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Innovation in Soil Improvement Methods

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ABSTRACT: To mark Prof S. L. Lee's contributions to the research and development on soil improvement, some of the innovative methods developed by Prof Lee and his team are reviewed. These include the dynamic replacement and mixing method for the improvement of peaty soil, the layered clay-sand method for land reclamation using clayey fill, and the biodegradable fiberdrain. Other new soil improvement methods in the related areas are also presented to illustrate the role of innovation in the advancement of soil improvement technologies. These include the drainage enhanced dynamic compaction method for the improvement of clay layers, the underwater dynamic replacement method for the treatment of seabed clayey soil, the vacuum preloading with horizontal drains method, methods to form working platform on top of soft fill for land reclamation using soft fill materials, the NEUSpace method for land reclamation in deep water, and the new types of prefabricated vertical drains (PVDs). Methods for mitigation of liquefaction hazard, making water pond in sand, and prevention of dike failure from overtopping using biotechnologies are also introduced.

KEYWORDS: Land reclamation, Soft soil, Soil improvement, Vacuum preloading, Vertical drains, Horizontal drains

1. INTRODUCTION

Soil improvement is one area in which Prof S. L. Lee has contributed considerably in the past. In this paper, several special soil improvement methods are presented to illustrate the role of innovation in the advancement of some of the soil improvement technologies. Some of the soil improvement methods and products that Prof Lee and his team developed are reviewed. These include the dynamic replacement and mixing method for the improvement of peaty soil, the layered clay-sand method for land reclamation using clayey fill, and the biodegradable fiberdrain. Other soil improvement methods that are discussed in this paper include the drainage enhanced dynamic compaction method for the improvement of clay layers, the underwater dynamic replacement method for the treatment of seabed clayey soil, the use of the vacuum preloading with horizontal drains method, methods to form working platform on top of soft fill for land reclamation using soft fill materials, the NEUSpace method for land reclamation in deep water, and the new types of prefabricated vertical drains (PVDs). Some new developments in the use of microbial technologies for ground improvement are also presented in this lecture.

2. SPECIAL USE OF DYNAMIC COMPACTION OR DYNAMIC REPLACEMENT METHODS

2.1 Dynamic Replacement and Mixing Method

Dynamic compaction (DC) and dynamic replacement (DR) are two common types of soil improvement methods. It is well known that DC is mainly used for sand and DR for clay. A third method, the so-called Dynamic replacement and mixing (DRM), was also developed by Prof S.L. Lee and his team at the National University of Singapore (NUS) for the treatment of peat or other types of highly organic clay (Ramaswamy et al., 1979; Lee et al. 1985; Lo et al., 1990a, 1990b). This method can be considered as an extension of the DR method. It consists of DR and an additional step to compact the DR columns installed in the clay as shown schematically in Figure 1. DR columns are formed by tamping using low energy blows (Figure 1a). After the DR columns are formed (Figure 1b), tamping using sufficiently high compacting energy per blow of a pounder is applied to cause jets of sand to be ejected from columns into the peaty clay surround by a process resembling claquage (Figure 1c). The rationale for this method is to disrupt the in-situ soil fabric to such a degree that its inherent secondary compression characteristics will effectively be nullified and thus the secondary compression would be controlled under the future work load. A full scale field trial was carried out in 1983 at a MRT depot site in Singapore to evaluate the feasibility of this method as shown in Figure 2 (Lo et al., 1990a).

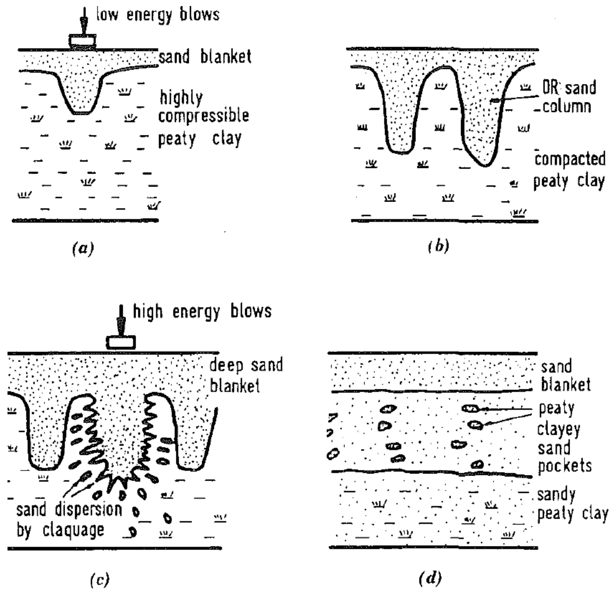


Figure 1 Mechanisms of DRM: (a) Formation of DR Column; (b) Subsoil Profile after DR Treatment; (c) DRM Process; (d) Subsoil Profile after DRM Treatment (after Lo et al. 1990a)

In this trial, a 15 t pounder with 15 to 20 m falling height was used for 6 passes for the DRM step. It was concluded from this trial that the DRM method with sand charges can effectively minimize secondary compression of highly organic clays due to disruption of the soil fabric attributable to such a property and strengthening of the in situ soil mass with sand infusion (Lo et al., 1990b).

A method similar to the DRM method has also been adopted for a rock fill land reclamation project over a soft seabed marine layer of up to 8 m deep in China for a residential property development project (Cao and Wang, 2007). In this project, blasted surplus rock with a maximum diameter of 1–2 m and a total volume of 2,210,000 m^3 was placed on top of the ultra-soft seabed clay as a fill of 6.5 m in average thickness to displace or replace the seabed ultra-soft clay. Heavy tamping using a 12 t tamper with a drop height of 13 m was then carried out to further improve the ground. For the residential building area, a three pass compaction plus two ironing passing were adopted. A preloading test using a 6 m fill applied using sand bags over an area of 12 m by 30 m was carried out. The maximum settlement over 6 months was 280 mm (Cao and Wang, 2007).

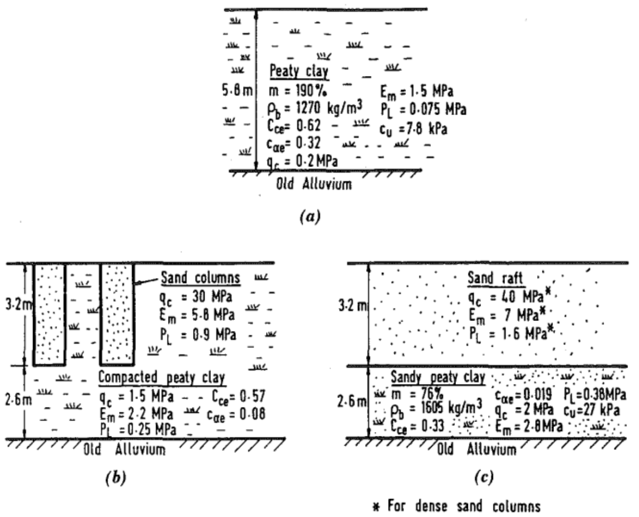


Figure 2 Application of DRM to the peaty soil at Bishan Depot (After Lo et al. 1990a)

2.2 Drainage Enhanced Dynamic Compaction

When the term "dynamic consolidation" was coined by Menard (Menard and Broise, 1975), he envisaged the method would be used for fine-grained soils. Although there are a few successful cases, it is generally believed that the dynamic compaction (DC) method using heavy tamping is not suitable to fine-grained soils, especially for soils with a plasticity index larger than 10 (Mitchell and Katti, 1981; Charles and Watts, 1982). The following observations have been made from the previous studies (Zheng et al., 2004):

1) The DC method is generally not desirable when treating soft clay, particularly when there is no proper drainage system.
2) The effect of compaction may be improved if sand drains or PVDs are used to facilitate the dissipation of pore pressures.
3) The compaction energy and the compaction procedure affect the results of compaction considerably. When compacting fine-grained soil, the compaction energy should be controlled within a limit as not to destroy the structure of the soil.

For the construction of a new airport in China, the drainage enhanced dynamic compaction method was adopted to improve the soft ground. The typical soil profile along the cross-section of the runway as shown in Figure 3 (Zheng et al. 2004). The soil strata varied considerably across the runway and the thickness of the soft clay ranged from 2 to 7 m. The soft clay was recently deposited under marine environment. The average water content of this layer was as high as the liquid limit and the average undrained shear strength was about 20 kPa.

The drainage system adopted was PVDs at an interval of 2 m together with a 300 mm thick sand blanket. Compaction was carried out using the following procedure.

The compaction began with low compaction energy for the first pass and the energy was then increased gradually for the subsequent passes. The rationale was to consolidate the top soil to form a "hard crust" first. Once a "hard crust" was formed, larger compaction energy can be applied and soil at a deeper depth could be compacted. This differs from the procedure used for compacting granular soil in which higher compaction energy is suggested to be used for the first few blows to extend the compaction as deep as possible (Broms, 1991). A compaction scheme with compaction energy gradually increased from 500 to 800, and then 1600 kNm appeared to be suitable for the compaction of soft silty clay at this site. The method would be more effective to use more passes, but only 1 - 3 numbers of blows per pass for compaction. A resting period between each pass of compaction is required to allow the pore pressure to dissipate. The pore water pressure dissipation versus time curves measured during compaction at 3.0 m and 6.3 m below the ground surface are shown in Figure 4. It can be seen that in this case, with a properly installed drainage system, more than 80% of the excess pore water pressure was dissipated within 1 to 2 days. Therefore, there was adequate dissipation of pore water pressures. The whole compaction work was completed in 4 weeks. A comparison of CPT tip resistance profiles before and after compaction is shown in Figure 5. Considerable increase in the tip resistance can be seen in the top 6 m. The average surface settlement incurred by compaction was 240 mm.

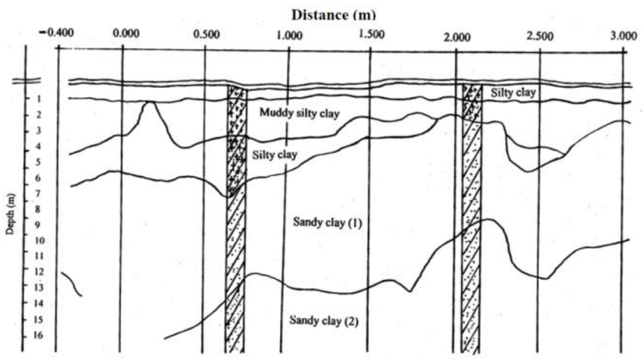


Figure 3 Soil profile along the runway (After Zheng et al. 2004)

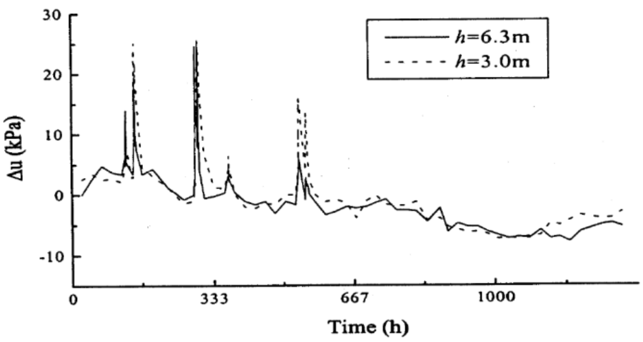


Figure 4 Variation of pore water pressure with the use of PVD (after Zheng et al., 2004)

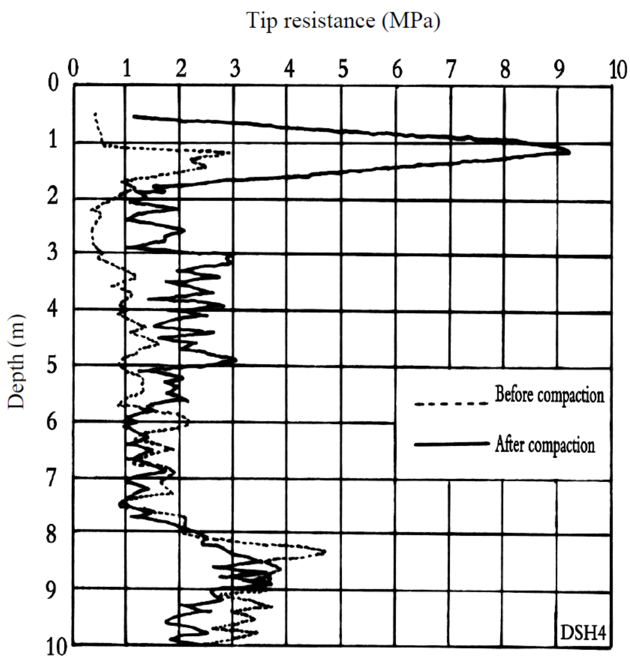


Figure 5 Compaction of CPT tip resistance before and after dynamic compaction (after Zheng et al. 2004)

2.3 Underwater Dynamic Replacement

It is not common, but dynamic replacement has also been used for seabed sediments in a port construction project in Singapore. The schematic illustration of this method is shown in Figure 6. The pounder used was hollow (See Figure 6) to reduce the friction and uplift in water. The DR column had a nominal diameter of 2.4 m with one column per 20 m^2 with 30 – 40 blows. A rock mat was also placed as shown in Figure 6 and was compacted using 3 - 6 blows.

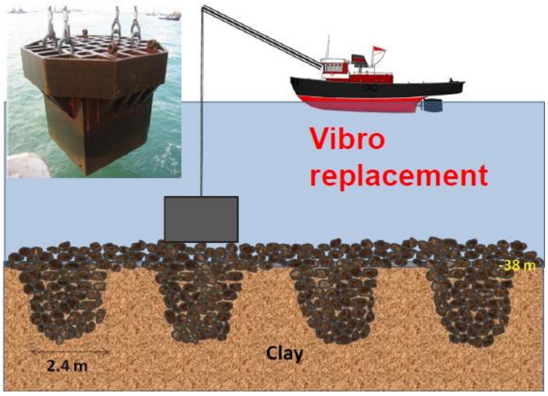


Figure 6 Schematic illustration of the underwater dynamic replacement method used for a port project in Singapore

3. LAND RECLAMATION USING SOFT SOIL OR CLAY SLURRY

3.1 Layered Clay-Sand Method

Another major contribution of Prof S. L. Lee is in the area of land reclamation. One of innovative solutions developed by Prof Lee and his team is the layered clay-sand reclamation method as shown in Figure 7 (Lee et al, 1987; Tan et al., 1992). The key of this method is to use a thin sand layer as the horizontal drains for the consolidation of the clay fill. A feasibility study of this method has been carried out as a field trial at Changi, Singapore, as shown in Figure 8. The thin sand layer with a thickness ranging from 0.6 to 1.5 m was placed. The thickness of the clay layer used in this project was 1.5 to 2 m (Tan *et al.*, 1992).

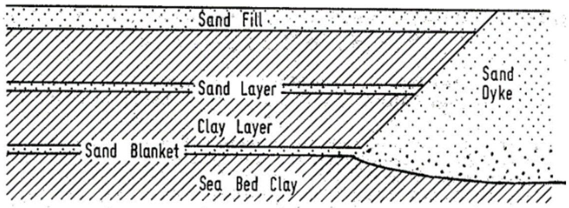


Figure 7 Layered clay-sand reclamation method (after Tan *et al*. 1992)

Figure 8 Field trial of the layered clay-sand reclamation method at Changi, Singapore

3.2 Vacuum Preloading with Horizontal Drains

With the popular use of geosynthetic materials, the prefabricated horizontal drain offers a better alternative to the horizontal sand layers as used in the layered clay-sand scheme. The layered clay-sand method which was originally proposed by Lee et al (1987) relies on the surcharge of fill to consolidate the clay. A more effective way is to combine vacuum preloading with horizontal drain. 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 9.

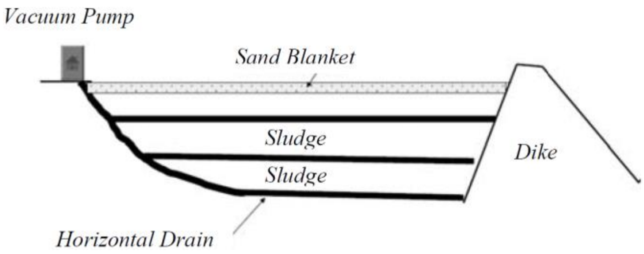


Figure 9 Use of horizontal drains plus vacuum preloading for the consolidation of sewage sludge for land reclamation (Chu and Lim, 2008)

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. Third, the strength of the clay can be increased before the next layer of clay is placed. Forthly, with the use of horizontal drains, all the fills placed on top becomes the fill surcharge as well. So 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). 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 10.

Some large scale model tests have been carried out to evaluate the performance of the HDeG product using the setup shown in Figure 11. In this setup, HDeG was placed at the base of the consolidation tank which was 1.5 m (L) by 1 m (H) by 1 m (W). A vacuum pump was used to apply a vacuum pressure. After placing 1 m thick clay slurry, vacuum pressure was applied via the HDeG at the bottom. The settlement versus time curves in the first 3 days with vacuum application of about 8 hrs per day is shown in Figure 12. The soil had experienced 23% of strain and the water content had reduced from 96% to 53%. Therefore, the use of HDeG was effective. It should also be noted that no membrane was used in the model test. Furthermore, all the problems related to the use of sand blanket, the formation of a working platform and the possibility of punching of membrane was eradicated. This is the other advantages of using horizontal drains.

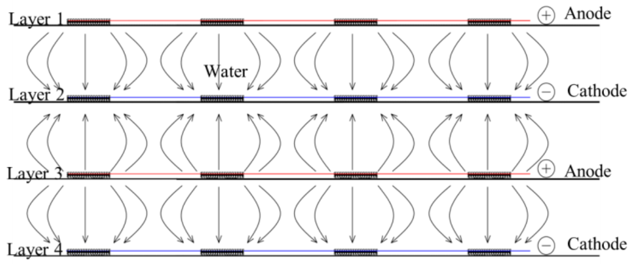


Figure 10 Use of electro-osmosis together with HDeGs

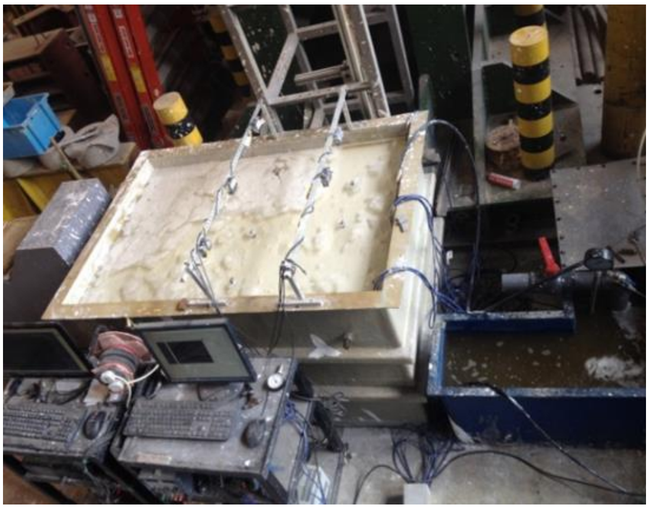


Figure 11 Model test of consolidation of clay slurry using HDeG

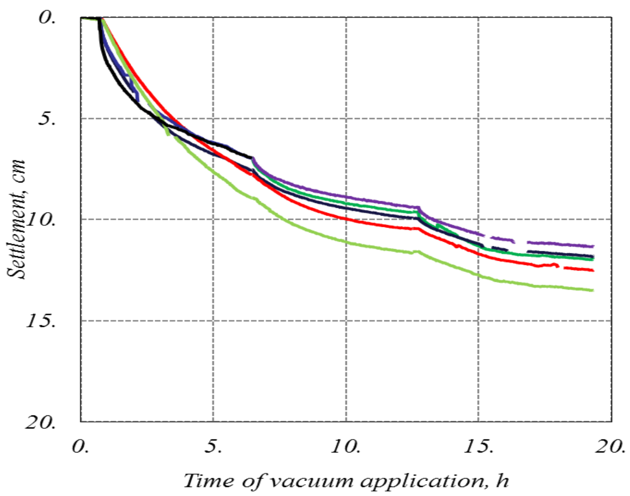


Figure 12 Settlement versus time curves obtained from a model test using HDeG

Despite of the many advantages, there were not many practical applications of horizontal drains in the past. A few examples include the Yeocheon Industrial Complex Project in South Korea (Shin and Oh, 2007) using a scheme shown in Figure 13 and a case originally reported in Japanese by Shinsha *et al.* (2013) and quoted by Chai *et al.* (2014). In terms of design, a nice analytical method has been proposed by Chai *et al.* (2014) and verified using the case reported by Shinsha *et al.* (2013). With the above new developments, I believe that we are able to use horizontal drains for large scale land reclamation particularly for projects with the use of high water content soft soil as land reclamation fills.

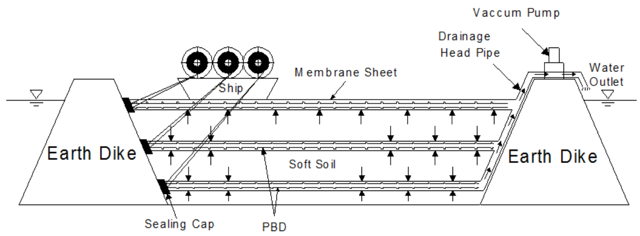


Figure 13 Horizontal vacuum consolidation method for the Yeocheon Industrial Complex Project in South Korea (after Shin and Oh, 2007)

3.3 Formation of Working Platform

If we do not use horizontal drains, we can still continue to use vertical drains. In this case, we need to place the soft soil fill all the way until an evaluation well above the mean sea level. To place fills above a water depth where a bottom open barge cannot be operated, slurry pumping may have to be used particularly when the amount of fills to be placed is large. When soft soil is used as fill, the top surface of the fill will be too soft for machines to go on top to carry out soil improvement works. In this case, a working platform has to be formed by treating the top few meters of fill first. The methods that can be used to create a working platform on top of the soft soil include (1) sun drying; (2) capping it with sand or other good soil; (3) use of geotextile; (4) cement mixing; and (5) dewatering using drainage. Those methods were reviewed with advantages and limitations of each methods discussed in Chu et al. (2012b).

Among the methods listed above, the use of geotextile may be the most expedient. A method proposed by Broms (1987) is to place a layer of fabric on top of the mud and then place fills o top of the fabric sheet as "berms" at a given interval to create tensile stress in the fabric as shown in Figure 14. The fill in the berms is then spread out to form the first layer of fill. A method similar to Broms' method has been adopted for the land reclamation of an ultra-soft slurry pond in Singapore as presented in detail by Chu *et al.* (2006; 2009a). A picture showing the placement of geofabric for this project is shown in Figure 15. The whole piece of geotextile was pulled from one side of the pond to another and placed on top of the slurry. Sand fill was then placed on top of the geotextile layer. Prefabricated vertical drains and fill surcharge were used for the consolidation of the clay slurry.

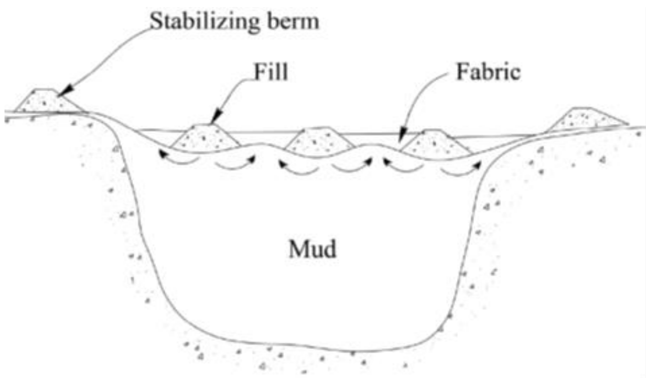


Figure 14 Formation of a working platform on top of mud using fabric (after Broms, 1987)

A similar method was adopted for the land reclamation for the New Kitakyushu Airport in Japan (Terashi and Katagiri, 2005). In this project, soil or spoils collected from maintenance dredging. The soil deposited was in the slurry form and was extremely soft PVDs and fill surcharge was adopted to improve the soft soil. To provide a working platform, geotextile with a tensile strength of 100 kN/m was used to cover the slurry before sand fill was placed to form a working platform and used as surcharge.

Figure 15 Installation of geotextile sheet for the slurry pond land reclamation project in Singapore (after Chu et al. 2009a)

As land reclamation involves the use of a huge amount of fill, the unit cost of each method adopted makes a big difference. For this reason, we should strive to adopt a method with the lowest possible unit cost. One method that could be more cost-effective than the use of geotextile is to form a working platform using consolidation or dewatering method. This can be achieved by using vacuum preloading together with short vertical drains to consolidate the top 4 to 5 m of soft fill as illustrated schematically in Figure 16. As the clay fill is ultra-soft with low permeability, we can install vertical drains easily by inserting drains manually from a platform made of foam boards as shown in Figure 17 or from a floating vertical drain installation rig as shown in Figure 18.

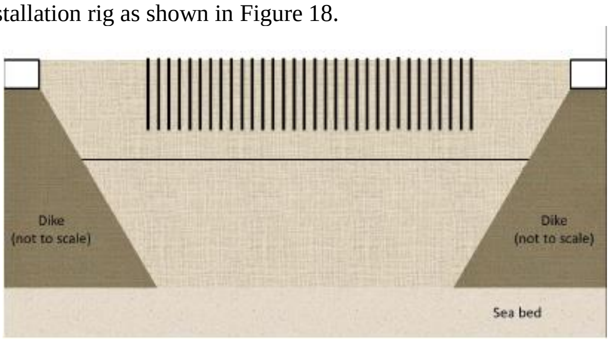


Figure 16 Use of short PVDs and vacuum preloading to form a working platform

Figure 17 Installation of PVDs from a platform made of foam boards (after Wang et al. 2016)

To apply vacuum pressure to the vertical drains, the short PVDs can be connected to the vacuum pipe using connectors shown in Figure 19 as an example. The top of the fill together with PVDs and connectors can be covered using a layer of membrane (Figure 19) if the ground conditions permits or by a layer of clay slurry pumped on top (similar to that showing in Figure 20). In this way, vacuum pressure can be applied to consolidate the top 4 to 5 m of soft fill. Once this layer of fill has gained the required strength, a layer of sand blanket of about 1 m can be pumped on top and the working platform is thus formed.

Figure 18 Floating vertical drain installation rig for installation of short drains (Courtesy of Yan S.W.)

Figure 19 Connectors used to connect PVDs directly to the vacuum distribution pipes (after Wang et al. 2016)

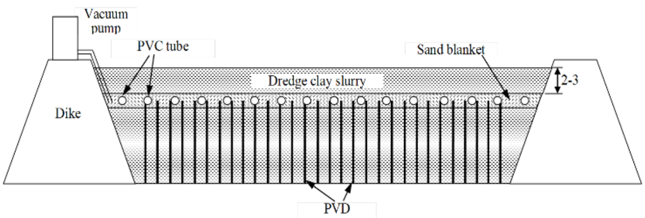


Figure 20 Use of a layer of clay slurry as a seal for vacuum preloading (after Chu et al. 2008)

4. LAND RECLAMATION IN DEEP WATER

When land reclamation has to be carried out in a water depth more than 15 m, it may not be economical to use earth fill. One method is to use large-sized cylindrical structures for land reclamation and creating space underwater at the same time as illustrated in Figure 21. This so-called NEUSpace method is currently being studied. NEUSpace stands for NEw Underwater Space. The method is to make use of the sea space to construct underwater infrastructure and at the same time use the top-side of the infrastructures as reclaimed land. Using this method, the amount of fill materials required can be greatly reduced and more space can be created.

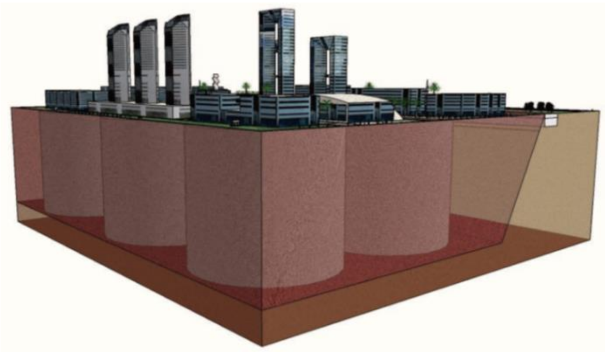


Figure 21 New method for land reclamation and underwater space creation

The large-scale concrete cylindrical structures can be installed using a method showing in Figure 22 which is similar to the installation of seawalls or suction anchors for offshore oil platforms. One example of using this method for the construction of breakwater in the sea in Tianjin Port, China, is shown in Figure 23 (Chu *et al.*, 2012c). Suction caissons can be used for the foundations of the cylinders (Chu *et al.*, 2009b; 2012c; Liu *et al.* 2013). However, the use of suction caisson in relatively shallow water is challenging. More research has to be carried out (Guo and Chu, 2013; Guo *et al.*, 2016).

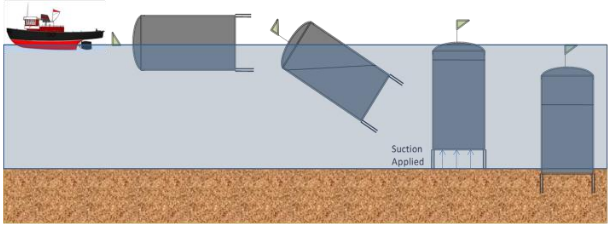


Figure 22 Installation of large scale concrete cylindrical structures

Figure 23 An offshore breakwater constructed using suction caissons (Chu et al. 2012)

Using the same method, we will be able to construct a wall and use the space behind it without the need to use fill as shown in Figure 24. This so-called polder system is not uncommon in Netherlands.

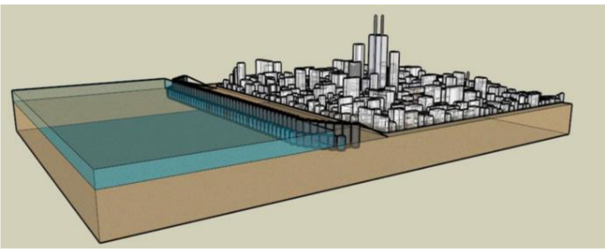


Figure 24 Use of seawalls to reclaim land without using fill materials

5. NEW VERTICAL DRAINS

One problem with the use of plastic PVD is that most of these drains are not biodegradable. In other words, the PVDs will stay underground for a long time. The PVDs underground could cause problems for future development, such as tunneling activities. Another contribution of Prof S. L. Lee and his team is the development of *Fibredrain* (Lee *et al.* 1994). As this drain is made mainly of jute, it is biodegradable. Fibredrain has a cross-section of 80-100 mm in width and 8-10 mm in thickness. Four coir strands of 3-6 mm in diameter obtained from coconut fibre are enveloped by two layers of jute burlap to arrive at the above dimensions. Jute burlap is manufactured from the jute plant available in many parts of South and Southeast Asia. Three longitudinal stitches hold the coir strands in separate flow channels within the jute burlap as shown in Figure 25.

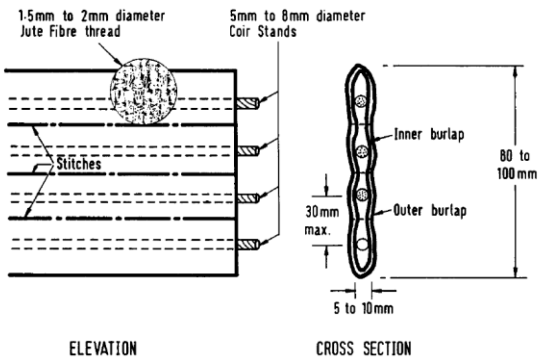


Figure 25 Design of Fibredrain (After Lee *et al.*, 1994)

With the use of biodegradable polymer, it is now also possible to make PVDs to be biodegradable (Park *et al.*, 2010). Nevertheless, Fibredrain sets a good example for using local and natural products in construction.

A conventional PVD has also been involving. PVD normally consists of a core and filter and the core and the filter are fitted loosely together and are separable. Recently, a new type of PVD, the so-called *integrated PVD* has been developed (Liu and Chu, 2009). For this type of PVD, the core is adhered to the filter, as shown in Figure 26. This new type of PVD offers a number of advantages over the ordinary type of PVDs. For examples, the discharge capacity and tensile strength can become 40% and 19% higher than those of conventional drains, respectively, as shown by Liu and Chu (2009).

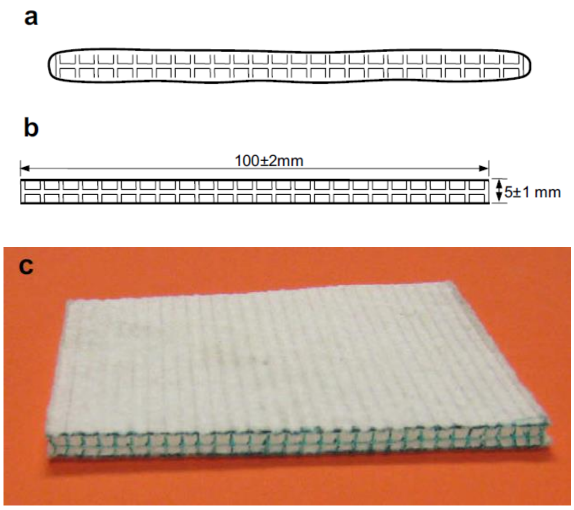


Figure 26 (a) Cross-section of conventional PVD; (b) Cross-section of integrated PVD; and (c) Picture of integrated PVD (after Liu and Chu, 2009)

There are also PVDs that allow penetration depths to be measured. The first type has a meter scale printed on the surface of the filter as shown in Figure 27 and the second is a PVD with a metal wire embedded along the joint of the filter to measure the penetration depth as shown in Figure 28. For details, please refer to Liu *et al.* (2009).

Furthermore, electric drains or thermal drains have also been developed to improve the performance of PVDs, e.g., a field test using thermal PVD was reported by Pothiraksanon *et al.* (2010).

Figure 27 PVD printed with a meter scale (after Liu *et al.*, 2009)

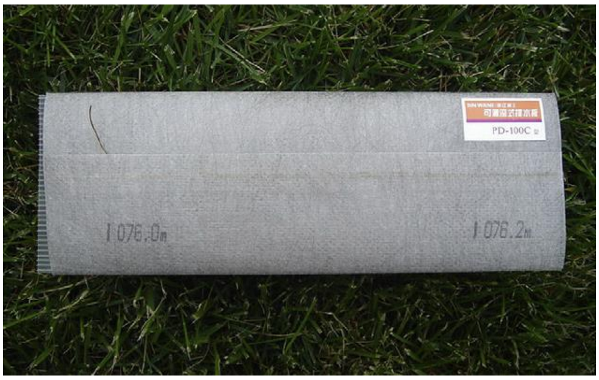


Figure 28 PVD with a metal wire for the measurement of penetration depth (after Liu et al. 2009)

6. SOIL IMPROVEMENT USING BIOTECHNOLOGIES

Cement or chemicals have often been used as binders for soil improvement. However, the use of cement or chemicals for soil improvement is not sustainable in the long run as cement or chemicals require a considerable amount of natural resource (for example limestone) and energy to produce. The use of cement or chemicals for soil improvement is also expensive. The cost of a soil improvement method itself can be a factor in deciding whether or not soil improvement works should be carried out. For example, liquefaction has long been identified as one of the major hazards as seen in the 2011 earthquake disasters in New Zealand and Japan. However, ground treatment for mitigation of liquefaction hazard is normally only carried out for sites where important infrastructures such as sea ports and airports are constructed. This is because the cost involved in ground treatment for liquefaction is high. If a much cheaper liquefaction mitigation method can be developed, ground treatment for liquefaction can thus be applied over a wider range of projects to reduce the impacts of the damages associated with liquefaction. Therefore, there is an urgent need to develop new soil improvement methods or new materials that can be used to reduce the cost of soil improvement.

Using the latest microbial biotechnology, a new type of construction material, biocement, has been developed as an alternative to cement or chemicals (Whiffin, 2004; Ivanov and Chu, 2008). Biocement is made of naturally occurring microorganisms at ambient temperature and thus requires much less energy to produce. The microorganisms that are suitable for making biocement are non-pathogenic and environmentally friendly. The application of microbial biotechnology to soil improvement will also simplify some of the existing construction processes. For example, the biocement can be in either solid or liquid form. In liquid form, the biogrout has much lower viscosity and can flow like water. Thus, the delivery of biocement into soil is much easier compared to that of cement or chemicals. Furthermore, when cement is used, one usually has to wait for weeks for the full strength to be developed, whereas when biocement is used, the reaction time can be reduced if required.

A number of methods for the use of biotechnologies in soil improvement have been developed in recent years. These include a liquefaction mitigation method using biogas desaturation, construction of temporary water storage pond in sandy soil using the biocrust method, the use of biogrouting for prevention of levee failure due to overtopping and erosion; and road construction using biogrout made of waste. Some of the methods presented here are still at the laboratory stage and need to be developed further before they can be used in practice. Nevertheless, it will be only a matter of time before some of those methods become reliable technologies.

The principle of microbial treatment is to use the microbially-induced calcium carbonate precipitation (MICP) or other approaches to produce bonding and cementation in soil so as to increase the strength and reduce the water conductivity of soil as shown schematically in Figure 29.

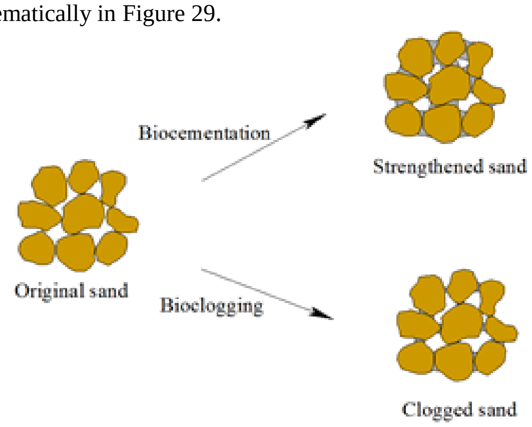


Figure 29 Principle of (a) biocementation and (b) bioclogging

6.1 Mitigation of Liquefaction Using Biogas Desaturation Method

The common methods that can be adopted for mitigation of liquefaction include the following four broad categories: (1) Replacement or physical modification; (2) Densification; (3) Pore water pressure relief; and (4) Foundation reinforcement, as summarized by Chu *et al.* (2009b). However, it is difficult to treat ground for the purpose of mitigation of liquefaction because the scale of the ground to be treated is normally huge and it becomes too expensive to be implemented. Therefore, there is a need for more cost-effective solutions for liquefaction treatment.

A new approach for the mitigation of liquefaction potential of sand is to introduce gas bubbles into potentially liquefiable, saturated sand. Soil liquefaction is caused by a large generation of pore water pressure. Several studies (e.g., Okamura et al. 2006) have shown that when saturated sand is made slightly unsaturated (with a degree of saturation between 85 to 95%) by inclusion of gas bubbles, the excess pore water pressure generated in soil under a dynamic load will be greatly reduced.

However, it is difficult to introduce gas into the ground for desaturation and maintain the same amount of degree of saturation for a long time. This is because the gas bubbles tend to dissolve in water or escape from the ground over time. Pumping can be used as illustrated conceptually in Figure 30. However, the distribution of gas bubbles introduced by pumping will not be uniform. Furthermore, the gas pumped into the ground tends to form aggregated gas pockets rather than individual bubbles. As a result, the sizes of the gas bubbles or aggregates are not small enough to be kept in the ground for a long period of time.

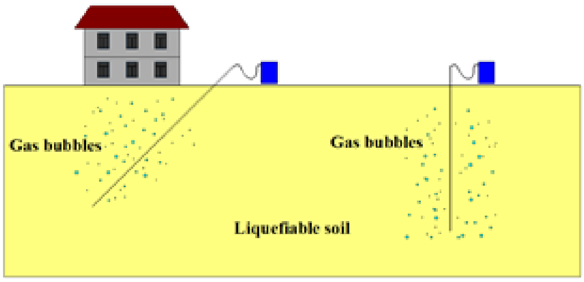


Figure 30 Mitigation of soil liquefaction by air injection

One innovative method to overcome the above problems is to generate tiny gas bubbles in-situ using microorganisms. This method is promising as it has the following three advantages: (1) It consumes the least energy as the low viscosity bacteria and nutrient fluid can be delivered easily into sand; (2) The gas generated by bacteria can be distributed more evenly than other means; (3) The gas bubbles generated by bacteria are tiny so the gas bubbles are less prone to escape from the ground. This so-called *biogas desaturation method* for mitigation of liquefaction has been developed by my research group (He et al., 2013; He and Chu, 2014). The effectiveness of this method has been verified by shaking table tests. Figure 31 shows a comparison of pore water pressures generated during ground shaking under an acceleration of 1.5 m/s^2. Figure 31a shows the pore water pressure for a saturated sample and Figure 31b the pore water pressure for a sample with a degree of saturation of 80%.

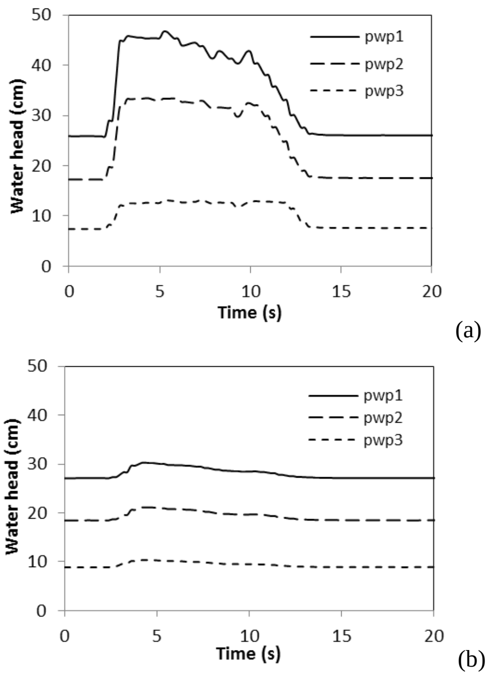


Figure 31 Pore water pressures generated during shaking at an acceleration of 1.5 m/s^2: (a) for sample with D_r = 0.52 and S_r = 100%; and (b) for sample with D_r = 0.43 and S_r = 80%.

It can be seen from Figure 31 that by merely reducing the degree of saturation using biogas, the amount of pore water pressure generation can be much reduced.

Densification is a common method adopted to increase the resistance of soil against liquefaction. When the degree of saturation of the sand is lowered down to 95%, the pore pressure ratio would be reduced to 0.4 for sand with the same density as observed from the shaking table tests as shown in Figure 32. The cost and energy required to lower down the degree of saturation from 100% to 95% is much less than the other types of densification methods. If we lower down the degree of saturation to 90%, the pore water pressure ratio can be controlled to be less than 0.2 as shown in Figure 32. Therefore, the biogas method can be very effective for liquefaction mitigation. It is also less expensive than any other conventional methods.

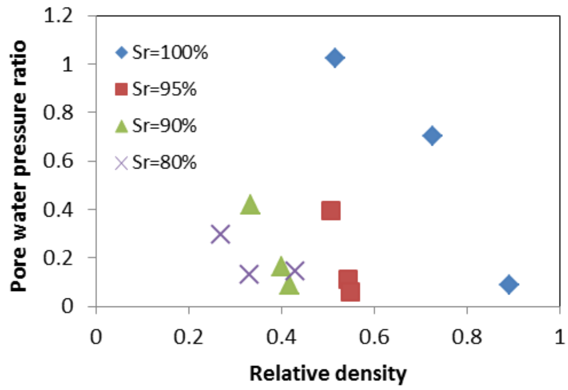


Figure 32 Plot of pore water pressure ratios against relative densities under an acceleration of 1.5 m/s^2 for samples with different degree of saturation

A comparison of ground settlement for a fully saturated sand layer and a sand layer treated with biogas with a degree of 95% is made in Figure 33. The settlement is expressed as a settlement ratio where the maximum settlement for fully saturated sand is 100%. It can be seen from Figure 33 that with only 5% of gas replacement, the ground settlement generated under ground shaking with an acceleration of 1.5 m/s^2 can be reduced by more than 90%. Thus, the biogas method is effective in preventing the occurrence of soil liquefaction as well as reducing the damage caused by liquefaction.

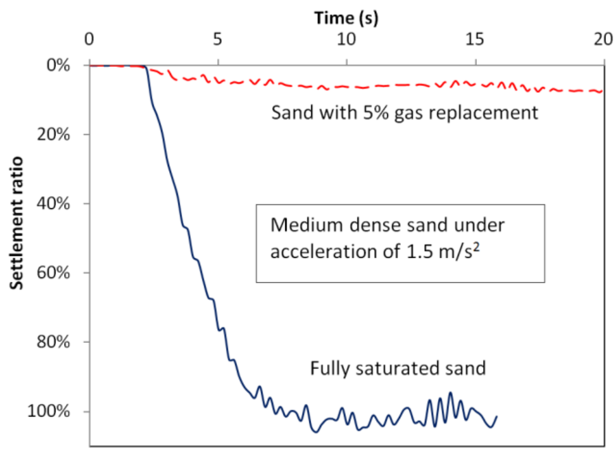
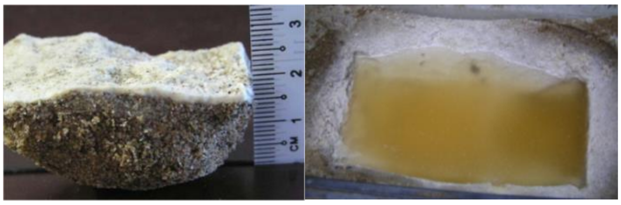


Figure 33 Comparison of ground settlement induced by ground shaking under an acceleration of 1.5 m/s^2 for a saturated sand layer and a sand layer with 5% gas replacement.

6.2 Biocrust

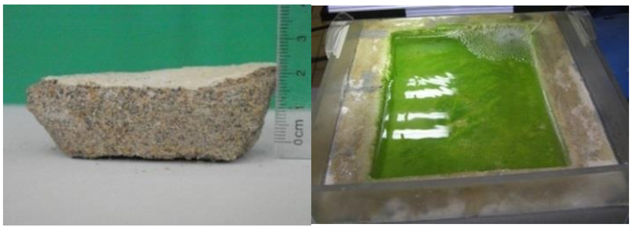
Biocement can also be used to reduce the water conductivity of sand through bioclogging as illustrated in Figure 29. One of the methods developed by my research group is biocrust. This method is to precipitate a layer of calcium carbonate on top of sand as shown in Figure 34a through the MICP or other method. This hard curst layer has a permeability of less than 10^{-7} m/s (Chu *et al.* 2012a) and thus can be used as an impervious layer for water storage or as erosion control for beach or sandy riverbank. One model for water storage is shown in Figure 34b. As the layer of curst is rather thin, 2 to 3 mm, the amount of biogrout used is small. Thus this method is much more economical than any other conventional methods. The detail of this method is described in Chu *et al.* (2012a).



(a) (b)

Figure 34 Formation of (a) a thin impervious layer on top of sand and (b) an impervious layer to form a water pond in sand (after Stabnikov et al. 2011)

However, this thin calcium carbonate layer is brittle and may break under bending. Another method, the so-called bulk bioclogging method is also developed (Chu *et al.*, 2012a). In this method, bacterial solutions and calcium ions and urea solutions can be sprayed on top of the sand surface for 3 to 6 times (Chu et al., 2012a). An impervious layer of 20 to 25 mm thick can thus be formed by surface spraying as shown in Figure 35a. Using this method, an aquiculture pond model has been made as shown in Figure 35b (Chu *et al.,* 2013). The permeability of this layer is in the order of 10^{-7} m/s. The bioclogging effect also increases the shear strength of sand. As a result, the sand in the impervious layer has gained an unconfined compressive strength in the range of 215 to 930 kPa.



(a) (b)

Figure 35 Bulk bioclogging method to form (a) an impervious layer and (b) to make an aquiculture pond (after Chu et al. 2013)

6.3 Bio-Protection of Dikes

By using the MICP method, the shear strength of soil can be increased through biocementation. The uniaxial compressive strength (UCS) of biocement treated sand increases with the calcium carbonate (or calcite) content by weight. The highest UCS reported is 27 MPa at about 33% calcite content (Van der Ruyt and van der Zon, 2009). For normal applications, the UCS strength required is less than 2 MPa. This will only require a calcium content of 5 to 10% or 90 to 180 kg/m^3. To achieve the same UCS strength for sand using cement grouting, the amount of cement used would be between 250 to 300 kg/m^3. As the production of biocement can be cheaper (Ivanov and Chu, 2008), the overall cost for biogrouting can potentially be lowered. The precipitation of calcium carbonate also reduces the permeability of soil as discussed above.

Many previous case histories have shown that erosion due to overtopping is one of the major causes for dike failure. A method for dike rehabilitation is to us e biogrout to enhance its ability against erosion under overtopping and seepage through the dike and the base of the dike. This so-called bioshotcrete method is illustrated in Figure 36. In this method, bacteria solution and biogrout consisting of fibre, calcium source, and urea are sprayed on top of the levee surface to form a biocoating. Biogrouting columns can also be installed under the dike to form a cutoff wall as shown in Figure 36.

The effectiveness of the bio-shotcrete method was evaluated using model tests carried out in a hydraulic flume. The biogrouting solution was applied by spraying the surface of the levee model with this solution 6 times. The biogrout included a urease-producing bacteria suspension solution, calcium chloride, and urea. The model was then placed inside a hydraulic flume as shown in Figure 37 for testing. This model did not erode or collapse after it was subjected to an overtopping flow under different flow rate for 30 days. More detail on the model tests is given in Naeimi (2014).

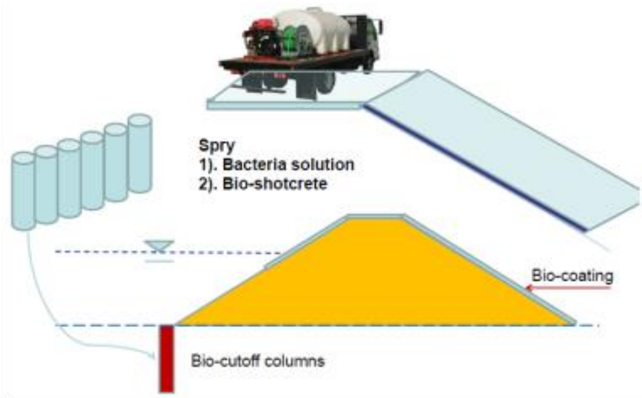


Figure 36 Use of bio-shotcrete for dike protection against erosion due to overtopping and biogrouting for seepage through the base of the dike

Figure 37 A bio-shotcrete treated dike model after undergoing overtopping flow in a hydraulic flume for 30 days

7. SUMMARY

In this lecture, examples are given to illustrate the role of innovation in advancing some of the soil improvement technologies. Some of Prof S. L. Lee’s methods are reviewed to mark his contributions to soil improvement. These include: 1) the dynamic replacement and mixing method for the improvement of peaty soil; 2) the layered clay-sand method for land reclamation using clayey fill; and 3) the biodegradable fiberdrains.

Other methods discussed in this lecture include: 1) the drainage enhanced dynamic compaction method for the improvement of clay layers; 2) the underwater dynamic replacement method for the treatment of seabed clayey soil; 3) the use of the vacuum preloading with horizontal drains method for land reclamation using soft fill materials; 4) methods to form working platform on top of soft fill for land reclamation using soft fill materials; 5) the NEUSpace method for land reclamation in deep water; and 6) other types of prefabricated vertical drains (PVDs).

Methods for soil improvement using biotechnologies for mitigation of liquefaction, making water pond in sand, and prevention of dike failure from overtopping are also introduced.

9. ACKNOLWSGWMWNTS

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