Soft clay properties in a layered clay-sand reclamation

Les propriétés des argiles molles dans la reclamation constituée par des couches d'argile-sable

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SYPNOSIS: An economically viable method of land reclamation, the layered clay-sand scheme, has resulted from a series of research and development works at the National University of Singapore. The scheme replace scarce and costly sand with hydraulically dredged marine clay by sandwiching clay layers between thin sand seams to reduce the drainage path. The key to the success of the scheme is the ability to form a thin sand seam on top of the hydraulically dredged marine clay with minimal sand losses and within a short period of time from the completion of clay filling. This is demonstrated to be feasible in the laboratory through controlled sand penetration experiments as well as in a field trial. The method is now adopted for a 40 ha reclamation at Changi and preliminary results are discussed in this paper.

1 INTRODUCTION

Since 1964, additional land to the extent of approximately 500 ha has been created through land reclamation near the coastal areas of Singapore (Wei, 1983; Ministry of Communications and Information, 1986). The estimated volume of about 400 million cu m involved in these projects comprised hill cut soil and dredged sand (Fig. 1). Due to the depletion of hill cut soil and sea bed sand, it has become necessary to study the use of alternative fill materials for future reclamations.

Figure 1. Extent of land reclamation in Singapore (1964-1986).

The sea bed surrounding the Singapore island has been examined by sonic prospecting with borehole verification and revealed that soft marine clay is extensively deposited to depths reaching 40 m (JICA, 1979). Further, the marine clay which is abundantly available can also be easily dredged by cutter suction dredgers and the clay slurry can be transported more economically than clayey sand or stiff clay (JICA, 1979).

Thus an economically viable alternative method for land reclamation has to rely on the marine clay as fill material. However, reclamations using hydraulically placed soft marine clay require a long construction time. Furthermore, expensive surface treatment is needed before light equipment can be mobilized for normal soil improvement works. As a result, the layered clay-sand scheme, which has been shown to be feasible in a field trial at Pulau Tekong Besar (Lee et al., 1985, 1987a) was developed. This scheme significantly reduces the consolidation time by sandwiching clay layers between thin sand seams to reduce the drainage path.

In a layered clay-sand scheme, the clay slurry is hydraulically pumped into an enclosed containment area with dykes and sedimentation takes place under gravitational and seepage forces. When the clay slurry has reached a certain strength, a thin sand layer can be spread on the surface of the clay slurry. After a sufficient thickness of sand layer has been formed, another layer of clay will be built up in a similar manner while the bottom clay layer undergoes consolidation.

The key to the success of the layered clay-sand scheme is the ability to form sand seams on top of hydraulically dredged marine clay within a reasonable length of time after the clay has been pumped into the containment. This feature has been demonstrated both in the laboratory and the field trial at Pulau Tekong Besar. Based on the experience of the Tekong trial, the layered clay-sand scheme is being used to reclaim 40 ha of land off Changi South Bay, Singpore (Fig. 1).

In this paper, the results of the laboratory studies and the Tekong field trial that demonstrated the feasibility of the layered clay-sand scheme are summarized first. Then the early findings in the reclamation off Changi will be discussed to illustrate problems encountered in a large scale implementation of the scheme and how they can be overcome in order to successfully form the sand seam on top of the dredged marine clay.

2 LABORATORY STUDIES

In a simple sand penetration experiment, sand is spread in thin layers into a cylinder containing clay slurries at different strength represented by the different water contents. The result is shown in Fig. 2. The method for density measurement in very soft clay using Gamma-rays has been reported by Lee et al. (1987b) and Tan et al. (1988). It is clear from this experiment that the sand particles settle to the bottom when the slurry has a water content higher than 270% (ρ = 1.2 g/cc). This suggests that the slurry has some form of strength besides the viscous drag, otherwise all particles will settle to the bottom for any water content. The viscosimeter is then used to measure the shear stress versus strain rate relations for a series of slurries with different water contents and the results are shown in Fig. 3. The results suggest that the slurries behave like a Bingham fluid.

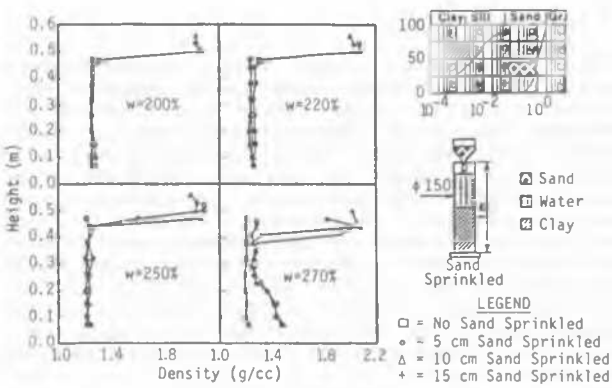

Figure 2. Density profiles from sand spreading experiments.

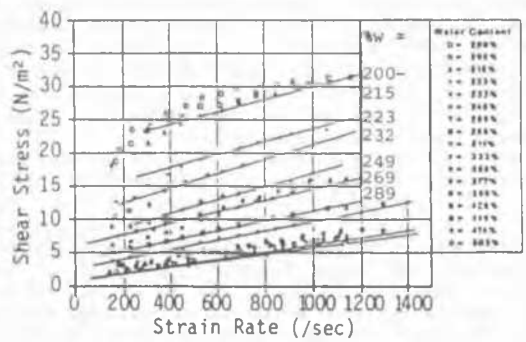

Figure 3. Viscosimetric test results of clay slurries

In Fig. 4, the shear stress at zero strain rate is plotted against water content. This shows that there is a dramatic increase in shear strength when the water contents decrease below 250%, and this is consistent with the observations of the sand penetration experiment where below this, the slurry can support a thin sand seam.

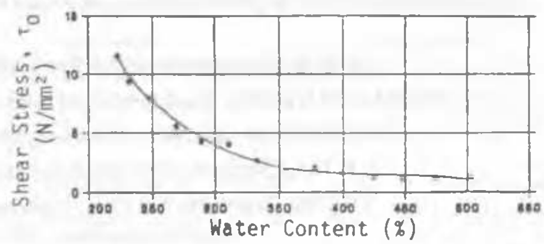

Figure 4. Slurry shear strength at zero strain rate versus water contents.

3 TEKONG FIELD TRIAL

A field trial of the layered clay-sand scheme was completed by 1985 in the reclaimed area of Pulau Tekong Besar. The details of the procedure involved in this trial are given in Lee et al. (1987a). A rectangular test pond with a base of 20 m x 10 m, a side slope of 1(v):2(h) and an effective filling height of 3.7 m was excavated in the sand reclamation for this test.

The schedule of the filling operation, the change in height of each layer with time, and the details of the clay-sand interface are shown in Fig. 5. At the end of clay pumping, a

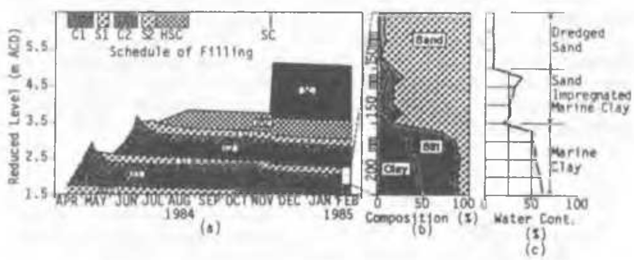

Figure 5. Formation of sand seam at Tekong field trial.

duration of five days was allowed for completion of sedimentation and partial self weight consolidation of the clay fill. At this stage water contents of the clay slurry 10 cm below its surface varied from 170% (ρ = 1.3 g/cc) to 220% (ρ = 1.25 g/cc). Based on the laboratory sand penetration results (Fig. 2), these water contents posed no problem in supporting a thin sand spread of 5 cm. Sand was dredged, hydraulically transported, and uniformly spread throughout the clay surface by winching a discharge float. With this method, a thin sand seam of 4-5 cm thickness was deposited with one pass. A two-day period was allowed for the sand-impregnated surface clay to gain strength to prevent further penetration of sand. The sand spreading was continued in 5 cm thick lifts in two to three days until the total thickness of sand reached about 30 cm forming the first sand layer, S1.

The particle size distribution at the clay-sand interface is shown in Fig. 5(b) and the water content variation in Fig. 5(c). During the spreading of sand to form the first thin seam, most of the coarser sand particles penetrated to a depth of 15 cm into the soft clay, leaving behind the finer sand particles trapped above. The surface layer of the clay, which was impregnated with sand, gained sufficient strength to support the subsequent sand grains with reduced penetration. Eventually a "clean" sand layer of about 15 cm thick was observed above the sand-impregnated clay layer of 15 cm as shown in Fig. 5(b). Clearly this trial demonstrates that a sand seam can be formed on top of a sedimented hydraulically pumped clay. The success of this trial led to the authority's decision to adopt the scheme in a 40 ha reclamation off Changi South Bay.

4 CHANGI SOUTH BAY FIELD TEST

The 40 ha reclamation off Changi South Bay was begun in early 1988. The area is divided into two large compartments labelled as "A" and "C" of about 10 ha each formed by a central dyke, two parallel sub-dykes and a seafront dyke as shown in Fig. 6. After the laying of the sea-bed sand blanket, each compartment has an average effective filling height of about 5 m. For "C", the intention is to form two hydraulically dredged marine clay layers sandwiched by a sand seam and a sand topping above the second marine clay layer. For "A", the first marine clay layer is mechanically dredged and dumped into the deeper sections A2 and A3, followed by forming a sand seam before filling the second marine clay layer hydraulically, above which will be formed the final sand topping. Work in "C" began earlier as two layers of clay were required, therefore only the preliminary results of "C" will be discussed in this paper.

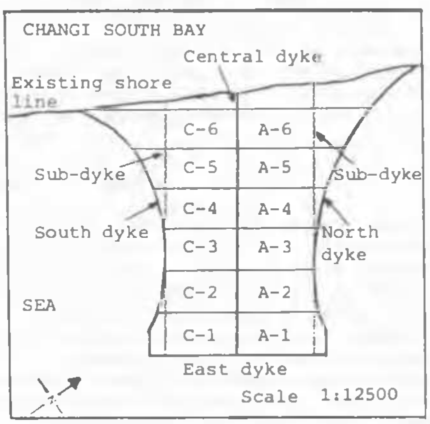

Figure 6. Schematic plan of Changi reclamation site.

5 FIELD OBSERVATIONS

5.1 Particle segregation effects

The first marine clay layer in compartment "C" was hydraulically pumped over a period of one month from one discharge point only near the central dyke located in the vicinity of C1. This is unlike the Tekong trial where the marine clay is spread uniformly over the area. Discharging the clay from one point has the consequences of segregation of coarse materials from the fine clay with distance from the discharge point. This leads to a slower rate of sedimentation and hence slower improvement in density and strength for the clay in the sections further away from the discharge point.

Indirect evidence of this segregation process is obtained from both gamma-ray density measurements and slurry samples taken from different locations of the pond at the same time.

The slurry samples results taken from section C1 and C3, 15 days after the end of clay filling are compared in Fig. 7. It is clear that the clay in section C1 right in front of the discharge point is denser than the clay in section C3, located 200 m away from the discharge point. After 15 days of sedimentation and self-weight consolidation, the clay in C1 has an average density of 1.35 g/cc (w = 145%) whereas the clay in C3 has an average density of 1.14 g/cc (w = 400%). It is quite clear that this significant difference in density is due to segregation, the coarse particles in section C1 resulting in a denser slurry while section C3 being further away contains the finer particles. This is similar to segregation in mine tailings.

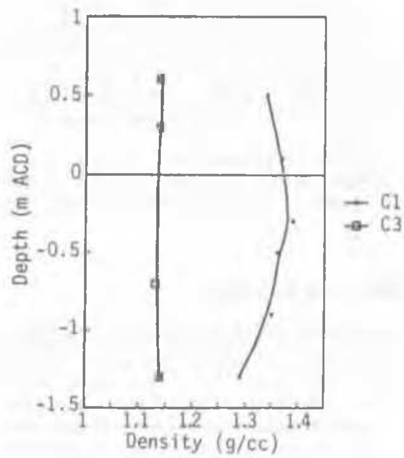

Figure 7. Density from slurry samples 15 days after clay filling.

5.2 Sand penetration in clay

About 20 days after the end of clay pumping measurements in C2 indicates a surface density less than 1.2 g/cc (w = 280%) to a density of 1.3 g/cc (w = 170%) about 1 m below the surface (Fig. 8). At this stage, sand spreading commenced with the first lift 5 cm thick. The density profile is shown in Fig. 8. It is clear that the sand is formed above 0.5 m ACD where the water content is about 250%. This is consistent with both the laboratory and Tekong field observations. In the next lift, 10 cm sand was spread and it seemed that the sand

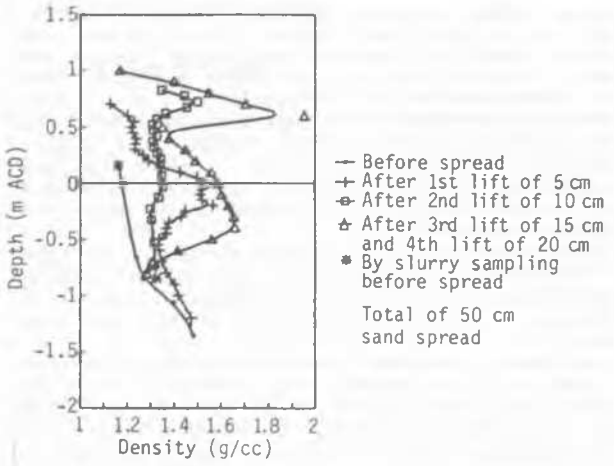

Figure 8. Density profiles of C2 after various sequences of sand spreading.

layer was formed at a point where the water content is about 220% to 250%. Thus even at this early stage, the sedimented clay has gained sufficient strength to prevent the penetration of 10 cm of sand. Because of operational constraints, the density measurements after the 3rd lift of 15 cm was not carried out. In the final lift, 20 cm was spread. Fig. 8 shows that a large proportion of the sand has penetrated the clay and stopped at around -0.5 m ACD. Thus, even after 3 lifts of sand, the gain in strength was insufficient to prevent penetration. This suggests that in order to form a sand layer, sand must be spread in thin layers, as in the successful Tekong trial.

However, these results also clearly demonstrate that sand layers can be formed and the critical water content is around 220% to 250%.

6 SUMMARY AND CONCLUSIONS

Research done by the geotechnical group at the National University of Singapore has led to the development of the layered clay-sand scheme as an alternative method for land reclamation. The scheme uses a cheap and easily available fill material, marine clay, but significantly reduces the consolidation time by sandwiching the clay layers between thin sand seams to reduce the drainage path. The key to the success of the layered clay-sand scheme is the ability to form sand seams on top of hydraulically dredged clay within a short time after the clay has been pumped into a dyke containment.

This has been shown to be feasible in both laboratory tests and a field trial. However, the marine clay must be allowed to gain sufficient strength before thin sand layers are spread. The critical water content where tests show a dramatic increase in shear strength is about 220% to 250%.

The preliminary results of the reclamation at Changi has validated some of these observations but also highlights other problems. One of these is the disadvantages of pumping from one point, though it is more economical. For a large project, pumping from a point results in segregation which can cause problems for areas far from the source due to the presence of finer particles.

Secondly, the preliminary results also affirm the importance of spreading in thin sand layers. When sand is spread in 5 or 10 cm, the results clearly show the gradual formation of the sand layers. However, when 20 cm is spread, a large proportion penetrated the clay and settled. The preliminary results concur with both the Tekong field trial and laboratory tests that the water content of the clay must reach 220% to 250% before thin sand layers can be spread.

The preliminary results have clearly shown that the conclusions of both the laboratory tests and the field trial are valid even for a large project. There are two critical factors that will ensure the success of the method. These are the need to wait for the marine clay to gain sufficient strength and to spread sand in thin layers initially.

ACKNOWLEDGEMENTS

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