Dry-air technology for stabilizing weak deposits

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ABSTRACT

Many of the ground improvement techniques available in the market are effective but equally they release a large amount of CO_2 into the atmosphere. Therefore, any green-ground improvement technique can be considered as a sustainable construction technology in the modern world. The work presented in this article uses dry-air supplied at a low pressure and relative humidity to remove water from a soft soil deposit. The investigation was carried out in a form of model study in which a soft soil layer was formed in a box having a size 1.0 × 1.0 × 0.75m. The soil bed was included with slender granular columns to inject the dry-air at a low humidity. The technique adopted here is a reverse process to the vacuum consolidation. In the vacuum consolidation technique, the magnitude of negative pore water pressure that can be applied to the soil is limited, abating the fact that it requires careful construction procedures. The approach adopted here is simple and does not require any complex construction procedures. The investigations carried out in a limited period have shown a significant improvement in the strength of the soil bed, leading to a possible way forward for a full-scale implementation. An implementation of this technique at a full-scale may not require any new construction methods as the procedure is very similar to that adopted in vacuum consolidation technique. However, variabilities in the ground conditions including the ground water table may pose additional challenges. Supplementary information in the form of soil-water characteristic data combined with numerical modelling may be necessary to implement this technique at a full-scale level in a readily manner.

KEYWORDS: clays; permeability; partial saturation; pore pressures; suction

INTRODUCTION

Infrastructure developments on marginal lands have become common in recent years. The marginal lands include the sites with poor ground conditions in terms of geotechnical characteristics and these conditions are globally widespread. Therefore, the challenge presented to the construction industry today is to meet the demand for continued infrastructure developments on these difficult ground conditions while ensuring that the constructions are carried out within safe design limits with respect to both bearing capacity and settlement, while considering limiting excessive emissions of CO_2 into the atmosphere (Shillaber e*t al.,* 2016). There are many ground improvement techniques available in the construction sector as reported by Mitchell and Jardine (2002) and the selection of which technique to use in a particular site depends on various factors: (a) the design requirements such as bearing capacity and settlement, (b) site accessibility and (c) CO_2 emissions. Sustainability is a growing issue in the world, particularly in the construction industry. A direct solution for construction on weak deposits is (or has had been generally in the past) piling. However, in this application, 92% of the CO_2 emission emerges from the cost of material (i.e., concrete) (Lemaignan and Wilmotte 2014). Therefore, any effective (both cost and performance) and net zero CO_2 construction techniques can be seen as “opportunity for meeting global warming targets by 2050”. Deep soil mixing and grouting are the most effective ground improvement techniques. However, these methods are relatively expensive and the production of additives such as cement or lime will inevitably contribute to CO_2 emissions. On other hand, vibro-columns are also popular among contractors as the process is relatively quick, however the extraction of quality granular backfill material will lead to some level of CO_2 emissions (Hughes and Withers, 1974; Watts *et al.,* 2000; Serridge, 2016). In addition, this method is only suitable for low-to-moderate loading and the potential improvement with respect to settlement control is limited (Sivakumar *et al.,* 2021, McCabe, 2009).

The key requirement to improve the geotechnical characteristics of weak deposits is to activate the removal of some water from the void spaces. This process is explicitly done in de-watering-process. However, this method may not be suitable in case of fine soils. In these soils, vacuum consolidation can be employed to reduce the water content (Chu *et al.*, 2014; and Chai, 2005). The process involves by installing a series of vertical drains through the soil and a seal over the area being treated. Subsequently, the vacuum is applied to the top blanket layer to reduce the pore water pressure in the deposit. The process will in effect increase the effective stress in the ground (Chu *et al.*, 2000; Mitchell and Jardine, 2002; Griffin and O'Kelly, 2014; Rujikiatkamjorn and Indraratna, 2013; Marques and Leroueil, 2015). The maximum vacuum that can be applied on the site is about 60-75 kPa (Long *et al.,* 2015). The work reported in this article explores a possibility of pumping dry-air (low humidity) into a soft deposit at a small positive pressure, using similar but less complex construction process than that adopted in the vacuum consolidation method. Using the dry-air technique, any value of negative pore water pressure can be achieved in the deposit depending on the duration of the treatment process. This approach has been examined by Martini *et al.* (2020) that proved to be feasible in enhancing the strength and stiffness of a tunnel lining.

EXPERIMENTAL WORK

The approach reported in this article uses typical compressed air supply line, circulated through a salt chamber to ensure a very low humidity, to generate suction (or negative pore water pressure) in soils. Typical compressors supply air at a very low humidity to prevent any damages to mechanical components due to corrosion and build-up of residues. However, due to contaminations and other reasons, the humidity of the air from the compressor can be much higher than the stipulated values and therefore the purpose of using NaCl in the present investigation was to reduce any small amount of vapour that may be present in the compressed air system. The approach was adopted in several research programmes undertaken at the Queen's University of Belfast for different purposes using different configurations. Lynch *et al.* (2018) and Pandey *et al.* (2020) established water retention curves and permeabilities of unsaturated soils. These investigations have prompted for a further investigation on the subject to improve the geotechnical characteristics of soft soil using a large-scale model study involving measurements of suction and water content.

Test-bed preparation and instrumentation

The investigation was carried out in a large box (1.0 m ×1.0m (plan) × 0.75 m height) containing a soft deposit. The box was made of water-proof plywood and braced extensively to limit the deformation of the side wall under the lateral thrust from the soil mass (Figure 1). The soil used in this investigation was classified as soft gravelly sandy silty CLAY. The liquid limit and plastic limit of the soil were 49 and 25% respectively.

The ground improvement using the vacuum consolidation requires an application of a vacuum through pre-formed granular columns in the deposit and in some cases, it is carried out in conjunction with some preloading. The approach adopted here took the same strand, but instead of a vacuum, a positive air pressure at low humidity (referred to as dry-air) was pumped into the soil. In order to pre-form the slender granular columns, four PVC pipes (60 mm diameter), length about 1 m were positioned as shown in Figure 1. The columns were 0.5 metres away from each other in lateral directions and that they were also 0.25 metres away from the side of the box. The box was then filled with the soil in layers, each having about 0.1m thickness. Each layer was compacted using a heavy steel plate, though no specific procedure was adopted to control the level of compaction, as the soil was saturated and will not response to compaction in terms of increasing bulk density (Figure 2). The soil bed was levelled to the rim of the testing box.

TEROS 21 Soil Water Potential sensors (Figure 3a) and TEROS 11 Soil Moisture sensors (Figure 3b) (METER Group 2017) were used to measure suction and volumetric water content during the period of the investigation. They were installed at different locations and heights in the box, as shown in Figure 4. The water potential and moisture sensors were buried side by side during the formation of the bed at 0.15 and 0.50 m below the top surface. The measurements from these sensors will be referred to as “top” and “middle” respectively.

Once the soil bed was formed, slender granular columns were installed using the following procedure. Firstly 6 mm internal diameter thin plastic tubes were inserted through the PVC piles (Figure 3). A small amount of uniformly graded gravel having particle size of 6.3 mm was poured in the annulus between the PVC and the thin slender plastic tubes. This gravel was gently compacted using a compaction rod. The PVC tube was then lifted by about 100 mm and further gravel was poured into the tube and compacted. This procedure was adopted until the columns were formed to the surface and the PVC tubes were taken-out. At this stage the granular columns were surrounded by soil. Upon the removal of the long PVC tube, a further 60 mm diameter and 100 mm long plastic tubes were inserted around the granular columns at the top to avoid the gravel being dispersed at the surface (Figures 2 and 4).

Natural evaporation of water in the soil was prevented by placing a rubber sheet covering the entire area sealing on the rim of the box except where the granular columns were exposed to the surface (Figure 4). Approximately 4 kPa of overburden pressure was applied on the surface by stacking concrete blocks. The small four plastic tubes emerging from the granular columns were then connected to a common air supply unit. This air supply unit contained standard dry table salt at the bottom and air was circulated above the salt at a pressure approximately 50kPa on the understanding that the air leaving this unit from the top would have a low humidity. The air pressure entering the bottom of each granular column was approximately 9 kPa (measured just above the top of the soil bed, Figure 4). The loss in air-pressure from the salt chamber to the bottom of the column was attributed to long and small tubing used for plumbing purposes.

A settlement gauge was located closest to a mid-point on the testing bed. After the application of surcharge, the test bed was allowed to attain an equilibrium for two weeks before the low humidity air circulation was initiated. The investigation lasted further about 6 weeks during which time settlement, suction and volumetric water content were monitored. At the end of the investigation a thin-walled sample tube (70 mm diameter) was used to extract six samples, two each at the top, middle and bottom. At each horizon, the samples were taken between columns and middle of the test bed. The extracted samples were tested to determine the undrained shear strength, particle size distribution, index properties, and water content.

RESULTS AND DISCUSSION

Suction and volumetric water content

The suction and volumetric water content probes buried at two locations along the depth have yielded very interesting information as shown in Figure 5, where the broken line shows suction at shallow depth (referred to as top, 0.15m below the surface of the bed) and the solid line at a deeper depth (referred to as middle, 0.50 m below the surface of the bed). Since the bed was made from soft clay, there was an accumulation of water at the bottom of the granular columns in the box at the beginning. No attempt was made to measure the depth of it. However, as the dry-air was pumped to the bottom of the column, (Figure 4) it generated some boiling noise which was audible at the beginning of the investigation and soon subdued.

The pore water pressures at both the top and middle were about –9 kPa (Figure 5). It reduced to -25 kPa at the middle, but remained generally unchanged at the top after 490 hours of air circulation. At this time, the pore water pressure at location top reduced significantly to a value of -39 kPa. Since then, the rate at which the pore water pressure changed at the middle location increased significantly, reaching a value of -50 kPa after 600 hours of air circulation. In the meantime, the pore water pressure started to reduce at the top and reaching a value of

-17 kPa. In order to assess and confirm the development of negative pore water pressure in the soil bed was entirely due to the moisture transfer from the soil to the air, the circulation of dry-air was stopped for a period of 24 hours. The observations made in this regard are discussed later in this paper.

Upon the recommencement of the dry-air circulation, the pore water pressure further reduced rapidly with time and reaching a value of -185 kPa at the middle when the investigation was terminated. A similar trend was observed at the top where the pore water pressure reduced to a value of -110 kPa. As observed with the middle suction probe, the suction probe at the top responded in a similar manner whereby the pore water pressure dropped dramatically when it reached a value of -59 kPa. The magnitudes of the reduction in pore water pressures are similar in both probes and a possible reason for this can be attributed to the characteristics of the probes which rely on the water retention characteristic of the fixed-matrix ceramic discs (METER Group 2017). These observations are promising as such a much higher negative pore water pressure can be achieved as opposed to vacuum method where the maximum negative pore water pressure is limited to about 60-70 kPa.

The negative pore water pressure measured at the middle was consistently higher than that measured at the top. The reason for this can be explained using the manner in which the dry-air was circulated. The dry-air was pumped directly to the very bottom of the soil bed using a slender plastic tube. This air percolated through the gravel and exited to the atmosphere (Figure 4). The humidity of the air entering the bottom of the chamber was 29%. It can be expected that the humidity of the circulated air to increase further as it was rising through the annulus of the granular columns and the plastic tubes due to the vapour transfer from the soil to the air. Therefore, it can be expected that the air would have less tendency to attract vapour from the surrounding soil at shallow depths.

The observations as to the variation of the volumetric water contents at two different locations are shown in Figure 6. The volumetric water content at the middle reduced continually throughout the air circulation period (shown in solid line) except during the period when the circulation was stopped for 24 hours. Its magnitude reduced from 0.48 at the beginning to 0.38 at the termination of the investigation. However, the initial volumetric water content of the soil at the top was 0.52 and it reduced slowly to a value 0.50 (shown by broken line) at the time when the investigation was terminated. There are possible reasons for the observed differences.

- Negative pore water pressure at the top was less than at the middle and therefore the relevant reduction in the volumetric water content can be expected to be less at the top than the middle.
- The reliability of the observations from the probes relies on a perfect burial of the probes in the soil bed and the presence of gravel can hinder a perfect installation.
- The post-investigation particle size distribution revealed that the percentages of combined clay, silt and sand fractions were 80, 58 and 67% at top, middle and bottom respectively. It would require a substantial increase in suction in fine-grained soil for a higher reduction in the volumetric water content.

The above observations have clearly indicated a reduction in volumetric water content and an increase in suction due to circulation of a low-humidity air. Similar observations have been reported by Lynch et al. (2019) and Martini and Tarantino (2020) respectively while establishing soil-water characteristic curve and stabilising tunnel lining using dry-air circulation technique.

Settlement

The drop in pore water pressure will lead to settlement of the soil bed. Figure 7 shows the settlement response during the period of dry-air circulation including the resting period of 24 hours. The clay bed settled continuously and reached a settlement of about 14mm at the end of the investigation. As stated above, an attempt was made to confirm if the observed response of the soil bed was entirely due to the dry-air circulation or due to other factors. In order to confirm this, the air circulation was stopped for a period of 24 hours after 4 weeks into the investigation. The effects of it on the settlement is highlighted by a circle in Figure 7 and further zoomed in Figure 8a during the resting time. It is clear that the settlement ceased to take place during this period confirming that the observed response of the bed is entirely due to the dry-air circulation.

Further support for the above is shown in Figures 8b and 8c where pore water pressure and volumetric water contents at two different locations are plotted against time during this resting period. During this period, the pore water pressure read by the probe at the middle begun to increase whereas the opposite prevailed at the top. In the similar manner the volumetric water content at the middle begun to increase and the opposite prevailed at the top. This is only confirming that there were moisture movement from the top of the box to the middle (or even below) due to pore water pressure gradient existed in the soil bed before initiating the resting phase.

Post-treatment testing

The observations above were further validated by carrying out typical laboratory tests on the excavated material. Figure 9 shows the digital image of the uncovered test bed after the investigation. The soil bed vertically compressed about 14mm while a very interesting observation was a clear gap between the soil bed and the supporting wall around the box with an approximate width of 5 mm. The bed was excavated in layers. As part of the initial investigation an attempt was made to determine the strength using laboratory shear Vane. However, it was proved impossible as the strength of the soil exceeded the maximum capacity of Vane along the entire depth (that is, 130 kPa). Therefore, a decision was made to extract samples using thin wall sample tubes at three different depths (Top, Middle and Bottom) and at each level between the granular columns and middle of the test bed. Physical observation of the soil bed appeared to be very fried and crumbly. That made the sampling process difficult, with additional difficulty caused by gravel contents.

Figure 10 shows the stress-strain curve of five samples extracted for undrained shear strength in triaxial cell. The samples were subjected to 50 kPa of confining pressure and sheared under undrained conditions using the procedure recommended by BS1377:1990 7/8. One of the samples was very badly disturbed and not tested. Although the soil bed at the top inherited lower suction than the bottom, the undrained shear strength at top of the bed was noticeably higher than the middle or bottom. The reason for this is the fried nature of the soil and sample disturbances which appeared to be more severe at the bottom than at the top.

Figure 11a shows the undrained shear strength of the soil bed with the depth. The square data points indicate the maximum capacity of the Vane and at none of the locations the Vane yielded a failure strength implying the undrained shear strength of the bed was higher than 130 kPa. The circular data points indicate the undrained shear strength measured in triaxial cell and the blue data points indicate the original undrained shear strength of the bed, based on the identification of the material. Even on the basis of the measured undrained shear strength in triaxial testing, it is interesting to note that the strength of the soil bed has increased significantly, abetting the fact that these samples were fried in nature and badly disturbed. The relevant water content profiles are shown in Figure 11b which also confirmed that dry-air circulation has resulted a reduction in the water content that led to an increased strength and the settlement of the soil bed as discussed earlier.

Interpretation and potential full-scale application

In the current investigation, the dry air was pumped at 9 kPa at the bottom of each column. The exit velocity at the top of the column was approximately 0.33 m/s. No attempt was made to measure the humidity of the air exiting the box. As the air was allowed to exit to the atmosphere, a simple calculation would show that the volume of the air pumped through the system (all four columns) would be 0.93 litres per second. This also allows the air permeability of the granular column to be calculated and its value is approximately 2.4×10^{-2} m/s. This value is in reasonable agreement with the water permeability value of a medium gravel (REFERENCE). The total volume of air circulated through the system at a humidity of 29% at the bottom of the columns (4 numbers) is approximately 33847 m^3 during the course of the investigation. The question is that how much water in vapour form this dry air can attract as it flows through the granular columns. Consider for example, the average conditions that prevail at the middle of the bed; the reduction in the volumetric water content is approximately 0.10 and the total volume of the soil in the model box is approximately 0.563 m^3. Therefore, the amount of water that escaped from the system is approximately 56.3 litres. On other hand, the visual observations have shown that the clay bed shrunk by about 5 mm in lateral directions and about 14 mm in vertical direction. Therefore, the overall volumetric strain is approximately 3.9 % equating to a volume change of 29 litres. This confirms that the soil bed has had undergone desaturation process. It was also evident from the visual observation during the dismantling process that the soil bed was fried and crumbling in nature.

More research will be needed to optimise the design procedure for a potential full-scale application of dry-air technology. There are several variables that may have to be taken into account when considering this technique for imposing negative pore water pressure in the ground (insitu conditions, velocity and relative humidity of air and spacing of the permeable granular columns). Any future work should consider incorporating these factors to optimize a solution using finite element in conjunction with the water retention curve of soil. At this stage it is beyond the scope of this technical note. Also note that there is no requirement to install granular columns to inject air. The injection process can be facilitated using the existing wellproven technology (i.e., wick drains). It is worth noting that equal distribution of dry-air pumped into the soil can be achieved by perforating the injection tube.

CONCLUSION

The present investigations considered the use dry-air to reduce water content of soft soil bed contained in a large box. The soil considered in this investigation is classified as intermediate plasticity clay having certain amount of gravel and sand. The dry-air was circulated for a total of 7 weeks during which the suction developed in the soil bed and the reduction in the volumetric water contents were measured. At the end of the investigation the suction in the soil bed at intermediate depth increased to 180 kPa with a reduction in the volumetric water content of 0.10. This magnitude of suction is significantly higher than that can be achieved by widely accepted existing technology (vacuum consolidation). Also note there is no maximum limit to the magnitude of suction that can be applied. However, a prolonged circulation of dry-air may lead to desiccation of certain soils that may be not be desirable in some geotechnical applications.

Post treatment process revealed a substantial increase in the undrained shear strength of the soil bed, paving a way for a confidence level in adopting this technology at full-scale. Full-scale applications can pose several challenges regarding the spacing of the granular columns, the velocity of air flow, the humidity of the circulated air, and the depth of treatment. These aspects require further research

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