Land reclamation using clay slurry or in deep water: challenges and solutions

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ABSTRACT

Offshore land reclamation has become more challenging in recent years. One of reasons is the use of soft soil such as dredged clay slurry when there is lack of granular fill materials and the improvement of soft soil to meet the design requirements is challenging. Another reason is that the water depth in which land reclamation has to be carried out is getting deeper and deeper and the supply of a huge amount of fill materials becomes another challenge. In this paper, methods for land reclamation using clay slurry and the associated soil improvement methods are introduced. Case studies for land reclamation over ultra-soft soil are presented. Methods to use sewage sludge or other waste for land reclamation are also proposed. To overcome the difficulties in land reclamation in deep water, a new land reclamation method, NeuSpace, is also introduced.

Keywords: clay slurry, land reclamation, soil improvement, suction caisson

1 INTRODUCTION

Singapore is a country with limited land space. Land reclamation has been a major method for land creation in Singapore since the 19th century. Much of the old Singapore port area and the old city around the Kallang and Geylang river estuaries were built on reclaimed land. However, large-scale land reclamation took place from the early 1970’s when economic expansion was accelerated. As a result of land reclamation, the total area of Singapore has increased from 580 km² in 1962 to around 700 km² in recent years. Another 100 km² land will be reclaimed until 2030.

Land reclamation has become more challenging in recent years due to the following factors. First, the available granular fill materials are depleting and soft or excavated soil such as dredged clay slurry may have to be used. 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. Second, disposing of some industrial waste such as sewage sludge is becoming a problem due to the lack of dumping ground. One solution is to use these waste as fill materials for land reclamation. Third, the water depth in the areas where land reclamation will 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. (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 (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.

In this paper, the methods that can be adopted for land reclamation using soft soil are reviewed. Five different methods that could be used to form a working platform on top of the slurry are introduced. A few
practical examples of some of these methods are given. A method to use sewage sludge or other types of waste materials for land reclamation is also proposed. To overcome the difficulties in land reclamation in relatively deep water, a new land reclamation method, the so-called NeuSpace method, is also introduced.

2 LAND RECLAMATION USING SOFT FILLS

One difficulty in the use of slurry for land reclamation is that the top surface is too soft for machines to go on top to carry out any types of soil improvement work. Therefore, a working platform has to be formed by treating the top few meters of soil 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. The advantages and limitations of each method are listed in Table 1. Details are discussed in Chu et al. (2012).

Table 1. Methods for creation of a working platform

| Method                      | Description / Mechanisms | Advantages                  | Limitations                                                |
|-----------------------------|--------------------------|-----------------------------|------------------------------------------------------------|
| (1) Sun drying              | Reduce the water content of soil and form of a desiccation layer by weathering | Time consuming and ineffective as the depth of improvement is very limited. |
| (2) Capping with sand or competent soil | Place sand or good earth in thin layers | Relatively cheap | Slow and difficult to implement. |
| (3) Use of geotextile       | Place a layer of geotextile to the top of soft soil before soil or fill is placed. | Relatively expensive | Relatively quick and reliable. |
| (4) Cement mixing           | Use cement mixing to strengthen a layer of soil at the top to form a working platform | Expensive | Difficult in controlling the properties and consistence of the cement treated layer. |
| (5) Dewatering              | Use special drainage method to dewater or consolidate the a layer of soil at the top to form a working platform | Relatively cheap | Require special equipment and procedure. The method needs to be further developed. |

For use of geotextile, a method proposed by Broms (1987) may be used. A method similar to the 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 Fig. 1. The whole piece of geotextile was pulled from one side 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. 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 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.

Deep cement mixing (DCM) has also been used to for a work platform. One example is the improvement of very soft dredged mud for a container terminal for the Port of Valencia in Spain (Burgos et al., 2007). In this project, the deep cement mixing (DCM) method was used in conjunction with the vacuum consolidation method. The soil improvement was carried out in two steps. The first was to treat the top 4 m of mud using the DCM method to form a soil-cement crust which provided a working platform for the other sections to be treated. The second step was to treat the deeper layer of soft soil using the conventional vertical drain and surcharge method. Another way of treating soft soil for land reclamation is to mix the soft slurry soil with cement and pump the cement mixed soil as fill. In this way, no further treatment of the soft soil is required. Such a method has been adopted for the Central Japan Airport and for the containment bund construction for a land reclamation project in Singapore. However, this method can be too expensive to be used in a large scale.

Another method to improve the engineering properties of soft soil to form a working platform is by consolidation or dewatering. As clay has low permeability, it is possible to install horizontal drains or vertical pipes to the top few meters of the soft clay.
layer and improve it using vacuum preloading. A project of using horizontal drains for the formation of a working platform is described by Shin and Oh (2007). Another method of using short PVDs and vacuum preloading has also been suggested as shown in Fig. 2. In this case, the PVDs have to be installed either from a floating platform made of foam boards (Fig. 3) or from a floating installation rig.

![Figure 2. Use of short PVDs and vacuum preloading to form a working platform](image)

In this case, the PVDs have to be installed either from a floating platform made of foam boards (Fig. 3) or from a floating installation rig.

![Figure 3. Installation of PVDs from a platform made of foam boards (after Wang et al. 2015)](image)

3 LAND RECLAMATION USING WASTE

A large amount of sewage sludge is generated every year from water treatment in Singapore and many other cities. The dumping of sewage sludge becomes a challenge. One way is to use the sewage sludge for land reclamation (Chu et al. 2005; Lim et al. 2004; 2006).

For this purpose, a study was made to mix sewage sludge with other wastes using a mixer. The optimum ratios for different waste have been established through laboratory tests. For land reclamation, the mixed sludge can be pumped directly through pumping pipes into the designated land reclamation area. Horizontal drains plus vacuum pressure can be used to consolidate the mixed sludge slurry. As the sludge mixer has low permeability, the vacuum can be applied as soon as the first layer of sewage sludge has been placed, see Fig. 4.

The advantage of using vacuum pressure is that there will be little environmental risks as the water from the sludge is centrally collected. The mixed sludge treated in this way will have geotechnical properties that are much better than the seabed marine clay (Chu et al. 2005). One established ratios is to use 77% of sludge, 15% of copper slag and 8% of cement by weight or 54% of sludge, 37.5% of marine clay and 8.5% of cement (Chu et al. 2005). However, this method is only useful when the main purpose is to dispose sewage sludge and other waste materials as the amount of sludge produced each year is not sufficient for the purpose of large scale land reclamation.

![Figure 4. Use of sewage sludge for land reclamation](image)

4 NEUSPACE METHOD

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 Fig. 5. 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 5. New method for land reclamation and underwater space creation](image)

![Figure 6. Installation of large scale concrete cylindrical structures](image)
The large-scale concrete cylindrical structures can be installed using a method shown in Fig. 6 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 a seaport is shown in Fig. 7. Suction caissons can be used for the foundations of the cylinders (Chu et al., 2009b; Yan and Chu, 2010; Liu et al., 2012). However, the use of suction caisson in relatively shallow water is challenging. More research has to be carried out (Liu et al., 2012; Guo and Chu, 2013).

Figure 7. One method for the construction of a sea port using the NEUSPACE method

5 SUMMARY

The challenges and solutions for offshore land reclamation using soft soil and waste materials such as sewage sludge are discussed. A new method for land reclamation in deep water is also proposed.

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