New Solutions to Geotechnical Challenges for Coastal Cities

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ABSTRACT: Coastal cities like Singapore and Jakarta have undergone rapid economic development in the past decades. There is an increasing demand for infrastructure upgrading. With climate changes and population increase, geotechnical design and construction are getting more and more challenging for coastal cities. We need to develop new technologies and new solutions to tackle the challenges and enhance our ability to fight disasters such as earthquake and flood. In this paper, four different solutions pertinent to geotechnical engineering for coastal cities are presented. The first is the establishment of a web-based 3D geological map to make better use of geological and geotechnical data and information for more reliable geotechnical design. The second is a new method for using dredged slurry or soft materials for land reclamation, as there is a shortage of granular fill materials in many cities. The third is the technology for construction of seawalls using suction caissons. The last solution is the biogas desaturation method for mitigation of soil liquefaction which is becoming the most cost-effective solution for prevention of liquefaction for a large area.

KEYWORDS: Coastal cities, Geological model, Geotechnical engineering, Land reclamation, Liquefaction, Underground construction.

1. INTRODUCTION

Many big cities are situated along the coast. Examples in Asia include Hong Kong, Ho Chi Minh City, Jakarta, Manila, Shanghai, Singapore, Thailand, and Tokyo. To cater for further economic development, there is an increasing demand for infrastructure expansion or upgrading along the coast. With global warming and climate changes, geotechnical design and construction for coastal cities are getting more and more challenging. Some of the challenges include the need for more space and more land. This requires large-scale land reclamation and underground development. For land reclamation, a more cost-effective and operation-efficient way is to reclaim land along the coast. This involves the use of a huge amount of fill materials. Sand as s traditional land reclamation fill material is not always available. In this case, soft fill materials or waste may have to be used. Then the placement and treatment of soft fill materials become difficult. For underground development, one of the major challenges is the uncertainties in the geological conditions. Another challenge facing coastal cities is sea level rise and the increasingly frequent coastal disasters such as earthquake and flood. This requires higher or stronger seawalls to be constructed. Liquefaction of soil is often one of the main causes for the losses in lives and properties during earthquake. Mitigation of liquefaction over a large area is another technical challenge. In this paper, some of the solutions developed to overcome the above challenges are presented.

2. 3D GEOLOGICAL MODEL

2.1 Background

It is well-known that geological uncertainties is one of the major challenges for underground construction. One way to overcome this is to establish a three-dimensional (3D) geological model using available geological and geotechnical data. With a 3D model, engineers and urban planners can comprehend and visualize the subsurface conditions in a more systematic way. A research project, named web-based 3D geo-data modelling and management system (GeM2S), has been carried out by Nanyang Technological University (NTU) together with the Building Control Authority (BCA), Land transport Authority (LTA) and Urban Redevelopment Authority (URA) in Singapore to manage and utilize the existing shallow borehole data to build a 3D geo-model of the subsurface layers. BCA will combine this 3D subsurface geology model with information from the deep geological surveys to develop a whole 3D geological model for Singapore. This model will become a valuable resource for future underground development as it can lead to a better understanding of the subsurface geology structures in Singapore, reduction in the uncertainties involved in the design, and eventually a safer and more cost-effective design and construction for future underground projects.

2.2 3D Geological Modelling

The GeM2S developed is a web-based design tool for future underground projects. This system enables a geotechnical engineer to a) utilize both geological and geotechnical data to construct a geo-model as part of desk study, identify risks and design a targeted site investigation program; b) enhance the reliability of the design for underground construction by accounting for the uncertainties and spatial variability in the geo-model and geotechnical design parameters; c) provide a web-based system for geological formations and cross-sections with key engineering properties and geotechnical design parameters to be analysed and visualized in 3D models, or be incorporated into the Building Information Modelling (BIM); d) set up a site rating system as required by the project based on the quantity and quality of the geo-data and spatial statistical analyses to guide future site investigation for underground construction and highlight potential geological hazards.

SubsurfaceViewer was employed as the 3D geological modelling software. The software methodology of 3D geological modelling is based on a single simple philosophy—the construction of geological subsurface models has to proceed with an understanding of the complete geological sequence and the likely geomorphological evolution of the study area. The procedure for the construction of the 3D geological model consists of the following steps: 1) preparation of the geological data, 2) creation of geological cross-sections and fence diagrams; and 3) construction of 3D geological models. More detailed descriptions are available in Pan et al. (2018).

As an example, the fence diagram constructed for one area in Singapore is shown in Figure 1. Using this fence diagram, a 3D geological model can be constructed as shown in Figure 2.

The 3D geological model can not only assist engineers to understand or visualise the underground geological conditions better, but also help to make better interpretation of geotechnical properties of the soil or rock. For example, using the 3D geological model established for Singapore, we could identify the ancient river channels. One example is given in Figure 3 (Pan et al. 2019). Knowing the positions and extent of the ancient river channels, we will be able to construction more accurate soil profiles or ground models to enable more reliable geotechnical design to be achieved for underground construction.

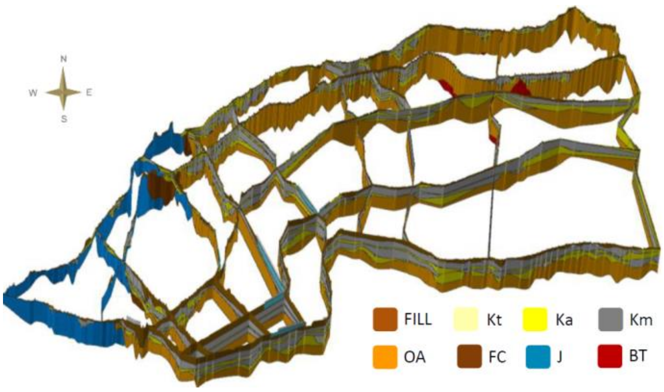

Figure 1 Fence diagram for one area in Singapore

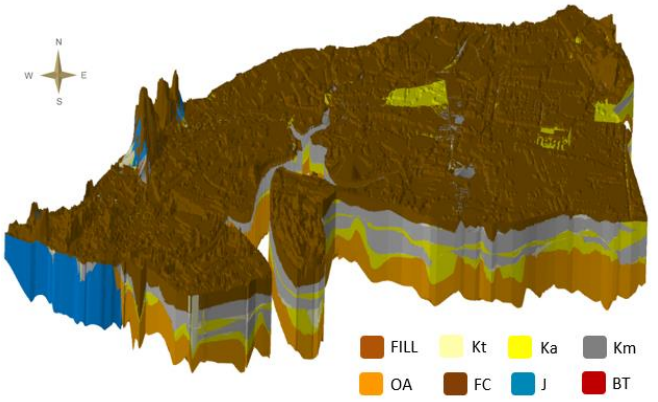

Figure 2 3D geological model for one area in Singapore

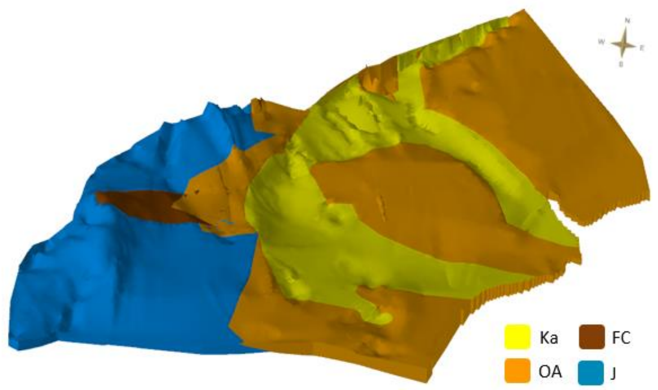

Figure 3 Ancient river channel identified using 3D geological model

3. NEW LAND RECLAMATION METHODS

Land reclamation has become more challenging in recent years due to the following factors: 1) the available granular fill materials are depleting and soft or excavated soil such as dredged clay slurry have to be used instead. How to improve the soft soil to enhance its shear strength and reduce the ground settlement due to the load by the upper structures becomes a challenge; 2) disposal of industrial waste such as sewage sludge or incinerated ashes becomes a problem due to the lack of dumping ground. One solution is to use these waste as fill materials for land reclamation; and 3) the water depth in the areas where land reclamation to be carried out is getting deeper and deeper. The supply of a huge amount of fill materials becomes a challenge. The large amount of settlement induced by the heavy fill materials is another challenge.

Various methods have been adopted for the treatment of soft soil. A review of some of the methods is given in Chu et al. (2009a, 2009b). For large scale land reclamation, one of the most economical methods is preloading together with prefabricated vertical drains (PVDs) (Chu and Raju, 2012). However, for very soft or slurry types of fill materials, the use of fill surcharge becomes difficult. Vacuum preloading, combined vacuum preloading and fill surcharge, or improved dynamic consolidation methods may be used instead (Chu et al., 2009b; Varaksin and Yee, 2009). Another method is to premix cement with soft soil or mixing cement and soil on-site or to use a combined cement mixing and consolidation method (Chu et al., 2005). However, the use of cement is expensive. When there are million cubic meters of fill to be treated, a slight reduction in the unit cost can lead to a huge saving. Clay slurry may also be dewatered using the geotextile tubes method in which clay slurry is pumped into tubes made of woven geotextile. The solids of the soil are retained by the geotextile and the water is consolidated under the pumping pressure or self-weight. However, this method may only be useful when the amount of soil to be improved is small. Rigid inclusions or composite foundation methods by using columns and reinforcements such as stone columns or deep cement mixed columns are another type of methods to treat soft ground (Chu et al., 2009b). However, these methods may not be suitable when the soil is too soft to provide enough lateral support.

An alternative to vertical drains is to combine vacuum preloading with horizontal drains. One application as proposed by Chu et al. (2005) and Chu and Lim (2008) is to use binders treated sewage sludge as fill materials for land reclamation as illustrated schematically in Figure 4.

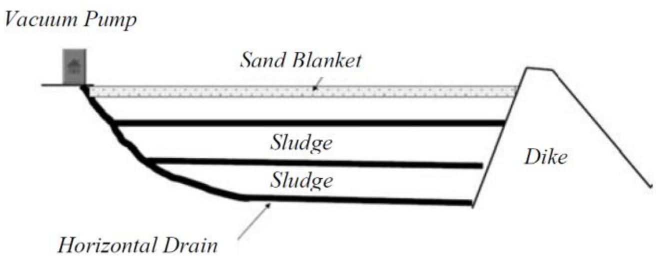

Figure 4 Use of horizontal drains plus vacuum preloading for the consolidation of sewage sludge for land reclamation (Chu and Lim, 2008)

There are a number of advantages in the use of horizontal drains with vacuum preloading. Firstly, consolidation can take place as soon as the clay layer is placed. The conventional method using vertical drains, on the other hand, will have to wait until all the fill materials have been placed. Secondly, the horizontal drains accelerate the sedimentation process of the clay mud layer and thus shorten the construction time. Thirdly, the strength of the clay can be increased before the next layer of clay is placed. Fourthly, with the use of horizontal drains, all the fills placed on top becomes the fill surcharge as well. Hence the fill surcharge load increases with the height of the fills. Finally, for the improvement of the soft soil fill from the ground elevation, a relatively thick layer of fill needs to be topped up to compensate for the large settlement. The new fill will induce new consolidation and further settlement. Thus, it takes extra time for consolidation. It also requires a fairly accurate estimation of the settlement caused by fills placed at different times.

In the past, vertical drains or composite drains with a width of 100 to 300 mm have been used as horizontal drains. One problem with the discrete use of horizontal drains is that the positions of the horizontal drains become uncertain after the fill is placed on top or as the soil is undergoing consolidation. This causes uncertainties in the design, analysis and quality control. Furthermore, the placement of horizontal drains may involve in the intermittent use of a barge during the projects which increases operational costs. To overcome the above problems, a new product called Horizontal Drainages enhanced Geotextile sheet (HDeG) has been developed by Chu and Guo (2015). A schematic illustration of the HDeG is shown in Figure 5. Using this product, the horizontal drains will be placed at more or less the same elevation and the intervals between the drains are more or less maintained. The new product HDeG also made it possible for horizontal drains to be placed without the use of a barge. Using the HDeG, the positions of the horizontal drains will be more predictable and the reliability of the design and quality control of the construction can be improved. If there is a need to accelerate the consolidation process even further, electrolytes as either anode or cathode can be embedded into the HDeGs to create electro-osmosis effect that can also be incorporated into the horizontal drains as shown in Figure 6.

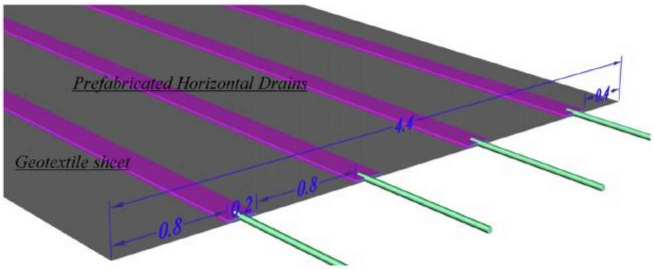

Figure 5 Schematic illustration of one of the designs of the Horizontal Drainage enhanced geotextile sheet (HDeG)

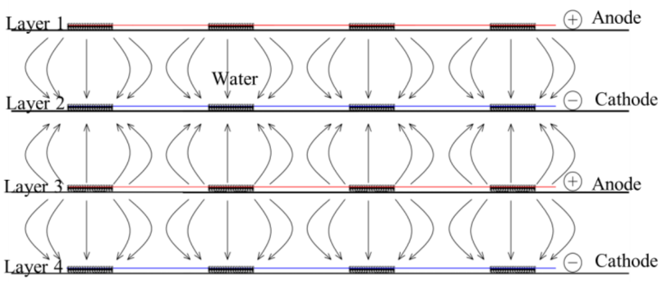

Figure 6 Use of electro-osmosis together with HDeGs

The performance of the HDeG product has been evaluated using model tests and the testing results indicate that the use of HDeG is effective (Chu, 2016; Chen, 2018). It should also be noted that no membrane is required in this method as was case for the model tests. Thus all the problems related to the use of PVDs and vacuum preloading, such as sand blanket, the formation of a working platform and the possibility of punching of membrane, were eradicated. This is the other advantage of using horizontal drains. As a first practical application, the proposed method has been used in the design for a project under tendering.

4. CONSTRUCTION OF SEAWALLS

Seawall construction has become more important for coastal protection against the effects of sea level rising and natural disasters. Seawalls can also be a way to fight flooding. The Giant Sea Wall Jakarta is one of the examples.

The traditional method for seawall construction is to use sand key to support embankment as shown in Figure 7. However, the sand key construction involves dredging of a large amount of soft clay from the seabed and placement of an equally large amount of sand fill. Both the disposal of the dredged clay and the supply for sand fill become problems. An alternative method is to use the so-called non-dredging seawalls, or in other words, to build seawalls without dredging of soft soil. This requires the soft seabed soil to be improved. The methods adopted to treat soft seabed soil in the past include the use of PVDs plus preloading (see Figure 8), deep cement mixing or stone columns as shown in Figure 9 for a sand bund construction in Singapore (Leong and Raju, 2007).

When water depth is relatively deep, the above methods may no longer be applicable. In this case, suction caissons may become a better foundation type for seawalls. The suction caissons are made of one or a group of steel or concrete cylinders as shown in Figure 10 as an example. Four suctions are used as a group and installed together to allow the penetrations of the 4 cylinders to be adjusted so that the four suction caissons can sink into the clay evenly without any titling. This method is particularly suitable for the construction of breakwater on soft seabed or in deep water. Suction caissons are sunk into seabed using suction until sufficient bearing capacity is obtained. In this way, the treatment of soft seabed soil is not required. This will save both time and construction cost. This method can also be used for disaster rehabilitation or restoration of failed seawalls. The concrete caissons can be fabricated using standard modulus in a casting yard connected to the sea. The fabricated caissons or structures can be towed into the seawall location and installed into the seabed using suction. With proper design, the side friction of the caissons will provide sufficient bearing capacity to safeguard stability and serviceability for the seawalls. After the installation of suction caissons, the seawalls can be installed on top of the suction caissons. One example of using suction caissons as the foundation for a breakwater is shown in Figure 11. The detail of this project can be found in Yan et al. (2009).

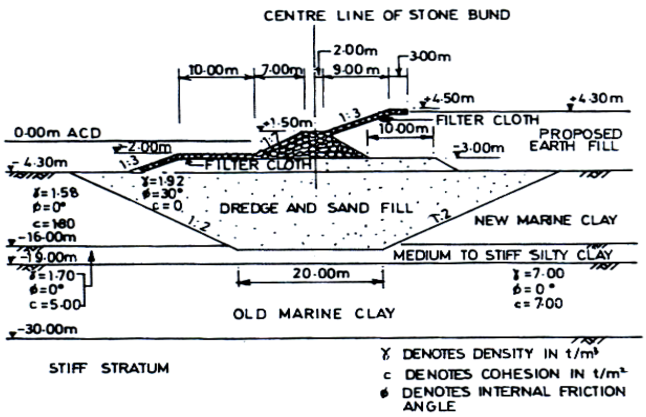

Figure 7 Use of sand key as foundation for a rock bund for reclamation in Singapore (Chew and Wei, 1980)

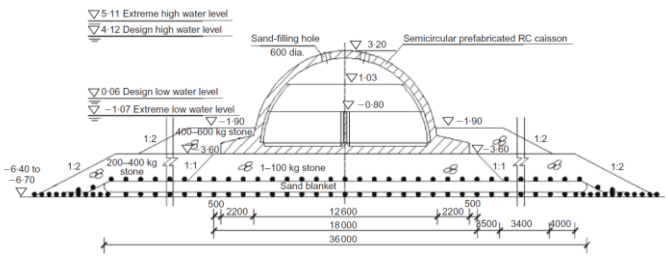

Figure 8 Use of PVDs (not shown) and the weight of the rubble mount to consolidate the soft seabed soil (not shown) before semicircular concrete caissons were placed to form a breakwater in China (after Yan et al. 2009)

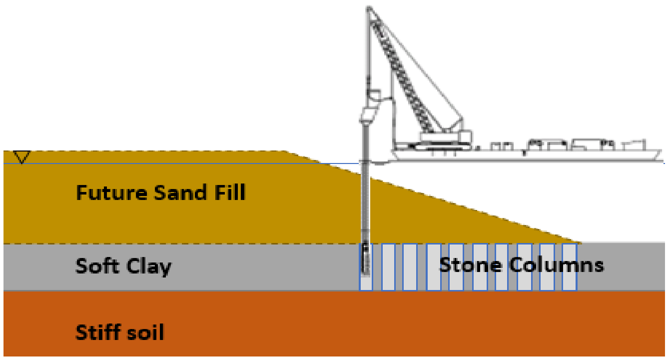

Figure 9 Use of stone columns installed into soft clay from a barge to support sand bund (after Leong and Raju 2007)

However, when the water is deep, or in other words, the upper structures or caissons to form the seawall is too big or too heavy, it will require a special offshore crane to install the upper caissons.

This can be difficult or expensive. An alternative is to assemble the upper caissons with the suction caissons in the casting yard and install the whole segment as one piece as shown in Figure 12. Upon reaching the site, the whole segment can be ballasted using water to the seabed level before suction is applied to sink in the suction caissons. The sea wall formed with back fill behind is shown in Figure 13.

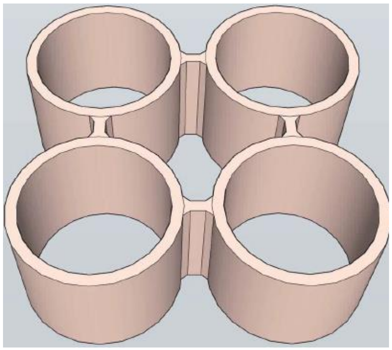

Figure 10 Suction caissons used as foundation for seawalls

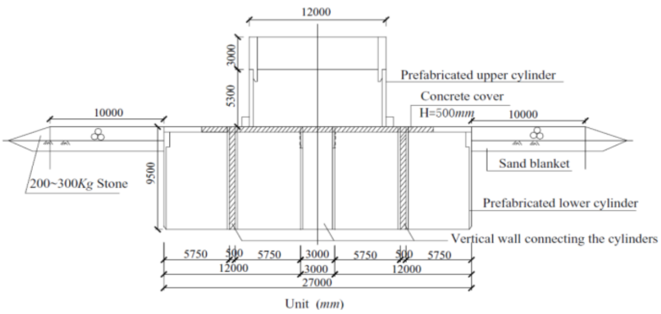

Figure 11 Use of suction caissons for a breakwater construction in China (after Chu et al. 2012)

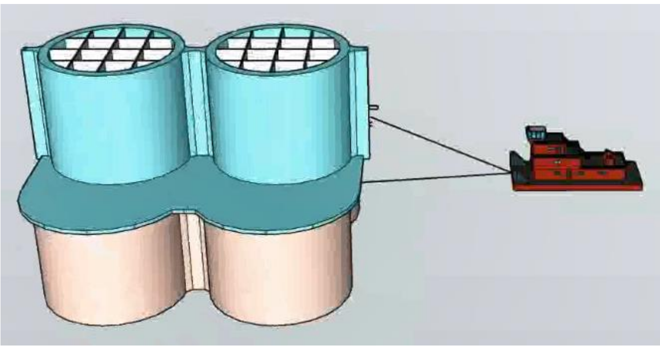

Figure 12 Towing of suction caissons with seawall structures into the seawall site for installation

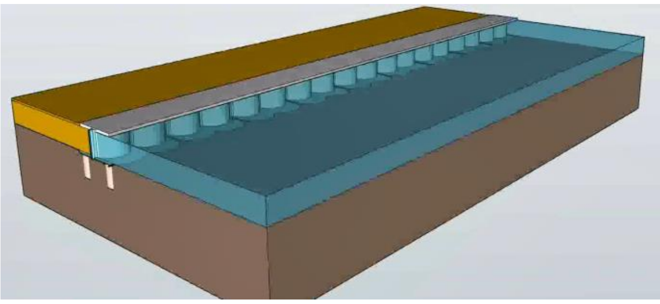

Figure 13 Illustration of seawall formed using the proposed suction caisson method with backfill placed behind the wall

5. MITIGATION OF SOIL LIQUEFACTION

Liquefaction of granular materials is one of the major geohazards. Conventional methods for mitigating liquefaction include soil compaction or deep cement mixing. However, both methods are expensive for large-scale deployment. It is necessary to develop methods for liquefaction mitigation to be effective as well as economical. An experimental study for the development of a more cost-effective approach for mitigation of liquefaction hazard is presented in this paper.

It has been found by some researchers that inclusion of some gas bubbles in a fully saturated sand can lead to an increase of shear strength in cyclic triaxial tests (Yoshimi et al. 1989; Xia and Hu 1991). Use of the desaturation method to enhance the resistance to liquefaction has been attempted before (Yang et al. 2004; Okamura and Soga 2006; Yegian et al. 2007; He and Chu 2014).

A biogas-desaturation method has been developed in this study as a liquefaction mitigation approach. The denitrification process is employed to generate nitrogen gas bubbles in sand to reduce the degree of saturation of a fully saturated sand and thus increase its resistance against liquefaction. Denitrification is a microbially facilitated process of nitrate reduction that produces molecular nitrogen (N_2) through a series of intermediate gaseous nitrogen oxide products. The complete denitrification process can be expressed as a redox reaction as Eq. (1).

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O \tag{1}$$

A series of shaking table tests were also carried out and the results also show that the pore pressure generation and settlement in the bio-desaturated sand was largely contained by using the proposed method. Figure 14 shows the development of pore pressure ratio in sand with different degrees of saturation under the same input acceleration of a = 1.5 m/s^2. R_u is defined as the ratio of maximum excess pore pressure generated by the cyclic load to the initial effective overburden stress. The pore pressure increased during the cyclic loading and dissipated afterwards. For fully saturated sand, there was a considerable amount of increase in excess pore pressure as the shaking took place. The pore pressure ratio exceeded 0.9 which indicates that the liquefaction occurred (He et al. 2013). The pore pressure generated in biogas desaturated sand were substantially lower than that in fully saturated sand. When the degree of saturation S_r dropped slightly to 90%, the increase in pore pressure becomes insignificant. The maximum R_u ratio in the biogas desaturated sample (S_r = 90%) was less than 0.2 which is far less than a trigging value of R_u = 0.5 when liquefaction could occur (He et al. 2013).

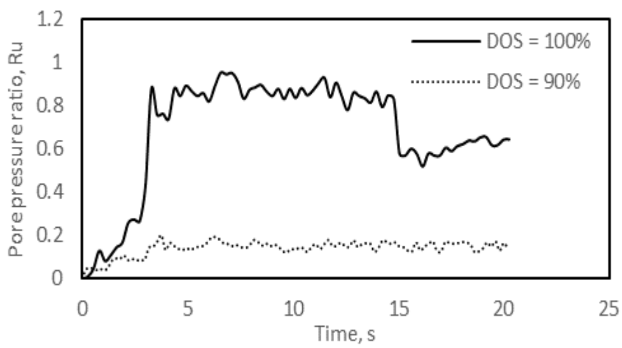

Figure 14 Change of pore water pressures in shaking table tests for fully and desaturated sand with a degree of saturation of 90%

There is a significant difference in the vertical strain between the saturated and the biogas desaturated sand specimen as shown in Figure 15. When the sample was fully saturated, a considerable settlement occurred which indicated that the sand sample liquefied. When the degrees of saturation dropped to 90 percent, the volumetric strain caused by the ground shaking were mostly confined within only 1%. This is evident that the biogas desaturated sand had strong resistance to liquefaction. This finding corroborates the description of Tokimatsu and Seed (1987), who reported that volumetric strains observed in non-liquefiable soils were usually less than 1%.

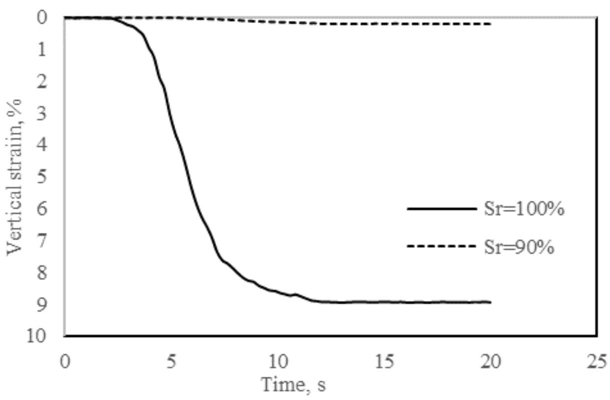

Figure 15 Vertical strain development in sand under shaking for fully and desaturated sand with degree of saturation of 90%

When there is no or very small seepage flow in the soil, the biogas desaturation method is sufficient for mitigation of liquefaction hazards. However, when there is a relatively big seepage in soil, the stability of the gas bubbles may become a concern. In this case, a combined biogas desaturation and bioclogging or the so-called “combined biodesaturation and bioclogging” method could be used instead (Wu, 2015). In this combined approach, the purpose of bioclogging is to “block” the passage for small gas bubbles to aggregate into bigger bubbles so as to pre-empt the conditions for gas bubbles to escape from the ground. The amount of biogrout required for bioclogging in this case is much less than that for biocementation for the purpose to increase the shear strength of sand. In terms of cost-effectiveness, the construction cost involved in the combined biodesaturation and bioclogging method for liquefaction mitigation will still be significantly lower than the cost in the solo biocementation method. The detail of the combined biodesaturation and bioclogging method will be presented in a separate paper.

6. CONCLUSIONS

Four different solutions pertinent to geotechnical engineering for coastal cities are presented: 1) web-based 3D geological map to make better use of geological and geotechnical data and information for more reliable geotechnical design; 2) horizontal drain enhanced geotextile method to use dredged slurry or soft materials for land reclamation; 3) technologies for construction of seawalls using suction caissons; and 4) biogas desaturation method for mitigation of soil liquefaction. The following conclusions can be made:

1) The web-based 3D geological map allows all the existing geological data and information as well as geotechnical data and information to be systematically ultilised for better geological design. This system makes future site investigation much more effective and reliable by providing more data and additional geological processes (such as ancient river channels or igneous intrusion etc) for geological profiling. The data interpretation also becomes more meaningful when integrating the new site investigation data with the existing geological data and geological map.
2) When there is a shortage of granular fill for land reclamation, soft slurry or other soft fill materials may have to be used. In this case, the conventional PVDs plus surcharge or vacuum method becomes inefficient or time consuming. The horizontal drainages enhanced geotextile sheet (HDeG) method offers several advantages over the conventional method. Firstly the HDeG method is much faster. The consolidation can take place as soon as the clay layer is placed. Secondly, the horizontal drains accelerate the sedimentation process of the clay mud layer and thus shorten the construction time. Thirdly, the strength of the clay can be increased before the next layer of clay is placed. Fourthly, with the use of horizontal drains, all the fills placed on top becomes the fill surcharge as well. Hence the fill surcharge load increases with the height of the fills.
3) For seawalls to be constructed in relative deep water, the suction caisson method is more cost-effective as treatment of the soft seabed soil is not required.
4) The biogas desaturation method is effective for mitigation of soil liquefaction as proven by the shaking take tests. When there is ground water seepage, the stability of the gas bubble may become a concern. In this case, the biogas desaturation method can be combined with biosealing method to prevent the migration of gas bubbles.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Chen, H. (2018) “Prefabricated horizontal drains with vacuum preloading for improvement of soft marine clay”, PhD first year report, Nanyang Technological University, Singapore.

Chew, S.Y., and Wei, J., (1980) “Major Reclamation Scheme for Marina City, Singapore”, Coastal Engineering 1980, pp2245-2260.

Chu, J. (2016) “Innovation in Soil Improvement Methods”, S L Lee Lecture, Proceedings of the 19th Southeast Asian Geotechnical Conference & 2nd AGSSEA Conf., Kuala Lumpur 31 May – 3 June.

Chu, J., Bo, M.W., and Arulrajah, A. (2009a) “Reclamation of a slurry pond in Singapore”, Geotechnical Engineering - Proc of ICE, 162(1), pp13-20.

Chu, J., and Guo, W. (2015) “A geotechnical apparatus and method of usage”, SG Patent Application, Serial No. 10201509039Y on 3 November 2015.

Chu, J., Goi, M. H., and Lim, T. T. (2005) “Consolidation of cement treated sewage sludge using vertical drains”, Canadian Geotechnical Journal, 42(2), pp528-540.

Chu, J., and Lim, T. T. (2008) “Use of sewage sludge and copper slag for land reclamation”, Geotechnics of Waste Management and Remediation, GeoCongress 2008, ASCE Geotechnical Special Publication No. 177, pp352-359.

Chu, J., and Raju, V. (2012) “Prefabricated vertical drains”, Chapter 4 in Ground Improvement, pp87-167.

Chu, J., Yan, S. W., and Li, W. (2012) “Innovative methods for dike construction – An overview”, Geotextiles and Geomembranes, 30(2), pp35-42.

Chu, J., Varaksin, S., Klotz, U., and Mengé, P. (2009b) “Construction Processes”, State-of-the-Art-Report, Proc. 17th Int. Conf on Soil Mech. and Geot. Eng., Alexandria, Egypt, 5-9 Oct., 4, pp3006-3135.

He, J. (2013) “Mitigation of liquefaction of sand using microbial methods”, PhD thesis, Nanyang Technological University, Singapore.

He, J. Chu, J., and Ivanov, V. (2013) “Mitigation of liquefaction of saturated sand using biogas”, Géotechnique, 63(4), pp267-275.

He J., and Chu, J. (2014) "Undrained responses of microbially desaturated sand under monotonic loading", Journal of Geotechnical and Geoenvironmental Engineering, 140(5), pp503-515.

Leong, K.W., and Raju, V.R. (2007) "Use of vibro replacement method for the stabilization of an offshore slope on soft clay", Proc 16th Southeast Asian Geotechnical Conference, 8-11 May, Malaysia, pp547-550.

Okamura, M., and Soga, Y. (2006) "Effects of pore fluid compressibility on liquefaction resistance of partially saturated sand", Soils and Foundations, 46(5), pp695-700.

Pan X., Aung Z., Nyo A.K.K., Chiam K., Wu D.F., and Chu J. (2019) "Interpretation of distribution of ancient rivers in Singapore using 3D geological model", In the Eighth International Conference on Case Histories in Geotechnical Engineering, Philadelphia, PA, USA.

Pan, X., Guo, W., Aung, Z., Nyo, A. K., Chiam, K., Wu, D., and Chu, J. (2018) "Procedure for Establishing a 3D Geological Model for Singapore", In GeoShanghai International Conference, Springer, Singapore, pp81-89

Tokimatsu, K., and Seed, H. B. (1987) "Evaluation of settlements in sands due to earthquake shaking", Journal of Geotechnical Engineering, 113(8), pp861-878.

Varaksin, S., and Yee, K. (2007) "Challenges in ground improvement techniques for extreme conditions: Concept and Performance", Proc. 16th Southeast Asian Geot Conf, 8-11 May: Kuala Lumpur, pp101-115.

Wu, S.F. (2015) "Mitigation of liquefaction hazards using the combined biodesaturation and bioclogging method", PhD thesis, Iowa State University, Ames, IA, USA.

Xia, H., and Hu, T. (1991) "Effects of saturation and back pressure on sand liquefaction", Journal of Geotechnical Engineering, 117(9), pp1347-1362.

Yan, S.W., Chu, J., Fan, Q.J., and Yan, Y. (2009) "Building a breakwater with prefabricated caissons on soft clay", Proceedings of ICE, Geotechnical Engineering, 162(1): pp3-12.

Yang, J., Savidis, S., and Roemer, M. (2004) "Evaluating liquefaction strength of partially saturated sand", Journal of Geotechnical and Geoenvironmental Engineering, 130(9), pp975-979.

Yegian, M., Eseller-Bayat, E., Alshawabkeh, A., and Ali, S. (2007) "Induced-Partial saturation for liquefaction mitigation: experimental investigation", Journal of Geotechnical and Geoenvironmental Engineering, 133(4), pp372-380.

Yoshimi, Y., T., K., and Kohji, T. (1989) "Liquefaction resistance of a partially saturated sand", Soils and Foundations, 29(3), pp157-162.