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Optimizing soil improvement works for soft soil reclamation based on a PVD trial area and numerical back-calculation

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ABSTRACT: Performing land reclamation works by dredging and hydraulic fill placement of soft soils presents significant engineering challenges. These engineering challenges include volume change over time (bulking), stability, accessibility, and settlements. Typically, soil improvement is required to meet geotechnical criteria for such reclamation projects.

This paper discusses a project in Italy where a reclamation was constructed using hydraulically pumped soft soil from dredging works. To design for optimal conditions while considering various boundary conditions, a trial area for soil improvement was established. This involved the installation of surcharge in combination with prefabricated vertical drains (PVDs) in different configurations. In the trial area, PVDs were installed in three different configurations, varying in length and spacing. Subsequently, a surcharge of 100kPa was applied and left in place for several months. Data was collected using various monitoring instruments, including borehole and lab testing, Cone Penetration Testing (CPT), multipoint magnetic settlement monitoring, piezometers, horizontal profilometers, settlement plates, and inclinometers. The measured data served as input for calibrating an axisymmetric finite difference consolidation model. Based on the outcome of the calculation model, the optimum soil improvement layout could be selected.

KEYWORDS: Land reclamation, Soft soils, Observational method

1 INTRODUCTION

Following the completion of a hydraulic land reclamation project serving as extension of port facilities, a comprehensive soil improvement campaign is planned to ensure the long-term performance of the port facilities. As part of the design process, a trial embankment has been constructed to evaluate the behavior of the hydraulic fill under controlled loading conditions, similar to the operational loading conditions. The data obtained from the trial embankment will be used for detailed design of the soil improvement.

2 SOIL IMPROVEMENT

2.1 *Preloading in combination with surcharge*

The objective of the soil improvement works is to mitigate post-construction settlements to acceptable levels during the operational phase of the port facilities. To achieve this, a ground improvement design is made that combines preloading with the installation of prefabricated vertical drains (PVDs).

The underlying principle of this technique is to apply a temporary surcharge load that induces settlements, while the PVDs significantly reduce the drainage path, leading to shorter consolidation times. This makes it possible that the induced settlements will occur during the construction period and that the residual settlements are acceptable for safe port operations.

The design variables in the soil improvement method area:

- The magnitude of the preload
- The grid spacing and installation depth of the PVDs
- The duration of the consolidation period

2.2 *Boundary conditions*

The original seabed level at the project site ranges in between -3.0m to -4.0m local datum. During the hydraulic reclamation process, this ground level was raised to an average elevation of +4.50m local datum. The preload embankment will be constructed from +4.5m to +10.0m local datum, corresponding to the loading conditions of 100kPa. The trial area is divided into 3 tests fields:

- Field 1: PVD spacing of 2.5m, installation depth 10m (from +4.5m to -5.5m)
- Field 2: PVD spacing of 3.0m, installation depth 10m (from +4.5m to -5.5m)
- Field 3: PVD spacing of 2.0m, installation depth 6m (from +4.5m to -1.5m)

These trial configurations are selected based on commercial and technical aspects. Note that the penetration of the PVDS into the natural subsoil is limited as the original seabed is situated around -3.0 to -4.0m local datum. Meaning that test field 1 and test field 2 slightly penetrates in the natural subsoil, while test field 3 only allows for partial drainage in the fill material.

2.3 *Monitoring*

For each test field, a comprehensive amount of soil instrumentation is foreseen, see Figure 1. In this article the focus will be the interpretation of the horizontal settlement tubes (horizontal profilometer) situated at the bottom of the preload. These measurements will be used for back-calculating the in-situ soil characteristics. Meaning the finite difference model will be calibrated on these data. The results for the magnetic settlement monitoring will be used as an independent verification of the obtained calibration. The results of the inclinometers will not be discussed in this article, as the stability of the preload was not a critical issue during the preload period. The piezometers will not be discussed as no continuous measurements were obtained. The settlement plates were installed at the top of the preload, measuring the settlement of the subsoil and densification of the preload. The intention of the article is to discuss the soil improvement of the subsoil and therefore also the results of the settlement plates will not be discussed.

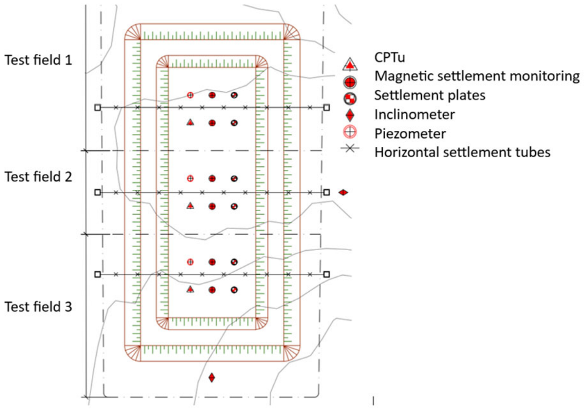

Figure 1: Monitoring layout.

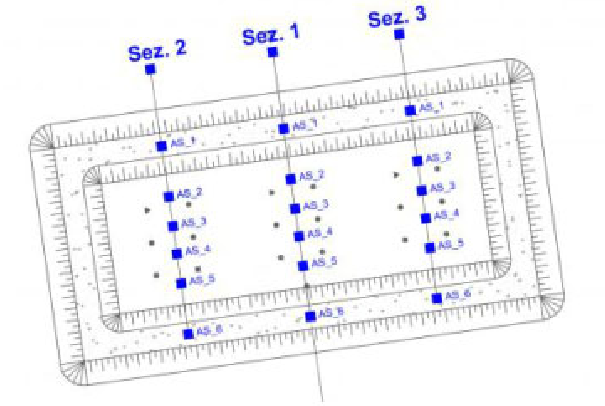

Figure 3: layout of the testing.

3 HORIZONTAL SETTLEMENT TUBES

3.1 *Configuration*

This equipment allows to monitor the settlements at different locations along the trajectory of the profilometer. The configuration of the settlement tubes is given in Figure 2. The locations (AS_1, AS_2, AS_3, AS_4, AS_5 & AS_6) of the monitoring points are given in Figure 3, whereby:

- Sez. 2: PVD spacing 3.0m x 3.0m, PVD length 10m
- Sez. 1: PVD spacing 2.5m x 2.5m, PVD length 10m
- Sez. 3: PVD spacing 2.0m x 2.0m, PVD length 6m

Due to the test layout of the preloading, the full loading of the surcharge will only be felt by locations AS_3 & AS_4. The other locations will always be influenced by the slopes. Meaning that the loading conditions at the locations AS_1, AS_2, AS_5 & AS_6 will be smaller than 100kPa.

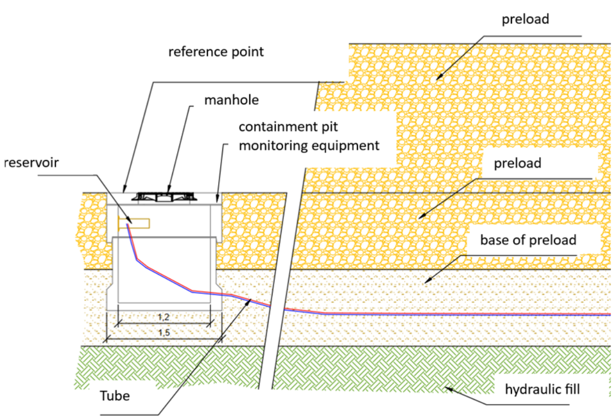

Figure 2: Configuration settlement tubes.

3.2 *Test results*

The results, settlement in time, for test locations AS_3 and AS_4 are plotted in Figure 4 and Figure 5, respectively. In every figure a distinction is made between the different PVD configurations. According to the consolidation theory, the ultimate settlement is not influenced by the spacing or the length of the PVDs. The grid spacing only shortens the drainage path, leading to a faster consolidation speed. This is more or less supported by the data as the magnitude of the primary settlements is more or less equal over the different grid spacings. However, the largest total settlement is observed for the PVD spacing of 3.0 by 3.0m. This deviation is likely to be attributed to local variations in the geotechnical properties of the fill material, locally a slightly more compressible material can be present due to the local heterogeneities of hydraulic fill.

The degree of consolidation, expressed as the ratio of settlement at time t to the final settlement is plotted in Figure 6 and Figure 7. These figures confirmed that the highest degree of consolidation occurred with the densest PVD grid (2.0 x 2.0m). Note that the densest PVD grid spacing goes with shorter PVD's length leading to partial drainage in the fill layer as the hydraulic fill layer thickness is constant. This finding, densest spacing gives fastest consolidation, is consistent with theoretical expectations. The difference in degree of consolidation between grid spacing 3.0m and 2.5m is less pronounced. This has probably to do with the initial site conditions. Evidence of early swelling is suggested by measurements, but this may have been caused by construction activities.

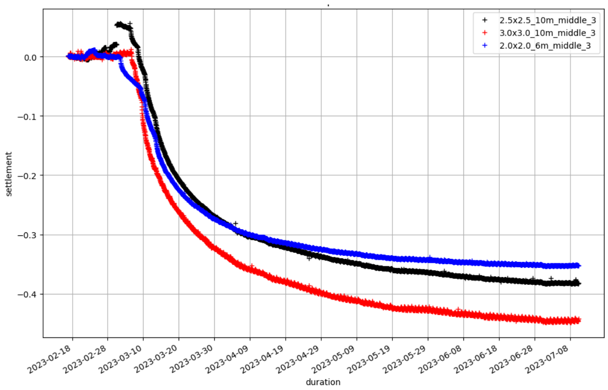

Figure 4: Test location AS_3.

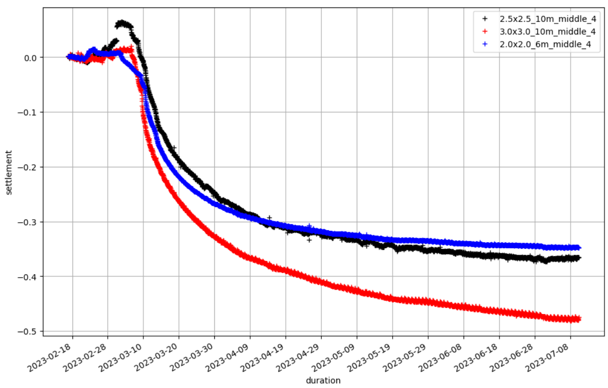

Figure 5: Test location AS_4.

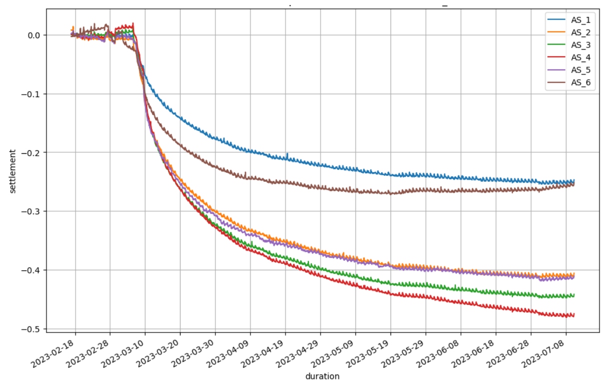

Figure 8: Profilometer grid spacing 3.0m x 3.0m.

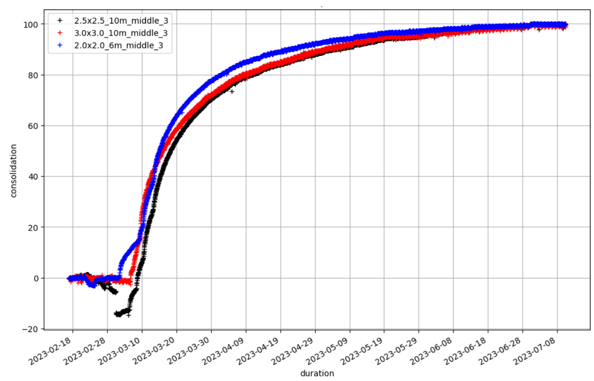

Figure 6: Degree of consolidation AS_3.

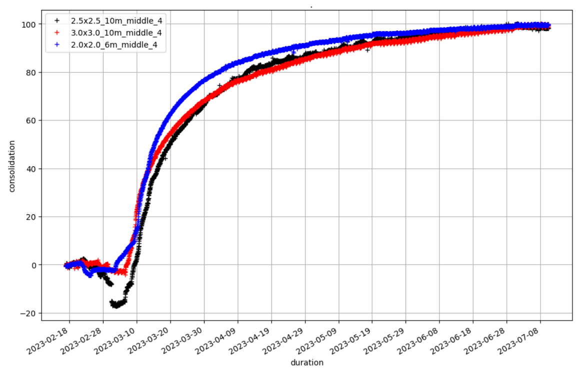

Figure 7: Degree of consolidation AS_4.

Figure 8 presents time-dependent settlement profiles for various locations along the trajectory in the test field of the 3.0m by 3.0m grid spacing. As the magnitude of the settlement is linked to the fill conditions and the surcharge magnitude, it is expected that for the same fill conditions the final settlements increase with increasing load conditions. This is confirmed by the data:

- Smallest settlement: AS_1 & AS_6 – smallest preloading due to slope of the preloading
- intermediate settlement: AS_2 & AS3 – intermediate preloading due to slope of the preloading
- largest settlement: AS_4 & AS_5 - largest preloading, 100kPa

4 OBSERVATIONAL PREDICTION

The Asoaka method (Asaoka 1978) is used to predict the final settlements. Based on the measured settlement and the obtained final settlement, the consolidation degree can be calculated. In the Asoaka method settlements measured at equal time are plotted versus time. Using the settlement values measured at equal time intervals Δt, the graph between s_i and s_{i-1} can be plotted and the straight line can be fitted. As a standard practice, the initial erratic value (if any) will be ignored. The slope of the line is defined as β. Extrapolation of the straight line to intersect the line $s_i = s_{i-1}$ gives an estimated ultimate settlement at 100% consolidation. This methodology is applied to the measured data. Figure 9 is an example whereby the plot is made for location AS_3 with a PVD spacing of 2.0 x 2.0m. The final settlements derived with this theory are summarized in Table 1.

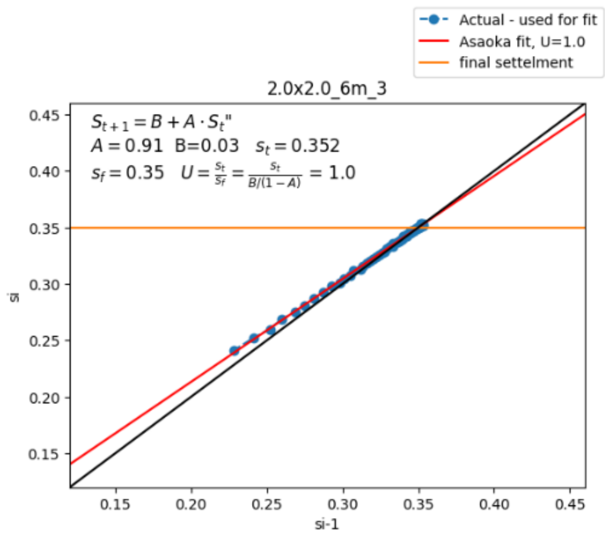

Figure 9: Asaoka interpretaion, PVD spacing 2.0m x 2.0m, AS_3.

Table 1. Asaoka interpretation – 100% consolidation.

PVD grid	2.0 x 2.0m	2.5 x 2.5m	3.0 x 3.0m
AS_1	*0.190*	*0.197*	*0.248*
AS_6	*0.184*	*0.225*	*0.262*
AS_2	*0.335*	*0.471*	*0.408*
AS_5	*0.280*	*0.329*	*0.409*
AS_3	*0.350*	*0.380*	*0.442*
AS_4	*0.346*	*0.365*	*0.476*

5 BACK-CALCULATIONS

5.1 *Calculation method*

The calculations are performed with an in-house developed Python package, fdmxcpt (Olsen et al. 2003, Vergote et al. 2019, den Haan et al. 1994). The fdmxcpt model is an axisymmetric (r,z) finite difference model for soil consolidation.

The primary consolidation of the soil is modelled by a partial differential equation based on the Terzaghi theory of consolidation to model the evaluation of the excess pore pressures in the soil:

$$u(r,z,t) = u_0(z,t) + u_e(r,z,t)$$

- u: total pore pressures
- u_0: hydrostatic pore pressures
- u_e: excess pore pressures

The partial differential equation to be solved is:

$$\frac{\partial u_e}{\partial t} = c_v \frac{\partial^2 u_e}{\partial z^2} + c_h \left(\frac{\partial^2 u_e}{\partial r^2} + \frac{1}{r} \frac{\partial u_e}{\partial z} \right) + \frac{\partial \sigma_v}{\partial t} - \frac{\partial u_0}{\partial t} \tag{1}$$

According to this equation, the soil is allowed to drain vertically and radially and the excess pore pressures are affected by changes in the total stress change $\frac{\partial \sigma_v}{\partial t}$ as well as changes in the water level $\frac{\partial u_0}{\partial t}$.

The partial differential equation is solved by the finite difference method. The model contains three dimensions, time t, dept z, and a radial dimension r, The axisymmetric discretization is presented in the figure below.

The discretization is further also done along the time direction. To ensure an efficient solution, an implicit solution with backward finite difference was implemented. The implicit solution is unconditionally stable and allows for larger time steps. The finite difference relations are implemented in a matrix A along the radial and vertical dimensions which expresses the partial differential equation as:

$$A \cdot u_{i+1} = u_i \tag{2}$$

The unknown pore pressure vector at the next time step u_{i+1} is solved by inversion of matrix A and multiplication with the known pore pressure vector u_i. The solution u_{i+1} provides all pore pressures within the axisymmetric (r,z) grid at the given point in time $i + 1$.

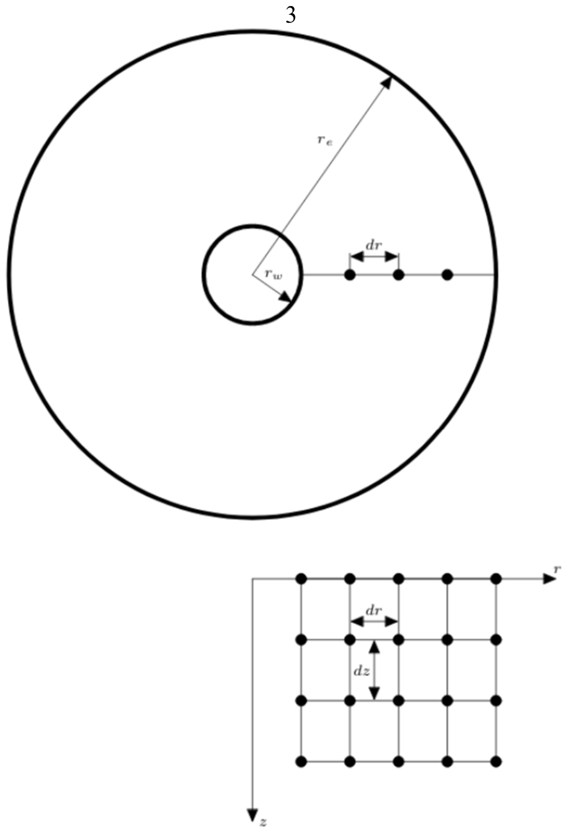

Figure 10: Discretization.

To initiate the model, adequate initial conditions should be defined. Several initial conditions are required:

- Initial overconsolidation ratio
- Initial excess pore pressure
- Drainage conditions (only vertical or also horizontal)

Additionally, each layer has a number of parameters that should be defined:

- Compression parameters: Cc, Cr, Cα
- Consolidation parameters: c_v, c_h
- Bulk density: ρ_n

5.2 Results

Based on the measured data the parameters of the fill are recalibrated for every testing field, the results are summarized in Figure 11 to Figure 13. The outcome of the recalibration is summarized in Table 2 to Table 4. It can be concluded that in general the fitted parameters for the independent 3 test field are similar. In Figure 11 to Figure 13 also a prediction is made for the further settlements of the area in function of the usage. As input it is assumed that the preload stays in place till December 2023. After removing the preload, a clear bounce back is present in all the results. From December 2024 an operational live load of 60kPa will be installed. It can be observed that the total settlement under the live load (5 to 10cm) remains limited compared to the settlement induced by the preload (35 to 45cm).

In addition to the settlement tubes, multipoint magnetic settlement gauges were installed to monitor settlements throughout the height of the reclamation. This instrument provides a detailed settlement profile over depth in function of time. Figure 14 and Figure 15 presents the measured settlement data (full green line) for the test field with a PVD spacing of 2.0 m × 2.0 m, recorded on 24 May and 21 June 2023. The corresponding calculated settlement profile is shown in blue.

The comparison indicates a generally good agreement between the measured and predicted values. The numerical model, calibrated using data from the settlement tubes, slightly underestimates the final settlement. However, the magnetic settlement system appears not to be fully anchored at its base, as indicated by a non-zero displacement at the bottom of the profile. Accounting for this offset would result in an even closer match between the measured and calculated settlements.

The second and third figure in Figure 14 and Figure 15 represents the respectively the calculated stress profile and pore pressure distribution over depth for a certain time. These figures can be used for calibration amongst other measurement devices, such as vibrating wire piezometers.

Table 2. Testing field PVD: 2.0m x 2.0m.

Layer	OCR [-]	e_0 [-]	c_c [-]	c_r [-]	c_v $[m^2/y]$
Fill	*1.0*	*1.75*	*0.115*	*0.023*	*70*
Subsoil 1	*1.0*	*1.06*	*0.158*	*0.038*	*60*
Subsoil 2	*1.0*	*0.65*	*0.042*	*0.013*	*>>>*
Subsoil3	*1.2*	*1.36*	*0.194*	*0.136*	*60*

Table 3. Testing field PVD: 2.5m x 2.5m.

Layer	OCR [-]	e_0 [-]	c_c [-]	c_r [-]	c_v $[m^2/y]$
Fill	*1.0*	*1.75*	*0.127*	*0.025*	*30*
Subsoil 1	*1.0*	*1.06*	*0.158*	*0.038*	*60*
Subsoil 2	*1.0*	*0.65*	*0.042*	*0.013*	*>>>*
Subsoil3	*1.2*	*1.36*	*0.194*	*0.136*	*60*

Table 4. Testing field PVD: 3.0m x 3.0m.

Layer	OCR [-]	e_0 [-]	c_c [-]	c_r [-]	c_v $[m^2/y]$
Fill	*1.0*	*1.75*	*0.171*	*0.034*	*40*
Subsoil 1	*1.0*	*1.06*	*0.158*	*0.038*	*60*
Subsoil 2	*1.0*	*0.65*	*0.042*	*0.013*	*>>>*
Subsoil3	*1.2*	*1.36*	*0.194*	*0.136*	*60*

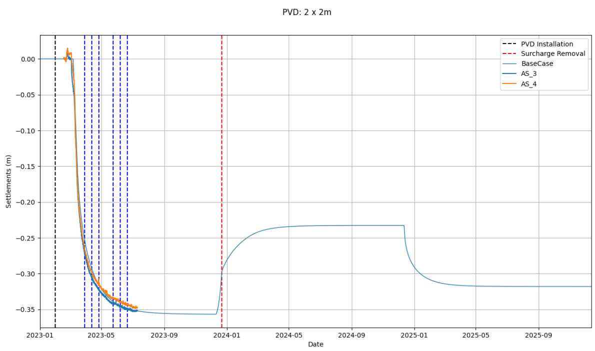

Figure 11: Measured versus predicted data (back-analysis) - PVD grid: 2.0 x 2.0m.

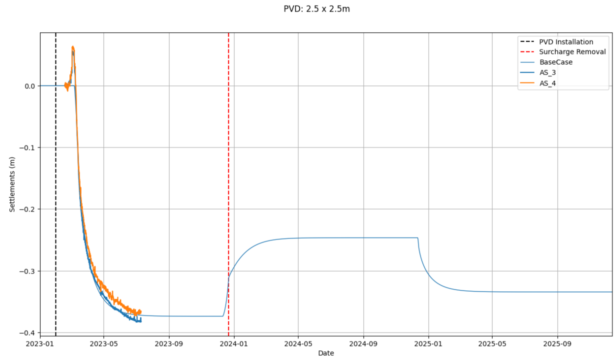

Figure 12: Measured versus predicted data (back-analysis) - PVD grid: 2.5 x 2.5m.

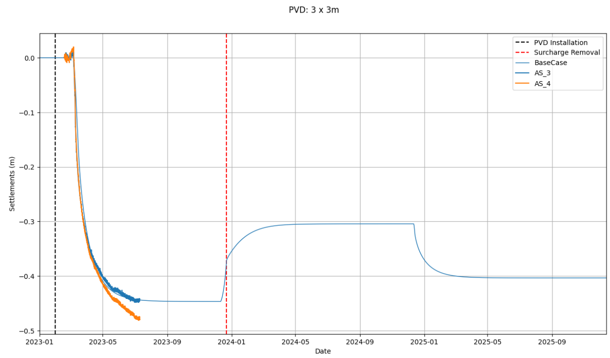

Figure 13: Measured versus predicted data (back-analysis) - PVD grid: 3.0 x 3.0m.

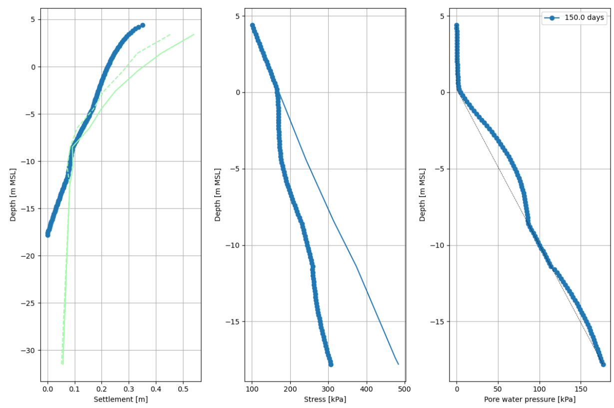

Figure 14: PVD grid 2.0m x 2.0 - 24/5/2023.

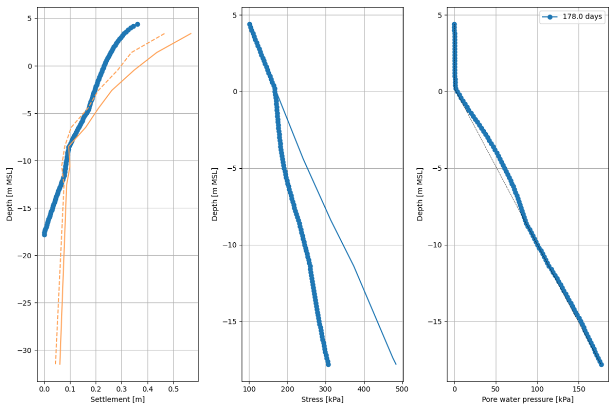

Figure 15: PVD grid 2.0m x 2.0 - 21/6/2023.

6 CONCLUSIONS

An improved design for the soil improvement works was developed based on the data collected from a full-scale trial test. The following testing methodology was adopted. First, the measured settlement data from the trial fields were verified and used to calibrate an in-house numerical model. This model was then used to simulate the long-term behavior of the soil under operational live loads, with a particular focus on predicting residual settlements.

The trial embankment consisted of three distinct test fields, each characterized by a unique configuration of grid spacing and installation depth. Back-analysis of the monitoring data from these fields yielded almost uniform soil parameters across the different configurations. This convergence of results reinforces the reliability of the back-calculated parameters and supports their use.

7 ACKNOWLEDGEMENTS

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