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Monitoring pile construction impact near sheet pile quay walls: Some remarks

Auscultation de l'impact de la construction de pieux près des murs de quai en palplanches: Quelques remarques

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ABSTRACT: During structural renovation of sheet pile quay walls, monitoring is an essential tool to anticipate possible failure events. When monitoring displacements, the objective is to compare measured with expected values to detect possible reduction of the safety margin. This study presents findings from monitoring activities during execution of piles near an old sheet pile quay wall in the Port of Ravenna. Collected data include geodetic measurements of displacements of the top beam, an inclinometer profile and elongations from strain gages fixed on a horizontal anchor. The study highlights the influence of constructing a pile near the monitored quay wall; the possibility of predicting such effect by referring to analytical solutions and 3D finite element analysis is explored to provide a tool to anticipate anomalous behaviour of the structure and to minimize risk of brittle failures.

RÉSUMÉ: Cette étude présente les données d'auscultation pendant l'exécution de pieux à proximité d'un ancien quai portuaire en palplanches dans le port de Ravenna. L'objectif est de comparer les valeurs mesurées aux valeurs attendues afin de détecter une éventuelle réduction du facteur de sécurité. Les données d'auscultation comprennent des mesures topographiques des déplacements de la poutre supérieure, des mesures inclinométriques des déplacements horizontaux en profondeur ainsi que des déformations le long d'un tirant d'ancrage équipé de jauges de contrainte. L'influence de la réalisation des pieux a été mise en évidence et une rétro-analyse détaillée a permis d'explorer la possibilité de prédire les impacts des travaux sur la base de solutions analytiques ainsi qu'en exploitant les résultats de modèles 3D aux éléments finis.

Keywords: Sheet pile quay walls; monitoring; displacement; failure risk.

1 INTRODUCTION

Carrying out renovation works on old port quay walls is never an easy task, which is why careful monitoring during the execution of the site activity is essential to detect signs of structural distress and anticipate failure events. This is especially true when considering that normal site operations are often able to impact on existing structures, particularly when the structure is old and the soil soft. In addition, when the monitoring system is accurate, some effects are always detected. Consequently, the site engineers are charged to assess if the observed effects are a tolerable consequence of the ongoing operations or a warning sign of an impending failure.

In the outlined context this paper examines the monitoring data collected during the execution of medium diameter displacement piles behind an existing anchored quay wall, that are part of retrofitting works in an Italian major port. The installation of the piles caused a small displacement of the top wall beam which was clearly detected by the accurate monitoring systems even without any sign upon visual observation. This situation called the attention of the site engineer because it was not easy to assess with certainty the relevance of the observations. Also, as often, the project only provided the indication of a tolerable displacement based on general assessment of the entire work without offering any prediction of expected effects related to a single site activity.

Pile installation effect is a well-documented issue, even though not many experiences are available in the literature for piles near retaining walls. From a theoretical perspective, the theme is classically analysed referring to the cavity expansion theory, in which soil displacement is assumed to be caused by an expanding cylindrical cavity without considering soil movements at and below the pile toe. Randolph et al. (1979), by using radiographic techniques, investigated the deformation pattern around a pile driven into clay obtaining fundamental results in understanding the disturbance effect caused by pile penetration. Massarsch and Wersall (2013), based on model test and numerical analysis, proposed a method to estimate the cumulative lateral soil displacements caused by the installation of a pile group in soft clay. Regarding case studies, Vytiniotis et al. (2018) showed the relevant lateral movements of a pile-supported retaining wall caused by nearby pile driving in a clay soil, with not negligible effects produced from pile driven even at distances greater than 50 times the pile diameter.

After a brief description of the considered case study, the paper compares the observed effects with the expected ones on the bases of the analytical solutions of the problem provided in the literature for ideal scenarios. Also, a 3D finite element model was implemented to evaluate the potential of a numerical analysis on the estimation of the pile installation effect near the quay wall of interest.

2 THE CASE STUDY

The operative quay of interest is located in the port channel of Ravenna, a major Italian harbour on the Adriatic Sea, northern Italy, along the coast of the river Po Plain. The quay is a combined HZ/AZ steel sheet pile wall, constrained at the top by horizontal strands to an anchor plate, 40 m away from the wall. The work, completed in the 2000, was designed for a seabed of 11.5 m below m.s.l., by considering an operative surcharge of 60 kPa and a bitt force of 500 kN every 25 m. Each anchor is made up of 16 strands (0.6S″) every 4 m. The quay, that has a length of about 250 m, is divided in 5 segments by expansion joints on the top beam.

In the context of a general upgrading works of the port infrastructure of Ravenna (see also Ruggeri et al., 2021), the seabed had to be deepened to -14.50 m above sea level. To fulfil this target, a strengthening intervention was designed by considering the structural deficiencies of the current quay as well as its relatively robustness and young age.

2.1 Intervention of upgrading

The adopted solution for strengthening the work has focused on reducing the horizontal soil pressure by creating a series of piles in the active wedge capable of transferring large part of the operational surcharge to the deep soil layers. This type of intervention is part of the strategies outlined in Ruggeri et al (2019) for quay walls.

In the considered case, the treatment involved the construction of 4 lines of piles, spaced 4.00 m × 3.20 m, 600 mm diameter, 29 m long. To limit the cost of disposing excavated soil, screw displacement piles (SDP) were chosen (Krasiński, 2014). To improve the efficiency of the load transfer, a pile cap is built on each pile and a geogrid is adopted to complete the system. The plain view and the cross-section of the central segment of the quay is represented in Figure 1a-c. Here, both the existing structure and the new piles are represented. Note that only the new piles are represented in the cross section, because subsequent activities are of no interest in this context.

2.2 Geotechnical situation

The geotechnical situation of the area is characterised by the presence of a thick deposit of recently sedimented soils characterized by poor geotechnical properties. As shown in the cross section of Figure 1c, under an anthropic landfill, we find a layer of Soft Clay belonging to the old coastal marsh, followed by the Silty Sand of the ancient beach. Then, we find a thick layer of normally consolidated Clayey Silt, sedimented in a marine environment, of very poor geotechnical properties. Under this deposit we have a little stratum of Silty Sand that identifies the passage to the older deposit of continental origin. Here, at 26 m below m.s.l., the mechanical properties of the soil increase, both due to the different geologic history and the greater lithostatic level of stress.

2.3 Monitoring data and site observations

To limit the relevance of some confounding effects, we focused on the central sector of the quay wall. The response of the existing structure was monitored by specific instruments installed before the start of the activities. As shown in Figure 1, in the middle of the segment, just behind the top beam, a 38 m deep inclinometer tube was installed. Two topographic targets were placed on two bitts of the top beam, at 1/3 and 2/3 of the segment length. Also, a couple of strain gages were joined to two strands of a horizontal anchor, near the inclinometer tube. These sensors made it possible to estimate the initial load acting on the anchor by carrying out a specific test as well as to measure the evolution of the tensile load with time.

The installation of the displacement piles in the segment of interest took place between 12th and 27th of July 2022.

The zero reading of the inclinometer was made on 1-07-2022. Then, two readings are available, on 8-08-2022 and 14-10-2022. It means that all the piles were in place at the time of the second readings. Looking at the cumulative displacement of the inclinometer (Figure 1e), it is possible to recognize a maximum displacement of 10 mm at 10 m b.m.s.l., that reduces to 7 mm at the top and extends up to 25 m b.m.s.l., where the effects become negligible. The reading on 14-10-2022 exhibits the same shape of the first one but with an increase of the max displacement up to 15 mm and 12 mm at the top. Now, some effect appeared up to 30 m b.m.s.l. The lack of relevant site activity between the two readings may be interpretated as a short- vs long-term effect of the pile installation, respectively.

Topographic survey of the bitts begun on 27-06-2022. Next readings happened on 4th July, 11th July, 8th August 2022, then on 8th February and on 8th June 2023. Measurements give displacements between 14 and 17 mm which do not longer evolve after the 8th August 2023.

Strain gages measurements started on 4th July 2022, with two sensors placed on two different strands of the same anchor. Data was recorded daily from 18th to 29th July, then some sporadic reading is available until June 2023. The raw readings give the local deformation of the tendon and can be transformed in the displacement of the top beam by assuming a constant strain for the entire tendon. Doing that, we obtain an elongation of the anchor equal to 12 mm. However, this estimation represents the lower bound of the real displacement because any tensile force increment requires a further mobilization of the soil resistance in front of the plate which adds an amount of displacement that is not quantifiable by sensor readings alone. In this sense, the appearance of two millimetric cracks on the pavement near the plate confirms that the real displacement of the top beam exceeds what is evaluated from the strain gages measurements. The cracks could also explain the displacement recorded by inclinometer and targets that was not detected by the strain gages on the strands.

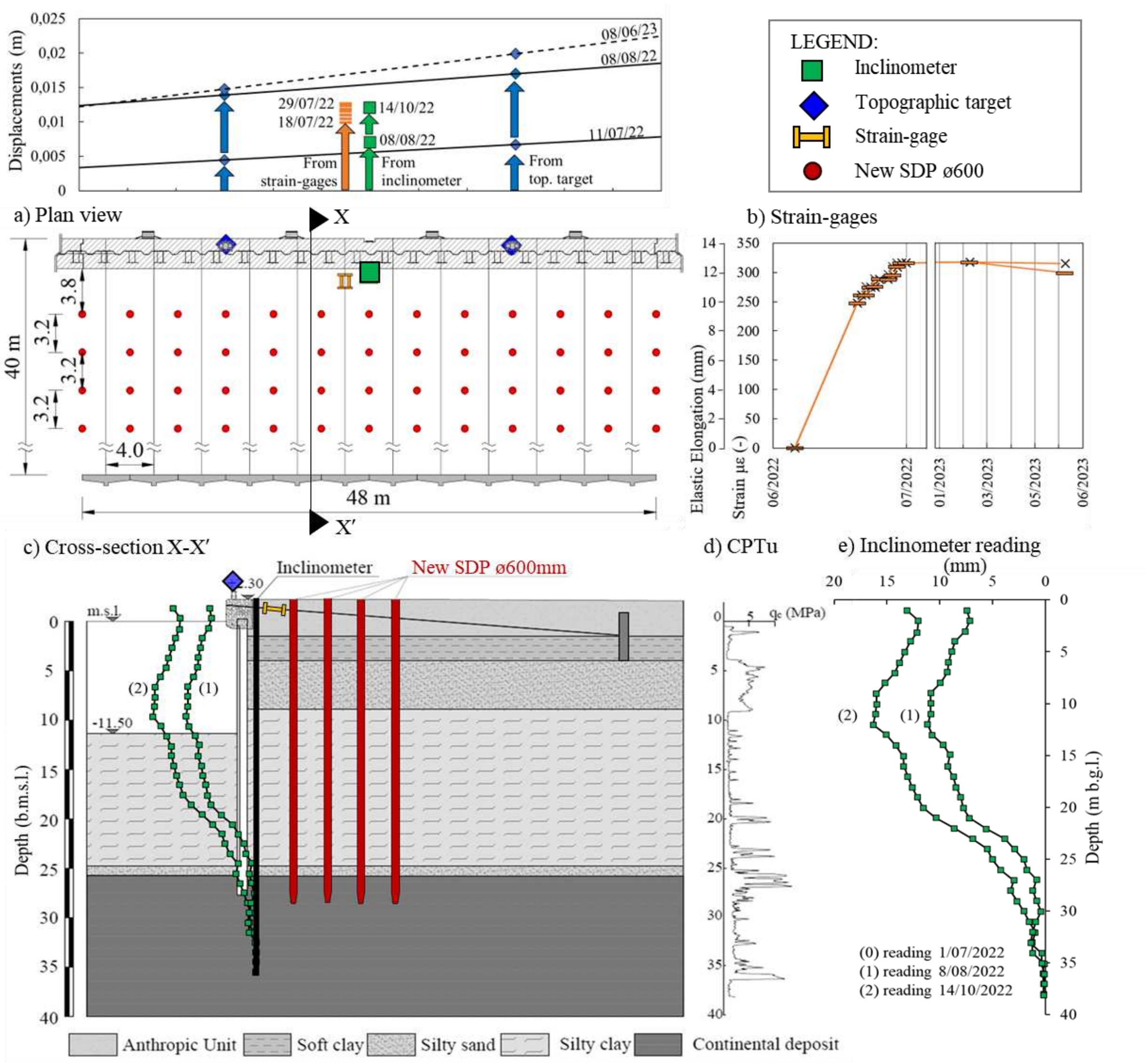

Figure 1. Plan view and cross section of the quay segment of interest with indication of SDP grid and monitoring data.

3 PILE INSTALLATION EFFECT ON THE QUAY WALL

While ground movement caused by the installation of driven pile on horizontal ground was investigated by several Authors, the effect of the pile installation close to a retaining wall does not seem extensively addressed in the literature. Therefore, the first idea is to adopt the superposition of the effects referring to some classical solutions developed for the installation of a single pile on horizontal ground, neglecting the presence of the excavation. Then, the possibility of obtaining a prediction using a 3D numerical analysis will be considered.

3.1 Analytical methods

Closed form solutions for displacement induced by pile installation have been developed under the hypothesis of linear elastic soil behaviour. In 1979, Randolph et al (1979) proposed an equation based on the cavity expansion theory in which only the pile radius (r_0) and the distance (r) affect the lateral displacement (u), as indicated in:

$$\frac{u}{r_0} = \left[\left(\frac{r}{r_0}\right)^2 + 1\right]^{0.5} - \frac{r}{r_0} \qquad (1)$$

More recently, Sagaseta and Whittle (2001) proposed an equation, based on the stress strain path method (SSPM), in which the lateral displacement (u) is function both of pile radius (r_0), distance (r) and pile length (L), in the form reported in:

$$u = \frac{r_0^2}{2} \frac{L}{r\sqrt{r^2+L^2}} \qquad (2)$$

It is worth noting that these two formulations were calibrated for clayey soil under undrained conditions and axial symmetric deformation field.

Equation (1) gives an estimation of the displacement at each depth while Equation (2) provides the displacement at the ground level only. As a first approximation, such value was considered constant with the depth.

The case study under examination does not match exactly all the hypotheses of the presented formulations, especially the undrained behaviour of the soil and the infinite half-space. However, they provide some reference values that can be compared with those observed on site or predicted by using numerical analysis. Also, the presence of multiple piles to be installed in the volume of interest has to be considered. Generally speaking, multiple piles generate an amplification of the effect, as well as the sequence and time interval of installation. In this study, we assumed that: (1) no shield effect due to construction sequence happens and (2) superposition principle can be applied to estimate the total displacement. Note that, according to Massarsch and Wersall (2013), the sequence of construction seems to play a secondary role on the final displacement produced by the pile group installation, so the first assumption appears acceptable.

Furthermore, limiting the distance of influence (i.e. the distance beyond which the installation of a pile has negligible effect on the point of interest) appears necessary. Here, we have considered the following situations (see Figure 2): a) only 1 pile produces effects on the wall; b) only the 4 piles included within 30 radii produce effects on the wall; c) all the piles in the circular sector enclosed between lines inclined ±45° from the orthogonal to the retaining wall and within 50 radii produce effects on the wall. By adopting these hypotheses, the displacement expected on the wall is indicated in Figure 2. It can be noted that the expected displacements are generally greater than those observed. Values similar to the observed ones are obtained if only the closest pile (situation “a”) or the 4 closer piles (situation “b”) to the quay wall are considered.

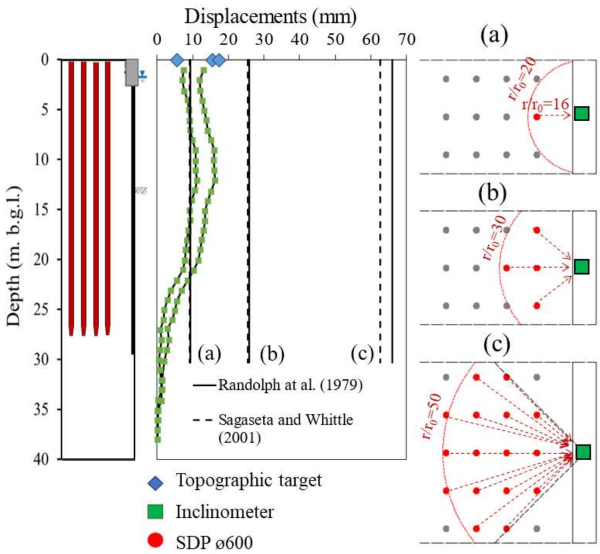

Figure 2. Prediction of displacement due to SDP installation according to analytical methods.

3.2 Preliminary numerical analysis

A 3D numerical model was implemented on the FE code Plaxis 3D to evaluate the pile installation effect on the quay wall. This method has already been applied to serviceability analysis of quay walls at the same site of interest, showing encouraging results (Alesiani et al., 2023).

The symmetry of the problem made it possible to limit the extension of a representative numerical model to a single row of 4 piles (see Figure 3).

Soil was modelled using 10-node tetrahedral elements with a linear elastic (LE) and Linear Elastic Perfectly Plastic Mohr-Coulomb (MC) constitutive relationship; the adopted soil parameters are shown in Table 1.

Table 1. Input parameters for soils.

Soil Unit	γ (kN/m³)	E (MPa)	υ (-)	φ′ (°)	c′ (kPa)
Anthropic	18.0	13	0.32	30	-
Soft Clay	18.0	3	0.35	28	-
Silty Sand	19.0	12	0.29	36	-
Clayey Silty	19.0	6	0.32	31	-
Silty Sand	19.0	12	0.30	35	-
Cont. Dep.	19.0	25	0.32	31	20

To model the piles installation in FE code, it is usual to activate a volume and then expand it simulating a cylindrical cavity expansion. Carter et al. (1979) suggest to activate an initial pile whose diameter is $a_0 = 0.577\ r_0$. This means that an expansion from a_0 to $2a_0$ (i.e. 100% expansion) reproduces the real volume displaced by the pile limiting at the 15% the extra-diameter of the modelled pile in its final configuration.

Two soil responses were considered:

1. drained (i.e. drained behaviour for all soils);
2. undrained (i.e. undrained behaviour only for fine-grained soils).

The undrained behaviour of soils were simulated by referring to effective stress parameters with invariability of the soil volume (i.e. so-called undrained A-Type behaviour).

Two models were considered to explore the reliability of the numerical analysis: the first one (Model A) with horizontal ground surface, without excavation or structures (see Figure 3a); the second one (Model B) in which the real situation is included (see Figure 3b). In particular, the measured value of the tensile stress on the anchors before the installation of the piles was reproduced by acting on the prestressing value.

In Figure 3 the results of the numerical modelling, in terms of induced displacements on a vertical section behind the wall, are shown. FE analysis for 100% pile expansion indicates that:

- the magnitude of displacements is in line with that expected from situation "c" of analytical method (i.e. all piles relevant for displacement are considered);
- undrained response produces larger displacements than drained response;
- LE and MC models predict similar displacements, despite the development of the plastic annulus around the piles for MC model;
- the magnitude of displacements ranges from 40 mm (for LE Model A in drained conditions) to 100 mm (for MC Model A in undrained conditions);
- MC-Model A (without structures and excavation) exhibits slightly larger displacements than MC-Model B (with structures and excavation);
- the overall shape of predicted displacements agrees with the observed one;
- all the considered models predict displacements 5-10 times greater than observed; even the predicted strand elongations are much larger than measured.

In Figure 4 the comparison of horizontal displacement field in the mid-section of the FEM model due to pile installation, in drained condition, is shown for the two model.

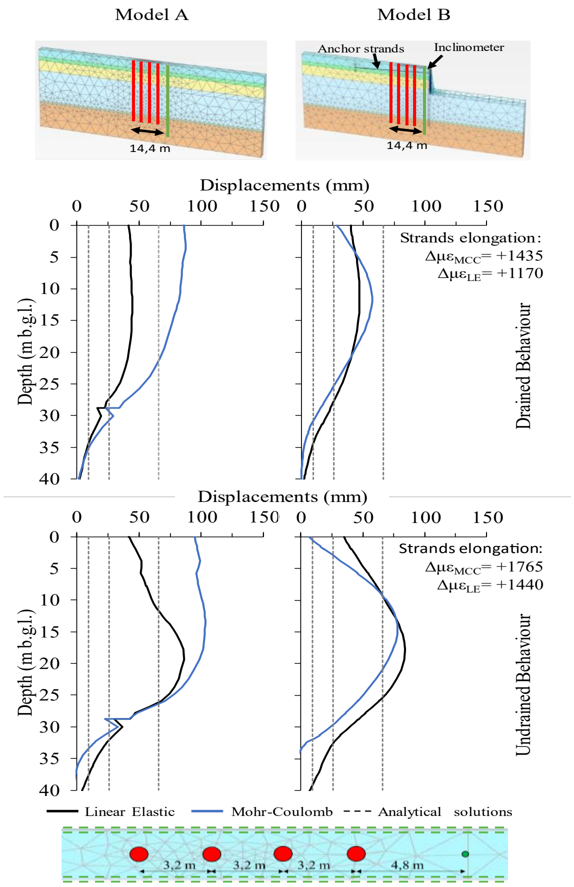

Figure 3. Prediction of displacement due to SDP installations from FEM analysis in drained and undrained condition: Model A) 4 rows of piles on horizontal ground; Model B) 4 rows of piles behind anchored sheet pile wall.

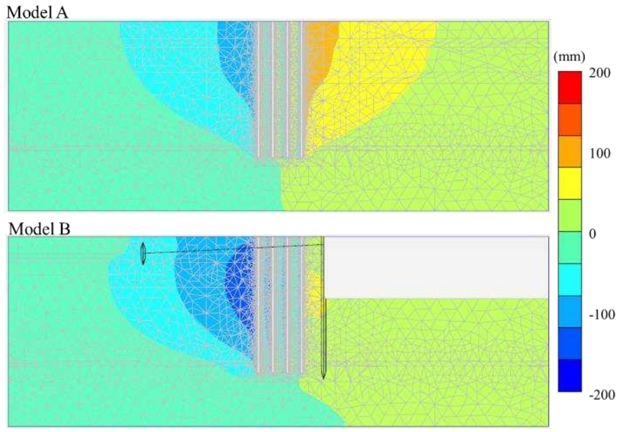

Figure 4. Comparison of horizontal displacement field due to pile installation for Model A and B, drained condition.

4 CONCLUSIONS

In the paper we have presented a case study in which the installation of several Screw Displacement Piles (SDP), medium diameter, near an existing anchored retaining quay wall induced not negligible displacement on the structure.

Being the issue relevant for the evaluation of the safety during the execution of the work, a number of analyses have been carried out to investigate whether the impact of the pile installation can be predicted at the design stage.

The adoption of analytical methods, even though not developed for similar situations, can provide some useful indications. However, the complex evaluation of the distance beyond which the pile installation impact is negligible makes it difficult to adopt such approach in practice.

On the other hands, the adoption of 3D finite element analysis is promising but difficult to implement. First results from 3D FEM analysis, developed by adopting linear elastic and elasto-plastic constitutive models for soils, indicate a general overestimation of the impact of the pile installation on the quay wall. Therefore, further investigations and analyses are underway to explain the mismatching and to reduce the current gap between displacements predicted by FEM analysis and monitoring data.

It is worth noting that the presented case study confirms the relevance of adopting a detailed and targeted monitoring when carrying out infrastructure works, especially considering the difficulties of obtaining accurate predictions in geotechnical situations involving existing structures.

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