Indonesian Geotechnical Journal, December 2023, Vol 2 (3). Page 159 - 168
DOI: https://doi.org/10.56144/igj.v2i3.67
E-ISSN:2829-7520
https://indonesian-geotechnical-journal.org/index.php/JGI/issue/archive

Ground Improvement and Monitoring for a Reclamation on Reclaimed Soft Soil in Singapore

Patrick Mengé[1], Thomas Vergote[1], Johny Van Acker[2], Handojo Ronald Yohanson[2]
[1]DEME, Activity Line Dredging, EDT Department, Geotechnical Division, Belgium
[2]DEME Group Indonesian branch, Jakarta, Indonesia
*Correspondence: menge.patrick@deme-group.com

SUBMITTED 18 August 2023 **REVISED** 21 August 2023 **ACCEPTED** 01 September 2023

ABSTRACT Land reclamation works for land development and harbor construction generally require large amounts of sand. At the same time the dredging of access channels, berth pockets and turning circles for shipping may generate both, 'suitable' and 'unsuitable' dredged sediments. The definition of suitable in general focusses on well compactable granular material with a low fines content. However, in the present times of environmental awareness and search for sustainable solutions, the offshore dumping and disposing of 'unsuitable' fine-grained material is not deemed sustainable anymore. In this paper the Tuas Terminal Phase 1 (TTP1) in Singapore will be discussed. All dredged soft clay and residual soils were used in the reclamation and capped with a layer of limited thickness of clean sand. To achieve the design requirements, ground improvement by means of surcharge with prefabricated vertical drains (PVD's) was performed. To demonstrate the effectiveness and results of the ground improvement works, extensive monitoring by means of settlement beacons and clusters of extensometers and porewater pressure meters was setup. Even on-site developed 'floating' piezometers were developed to monitor the consolidating slurry. The execution of these works required adapted execution and advanced design methods. The design and prediction of the behavior of the sediments during improvement and on the long term was a challenge. The correct prediction of deformations and the level of the soft soil-granular soil interface was important to guarantee the correct sand cap thickness after ground improvement. The long-term behavior after overconsolidation through ground improvement was studied in detail. This has led to the development of a more correct prediction method to estimate the secondary settlements of PVD-improved overconsolidated soft soil. The reclamation of the TTP1 terminal proved to be a success where stringent design requirements were met while re-using 'unsuitable' material and minimizing the import of clean sand.

KEYWORDS Ground Improvement; Vertical Drains; Monitoring; Land Reclamation; Dredging; Re-use of Dredged Sediments; Sustainability

1 INTRODUCTION

1.1 Project Description

In the South-West of Singapore, a major container terminal is being built with in total 4 'fingers', that will result in a the Tuas container port with a capacity of in total 65M TEU's. The Tuas Terminal Phase 1 project consisted of the construction of the second finger, representing the land reclamation of a new platform for a large container terminal, the construction of a caisson quay wall and the dredging of the adjacent basins and fairway. In figures, a total volume of 67Mm³ had to be dredged, 8.6km quay wall had to be built (221 caissons, 21 berths) and 88Mm³/415ha land had to be reclaimed. The water depth along the quay is about 20m with a final level of the terminal at +6m CD. The terminal is designed for a volume of 20 million twenty-foot equivalent units (TEUs) per annum.

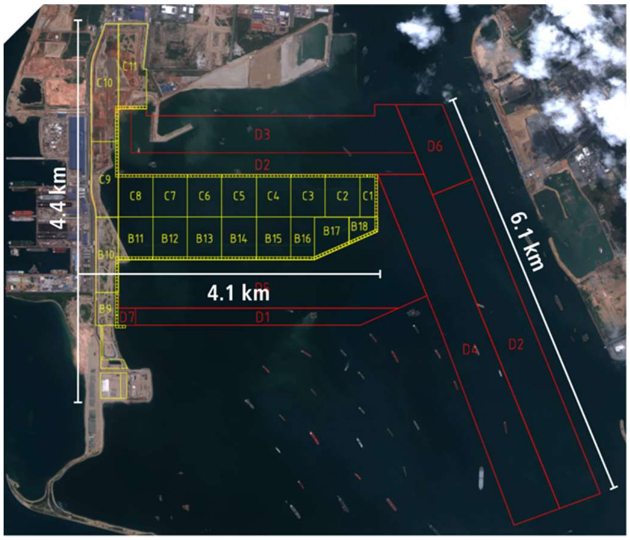

Figure 1. TTP1 Layout of the works

As from the start, the goal was set to re-use the dredged material from the dredged basins and fairway and 'good earth' from land-based sources. The use of clean sand, to be imported from sources outside Singapore, had to be minimized. As such, the total fill depth of about 26m, mainly consisting out of dredged silt and clay with a sand cap on top.

1.2 Geological / Geotechnical Information

The soil conditions in the Tuas area in Singapore consists of limited deposits of marine clay over residual soil of the Jurong formation. The residual soil consists of sandstone, mudstone, shale, tuff, conglomerate and limestone, (Leong et al. 2003). Due to its tectonic induced deformations the layering may vary strongly from point to point. The in situ strength of the weathered layers is defined by means of the SPT blowcount N. In general, an increase with depth is observed, although sometimes a softer layer can be found under a stiffer one. Figure 2 gives the soil layering as used in the geological model. Under the caisson, all material up to N=50 (undrained shear strength S_u = 250kPa) had to be removed and replaced by sand. In the basins and fairway, deeper dredging was required or the hard layers occurred at a higher level. In Figure 2 it is also indicated how the material was re-used.

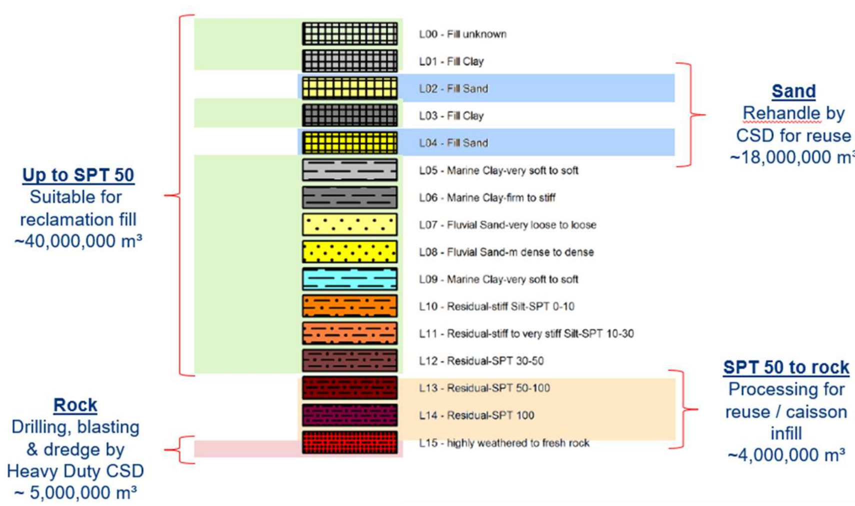

Figure 2. Typical soil layering on the project site, from the geological model prepared.

1.3 Material to be Used

The dredged material from the Jurong formation with N < 50 is very sensitive for disturbance and after dredging easily disintegrates in a soft slurry and a limited volume of lumps and stones. The prediction of the ratio disintegration into slurry versus harder material is difficult and requires a good knowledge of the material, the effect of dredging and reclamation methods.

The slurry material has a fines content (% particles < 63micron) varying from about 30% to 100% and a plasticity index of about 15% (PL≈22%; LL≈37%), mainly indicating silt behavior. Such material also exhibits a relatively fast consolidation under its own weight and under any limited fill, resulting in strength increase. Typically, densities starting from 1.3 t/m³ increase relatively fast to 1.6t/m³. But at the same time, such silt material has a low shear strength, even at relatively high density. This clearly differs from clay slurry behavior.

Only a limited volume of marine clay had to be dredged and when dredged mechanically, this formed lumps that did not disintegrate similarly to the weathered Jurong formation.

2 EXECUTION METHODS

As the subsoil consisted of weathered residual soil, at several locations along the footprint of the quay wall, soft material had to be removed and replaced by well compacted sand in order to guarantee the required bearing capacity. This technique of sand replacement under a structure is also called a ‘sand key’. The dredging of the sand key was done with grab dredgers (GD), as well as most of the dredging of the basins and fairway. Some dredging (hard rock outcrops) was realized with a cutter suction dredger (CSD) and even drilling and blasting; the rest of the dredging was realized with a Trailing Suction Hopper Dredgers (TSHD).

Figure 3 shows the cross section of the quay structure with sand key below (where necessary and varying depth) and sand fill behind the caissons. Also, the reclamation fill with ‘unsuitable’ material and capping is shown in this figure. The capping was maximized to a level of +4m CD, before ground improvement. Good earth from land based sources was used for the construction of bunds to contain the reclamation fill and to realize the top surface.

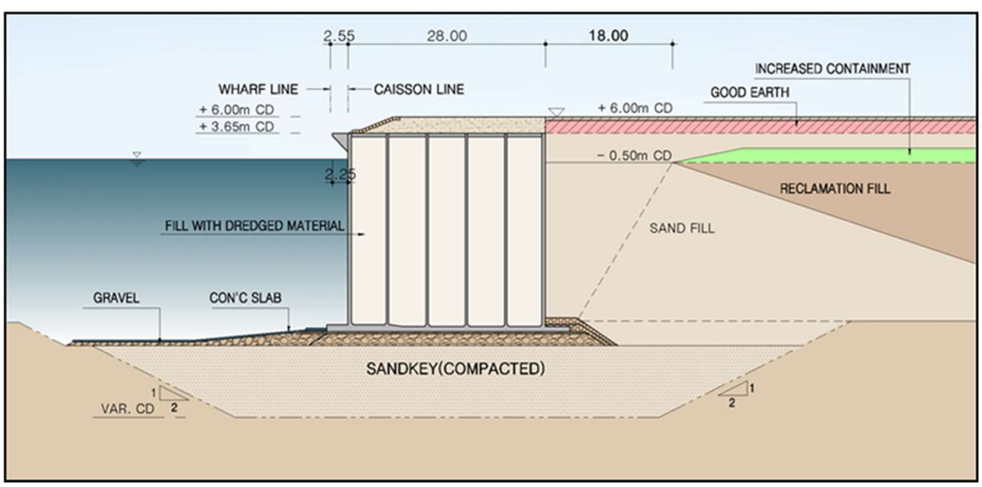

Figure 3. Cross section of quay wall and reclamation

To bring the dredged material up to the given level, different techniques were used: a reclaimer barge with 50m long conveyor belt, hydraulic filling with the TSHD and dry earth movement. As described in section 1.3, especially the heavily weathered soil disintegrated into a silt slurry which formed the top layer of the reclamation fill. Deeper the reclamation fill consisted of lumps of (non-disintegrated) dredged material, installed by means of direct dumping and reclaimer barges.

Once the final level with the reclamation fill was reached, the capping with sand became the main challenge. This was realized with sand slingers, fast rotating conveyor belts that were able to ‘project’ the sand to a distance of about 25m on top of the very soft silt slurry. This way, very thin layers of sand were realized. When allowing sufficient time in between layers, a stable fill was realized minimizing squeezing of the soft material. A specific execution procedure was worked out (practically and numerically) to guarantee a stable and safe working platform moving forward over the soft soil.

Figure 4. Sand slinger in action.

3 DESIGN CHALLENGES

3.1 Design Requirements

The reclamation design requirements were defined by client and consisted of well-defined loading and allowable long-term deformations for reclamation and caissons. The long-term deformations for the reclamation were very stringent: maximal 40mm residual settlement over 60y. This required a ground improvement technique with important preloading or surcharge. However, as good as a predictive design can be, this always needs to be checked during execution via monitoring and calibration of the design method.

3.2 Design Challenges

The ground improvement consisted of a surcharge with 180kPa, equivalent of about 10m sand fill. In order to accelerate the consolidation of the soft layers, PVD’s were used (Figure **5**). The PVD installation grids were defined based on the defined and assumed soil parameters for respectively the natural soil layers and the fill material. But as described, the soil conditions of the reclamation fill were difficult to predict exactly, so extensive monitoring was required.

Another reason for the need of a correct settlement prediction was that the level of the interface sand capping material and unsuitable fill in final stage (i.e. after full ground improvement), had to be between well-defined levels. This to limit the volume of clean sand needed for the project. In dredging industry, the ‘bulking’ (i.e. the volume change between the volume of material in situ and the material in the reclamation) of material is a constant point of attention and needs to predicted well. This, however, was difficult with the material at hand here; the slurry initially has a very high bulking factor while this changed importantly with self-weight consolidation and under the effect of surcharge.

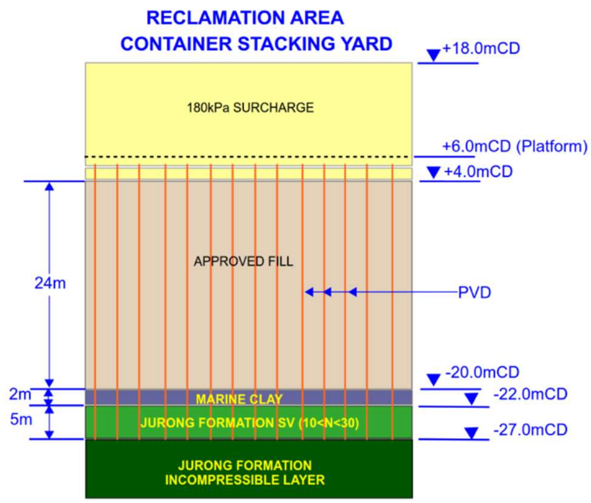

Figure 5. Typical profile for reclamation ground Improvement design

This has led to a few important design tools that were developed on site:

- Detailed understanding of the large strain consolidation and strength gain of the soft material during self-weight consolidation and further forced consolidation (Vergote and Mengé 2015);
- In situ monitoring of the self-weight consolidation (see section 4);
- Development of automatic settlement prediction starting from CPT's, including back-calculation and parameter fitting from monitoring (see section 5.1);
- Development of a theoretical base for the more correct prediction of secondary settlements for overconsolidated soft sediments (see section 5.3);
- Development of calculation methods taking into account multiple layers with or without vertical drains, a variable surcharge and variable water levels.

To this aim, lots of in situ testing was done and monitoring instruments were installed:

- Over 200 boreholes with over 2000 samples and lab testing;
- Over 5000 CPT's on land and marine;
- Over 400 monitoring instrument clusters (extensometers and piezometers);
- Over 1500 settlement beacons;
- Weekly topographical monitoring.

4 MONITORING

The contractually required monitoring consisted of settlement beacons, extensometers and porewater pressure meters. This together with extensive CPT testing and boreholes with sampling allowed to characterize the reclamation fill completely and, via back-calculation, to calibrate the material parameters.

Final primary settlement prediction could be realized from the settlement measurement (Asaoka method, (Asaoka 1978), hyperbolic method, (Tan et al. 1991), numerical fitting).

While not contractually required, additional monitoring techniques were used because of the need to predict at an early stage the behavior of the very soft, still fluid-like non accessible fill. This included topographical surveys by means of drones and in-house developed 'floating piezometers'. The drone survey allowed to follow up the self-weight consolidation via settlement estimations and this also allowed to obtain more correct volume balances between dredging and reclamation, a task that becomes rather difficult due to the large and varying bulking that can occur. The floating piezometers, (Vergote 2021) were used to follow the self-weight consolidation via the monitoring of porewater pressures within the consolidating mass, starting from a 'heavy liquid' evolving to a soil skeleton structure with hydrostatic porewater pressure. Such monitoring allowed to know the state of the silt deposit (density, degree of self-weight consolidation, shear strength via correlations) and was needed to predict its behavior upon capping and further filling.

Finally, it needs to be mentioned that for a project with the size of TTP1 a very large amount of data is produced, and this needs to be made available to all parties involved, reported, used for back calculation and for supporting the project management in their decisions. Such task becomes impossible without a good data management plan. While commercial software is available to store the data and produce reports, most commercial software lacks the possibility to link the database directly to calculations and data selection and presentation which needs to be geo-referenced. To do this, it was decided on this site to set up an inhouse database system in PostGIS using a Python framework that allowed to develop all the required reporting and calculations in house as required, (Vergote 2019).

5 RESULTS

5.1 Settlement Monitoring and Settlement Prediction

As an example of data management and fitting, the settlement monitoring and settlement prediction can be illustrated. Settlements were measured by means of settlement beacons, extensometers and drone surveys. The combination of these needed an evaluation of reliability and when needed a correction of the erroneous/unreliable data.

The degree of consolidation and final settlement is typically defined based on an evaluation of the settlement beacons with the Asaoka method and/or the hyperbolic method. Apart of the forementioned settlement information, also the loading (filling) and surcharge history needs to be known. Such information can be obtained from the surveys.

In Figure **6** the settlement prediction (uncorrected) and the really measured settlement data is shown for a limited zone of the work. Each black dot references a monitoring cluster and associated CPT. With uncorrected, is meant that this is the prediction before any monitoring, based on tender data, further soil investigation and an estimation of the fill material parameters. Although in general the order of magnitude is good, at some locations a clear difference can be found. By combining all available geo-referenced data the local layering and parameters as defined from boreholes and CPT's can be extracted from the database, as well as the filling and loading history. A new settlement prediction can now be made. In Figure **7** the result of an extensometer with the calculated settlements is shown before and after calibration. Integrated settlement and consolidation predictions with the real surcharge history and highly variable soil layers was done using an in-house axisymmetric consolidation model, (Vergote et al. 2019).

The application of such approach for one instrument may be possible by hand, but the application of such approach for all information coming available on the whole project can only be done by means of a powerful geotechnical database and software using this data. It also allows continuous update of the predictions while extra information comes in.

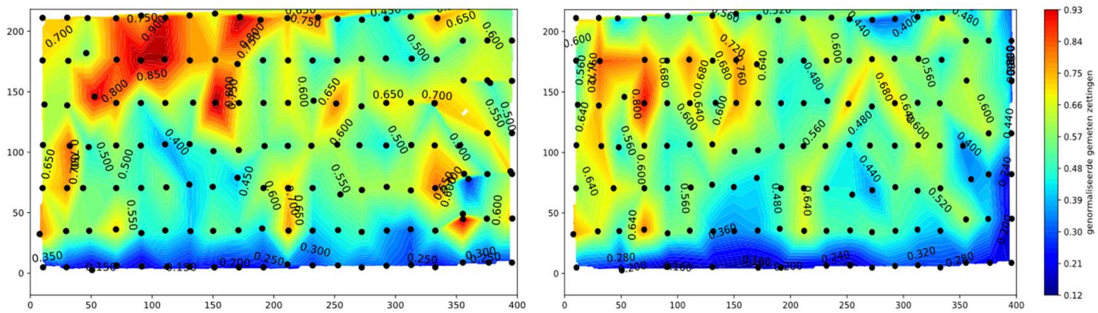

Figure 6. Settlement prediction (left) versus measurement (right)

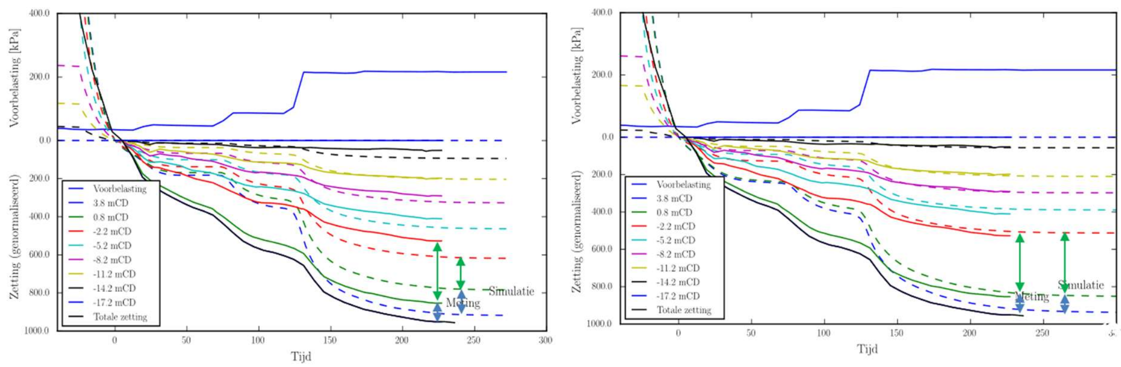

Figure 7. Extensometer measurement and settlement prediction per layer, left before calibration of the calculation model and right after calibration of the calculation model

5.2 Floating Piezometers

To enable real-time and high quality feedback of the sedimentation and consolidation process of the soft silt, a new pore pressure measurement device was developed, (Vergote 2021) . The devices were deployed in the middle of the large reclamation areas (**Figure 8**). Thanks to the measurements, the changes in water levels, volume weight of the soil and excess pore pressures could be estimated (**Figure 9**). These measurements were then adopted to optimize the use of the soft cohesive soil while ensuring the performance of the reclaimed land. In addition, long-term predictions could be made more reliably by calibrating the large strain consolidation models with such measurements.

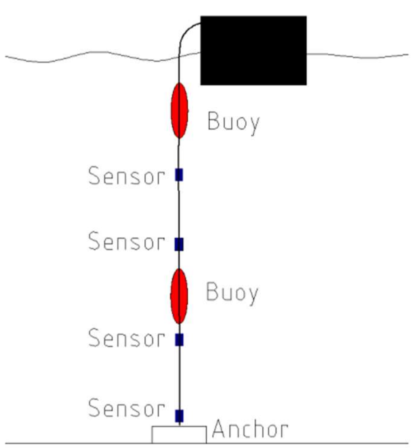

Figure 8. Sketch of the deployed sensors over depth with anchor and buoys

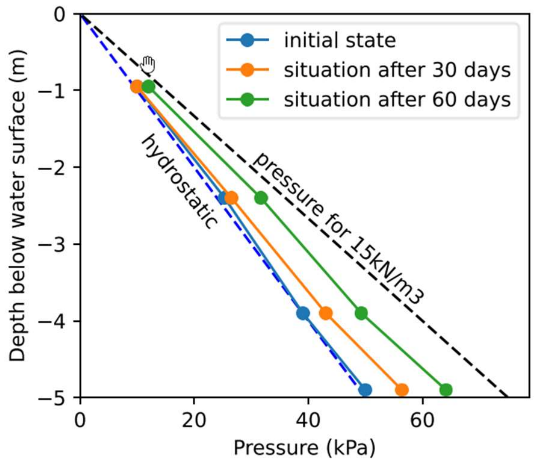

Figure 9. Example of pore pressure measurements over depth

5.3 Prediction of Long-term Creep of Overconsolidated Soft Soil

To ensure long-term performance of the reclamation with soft dredged soils, a good understanding is needed of the complete life cycle of the soil, from a very soft slurry to an improved stiff soil. Important time and (large) strain effects cannot be ignored, and in particular viscous effects play a significant role in the form of creep and (secondary) swelling. An extensive study was set-up in collaboration with the National University of Singapore to create a more accurate model of the behavior of the improved soil (Vergote 2020).

Laboratory tests were set-up to improve a soil from a slurry state to a strong overconsolidated soil, with load- and rate-controlled loading and unloading. When a soil is unloaded after soil improvement, elastic swelling, viscous swelling and creep reappearance is observed, strongly dependent on the overconsolidation ratio, see Figure 10. An isotache-like approach (Leroueil 2006) was adopted with non-linear isotaches which are distorted after unloading (Vergote et al. 2022). The model can be used in a simplified form to predict creep only, in a decoupled single-stage model (the C+S model) or as a fully coupled multi-stage FDM model (Vergote et al. 2021).

The experimental and numerical work shows that creep can be reduced significantly by preloading the soil. An OCR above 1.4 leads to very small creep occurrence, while preloading beyond this level will lead to larger long-term swelling. The most optimal preloading design will depend on the design life of the structure, the acceptable deformations and the properties of the soil. For the TTP1 project, long-term creep deformations where drastically reduced thanks to the extensive soil improvement, well within the acceptable residual settlements.

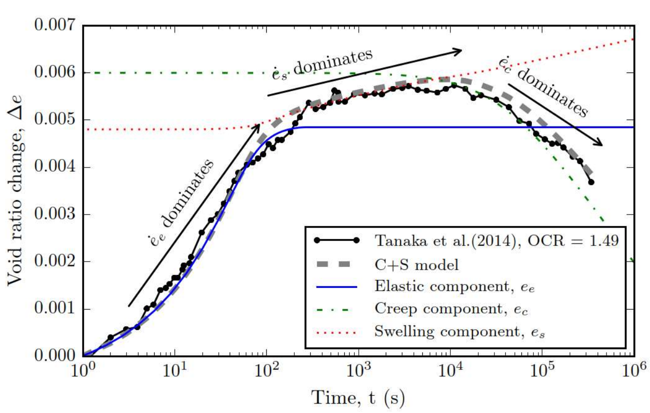

Figure 10. Illustration of reaction of soil to unloading

6 CONCLUSION

The TTP1 project was a major dredging and reclamation project where soft soil was used as a reclamation material. The main reason for this was sand saving in the first instance, but in these times of extra environmental awareness, this technique gets more and more attention. Very often there is doubt about the achievability and final result, a position that is mainly based on long term experiences with 'clean sand' only. This project has proven that a reclamation with soft silt and clay material is possible and clearly bearing capacity and long-term deformations can be within acceptable limits.

Execution-wise such reclamation requires a different approach and alternative techniques need to be used. Also, this has proven to be possible, with a successful result.

A large challenge lies in the field of the theoretical approach of such a work. First of all, the material that will end up in the reclamation is not fully known and assumptions have to be made. Subsequently, the really realized fill needs checking and its behavior needs to be monitored extensively. Based on this, the final behavior can be predicted correctly. This requires additional theories such as large strain consolidation analysis and advanced methods of secondary settlement prediction.

REFERENCES

Asaoka, A. 1978., Observational procedure of settlement prediction. *Soils and Foundations*, 18 (4), pp. 87–100.

Leong, E. C., Rahardjo, H., & Tang, S. K., 2003. Characterisation and engineering properties of Singapore residual soils. *Characterisation and engineering properties of natural soils*, 1, pp. 1279–1304.

Leroueil, S., 2006. The isotache approach. Where are we 50 years after its development by Professor Šuklje? (2006 Prof. Šuklje's Memorial Lecture). *Proceedings of the 13th Danube-European Conference on Geotechnical Engineering; Ljubljana,* 1*,* pp. 55–88.

Tan, T.S., Inoue, T., & Lee, S. L., 1991. Hyperbolic Method for Consolidation Analysis. *Journal of Geotechnical Engineering*, 117(11), pp. 1723–1737. https://doi.org/10.1061/(ASCE)0733-9410(1991)117:11(1723).

Vergote, T., & Mengé, P., 2015. Application of large strain consolidation theory in soft soil reclamation. *Advances in Soft Ground Engineering*, C. F. Leung, T. Ku, and S. C. Chian, eds., pp. 978–981. Singapore: Research Publishing

Vergote, T. A. 2019. Automatische verwerking van grote hoeveelheden data en parameter fitting voor grondverbeteringswerken met PostGIS en Python scripts. *Geotechniek*, (November).

Vergote, T. A., Leung, C. F., & Chian, S.C., 2019. Finite difference consolidation modelling to interpret piezometer data. *International Conference on Case Histories & Soil Properties 2019*. Singapore.

Vergote, T. A. 2020. Deformation of soils: time and strain effects after unloading. National University of Singapore.

Vergote, T. A. 2021. A Wireless Solar-Powered Pore Pressure Sensor For Monitoring Of Hydraulically Dredged Sediments Used In Land Reclamations. *7th International Symposium on Sediment Management*. Lille, France.

Vergote, T. A., Leung, C. F., & Chian, S. C., 2021. "Elastoviscoplastic modelling with distorted isotaches and swelling for constant strain rate and incremental loading." *Int J Numer Anal Methods Geomech*, 45 (13), pp. 1920–1933. https://doi.org/10.1002/nag.3248.

Vergote, T. A., Leung, C. F., & Chian, S. C., 2022. Modelling creep and swelling after unloading under constant load and relaxation with Bayesian updating. *Géotechnique*, 72 (6), pp. 496–509. https://doi.org/10.1680/jgeot.20.P.106.