Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-277

ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Designing a pre-load embankment for the construction of a stage over a sanitary landfill founded in soft soils

Conception d'un remblai de précharge pour la construction d'une scène au-dessus d'une décharge sanitaire fondée sur des sols meubles

A. Brito*, J. Carreto
Laboratório Nacional de Engenharia Civil, Lisbon, Portugal
**andreabrito@lnec.pt*

ABSTRACT: For World Youth Day event in 2023 (JMJ), the organizing committee selected an area in *Parque das Nações* that met the imposed requirements, notably in terms of area (for 1 million spectators) and proximity to the Lisbon center. This area, on the other hand, has the distinction of being a sanitary landfill, which was sealed in 1997 as part of the EXPO98 interventions, and which previously, in 1995, experienced a large-scale landslide in the direction of the river, with a front of 300 m of extension, enveloping the foundation up to significant depths. The fundamental cause of the landslide, according to studies undertaken at the time, was the low undrained strength of the foundation's soft soils that were still in the sub-consolidation phase, particularly at the deepest levels. Considering this scenario, LNEC performed limit equilibrium stability analyses as well as three-dimensional stress and strain finite-element analyses to estimate the magnitude and evolution of the settlements of the JMJ stage to be built in the southern area. The analyses carried out, the results of which are presented in the article, revealed the need of a pre-load embankment and were used to define criteria for the constructive phasing of the work, which was inherently dynamic and based on the outcomes of the monitoring system installed on site. Finally, values obtained from the monitoring system installed during the construction phase are compared to the values estimated during the design phase.

RÉSUMÉ: Pour les Journées Mondiales de la Jeunesse 2023 (JMJ), le comité d'organisation a sélectionné une zone du *Parque das Nações* qui répondait aux exigences imposées, notamment en termes de superficie (pour 1 million de spectateurs) et de proximité avec le centre de Lisbonne. Cette zone, en revanche, a la particularité d'être une décharge contrôlée, qui a été scellée en 1997 dans le cadre des interventions EXPO98, et qui auparavant, en 1995, avait connu un glissement de terrain à grande échelle en direction de la rivière, avec un front de 300 m d'extension, enveloppant la fondation jusqu'à des profondeurs importantes. La cause fondamentale du glissement de terrain, selon les études réalisées à l'époque, était la faible résistance non drainée des sols meubles des fondations, encore en phase de sous-consolidation, en particulier aux niveaux les plus profonds. À la lumière de ce scénario, le LNEC a réalisé des analyses de stabilité statique ainsi que des analyses par éléments finis de contraintes et de déformations tridimensionnelles pour estimer l'ampleur et l'évolution des tassements de l'étage JMJ à construire dans la zone sud. Les analyses réalisées, dont les résultats sont présentés dans l'article, ont révélé la nécessité d'un remblai de précharge et ont permis de définir des critères pour le phasage constructif des travaux, par nature dynamique et basé sur les résultats du système de surveillance installé sur place. Une comparaison est effectuée entre les valeurs obtenues dans le système de surveillance et l'estimation réalisée lors de la phase de conception.

Keywords: Sanitary landfill; pre-load embankment; soft soils; slope stability; consolidation.

1 INTRODUCTION

The use of an old sanitary landfill in the Lisbon area for the Catholic Youth World Event in August 2023 required some adjustments of the landfill. The first involved modelling the landfill in the northeast, expanding it north, and flattening the slopes. The second intervention was the construction of a stage in the southeast part of the area.

Given the history of instability of the landfill and the geological-geotechnical characteristics of its foundation, as described in the second chapter of this document, numerical analyses were performed using the limit equilibrium method to verify the global static stability of the landfill after the construction of the South stage. Given the short duration of the event, no seismic stability check was carried out.

Based on numerical analysis utilising three-dimensional finite element models and resorting to the PLAXIS 3D software, Chapter 3 presents an estimate of the magnitude and evolution of settlements and their impacts on the foundation caused by the stage load. These settlements are compared to the actual settlements measured during construction, as covered in Chapter 4, which also covers a number of other aspects of construction.

Some final considerations are made in Chapter 5.

2 GEOLOGICAL-GEOTECHNICAL FRAMEWORK

Extensive field testing was carried out in the Beirolas sanitary landfill site, since 1984 to 2020, including boreholes, field vane tests and cone penetration tests (Figure 1). According to this geotechnical investi-gation (Figure 2), beneath the deposit of contami-nated soil and municipal waste that reaches a maximum height of 20 m is a layer of heterogeneous landfill containing silt-clay materials mixed with sand and rubble, dumped on site in the 1980s. The average thickness of this “artificial” landfill is 4 to 5 metres but decreases closer to the river until it disappears in the area covered by the tide. In some localized areas the thickness of the landfill was discovered to be higher, probably as a result of prior instability.

An alluvial deposit made of compressible silt soils with very variable thickness occurs beneath the "artificial" landfill layer. The depth of the muddy soils in the south stage area increases towards the river from 2 m to 25 m but remains constant from north to south. After the large-scale landslide in 1995, studies revealed that these soft soils had a low undrained strength and were still in the sub-consolidation phase, particularly at the deepest levels. At the base of the alluvial deposit a layer of sand and pebbles ranging in thickness from a few centimetres to 2 m have been discovered. Immediately underneath, the Miocene formation includes sandstones, calcarenites, and limestones, that are more or less marly.

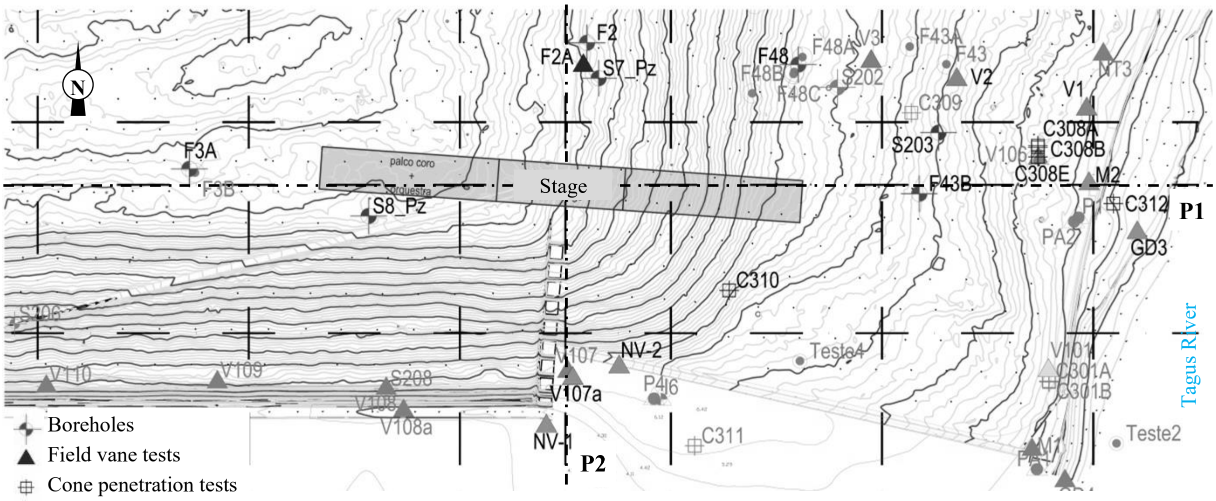


Figure 1. Ground investigations conducted around the southern stage's site.

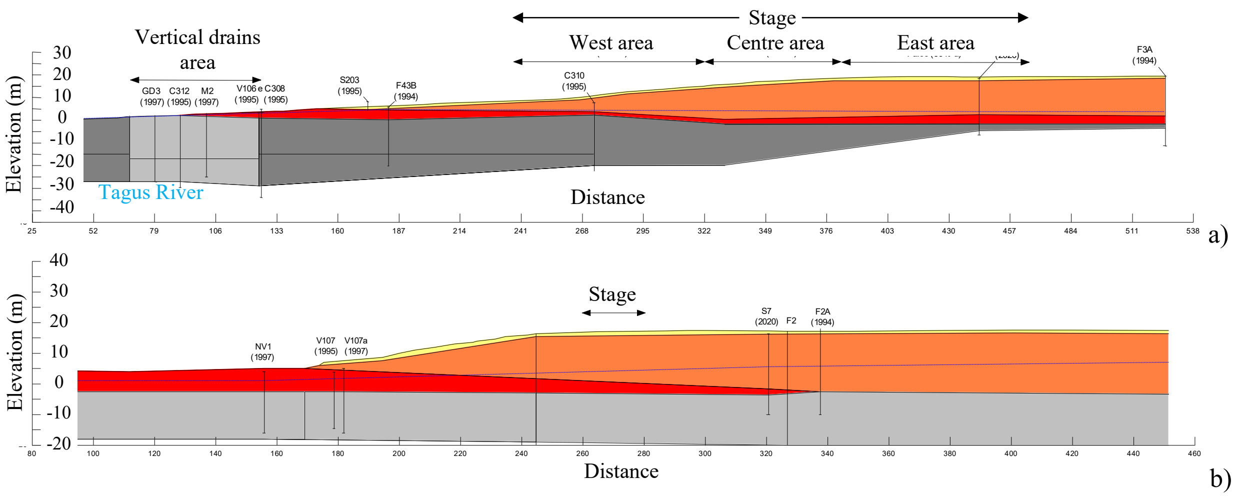


Figure 2. Geological-geotechnical cross-sections at the south stage site: a) P1; b) P2.

The sanitary landfill itself includes urban waste deposited in 1991 and layers of compost and contaminated soil deposited in cells and other areas from 1995 to 1997. Its thickness varies from about from 16 m to the west to about 4 m at the east end of the stage layout. It turned out to be a very heterogeneous landfill made up of layers of different materials with varying compressibility.

3 SETTLEMENTS ASSESSMENT IN THE SOUTH STAGE AREA

3.1 Calculation model description

The width of the calculation model illustrated in Figure 3 is equal to the width of the stage + 30 m on each side (1.5 times the width of the stage), to reduce the influence of the borders on the results. The base of the model is in the top of the Miocene formation, at -24 m. Due to calculating software constraints, the topography of the terrain was simplified by neglecting the slope in the south-north direction.

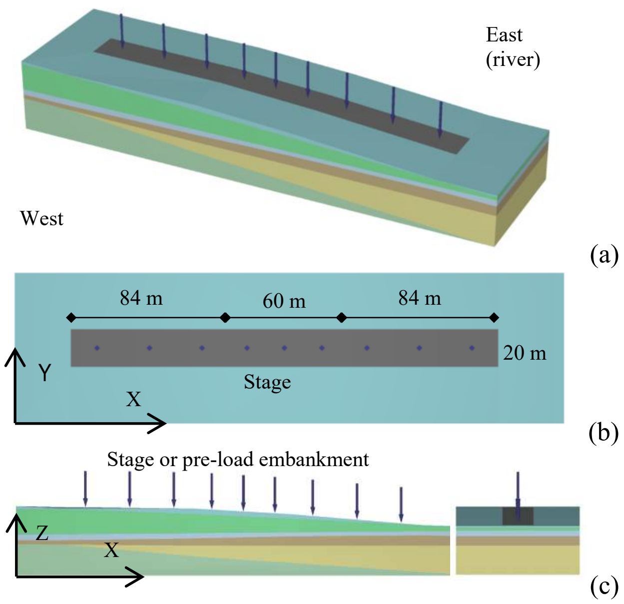


Figure 3. Calculation model geometry: (a) perspective; (b) plant; (c) elevations.

The preload embankment and stage were simulated by applying distributed loads on the area designated for the South stage. In the central and western areas, a value of 60 kPa was considered, whereas in the eastern area, a lower value, of 50 kPa, was used to ensure the overall stability of the landfill and its foundation. Calculations were carried out in two phases. Settlements caused by the construction of the stage were evaluated in the first phase. According to the JMJ organizing committee, the load imposed to the foundation due to the construction of this stage, would be 50 kN/m^2. In a second phase, a pre-load embankment was built prior to the stage, with a height of 3 m in the central and western areas. Due to stability issues, the height of this pre-load embankment was limited to 2.5 m on the east side.

Two options were considered in this second calculation. In the first option, the pre-load embankment would be removed one year after it was constructed, and the stage would be built immediately afterwards. The second option calls for the embankment to be removed six months after it is constructed and the stage to be built six months after the pre-load embankment is removed.

3.2 Materials characterization

The "soft soil" constitutive model (Bentley, 2020) was used to integrate the effect of consolidation process on the behaviour of muddy materials (superficial and deep clayey mud) as well as on the behaviour of the materials that form the sanitary landfill and the "artificial" landfill.

The elasto-plastic constitutive model with the Mohr-Coulomb failure criterion was used for the cover landfill, and the elasto-linear model was used for the Miocene formation.

Table 1 provides the values for the physical and mechanical parameters of the soft soil constitutive model materials, whereas Table 2 shows the values for the cover embankment and the Miocene formation. These parameters were based on laboratory tests conducted to date and prior LNEC studies (LNEC, 1996a, 1996b, 1997, 1999).

3.3 Calculation model results

Table 3 presents the settlement values of the stage for the most critical phases, assuming no pre-load embankment is built beforehand. The points in the table are fictious points at the top of the embankment, in the centre of each of the three regions of the stage, as shown in Figure 4. The time required to attain a consolidation degree of 95 % and 98 % is also provided in the same table. Table 4 presents the total settlement of the foundation considering the pre-load embankment construction.

According to Table 3, stage settlements can achieve significant values of the order of 0.29 m, but with reduced relevance in terms of differential settlements, although with the potential to affect its serviceability if built one year before the JMJ event.

Table 1. Parameters adopted for materials with soft soil constitutive model.

Description	γ (kN/m³)	e0	Cc	Ce	ϕ'(º)	c' (kPa)	k (m/day)
Sanitary landfill	15,4	0,5	0,2	0,02	25º	10	0,086
"Artificial" landfill	18,0	0,3	0,1	0,04	25º	0,3[1]	$1,64 \times 10^{-4}$
Superficial clayey mud (up to -5 m)	18,8	1,2	0,2	0,09	28º	0,3	$2,25 \times 10^{-5}$
Deep clayey silt	16,5	1,8	0,2	0,04	28º	0,3[1]	$1,11 \times 10^{-5}$

γ – unit weight; e_0 – initial void ratio; C_C – compression index; Ce – swelling index; ϕ` – effective friction angle; c` – effective cohesion intercept; k – permeability coefficient.

Table 2. Parameters adopted for materials with elasto-plastic and linear-elastic constitutive models.

Description	γ (kN/m³)	E (MPa)	ν	ϕ' (º)	c'(kPa)	k (m/day)
Cover landfill	20	25	0,35	30	0,3	3,456
Miocene Formation	21	100	0,33	-	-	$0,864 \times 10^{-3}$

γ – unit weight; E – deformation modulus; ν – Poisson ratio; ϕ` – effective friction angle; c` – effective cohesion intercept; k – permeability coefficient.

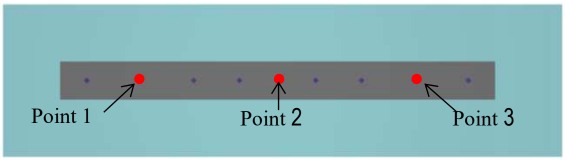


Figure 4. Location of calculation points.

Table 3. Stage settlements and time to attain a consolidation degree (without a pre-load embankment).

Point	δ_i (m)	δ_{1y} (m)	δ_{max} (m)	T_{95} (years)	T_{98} (years)
1	0.113	0.211	0.219	1,5	2
2	0.112	0.175	0.203	11	92
3	0.164	0.233	0.316	30	92
Max	0.213	0.290	0.407	-	-

δi – initial settlement; δ_{1y} – settlement 1 year after construction; δ_{max} – maximum settlement; T_{95} – time required to attain a consolidation degree (CD) of 95 %; T_{98} – time required to attain a CD of 98 %.

Table 4. Accumulated settlement of the foundation considering pre-load embankment construction.

Point	δ_{1y} (m)	δ_{3m} (m)	δ_{6m} (m)
1	0.256	0.245	0.246
2	0.213	0.205	0.206
3	0.227	0.235	0.239
Max	0.298	0.297	0.302

δ_{1y} – foundation settlement after 1 year of pre-load; δ_{3m} – accumulated settlement of the foundation 3 months after stage construction; δ_{6m} – accumulated settlement of the foundation 6 months after stage construction.

Because equal compressibility was assumed for both materials, stage settlement increases as the sum of the thickness of the sanitary landfill and the muddy soils increases. This explains why point 1 has a higher settlement than point 2 and point 3 has a higher settlement than point 1. However, results show that the closer the river, the slower the evolution of the settlements, i.e., the time necessary to achieve the same consolidation degree (CD). Therefore, even though the maximum settlement (considering a CD equal to 98 %) of point 3 is 40 % greater than that of point 1, this relationship is only 1.1 times at the end of one year.

Considering the magnitude of the settlements obtained in these calculations, as well as the fact that the consolidation of the muddy soils under the action of that load is still far from complete in a significant area of the stage at the time of the event, a method to reduce stage settlement, without causing environmental impacts was investigated. This approach entails constructing a pre-load embankment prior to the construction of the stage and leaving it *in situ* for 6 months to one year to allow the foundation ground to be consolidated. Table 4 shows the results of the model that simulates this solution. Figure 5 shows the distribution of settlements along a longitudinal profile of the stage and along three cross sections that include points 1, 2, and 3.

Table 5. Stage settlement after one year of pre-load.

Point	δ_i (m)	δ_{3m} (m)	δ_{6m} (m)
1	0.029	0.031	0.032
2	0.030	0.032	0.033
3	0.042	0.047	0.051

di – initial settlement; d_{3m} – settlement 3 months after construction; d_{6m} – settlement 6 months after construction.

According to the study's results, the highest foundation settlement caused by the pre-load embankment occurs in the west area, where the soft soil thickness is lower, and the sanitary landfill thickness is higher. This occurs because the time required to consolidate landfill materials is substantially shorter than the time required to consolidate muddy soils.

Six months after the construction of the pre-load embankment, the rate of settlement of the alluvial formation is already very low, which explains the reduced increase in settlements (in the range of 1 to 8 %) after an additional six months of pre-load. The removal of the pre-load embankment causes an expansion, which is followed by ground settlement with the construction of the stage. Since the stage load is lower than the load of the embankment in its central and western areas, the accumulated settlement of the foundation is smaller than that recorded before the removal of the pre-load embankment. Due to the process of consolidation of the foundation ground, the longer the stage's lifespan, the greater the settlements it will suffer.

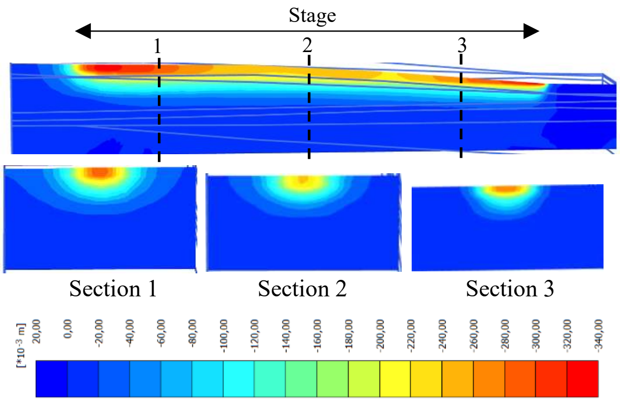


Figure 5. Foundation settlements, 6 months after stage construction (one year of pre-load).

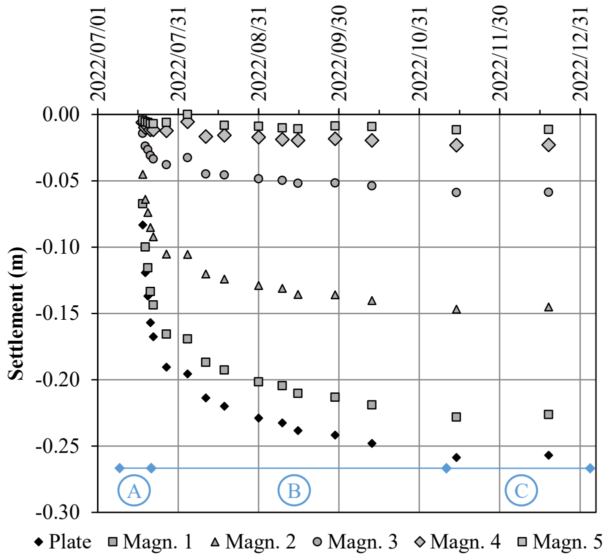
Figure 5 also shows that the settlements of the sanitary landfill are small from a distance of the order of 25 m from the centre of the stage and that this distance decreases to the east.

4 CONSTRUCTION OF THE PRE-LOAD EMBANKMENT

Construction of the pre-load embankment began on July 7, 2022, following the installation of two multi-point magnetic extensometers on the foundation, near point 2 of Figure 4, 12 topographic marks, distributed by the stage area, and 4 topographic marks in its surrounding region.

It should be noted that the final location and layout of the stage were changed during construction, with the western half being eliminated and the stage being enlarged to 40 m in the north-south direction.

Figure 6 exhibits the evolution of the settlements measured in one of the extensometer installed at the site during pre-load embankment construction and thereafter, until its complete removal on January 4, 2023. Figure 7 presents the accumulated settlement of the same extensometer at different depths after 4 months of pre-load.



A – Construction of the pre-load embankment.
B – Consolidation period.
C – Removal of the pre-load embankment.
Figure 6. Settlement of the extensometer magnets over time.

The following conclusions can be drawn from Figures 6 and 7:

- The settling rate fell significantly six days after the completion of the pre-load embankment, on 27 July. 75% of the total settlement took place during these first 20 days, which included the pre-load embankment construction.
- By mid-August the rate at which settlements occurred was gradually decreasing. At the time of removal of the pre-load embankment, settlement occurred at an approximately constant average rate of 3 mm/week.
- The total settlement recorded by the two extensometers was of the same order of magnitude as the adjacent topographic marks. At the end of 3.5 months, the greatest value of settlement was 0.26 m.
- Figure 7 demonstrates that the total settlement of the pre-load embankment was caused by the sanitary landfill settling up to 13.5 m depth. The clayey mud layer had just a minor effect, most likely because its compressibility was lower than predicted.
- The extensometer settlement was 18 % higher than calculated at the nearest point (0.22 m) at the end of six months, but less than the maximum calculated value (0.30 m). An explanation could be related with the higher consolidation rate of the sanitary landfill.
- The removal of the pre-load embankment was anticipated since a lighter structure than the modelled one (with half the load) was adopted for the stage during the works.

- As shown in Figure 6, a minor expansion occurred when the pre-load embankment was removed.

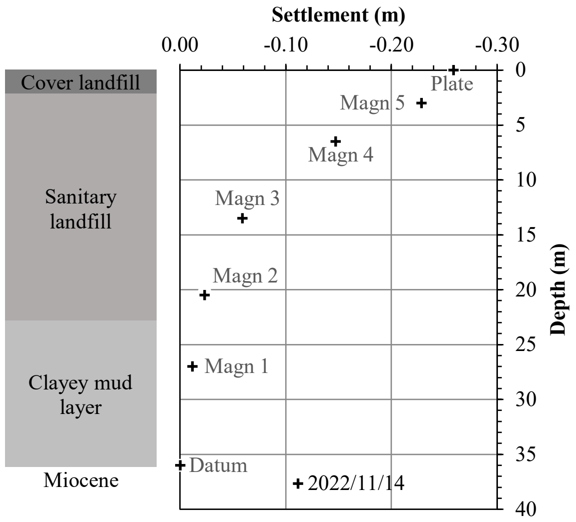


Figure 7. Accumulated settlement at different depths after 4 months of pre-load.

5 CONCLUSIONS

Given the history of instability at the Beirolas sanitary landfill and the geological-geotechnical characteristics of its foundation, numerical analyses were performed to verify the global static stability of the slopes and estimate the settlements caused by the construction of the JMJ stage.

Using a finite element model, it was also determined that stage settlements could reach an amount that would jeopardise its serviceability. Taking this into consideration, as well as the fact that the consolidation of the muddy soils under the action of that load could still be far from complete at the time of the event, a strategy to limit settlements without producing adverse environmental effects was investigated. This method entailed constructing a pre-load embankment prior to the construction of the stage, which would stay in place long enough for the consolidation of the sanitary landfill and the soft soils in the foundation to occur.

Data collected from the extensometers and topographic markers placed on the foundation and the pre-load landfill built at the forthcoming stage's location confirmed the results reached during the design phase. The use of a lighter structure for the stage, together with a small settlement rate observed by the monitoring system, allowed the pre-load embankment to be removed ahead of schedule. The stage was built without any sign of differential settlement.

ACKNOWLEDGEMENTS

The authors are grateful to *Lisboa Ocidental SRU - Sociedade de Reabilitação Urbana E.M., S.A.* for granting permission to disseminate the study's findings.

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