Liquefaction Mitigation Using Air Injection

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ABSTRACT

Soils most susceptible to liquefaction are loose, non-plastic and saturated. Because the compressibility of air is orders of magnitude greater than the compressibility of water, un-saturation or partial saturation can significantly increase the liquefaction resistance of a soil deposit. Nakazawa et al. (2004) have shown that cyclic strength in laboratory test specimens can be more than twice as high in partially saturated soil than fully saturated soil. It is hypothesized that sufficient de-saturation to increase the liquefaction resistance can be induced by injecting air or gas into the subsurface. Simple, qualitative shake-table experiments demonstrate the increase in liquefaction resistance as a result of de-saturation from air injection. Air sparging is a widely used environmental remediation method that involves the continuous injection of air into soil to promote volatilization of contaminants. This method can be readily adapted for use as a liquefaction mitigation technique. Although air sparging relies on a continuous flow of gas, Okamura et al. (2006) present data that indicate de-saturation from air injection can last for years or more after an initial, short-term injection period. In summary, intermittent or periodic air injection over the life of a structure may be useful in increasing the liquefaction resistance. This method would be particularly well suited for the protection of existing structures founded on soils susceptible to liquefaction.

INTRODUCTION

Liquefaction is a frequent problem that must be addressed by geotechnical engineers working in areas with moderate to high seismic hazards. Since the mid 1960s, a substantial portion of geotechnical research has been devoted to this topic and our understanding of the phenomena has improved dramatically over the last 30 to 40 years. Youd et al. (2001) and more recently, Idriss & Boulanger (2008) provide a thorough treatment of the evaluation of liquefaction triggering. If an evaluation indicates that liquefaction is likely and if its consequences are deemed unacceptable, there are numerous alternatives for mitigation of the risk. The liquefiable strata can be bypassed with an appropriately designed deep foundation system or one of many ground improvement methods (Elias et al. 2001) can be implemented to modify the liquefiable strata. The methods generally work by densifying, reinforcing/strengthening, or improving the drainage of the liquefiable soils. The deep foundation or ground improvement approaches are valid and economical for new construction but existing structures present special challenges.

Because much of the building stock in the US and elsewhere was constructed well before the recognition of the potential problems that liquefaction can cause, many structures are at risk of significant damage or catastrophic failure during an earthquake. Modifications can often be made to improve the structural performance of an existing structure but liquefaction mitigation options are limited (Andrus and Chung 1995). Access to the foundation soils is very problematic and many of the mitigation methods would induce displacements that would damage the structure even if access can be gained. In general, some form of grouting (e.g., compaction, permeation, jet, etc.) is currently the most feasible means of mitigating liquefaction beneath existing structures. The grout can be injected through relatively small diameter drill holes, which can be installed from within the interior of a structure. However, the cost of such mitigation is often very high.

A mitigation method that may provide a more economical option is de-saturation of the liquefiable strata using air injection. As currently envisioned, the method would be feasible for structures with very limited access and since air rather than grout would be injected, the costs should be substantially lower.

INFLUENCE OF PARTIAL SATURATION ON LIQUEFACTION RESISTANCE

Because the bulk modulus of water is four orders of magnitude greater than the bulk modulus of air, the fluid modulus will decrease dramatically with the addition of a very small volume of air (Santamarina et al. 2001). Accordingly, the behavior of a soil that is fully saturated will be markedly different from one that is partially saturated. Since liquefaction is due to an increase in pore pressure caused by cyclic loading, it seems logical that the cushioning effect of air in an unsaturated soil would decrease the buildup of excess pore pressure and thereby increase a soil's liquefaction resistance. Numerous researchers (Ishihara et al. 1998, Grozic et al. 2000, Tsukamoto et al. 2002, Nakazawa et al. 2004, Yang et al. 2004, Okamura et al. 2006, Yegian et al. 2007) have evaluated the influence of the degree of saturation, S_r, on liquefaction resistance and liquefaction resistance does increase with a decrease in the degree of saturation.

Grozic et al. (2000) performed cyclic triaxial testing on sands with S_r of 75% to 99% and found that the presence of the gas increased the cyclic resistance by 200% to 300% when compared to fully saturated samples. Yegian et al. (2007) designed and manufactured a flexible liquefaction box that permitted the application of cyclic simple shear strains in large loose sand specimens using a shaking table. Specimens were tested at with S_r of 84.2% to 99.7%. They found that a decrease in the degree of saturation by 3% prevented the onset of liquefaction in their testing. Okamura et al. (2006) performed undrained cyclic shear tests on undisturbed samples collected with ground freezing. The samples were tested at a range of saturations – from fully saturated to S_r = 70%. The liquefaction resistance of the partially saturated samples was as much as twice that of the fully saturated samples.

Several researchers have related body wave velocity to the degree of saturation and liquefaction resistance. The compression wave velocity of water is 1480 m/s and the compression wave velocity of a fully saturated soil is about 1500 m/s. The compression wave velocity, V_p, of a soil will decrease significantly as the degree of saturation decreases and it is possible to relate V_p, S_r and B (Skempton's pore pressure parameter).

Ishihara et al. (1998) performed laboratory tests on sand specimens with saturation of 97 to 100%. They measured V_p and cyclic resistance and observed that the cyclic strength increased approximately 150% as the saturation decreased from 100% to 96%. The corresponding reduction of Skempton's B parameter was from 0.95 to 0.15 and V_p dropped from 1600 m/sec to 500 m/sec. A relationship between V_p and cyclic resistance ratio (CRR_{ps}) was developed and normalized to the cyclic resistance ratio of a fully saturated specimen (CRR_{fs}) with V_p = 1600 m/s. Tabulated summary is presented in Table 1. They suggested that the relationship be used to correct the cyclic resistance obtained using the "simplified procedure" (e.g., Youd et al. 2001) when the soil strata is not fully saturated.

Table 1. Cyclic resistance correction values for unsaturated soils based on compression wave velocity (adapted from Ishihara et al. 1998)

V_p (m/s)	$(CRR)_{ps}/(CRR)_{fs}$
400	2.05
600	1.35
800	1.25
1000	1.15
1200	1.10
1400	1.05
1600	1.00

Similar methodologies were used by Tsukamoto et al. (2002), Nakazawa et al. (2004), and Yang et al. (2004). Testing was performed on undisturbed specimens as well as reconstituted specimens and all researchers observed a considerable increase in liquefaction resistance as the degree of saturation decreases. This is illustrated in Fig. 1, which relates the ratio of the strength of the partially saturated specimens to fully saturated specimens to the compression wave velocity, as developed by Nakazawa et al. (2004).

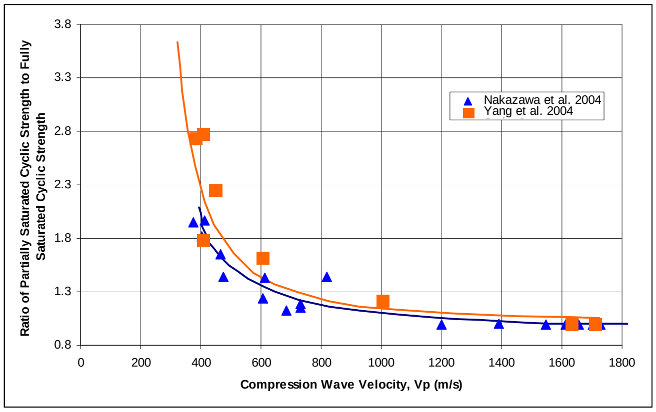

Fig. 1 Normalized cyclic resistance as a function of compression wave velocity (adapted from Nakazawa et al. 2004 and Yang et al. 2004)

Yang et al. (2004) also suggests the use of compression-wave velocity for an efficient characterization of saturation effects on the liquefaction strength of sand. Using four series of cyclic stress data from previously done laboratory tests, normalized liquefaction strength $(CSR)_{ps}/(CSR)_{fs}$ values were plotted against Skempton's pore pressure parameter, B. They then suggested the following empirical correlation:

$$(CSR)_{ps}=(CSR)_{fs}\, e^{[0.710(1.0-B)]} \quad (1)$$

Using a theoretical relation between B and V_p, Yang et al. (2004) established a correlation between liquefaction strength of sand and its compression-wave velocity. As shown in Fig. 1, their relationship indicates a slightly greater increase in liquefaction resistance as the degree of saturation decreases as compared to the work of Nakazawa et al. (2004).

DE-SATURATION METHODS

It is clear from the preceding discussion that partial saturation is very beneficial with respect to increasing liquefaction resistance. Many soils below the groundwater table are naturally unsaturated due to groundwater fluctuations and/or the natural generation of gasses in some geologies. In fact, Ishihara et al. (1998), Nakazawa et al (2004), Tsukamota et al. (2002) and Yang et al. (2004) worked with naturally unsaturated soils sampled below the groundwater table. Of particular interest with respect to liquefaction mitigation is how saturated soils can be de-saturated in situ.

One objective of Yegian et al. (2007) was to evaluate de-saturation methods. They investigated two approaches: electrolysis and drainage-recharge. For electrolysis, they installed an anode and cathode in their flexible liquefaction box. Both electrodes consisted of a titanium-coated, mixed metal oxide mesh. One, which served as the cathode, was located at the bottom of the box and the other was located at the top. The process generated hydrogen bubbles at the cathode which migrated upwards through the soil to the anode at the top of the specimen. A degree of saturation of 96.3% was obtained when they used this method. They also induced de-saturation by slowly draining the water out of the specimen from the bottom of the liquefaction box and then re-introducing it into the specimen from the top, a process they termed the drainage-recharge method. Air was trapped in the void space during the recharge phase and a degree of saturation of about 86% was obtained using this approach.

The unsaturated samples that Okamura et al. (2006) worked with were de-saturated in situ prior to sampling. At each of their research sites, the Sand Compaction Pile (SCP) ground improvement method had been used to reduce the liquefaction susceptibility. The principal objective of the SCP method is to densify the target strata by the addition of compacted sand via delivery through a downhole casing. The pushed or driven casing is repeatedly withdrawn and then re-penetrated to create compacted sand elements that densify the surrounding soil. Compressed air is used as an aid in the delivery of the sand to the bottom of the casing. Okamura et al. (2006) reported that during the SCP process, air "continuously spouted" from the ground surface within a several meter radius of the SCP casing location. Subsequent ground freezing and undisturbed sampling, as well as measurement of compression wave velocity, indicate that the SCP process does de-saturate both the sand fill and the treated soils. Many of their samples had a degree of saturation of 90% or less, indicating that the downhole introduction of compressed air was quite effective at causing de-saturation.

As with many of the currently available ground improvement methods, SCP is not a viable option for mitigation of soils beneath an existing structure but the results do indicate that air injection may be a feasible approach to de-saturation. As presented below, air injection or air sparging has been used in the environmental community for decades and much of the resulting experience is relevant with respect to using such a technique for liquefaction mitigation.

Air Sparging

Air sparging is a commonly used in situ environmental treatment technology that was introduced in about 1985 (Suthersan 1999). The process involves the injection of air below the water table, the purpose of which is to promote volatilization of contaminants like solvents or gasoline. It can also be used to stimulate microbial activity to remove less volatile contaminants such as diesel or jet fuel. The process is covered in detail in Battelle (2001), EPA (2004), Suthersan (1999) and US Army Corps of Engineers (1997). A review of these documents indicates the design process is mainly empirical or dependent on the performance of pilot test programs. In general, the method is best suited for sites with sandy soils having hydraulic conductivities of 10^{-4} or 10^{-3} cm/s or greater and is typically used at depths of less than 10 to 20 m.

A depiction of a typical system is shown in Fig. 2.

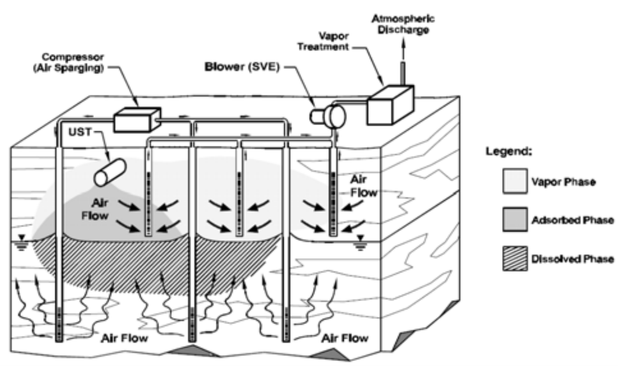

Fig. 2 Schematic representation of a typical air sparging operation (from EPA 2004)

As illustrated in Fig. 2, compressed air is introduced through an injection well (or sparge well) which is generally 25 mm to 100 mm diameter PVC pipe with a 0.3 to 0.6 m long slotted screen at the bottom. The location of the screen is usually 1.5 to 3 m below the area that is to be treated. The injection wells are typically spaced about 4.5 to 6 m apart. This spacing is consistent with the observations reported by Okamura et al. (2004) indicating that air bubbles were apparent several meters from the point of injection. The injection wells may be vertical or horizontal. Use of horizontal wells obviously requires direction drilling technologies or trenching.

The applied air pressure must be sufficient to displace the water in the injection well (i.e., greater than the hydrostatic water pressure), to overcome the air-entry pressure of the well screen and packing, and to overcome the air-entry pressure of the soil but it must not be so high as to cause fracturing. For sandy sites, air pressure is generally between 70 to 100 kPa with flow rates ranging from about 140 to 700 liters per minute (5 to 25 cubic feet per minute). The air is typically injected in a pulsed manner (e.g., 3 hrs on then 3 hrs off) rather than continuously. A higher flow rate improves the resulting air distribution but increases the compressor requirements. Intermediate layers of lower permeability (e.g., silts and clays) may limit its effectiveness.

An important objective with respect to the design of an air sparging system is to make sure the air is uniformly distributed throughout the zone requiring treatment. This would be true for the use of air injection for liquefaction mitigation as well. The injection well spacing of about 4.5 to 6 m has been found to be generally effective for environmental remediation and would presumably be appropriate for liquefaction mitigation. And as noted above, a higher flow rate improves the air distribution. For air sparging to be effective, air must be continuously or frequently introduced so that volatilization will continue. Liquefaction mitigation would not need a continuous or near continuous air supply so the increased air compressor requirement needed to achieve a higher flow rate (and thereby better air distribution) would not be a significant disadvantage. Adoption of air sparging methods for liquefaction mitigation appears to be feasible and major obstacles are not obviously apparent.

EXPERIMENTAL TESTING TO EVALUATE EFFECTIVENESS OF AIR INJECTION

To evaluate the effectiveness of in situ air injection as a liquefaction mitigation method, a series of simple, qualitative shake table tests were performed. The schematic of the testing apparatus is provided in Fig. 3.

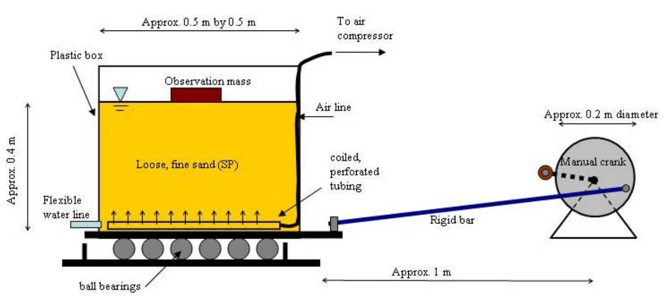

Fig. 3 Schematic representation of shake table testing

The test container consisted of a rigid plastic cubical box with side dimensions of approximately 0.5 m. The box was attached to a rigid base which could freely roll on ball bearings. One end of a rigid bar was attached to the base plate and the other end was attached to a rotating drum at an approximately 100 mm offset from the axis of rotation. A loosely coiled perforated air hose (6 mm diameter) was fixed to the base of the container. The air hose was attached to a small air compressor. The base of the container also included a coiled, 12 mm diameter, perforated plastic tube that could be connected to a water supply.

A poorly graded fine sand was placed in the container using wet pluviation. An approximately 15 N rectangular weight was placed on the surface of the sand as an indicator of strength loss and cyclic loading was induced by manually turning the rotating drum. Three series of tests were performed: 1) a control series without air injection, 2) a series with 1 minute of air injection prior to the loading, and 3) a series with air injection prior to and during the loading. Four or five tests were performed for each series. Between each series, the sand was removed and replaced using wet pluviation. Between each test, the sand was subjected to an upward gradient by applying a head through the perforated tubing at the base of the container. The upward gradient served to re-saturate the sand and to return the sand to a very loose state following the cyclic loading.

During each test, cyclic loading was applied until the sand specimen could no longer support the 15 N weight or until 50 cycles had been applied, whichever occurred first. For the two test series that included air injection, an air pressure of 35 kPa was applied. When the air was introduced, bubbling was observed on the surface of the sand specimen and a layer of water developed on the surface without any change in the height of the sand, indicating that de-saturation had occurred. The water layer on the surface was removed prior to shaking. The results of the testing are summarized in Fig. 4.

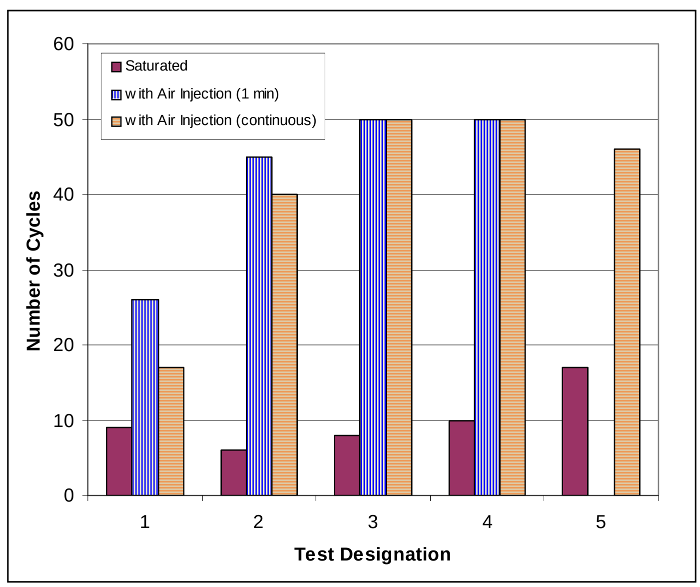

Fig. 4 Number of cycles to cause liquefaction with and without air injection. Tests were terminated after 50 cycles if liquefaction had not yet occurred.

Although the testing was rather crude, it is apparent that de-saturation by air injection substantially increased the liquefaction resistance. On average, when air injection was used, the specimens withstood more than 4 times the number of cycles without liquefying as compared to the untreated, fully saturated specimens. Although the degree of saturation was not determined, these results are generally consistent with the findings of other researchers. In particular, the lack liquefaction triggering is similar to the findings of Yegian et al. (2007), whose work also involved targeted de-saturation.

LONGEVITY OF INDUCED DE-SATURATION

Another important consideration is the longevity of the induced de-saturation. If the injected air diffuses or escapes in a short period of time (e.g., weeks or months), the method will be of little use with respect to liquefaction mitigation. This issue has been addressed by Okamura et al. (2006) and Yegian et al. (2007. Yegian et al. (2007) have monitored the degree of saturation in a sample with induced partial saturation using their drainage-recharge method. They report that after 442 days, the degree of saturation had increased from 82.9% to 83.9% and that nearly all of this increase occurred within the first few days after the initial de-saturation.

Okamura et al. (2006) collected samples or measured compression wave velocities at SCP sites at various times after completion of the ground improvement. The time between the completion of ground improvement and their undisturbed sampling or testing ranged from several years to as much as 26 years. They report that the degree of saturation does appear to increase with time but not significantly. Their results indicate that the increase was roughly about 5%, but the starting degree of saturation after SCP installation was generally in the range of 70% to 90%. Therefore, the long-term degree of saturation was still low enough to significantly increase the liquefaction resistance.

SUMMARY AND CONCLUSIONS

Liquefaction is a common challenge in the practice of geotechnical earthquake engineering. In particular, it presents significant difficulties when considering the protection of existing structures. Viable ground improvement methods to mitigate liquefaction risks for existing structures are limited and costly. Air injection to induce de-saturation appears to be a promising alternative.

Various researchers have documented the relationship between an increased liquefaction resistance and a decrease in the degree of saturation. A de-saturation of only a few percent may be sufficient to sufficiently reduce the liquefaction risk. Air injection methods that have been used for decades in the environmental community appear to be readily adaptable to inducing this magnitude of de-saturation. More specifically, as currently envisioned, small diameter (i.e., 25 mm or less) air injection pipes could be installed within a building's footprint. The installation of pipes of this size within the interior of a building is feasible with readily available equipment. Additionally, with directional drilling methods, interior work could possibly be avoided entirely. Assuming the experience from the environmental community is applicable, the spacing between the injection pipes would probably be on the order of 5 m. Furthermore, unlike the environmental application of air sparging, a single short-term air injection period would probably be sufficient for liquefaction mitigation.

However, additional research is necessary to confirm the feasibility of air injection as a liquefaction mitigation method. There are two significant questions that still must be answered. First, since the method is based on de-saturation increasing the liquefaction resistance, the resulting distribution of air voids around an injection well should be examined. Are there smaller zones of de-saturation surrounded by larger zones of saturated soil? In fine to medium sands, air sparging is known to create channels of air flow as opposed to uniformly distributed bubbles (Suthersan 1999). When the air flow is terminated, the channels will close resulting in trapped air bubbles. Are these channels and resulting bubble remnants sufficiently distributed such that the soil is appropriately represented as de-saturated? Second, since the method would be very attractive for mitigation beneath existing structures, it will be important to confirm that the degree of de-saturation does not change the compressibility of the soils. The method will be of little use for seismic retrofitting if the process of de-saturation induces intolerable displacements. Since the required degree of de-saturation is small, it is not likely that the compressibility of the soil will be significantly altered but this must be confirmed.

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