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In-situ Desaturation Tests by Electrolysis for Liquefaction Mitigation

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Abstract:

Electrolytic desaturation is a potential method for improving the liquefaction resistance of the liquefiable foundation by reducing the soil saturation. In this study, in-situ desaturation tests were performed to investigate the resistivity of soil at different depth and the water level of the foundation under different current. The test results show that at constant currents of 1 A (Ampere, unit of the direct current), 2 A and 3 A, the saturation of the treated foundation reached 87%, 83% and 80%. During the electrolysis process, the generated gas migrates vertically and horizontally under the influence of buoyancy and gas pressure. In the end of electrolysis, the gas inside the sand foundation basically migrates vertically only. The higher current intensity employed for electrolysis will affect the uniformity and stability of the gas. At constant currents of 1 A, 2 A and 3 A, the difference between the maximum and minimum degree of saturation in the treated foundation was 14%, 18% and 19%; and after electrolysis halted for 144 h, the saturation in the treated foundation was 90%, 85% and 87%. The electricity consumption analysis indicates that the desaturation method has excellent economic benefits in the treatment of saturated sand foundations.

Keywords: Electrolytic desaturation, Liquefaction resistance, Saturation, Field tests, Currents

Introduction

Past earthquake events have indicated that the excess pore water pressure will accumulate within the saturated sand foundations during earthquake, leading to liquefaction of soil and damaging deformations of buildings (Youd et al. 2001, Seed et al. 2003, O'Donnell and Kavazanjian 2018). The commonly used treatment methods for liquefiable foundations in engineering include vibro compaction (Duan et al. 2019), deep soil mixing (Hasheminezhad and Bahadori 2019), sand compaction piles (Feng et al. 2020), stone columns (Pal and Deb 2020), etc. These methods greatly improve the liquefaction resistance of foundations but still have the disadvantages of being expensive and cannot be applied to existing buildings (Xu et al. 2013). Many scholars have studied the liquefaction resistance of unsaturated sand soils and found that reducing the saturation from 100% to 95% can improve the liquefaction resistance ratio (*LRR*) of the Toyoura sand from 1.0 to about 1.4 (Tsukamoto et al. 2002, Ishihara and Tsukamoto 2004, Hossain et al. 2013). Based on this result, the treatment of liquefiable foundations by reducing the degree of saturation has been proposed and has received extensive attention in recent years (Huang and Wen 2015, Xu et al. 2019).

Okamura (Okamura et al. 2011) proposed a method of injecting air into a saturated sand foundation to reduce the saturation and increase the liquefaction resistance. The results of the field tests showed that the air-injection treated saturated sand foundations formed volume of less than 90% saturation with a maximum radius of 9 m. Zeybek (Zeybek and Madabhushi 2017a, 2017b, 2018) conducted centrifuge shaking table model tests of air injection to investigate the mechanism of foundation deformation and the effect of liquefaction resistance under overlying loading conditions. Eseller-Bayet (Eseller-Bayat et al. 2013a, 2013b) reduced the saturation of specimens by producing hydrogen peroxide (H_2O_2) from sodium perborate monohydrate ($NaBO_3 \cdot H_2O$), which decomposes to produce oxygen (O_2); an empirical model of the liquefaction response of unsaturated sand under dynamic shear stress was established by cyclic single shear model tests. He (He et al. 2013, 2014, 2016, He and Chu 2014) carried out triaxial model tests and shaking table tests of microbial denitrification to generate nitrogen (N_2) in saturated sand samples to reduce saturation; the size of

the generated bubbles reached the nanoscale, which guaranteed the stability and sustainability of the foundation treatment. Yegian (Yegian et al. 2006, 2007) performed shaking table tests to study the method of lowering the saturation by electrolyzing water to generate hydrogen (H_2) and oxygen (O_2), thus validating the feasibility of the method. The electrolysis method generates environmentally friendly gases, hydrogen (H_2) and oxygen (O_2), to reduce ground saturation with little environmental impact. After the electrodes are arranged in the foundation, the desaturation treatment can be conveniently repeated with low power consumption, which has a broad practical applications prospect (Yegian et al. 2006).

The existing experimental studies of desaturation methods are mostly small-scale model tests performed indoors. The unavoidable shortcomings, namely, the boundary conditions, lack of seepage, and small sample volume, cannot fully simulate the effects of desaturation methods in engineering applications. The few field tests of air injection for the treatment of liquefiable foundations also failed to investigate the process of gas injection and diffusion. In addition to the traditional mass-volume method, other parameters, including γ -value, compressive wave velocity and electrical resistivity are used to evaluate the saturation of soil. The convenient parameters to measure in field tests are the compression wave velocity and resistivity, where the saturation sensitivity of the compression wave velocity ranges from 93% to 100% with little variation in the compression wave velocity at degrees of saturation of less than 90% (Tsukamoto et al. 2002, Leong and Cheng 2016). Moreover, the apparent resistivity of the soil layer obtained by the high-density resistivity method is difficult to describe the resistivity variation of the soil at specific locations (Samouëlian et al. 2005).

In this study, a field test of the electrolytic desaturation method under four working conditions was conducted to study the effectiveness and gas diffusion patterns of the method. Instruments were developed to monitor the resistivity at specific locations in the foundation based on the relationship between resistivity change and degree of saturation to reflect the saturation changes in the field. The effect of electrolytic desaturation on the permeability of the foundations was studied by monitoring the water level. Finally, the electrical energy consumed by electrolysis was calculated,

and the effectiveness of the field application of the electrolytic desaturation method was comprehensively evaluated.

In Situ Test Site

Based on the deep quartz sand layer found in the exploration of a tunnel project in Bozhou city, China, a relatively flat site around the foundation pit was selected for the electrolytic desaturation tests. The locations of boreholes and a photo of the test site are shown in Figure 1. The test site is a rectangle with area of 25m^2 , adjacent to the river on the west and to the foundation pit on the east. Due to pit dewatering, the groundwater level at the test site is at approximately ground level (GL) -8.7 m to -8.9 m. The direction of seepage caused by dewatering is basically parallel to the connection line of boreholes No. 1 to No. 4 at the test site. The hydraulic gradient is approximately 0.13, so the effect of seepage on the gas distribution in the sand foundations can be considered minimal (Reddy and Adams 2000).

A total of 13 boreholes were deployed at the test site, in which boreholes No. 1 to No. 4 were used to place the electrodes for electrolysis, boreholes No. 5 to No. 10 were used to monitor the water level changes, and boreholes A to C were used to bury the resistivity monitoring instruments at various depths (GL -10 m, -15 m and -20 m) to monitor resistivity changes. Boreholes No. 1 to No. 10 were drilled to a depth of 22.5 m, and bentonite was used as the thinner mud retaining wall material during the drilling process. After the borehole was formed, rinsed and placed a 23 m-long polyvinyl chloride (PVC) pipe into the borehole. The lower 12 m part (GL -10 m to -22 m) of the PVC pipe was punched with small holes 8 mm in diameter and 50 mm apart, and the perforated section was wrapped with geotechnical fabric, which allows gas and water to enter and exit freely but prevents sand from entering. The void between the PVC pipe and the borehole was backfilled with in situ sand and compacted manually, repeated until the backfilled sand no longer settled. The compactness of the backfilled in situ sand is slightly less than the compactness of the sand foundation based on the quality and volume of the backfilled in situ sand. Boreholes A to C were drilled and backfilled in a manner similar to boreholes No. 1 to No. 10, with the resistivity monitoring instruments buried at three depths instead of placing PVC pipes into the boreholes.

The soil profile estimated from boreholes No. 1 to No. 4 and the grain-size distribution of sand are illustrated in Figure 2. The physical and mechanical parameters of each soil layer are shown in Table 1. The test site below GL -4.8 m is consisted of deep fine sandy layers over 20 m thick. Based on the results of the cone penetration test (CPT) and the standard penetration test (SPT) of the two sandy layers, the relative density (Dr) of the sand 1-1 is estimated to be 51%, and that of the sand 1-2 is 55%.

Test Methods and Conditions

Electrode Arrangement Method

The tests used a new type of electrokinetic geosynthetics (EKG) as the electrode materials, which have the advantage of high corrosion resistance and are widely used in electro-osmosis (Fourie et al. 2007). A schematic diagram of the electrode arrangement method is shown in Figure 3. Prior to the start of the electrolysis test for each condition, the electrodes are placed in PVC pipes and sealed to prevent gas leakage from the top. The electrode connecting the wire was inserted into the perforated section of the PVC pipe, a water-blocking gasbag (with designed pressures up to 60 kPa) was placed at the natural water level above the electrode and inflated to occlude the PVC pipe. Bentonite chips were poured into the PVC pipe, and water was continuously passed so that the Bentonite chips hydrated and formed a layer of clay of approximately 3 m in thickness above the gasbag, thus completely sealing the PVC pipe.

Resistivity Monitoring Instruments

The electrical resistivity is a common physical quantity that reflects the properties of soil. In 1942, Archie (Archie 1942) examined the relationship between soil parameters and resistivity by using different types of soil samples and cores and summarized the relationship between soil resistivity R_0 and degree of saturation S_r under conditions of constant temperature and pressure:

$$R_0 = \alpha R_w \theta^{-m} S_r^{-n} \quad (1)$$

where R_w = resistivity of pore fluid in soil; θ = soil porosity; α , m and n = empirical

parameters related to the soil structure. In subsequent studies, similar conclusions were reached thus verifying the correctness of the formula (Waxman and Smits 1968, Abu-Hassanein et al. 1996). Although the soil resistivity is related to the soil structure, particle gradation, temperature, pressure, pore fluid composition, and soil saturation, electrolysis does not react chemically with the quartz sand in the test site, so none of the factors in the sand foundation other than the degree of saturation changed significantly before and after the electrolysis test. Therefore, the resistivity change before and after the electrolysis test could be monitored to indirectly derive the variation of saturation within the foundation. The resistivity change ρ_c is defined as

$$\rho_c = 100(\rho_a - \rho_b)\rho_a^{-1} \quad (2)$$

where ρ_a = initial resistivity of sand samples and ρ_b = resistivity after electrolysis. Sand layers under natural water levels are generally saturated or nearly saturated (Tsukamoto et al. 2002), and the test site was continuously pumped with water through PVC pipes until the electrical resistance of resistivity monitoring instruments remained stable for a long time, thus the degree of saturation in the sand foundation below the natural water table before electrolysis can be considered as $S_r = 1$. The unique relationship between the rate of resistivity change ρ_c and the degree of saturation after electrolysis could be assumed as

$$\rho_c = S_r^{-n} - 1 \quad (3)$$

The constant n of fine sand is generally assumed to be 2.0 (Okamura et al. 2011). The relationship between the resistivity change and degree of saturation at different Dr ($Dr = 0.5, 0.6$ and 0.7) is measured by the remodeling sand samples obtained from boreholes at the test site as shown in Figure 4. The curves shown in Figure 4 basically conform to the exponential relationship given by formula (3), but the degree of saturation of the sand foundation after treatment by the desaturation method will generally still be over 70% (Kato and Nagao 2020). The curves from 70% to 100% degree of saturation are basically coincident and exhibit significant linearity at different Dr . Therefore, the change in the degree of saturation of the foundation could be detected by monitoring the process of resistivity variation before and after electrolysis.

The resistivity ρ of a sand column in the foundation could be represented by a simple formula:

$$\rho = R_s S L^{-1} \quad (4)$$

where R_s = resistance of sand column; S = cross-sectional area of sand column; and L = length of sand column. A resistivity monitoring instrument was developed according to formula (4), in which the resistivity of the device changes with the fluctuation of the saturation in the foundation. The schematic diagram of the resistivity monitoring instrument is shown in Figure 5. A cylindrical container of an insulating material with a length of 220 mm and an inner diameter of 42 mm was drilled with small holes of 6 mm in diameter and 20 mm apart and wrapped tightly with a layer of geotechnical fabric. Next, the container was filled with in situ sand of the appropriate quality according to the compactness of the sand layer at the depth where the instrument was placed, after which the ends of the container were sealed by insulating caps fixed with circular iron plate electrodes 10 mm thick and 40 mm in diameter. At one of the ends, there were holes 5 mm in diameter in both the center of the iron plate and the sealing cap, from which the wires connecting the electrodes could protrude. The instrument was saturated with degassed water and remained in the water as it was placed into the borehole. When the electrical resistance measured by the resistivity monitoring instrument remained stable for a long time, the resistivity of the instrument was taken as the initial resistivity ρ_a .

Test Conditions

The equivalent resistance of EKG electrodes with different lengths and distances was measured by using boreholes No. 1 to No. 10 at the test site. The equivalent resistance comprised the resistance of the electrodes and the resistance of the saturated sand between the electrodes. The relationship between the different lengths or distances of the EKG electrodes and the equivalent resistance is shown in Figure 6. The length and spacing of the electrodes used in the test were determined according to the curves, and the equivalent resistance of the electrodes exhibited basically a power function relationship with the length of the EKG electrodes and a linear relationship with the electrode distance. The electrode length corresponding to the minimum equivalent resistance of the

EKG electrodes was selected for the test. The 12-m-long EKG electrode was placed at the same depth as the drilling section of the PVC pipe, which ranged from GL-10 m to GL-22 m. Electrode distances of 1 m (boreholes No. 2 and No. 3 were used for the electrode placement) and 3 m (boreholes No. 1 and No. 4 were used for the electrode placement) were selected for the test, and the influence of different constant current sizes (1 A, 2 A and 3 A) on the performance of the electrolytic desaturation method was investigated. A summary of the test conditions is shown in Table 2. Although the distances from the midpoint of the electrodes to the resistivity monitoring instrument in test I_{3A-1m} and I_{3A-3m} were the same, the distances from each electrode to the resistivity monitoring instrument under the two conditions were different due to the different electrode spacing employed, so the appropriate electrode spacing chosen for the desaturation of the target volume in practical engineering was investigated in this test.

Results and Discussions

Resistivity Change Under Test I_{2A-1m}

The time-history of the resistivity change ρ_c calculated with formula (2) by monitoring the resistivity at each depth (GL-10 m, GL-15 m and GL-20 m) of test I_{2A-1m} before and after energization is shown in Figure 7. During the electrolysis process, the resistivity change ρ_c at each measurement point is increasing, but the rate reduces with the duration of electrolysis. As the depth increases, the peak values of resistivity change decrease, and the reduction in the rate of resistivity change becomes more pronounced. The volume of the gas produced decreases and the solubility increases with depth due to the hydrostatic pore pressures, which partly contributes to the lower peak value of resistivity change in the deep foundation. On the other hand, the gas is transported vertically upwards by buoyancy, which leads to an insignificant decrease in the rate of the resistivity change at shallow depths. As the distance from the electrode increases, the peak value of the resistivity change and the rate of the resistivity change decrease. The gas in the ground moves not only vertically but also horizontally owing to the raised gas pressure near the electrode during electrolysis; as a result, only a fraction of the gas moves further away from the electrode, and this migration pattern of the injected gas has been experimentally observed by time domain

reflectometry (Yasuhara et al. 2008). The peak values of resistivity change at the monitoring location closest to the electrode (borehole A) reach approximately 32%, 23% and 16% for depths of GL-10 m, GL-15 m and GL-20 m, respectively, which indicates that the degrees of saturation in the foundation are below 73%, 79% and 85%. Moreover, the peak values of resistivity change at the measurement point farthest from the electrode (borehole C) are only 18%, 13% and 11%, corresponding to degrees of saturation lower than 83%, 88% and 90%, respectively. With increasing depth, the difference between the peak values of resistivity change at each measurement point diminishes, which also proves that the transport of gas occurs horizontally and vertically simultaneously.

To facilitate visualization of the gas migration in the foundation during electrolysis, a 2D view of the resistivity change at different times during the 12 h electrolysis obtained by interpolation is shown in Figure 8. The distance between the boreholes of the resistivity measuring instrument and the midpoint of the two electrodes is used as the horizontal coordinate. The coordinate axes in the figure use a different scale; thus, the actual electrolytic desaturation region measured is a slender funnel shape, similar to the gas flow path observed in centrifuge tests of sand under high gravity (Marulanda et al. 2000). The saturation of the foundation remains essentially unchanged for the first 2 h, presumably because the accumulation of air pressure from electrolysis does not break through the capillary pressure in the sand (Marulanda et al. 2000). After a period of time, the gas starts to diffuse from the shallow position of the foundation, and the detection volume is basically covered by the effective desaturation volume (degree of saturation less than 90%) after approximately 8 h of electrolysis. The sand column tests done by O'Donnell and Kavazanjian (O'Donnell et al. 2017, O'Donnell and Kavazanjian 2018) using the microbially desaturation method found that the degree of saturation reduced to a final stable value fluctuating around 80% in around 7 days. And the saturation degree of sand samples treated by chemical desaturation method was 77% to 80% (Eseller-Bayat et al. 2013a). A number of studies on the air injection desaturation method have shown that the desaturation range obtained by air injection in shallow soil layers may extend to a radius of more than 3 m (Okamura et al. 2011, Marasini and Okamura 2015, Kato and Nagao 2020).

The diffusion range of the gas in fine sand is narrower than that in gravel (Marulanda et al. 2000); thus, the radius of the effective desaturation zone after 12 h of electrolysis was calculated by interpolation to be approximately 3.5 m. Nevertheless, since electrolysis produces gas throughout the length of the electrode, it has a better uniformity of desaturation along the depth. After the electrolysis is stopped, the resistivity change of the foundation is continuously monitored for 144 h, and the resistivity change fluctuates at all measurement points. When electrolysis ceases for 4 h, the resistivity change of the foundation remains almost stable with the fluctuation range being less than 5%. The resistivity change tends to be steadier with increasing depth or distance from the electrode, which is consistent with the distribution of gas volume in the electrolysis process. Varying gas pressures will result in different patterns of gas flow paths (Xie et al. 2018b), and the gas may not necessarily form preferential flow paths to the atmosphere due to the inhomogeneity of the in situ foundation, but wider flow paths formed by a higher gas pressure may explain the difference in gas stability at specific locations in the foundation. At the nearest detection position from the electrode (borehole A), the average values of the resistivity change after basic stabilization at depths of GL-10 m, GL-15 m and GL-20 m reach 26%, 19% and 13%, respectively, which correspond to degrees of saturation below 78%, 83% and 88%. Moreover, the average values of the resistivity change at the farthest measuring point from the electrode (borehole C) for depths of GL-10 m, GL-15 m and GL-20 m amount to 18%, 14% and 7%, respectively, which imply degrees of saturation less than 83%, 87% and 94%.

A 2D view of the resistivity change at different times after electrolysis achieved by interpolation is shown in Figure 9. Within 144 h after the end of electrolysis, the degree of saturation in the sand foundation shows few significant variations, and the desaturated region moves upward while the overall shape is basically unchanged, which suggests that the main direction of the gas migration is vertical with virtually no horizontal movement after the completion of electrolysis. In this test, the variations in the saturation of the foundation during and after electrolysis are quite similar to the numerical simulation results performed by Okamura (Okamura et al. 2011) for the air injection treatment of a saturated sand foundation. Figure 10 presents the simulation results of the saturation

distribution during and after air injection, where the gas migration and uplift are idealized due to the homogeneity of the soil layer. There was no ground settlement observed at the site before or after electrolysis, the same as in the field test with the air injection method (Okamura et al. 2011). Research conducted by Okamura (Okamura et al. 2003, 2006) on the stability of air trapped in sand compaction piles reveals that air in the gravel layer could remain stable for decades, whereas air in the sand layer tends to be more active. Six days after the electrolysis is halted, the average resistivity change in the measurement volume decreases from 19% to 17%; i.e., the degree of saturation goes back up from 83% to 85%, demonstrating the durability of the electrolytic desaturation method (at least in the short term). Model tests of the electrolysis desaturation method showed that the bubbles produced by electrolysis remained stable in the sand sample of a shear box for 442 days (Yegian et al. 2007), but the sustainability of the electrolytic desaturation method in practical engineering applications still requires further investigation.

Resistivity Changes Under Different Test Conditions

After one test condition is completed, water is continuously pumped into boreholes No. 1 to No. 10 until the resistivity measured at each measurement point is basically the same as the initial resistivity, and when the resistivity in the foundation remains virtually constant for a period of time after the water flow stops, the site is considered to be restored to the original saturated state. The saturation of the soil in the foundation is maintained at over 75%, thus the saturated-unsaturated cycles within the site has minimal impact on the characteristics of the soil (Malaya and Sreedeeep 2012). The temporal curves of the resistivity change at different depths (GL-10 m, GL-15 m and GL-20 m) in boreholes A, B and C under different conditions are shown in Figure 11. The distribution regularity of the resistivity change is similar under different test conditions, which proves the correctness of the gas migration pattern before and after electrolysis proposed in the previous section. The peak values of resistivity change at the end of electrolysis in conditions I_{1A-1m} , I_{2A-1m} and I_{3A-1m} are 24%, 33% and 37%, respectively, illustrating that the degrees of saturation at the corresponding locations reduce to 79%, 73%, and 71%, while the lowest values of resistivity change are 8%, 10% and 12%, reflecting degrees of saturation of 93%, 91% and 90%. After electrolysis is halted for 144 h, the

maximum values of resistivity change in conditions I_{1A-1m} , I_{2A-1m} and I_{3A-1m} are 17%, 33% and 29%, respectively, implying that the degrees of saturation would be 85%, 73% and 76%. The minimum values of resistivity change are 7%, 5% and 7%; thus, the degrees of saturation are 94%, 95% and 94%, respectively. It is illustrated that when a greater current intensity is applied, a poorer uniformity in the distribution of foundation saturation is achieved. The gas pressure increases rapidly due to the higher current, which may disturb the pore structure of the sand to some extent (Zeybek and Madabhushi 2017a), resulting in nonuniformity of the saturation distribution of the foundation. The peak values of resistivity change at the end of electrolysis in conditions I_{3A-1m} and I_{3A-3m} are 37% and 19%, respectively, illustrating that the degrees of saturation at the corresponding locations reduce to 71% and 83%, while the lowest values of resistivity change are 12% and 6%, reflecting degrees of saturation of 90% and 95%. After electrolysis is halted for 144 h, the maximum values of resistivity change in conditions I_{3A-1m} and I_{3A-3m} are 29% and 15%, respectively, implying that the degrees of saturation would be 76% and 86%. The minimum values of resistivity change are 7% and 4%; thus, the degrees of saturation are 94% and 96%, respectively. Increasing the electrode spacing significantly improves the uniformity of the desaturation treatment effect on the target volume, mainly due to the increase in the actual distance from the electrode to the resistivity monitoring instrument. It is reasonable to speculate that in the region closer to the electrodes, test I_{3A-3m} exhibits an inhomogeneous distribution of saturation similar to that of test I_{3A-1m} , but this at least proves that the electrolytic desaturation method with increased electrode spacing is still effective.

The temporal curve of the average value of the resistivity change in the resistivity monitoring volume is given in Figure 12. During electrolysis, the average value of resistivity change increases at a greater rate as the current increases, but also leads to a significant decrease in the rate at the final stage of electrolysis. This phenomenon is also present in condition I_{3A-3m} , which illustrates that prolonged high current energization does not bring about an unrestricted reduction in the saturation in the foundation. Eventually, the efficiency of desaturation will be greatly reduced due to the airflow channels formed in the foundation that connect to atmospheric pressure (Reddy and Adams

2000). After stopping the electrolysis, the average value of the resistivity change under each condition decays, and the magnitude of the decay improves as the current increases. Although a large current is employed in condition I_{3A-3m} , the distance of the electrodes from the resistivity monitoring instrument causes better stability of the gas. Before and after the completion of the electrolysis, the peak values for the average of the resistivity change in conditions I_{1A-1m} , I_{2A-1m} , I_{3A-1m} , and I_{3A-3m} are 14%, 19%, 22%, and 11%, respectively, which correspond to degrees of saturation of 87%, 83%, 80%, and 90%. In contrast, after 144 h, the average values of the resistivity change in these four conditions become 11%, 17%, 14%, and 9%, which represent that the degrees of saturation are back up to 90%, 85%, 87%, and 92%.

According to several studies (Okamura and Teraoka 2005, Bian and Shahrour 2009, Hossain et al. 2013, O'Donnell and Kavazanjian 2018, Mele and Flora 2019) on the *LRR* of sand samples with different degrees of saturation, a relationship to account for the increase in cyclic strength of sand with the change in degree of saturation, as:

$$LRR = \log (6500\varepsilon_v + 10) \quad (5)$$

where LRR = liquefaction resistance ratio, which is defined as the strength of unsaturated sand normalized with respect to that of fully saturated sand; and ε_v = potential volumetric strain, which is calculated as:

$$\varepsilon_v = \sigma'_c(p_0 + \sigma'_c)^{-1}(1 - S_r)e(1 + e)^{-1} \quad (6)$$

where p_0 = absolute pressure of the pore fluid; σ'_c = initial effective confining pressure; and e = initial void ratio. Since none of the other factors except saturation changes before and after electrolysis, the peak and residual *LRR* calculated by formula (5) and (6) under different conditions are plotted in Figure 13. The peak value of the liquefaction strength ratio increases with the application of greater current intensities, but the residual liquefaction strength ratio after 144 h is significantly weakened due to the poor stability of a high current. Therefore, when treating liquefiable foundations by the electrolytic desaturation method in practice, there exists an optimum value (2A in this tests) of the selected constant current magnitude to provide the highest liquefaction

resistance in the foundation after a period of time.

Water Level Changes Under Different Test Conditions

The variations in the water level around the electrode before and after electrolysis are monitored by using boreholes No. 5 to No. 10, with boreholes No. 6, No. 8, and No. 10 for conditions I_{1A-1m} , I_{2A-1m} , and I_{3A-1m} and boreholes No. 5, No. 7, and No. 9 for condition I_{3A-3m} , so the distance from the water level monitoring boreholes to the single electrode was the same for each condition. By subtracting the normal water level from the monitored value, the water level change solely from electrolysis could be obtained. The timescale curve of the water level change due to electrolysis is illustrated in Figure 14. During the electrolysis proceeds, the water level gradually rises, and the rate of water level rise decreases significantly as the distance from the electrode increases. Furthermore, the rate of water level rise increases when a higher current is applied, but the rate slowed down or even decreases after 8 h of electrolysis. The variation of the water level is agreement with that of the resistivity change, it means that the gas produced by electrolysis is the direct cause of the water level rise around the electrode, which is verified in the slope model test employing air injection (Xie et al. 2018a). After the end of electrolysis, the water level progressively recovers due to the openness of the site boundary and presence of seepage, and the rate of recuperation is related to the degree of saturation in the foundation. The reduction in the degree of saturation leads to a decrease in the permeability coefficient of the soil near the electrodes, which causes a redistribution of the saturation line, raising the steady water level near the electrodes (Xie et al. 2020).

Electricity Consumption Under Different Test Conditions

By recording the voltage varying across the electrodes during energization, the temporal curves of the equivalent resistance and power under different conditions are given in Figure 15. During the electrolysis process, the resistance of the electrodes remains essentially unchanged, while the resistance of the foundation between the electrodes increases because of the reduction in saturation, so the variation patterns of the equivalent resistance also reflect the evolution of the saturation in the foundation, and the equivalent resistance can also be taken as an effective parameter to measure

the overall saturation of the foundation. Conventional foundation treatment methods are usually more expensive than the desaturation methods, the cost of sand compaction piles is about USD 35/m³ (Liao et al. 2012), while the cost of electrolysis desaturation method in this study is only about USD 5/m³. The electrolysis desaturation method offers economic advantages in repeated foundation treatments. The maximum electricity consumption for 12 h electrolysis is 8.98 kW·h by integrating the power curve under condition I_{3A-3m} , and the cost is almost negligible. Therefore, it demonstrates that electrolysis desaturation method has excellent economic benefits in the treatment of saturated sand foundation.

Conclusions

In this study, field tests of the electrolytic desaturation method were performed to study the effectiveness and gas diffusion patterns of the method. The following conclusions were obtained from the tests conducted under four conditions.

1. Electrolytic desaturation treatment of saturated sand foundations was carried out for 12h using 12 m-long EKG electrode plates with spacing of 1 m. At constant currents of 1 A, 2 A and 3 A, the average saturation of the measured volume reached 87%, 83% and 80%. With the constant current of 1 A and the electrode spacing of 3 m, the average saturation rose to 90%.
2. During the electrolysis process, the generated gas migrates vertically and horizontally under the influence of buoyancy and gas pressure. After the end of electrolysis, the gas inside the sand foundation basically migrates vertically only.
3. A higher current intensity employed for electrolysis will lead to a reduction in the uniformity and stability of the gas in the foundation. At constant currents of 1 A, 2 A and 3 A, the difference between the maximum and minimum degree of saturation in the measured volume was 14%, 18% and 19%. And after electrolysis halted for 144 h, the average saturation in the measured volume was 90%, 85% and 87%.
4. Increasing the electrode spacing improves the gas uniformity and stability of the desaturation target volume, but reduces the desaturation effect. At electrode spacing of 1 m and 3 m, the

difference between the maximum and minimum degree of saturation in the measured volume was 19% and 12%. And after electrolysis halted for 144 h, the average saturation in the measured volume was 87% and 92%.

5. The maximum electricity consumption for 12 h electrolysis is 8.98 kW·h (3 A of constant current, 3 m of electrode spacing), which proves that the electrolysis desaturation method is cost-effective for repeated anti-liquefaction treatment of foundations.

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Table 1. Physical properties of the soil layers

Soil layer	Natural void ratio	Vertical permeability coefficient (10^{-6} cm/s)	Horizontal permeability coefficient (10^{-6} cm/s)	SPT N-value	CPT static point resistance (MPa)
Soft Clay	1.193	2.01	3.39	3.1	0.66
Sand 1-1	0.802	4990.00	5420.00	11.2	6.34
Sand 1-2	0.755	4350.00	5050.00	12.0	7.56
Silt	0.597	36.60	52.30	13.8	2.55

Table 2. Summary of the test conditions

Test number	Constant current (A)	Electrode distance (m)	Electrolysis time (h)	Electrode length (m)
I _{1A-1m}	1	1	12	12
I _{2A-1m}	2	1		
I _{3A-1m}	3	1		
I _{3A-3m}	3	3		

Figure Captions

Figure 1. (a) The locations of the boreholes; (b) the photo of the test site

Figure 2. (a) Soil profile of the test site; (b) grain-size distribution of sand

Figure 3. Schematic of the electrode arrangement method

Figure 4. Relationship between saturation degree and resistivity change of in situ sand samples

Figure 5. Schematic of the resistivity monitoring instrument

Figure 6. The equivalent resistance of EKG electrodes with: (a) different distances between electrodes; (b) different lengths of electrodes

Figure 7. Temporal curves of the resistivity change under test I_{2A-1m} : (a) depth of 10 m; (b) depth of 15 m; (c) depth of 20 m

Figure 8. 2D image of the resistivity change during the 12 h electrolysis process

Figure 9. 2D image of the resistivity change after electrolysis was ceased

Figure 10. Change in the degree of saturation during and after air injection (Okamura et al. 2011): (a) 162 h of conducting air injection; (b) 7 days after air injection was halted

Figure 11. Temporal curves of the resistivity change under different test conditions: (a) A-depth of 10 m; (b) B-depth of 10 m; (c) C-depth of 10 m; (d) A-depth of 15 m; (e) B-depth of 15 m; (f) C-depth of 15 m; (g) A-depth of 20 m; (h) B-depth of 20 m; (i) C-depth of 20 m

Figure 12. Temporal curves of the average resistivity change under different test conditions

Figure 13. Liquefaction strength ratio under different test conditions

Figure 14. Temporal curves of the water level changes under different test conditions: (a) 1 m from the electrode; (b) 2 m from the electrode; (c) 3 m from the electrode

Figure 15. Temporal curves of the equivalent resistance and power under different test conditions:

(a) equivalent resistance; (b) power

Draft

(a)

(b)

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(a)

(b)

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