methods. However, these methods are relatively expensive and technically complicated in engineering practice. A new approach of soil liquefaction treatment, soil desaturation, has drawn research attentions. The desaturation treatment can reduce the excess pore water pressure and improve the undrained shear strength of loose liquefiable soils. Gas bubbles in soils serve as a buffer to increase the compressibility of soil pore and alleviate the pore pressure change. Compared with traditional soil liquefaction treatment methods, the desaturation method has many advantages, such as low cost, simple operation and so on. This paper provides a comprehensive review and analysis on the mechanisms, the desaturation implementation techniques, as well as the limitations of the desaturation methods.

1. Introduction
Earthquakes can cause serious geological disasters. A large number of earthquake investigations show that soil liquefaction and associated seismic subsidence and ground lateral movement result in serious disasters, such as uneven settlement, collapse and incline of overground structures, crack of roads, uplift of underground structures and other forms of damages [1-3]. In recent years, many earthquakes are accompanied by soil liquefaction. For example, the 2011 Christchurch earthquake in New Zealand, the 2011 Great East Japan earthquake, and the 2008 Wenchuan earthquake in China. Nowadays, how to deal with soil liquefaction effectively is one of the key issues to ensure the safety of buildings and structures in the mass infrastructure construction in China. Soil liquefaction usually occurs in loose saturated sand and silty soil, because of their contractive behaviour and saturated state. Under certain level of seismic load, the water in the soil can not be discharged timely, the excess pore water pressure in the soil builds up, and the effective stress between soil particles decreases. As a consequence, the soil ground loses its bearing capacity and behaves like a fluid.

The traditional treatment methods against soil liquefaction, such as dynamic compaction, compaction sand pile, gravel pile and cement mixing pile, are effective technically. However, these methods are often too expensive and are not applicable to normal buildings and structures. Moreover, it is difficult to apply these methods to the grounds of completed buildings. Therefore, we urgently need to find new cost-effective methods for the treatment of liquefiable grounds.
The loose saturated sand and silt are easy to liquefy under earthquake. It is found that the undrained shear strength and liquefaction resistance of loose sand increase with the decrease in the degree of saturation. In cyclic triaxial and cyclic torsional shear tests, if the saturation degree of the saturated sand reduces slightly, the cyclic strength increases greatly [4-5]. In the shaking table test, the excess pore water pressure build-up and volume change of unsaturated sand are much smaller than those in saturated sand [6-8]. In the triaxial consolidation undrained test, when the saturation degree of loose sand decreases from 100% to a range below 90%, the stress-strain curve of loose sand will change from strain softening manner (liquefaction) to hardening manner (non-liquefaction) [9]. These results indicate that desaturation is a feasible method against liquefaction. This paper provides a comprehensive review and analysis on the mechanisms, the desaturation implementation techniques, as well as the limitations of the desaturation methods.

2. Mechanism and Mechanical Properties

2.1. Mechanism

The desaturation method is to reduce the degree of saturation of saturated soil by injecting insoluble bubbles. This is a new approach to mitigate the liquefaction susceptibility of soil ground. When the soil ground is subjected to dynamic load after desaturation treatment, the bubble can serve as a pressure buffer and effectively slow down the increase of excess pore water pressure in the soil. As a result, the decreasing trend of effective stress $\sigma'$ of the soil is alleviated and the reserved shear strength can still ensure that liquefaction will not likely to occur in the soil ground. The mechanisms of the desaturation method for the liquefaction control can be explained by the effective stress principle and the soil shear strength theory,

$$\sigma' = \sigma - u$$  \hspace{1cm} (1)

$$\tau' = c' + \sigma'\tan\phi' \text{ (clay)}$$  \hspace{1cm} (2)

$$\tau' = \sigma'\tan\phi' \text{ (sand)}$$  \hspace{1cm} (3)

$\sigma$, $\tau'$, $c'$, $\phi'$ are total normal stress, effective shear stress, effective cohesion and effective internal friction angle, respectively. It can be seen that, when the increase of excess pore water pressure in the soil retards, its effective stress will also counteract. Thus, the soil always maintains a certain shear stress to resist the liquefaction. Therefore, the desaturation method can induce stable gas bubbles into soil and reduce the saturation degree of soil, so as to achieve the prevention or mitigation of soil liquefaction.

2.2. Mechanical Properties

The results of dynamic and static triaxial tests also show that reducing the saturation degree of sand can effectively improve the strength and anti-liquefaction performance of the sand. For example, Martin et al. found that, under cyclic load, when the saturation degree of sand with a porosity of 40% decreases by 1%, the increment of excess pore water pressure decreases by 28% [10]. Chaneyd et al. found that, when the saturation degree of sand reduces from 100% to 90%, its anti-liquefaction strength will increase by a factor of 2 [11]. Xia et al. conducted anti-liquefaction tests on sand with different saturation degrees, and the results showed that the anti-liquefaction strength of soil increased significantly with the decrease of saturation degree. When the saturation degree of saturated sand dropped from 100% to 97.8%, the anti-liquefaction strength increased by 30%. Figure 1 shows the relationship between number of cyclic loads and cyclic stress ratio, as reported by Xia and Hu [12]. The anti-liquefaction strength of sand increases with the decrease of the pore pressure ratio B [13]. In the triaxial test, the pore pressure ratio B value reflects the saturation degree of sand, that is, the lower the B value, the lower the saturation degree. Under the static load, the strength of sand also increases with the decrease of saturation degree for loose sand under the undrained condition [8].
Based on the test results of the cyclic shear strength of desaturated sand, Okamura and Soga proposed that the improvement of strength is related to the compression characteristics of the soil voids [6]. If the content of air bubbles in the void is high, the compressibility of the soil void is high. The concept of potential volumetric strain is proposed to describe the dynamic strength growth of desaturated sand. The volumetric strain \( \varepsilon_v \) of desaturated sand is written by the equation,

\[
\varepsilon_v = \frac{\Delta p}{p_0 + \Delta p} (1 - S_r) \frac{e}{1 + e}
\]

in which, \( p_0 \), \( \Delta p \), \( S_r \), \( e \) are static pore water pressure (absolute pressure), excess pore water pressure, saturation degree and void ratio, respectively. In the undrained shearing, the excess pore water pressure \( \Delta p \) is variable and the maximum value can be the effective confining pressure \( \sigma_c' \). Therefore, the maximum possible value for the volumetric strain is defined as the potential volumetric strain \( \varepsilon_v^* \),

\[
\varepsilon_v^* = \frac{\sigma_c'}{p_0 + \sigma_c'} (1 - S_r) \frac{e}{1 + e} \geq \varepsilon_v
\]

The potential volumetric strain \( \varepsilon_v^* \) is a quantitative description of the compressibility of the soil voids. Okamura and Soga show the relationship between the strength growth LRR (the liquefaction resistance ratio) and the volumetric strain potential \( \varepsilon_v^* \) for desaturated sand, as follows,

\[
\text{LRR} = \log(\alpha \varepsilon_v^* + 10)
\]

The liquefaction resistance ratio LRR is defined as the strength ratio of the desaturated sand to that of the saturated sand under the same condition, \( \alpha \) is a fitting coefficient. Okamura and Soga pointed out that \( \alpha = 6500 \) can fit the strength increasing trend of desaturated sand under cyclic load, as shown in Figure 2. It is also interesting to know whether Eqn (6) is applicable to the results of the static triaxial tests. The data of the triaxial compression and extension tests on the desaturated sands from He and Chu are also plotted on Figure 2 [14]. The strength obtained in triaxial compression and extension tests follows the patterns of \( \alpha = 14000 \) and 1800, respectively. It can be seen from the figure that the strength of desaturated sand increases in a fastest way in the triaxial compression test, in a slowest way in the triaxial extension test. The growth trend of cyclic strength is in-between.
Figure 2. Liquefaction resistance ratio of desaturated sand soils in dynamic and static triaxial tests.

In addition to the triaxial tests, the effect of the soil desaturation for the liquefaction treatment is also studied in the shaking table model tests. It has been found is several studies that the desaturated loose sand has much stronger resistance to liquefaction than its saturated counterpart [6-8]. The non-liquefaction manner of the desaturated sand is manifested by a smaller excess pore water pressure generation, a smaller volume change of soil, and much smaller destructive effect of the structures resting on the soil.

3. Methods of Desaturation
The desaturation method is a new technology for the prevention or mitigation of soil liquefaction. The gas used in the desaturation method should meet the following requirements: (1) The degree of saturation can be controlled; (2) Gas bubbles should distribute relatively uniformly; (3) Gas bubbles can stay in soil for a relatively long time. Gases with low solubility in water and chemically inert are preferred. The following four methods are available in the literature.

3.1. Air Injection
Air injection method is simple and convenient, but it also has some technique difficulties [15, 16]. Okamura et al. investigated this method by field tests in 2011[15]. The test site is a liquefiable soil ground near a wharf. A plastic pipe with small holes on the wall was inserted into the ground. The injecting point was near the bottom of the liquefiable layer. The result showed that the soil within 4m from injecting point was desaturated. The degree of saturation was reduced to 68%-98% after injecting air. The cyclic shear strength was almost doubled. The injecting pressure should be higher than the summation of hydrostatic pressure and capillary pressure in the soil to ensure that air bubbles could enter into the soil. Meanwhile, the injecting pressure should be lower than effective stress to avoid cracking of soil around the injecting point. The air flow rate had linear relationship with injecting pressure. Test carried out by Catney and Lynch showed that: (a) The desaturated area spread rapidly when the injecting pressure was low, and the rate became slower when the pressure rose higher; (b) Small injecting pores can create small gas bubbles, which form a more stable desaturated area; (c) To avoid soil destruction caused by high injecting pressure, overburden load could be applied to the ground surface before injecting [16].

3.2. Water Electrolysis Method
Yegian et al. investigated the possibility of the water electrolysis method for desaturation of liquefiable sand [7]. The size of the model box used in this study was 20cm (W)×30cm (L) ×29cm (H). Hydrogen
gas and oxygen gas were generated at cathode and anode respectively, when an electric potential was applied between electrodes. The reaction equations are as follows:

At the cathode: \[4\text{H}_2\text{O} + 4e^- = 4\text{OH}^- + 2\text{H}_2 \uparrow \] (7)
At the anode: \[2\text{H}_2\text{O} - 4e^- = 4\text{H}^+ + \text{O}_2 \uparrow \] (8)

In the test, the cathode was installed at the bottom of the model box and the anode was installed at the top. The degree of saturation of soil was calculated by observing the change of water level in the model box. Under a current of 525mA, the degree of saturation of soil was reduced from 100% to 96.3% after 3-5.5 hours. The liquefaction resistance under cyclic loading was enhanced significantly, as found in the shaking table tests after the desaturation treatment.

3.3. Chemical Method

Chemical solution can be injected into soil and diffuses in pore void of soil. The chemical reactions can produce gas bubbles in the soil to reduce the degree of saturation. Eseller-Bayat used sodium perborate (NaBO₃) as a reactant to generate oxygen gas in soil [17]. The reaction was a two-step process. First NaBO₃ hydrolyzed in water to produce hydrogen peroxide, and then the hydrogen peroxide decomposed into water and oxygen gas:

\[2(\text{NaBO}_3 \cdot \text{H}_2\text{O}) + 2\text{H}_2 \rightarrow 2\text{H}_2\text{O}_2 + 2\text{BO}_3^{3-} + 2\text{Na}^+ + 4\text{H}^+ \] (9)
\[2\text{H}_2\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{O}_2 \uparrow \] (10)

This reaction generated a certain amount of oxygen gas bubbles in soil and reduced the degree of saturation. Eseller-Bayat pointed that the degree of saturation was closely related with the amount of NaBO₃ added, so the degree of saturation can be controlled by changing the amount of sodium perborate [17]. And the gas bubble generated by this reaction could be relatively uniformly distributed in soil.

3.4. Microbial Method

Microbial method is a new method that uses microbial processes to generate insoluble and stable gas in soil and reduce the degree of saturation. Microbial denitrification is ideal for this purpose. In the denitrification process, nitrate can be reduced to nitrogen gas by denitrifying bacteria eventually. The nitrogen gas is a stable and insoluble gas, which can reduce the degree of saturation and improve the liquefaction resistance. Ethanol can be used as the electron donor in dentification process and the reaction equation is as:

\[5\text{C}_2\text{H}_5\text{OH} + 12\text{KNO}_3 \rightarrow 6\text{N}_2 \uparrow +10\text{KHCO}_3 + 9\text{H}_2\text{O} + 2\text{KOH} \] (11)

In an experimental study, a laminar box was used to investigate the excess pore water pressure and volumetric strain of desaturated sand [8]. Comparative analysis of saturated sand and desaturated sand showed that the liquefaction resistance of sand was obviously enhanced after desaturation by denitrifying bacteria.

4. Problems and Limitations

A large number of studies have proved that the method of desaturation can effectively improve the liquefaction resistance of the soil ground. However, the stability of gas in the ground is always a matter of concern. The stability of gas bubbles in soil has been investigated in both the laboratory and field experiments. In a laboratory tests carried out by He and Chu [8], it was found that the gas bubbles in soil is stable at hydrostatic conditions, but unstable at water flow conditions. Such results imply that the use of desaturation method for the liquefaction control is more suitable for soil ground with no or little ground water flow. In a field experiment conducted by Okamura [15], it was found that the desaturation state of soil below the groundwater level maintained for more than 20 years. Therefore, the gas bubbles in soil are relatively stable, and the desaturation method is practical to be used as an engineering method for liquefaction control.
5. Conclusion
Desaturation is a new method for the treatment of liquefiable soil ground, which improve the liquefaction resistance of soil by introducing stable and insoluble bubbles into soil. This paper mainly introduces and analyses the mechanisms and techniques of soil desaturation. Compared with the traditional anti-liquefaction method, desaturation method has obvious advantages. For example, this method is cost-effective and easy to implement. However, the desaturation method is still at the stage of theoretical and experimental research, which is far from engineering application. So, it needs more studies and pilot applications to demonstrate its feasibility and technical advantages.

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7. References
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