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Landslide risk mitigation of "São Pedro de Alcântara Viewpoint Slope" in Lisbon Historical Center

Mitigation du risk de glissement de la coline du mirador de São Pedro de Alcântara, dans le centre historique de Lisbonne

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ABSTRACT: São Pedro de Alcântara is a viewpoint at the crest of one Lisbon's main hills. The correspondent slope has been under observation and monitoring aiming to follow up its behavior and to foresee possible instability phenomena affecting the slope behavior under both static and dynamic loads. Considering the last years monitoring campaigns, and specifically the records of inclinometers installed in 2010, it was observed the presence of horizontal cumulative movements at deep soil layers with a progressive tendency, together with the formation of cracks at the retaining walls. The slope and retaining structures overall behavior was investigated, leading to an intervention that included both structural and geotechnical reinforcement for global and local stabilization with the purpose to mitigate the landslide risk. The main implemented solutions included: confined buttress of concrete and reinforced bored piles, covered by a light weight aggregates fill, as well as the refurbishment of the drainage systems.

RÉSUMÉ: São Pedro de Alcântara c'est un mirador situe au sommet de une des plus importants collines de Lisbonne. Le talus de cette colline est sous observation et motorisation avec l'objective de suivre le comportement et d'anticiper de possibles problèmes de déstabilisation, pour des actions statiques e dynamiques. Tenant en compte l'évolution historique des déformations horizontaux profondes, mesures avec les inclinomètres installés depuis 2010, bien aussi comme des fissures observes dans les structures de supporte, la stabilité globale du talus a été analysé. La rétro analyse a confirmé qu'il était important le renforcement do talus avec l'objective d'incrémenter la stabilité local et global du talus pour les actions statiques e sismiques. La solution de stabilisation adopte a compris l´exécution des caisses à pieux moules en béton et en béton armé. Sur les pieux un remblai avec de agrégés légères a été exécuté, bien aussi comme le renforcement des systèmes de drainage.

Keywords: Landslide; risk mitigation, stabilization, bored piles.

1 INTRODUCTION

The acquisition of the São Pedro de Alcântara (SPA) garden by the Lisbon City Council (1732) was done in order to allow the construction of a water supply aqueduct, that would supply the eastern part of the city, spanning the Liberdade Avenue valley. In the second half of the 18th century a big platform was built with purpose to accommodate the aqueduct abutment, as well as to allow the installation of a fountain and a water tank. The aqueduct works have never been completed, except a masonry gravity wall, in order to support the embankment and the fountain. Since then, the whole area has suffered several changes until it has become a public garden, from 1835 until now. The site aerial view is shown in figure 1. The zone where the SPA viewpoint is located has several platforms, which are supported by masonry gravity retaining walls. The two main earth retaining structures divide the upper and lower platforms of the viewpoint, and the lower platform and the Taipas street. The levels differences between the upper and lower platforms are accommodated a wall with about 6m high and between the lower platform and the Taipa street by a wall with a maximum height of about 11mm with internal buttresses (Figure 1).

Figure 1. Site aerial view.

Between Taipas Street and Fala-Só Bystreet there is a third wall that, with a maximum height of about 15m. The overall slope is identified by the presence of terraces and retaining walls, with an overall height of about 40m, from Liberdade Avenue to SPA viewpoint. At the slope are located several water lines, that ran in the direction of the Liberdade Avenue. Nowadays, due to the intense urbanization, the water percolation through the slope leads to the erosion of the shallow and less compact ground, as confirmed by several repair works.

2 MAIN INSTABILITY INDICATORS

The behavior of the earth retaining structures at the SPA viewpoint, as well as the ones between São Pedro de Alcântara, Taipas / Glória Street and Fala-Só Bystreet has been monitoring and checked by several geological and geotechnical site investigations, which allowed to confirm some important ground horizontal movements. The cumulative result of those movements led to several and important cracking, mainly at the wall supporting the lower platform (see Figure 2).

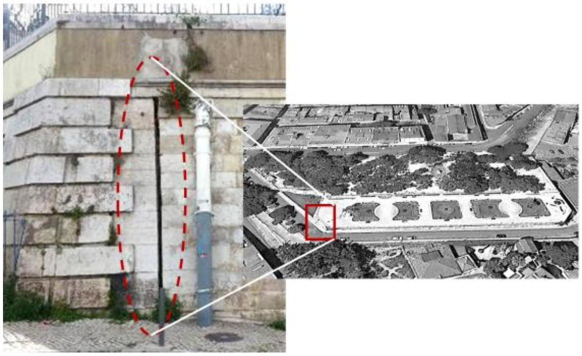

Figure 2. View of cracks at the existent wall's corners.

From the global appreciation of the displacements, it was possible to conclude that, during the last 5 years, horizontal movements were not negligible and showing some evolution with time. The largest displacements occurred at depths approximately coincident with the level of Taipas Street. However, displacements are recorded at lower depths, about 30m (Figure 3). These displacements indicated that a global instability phenomenon could be under development. Following this interpretation, stabilization measures would be needed.

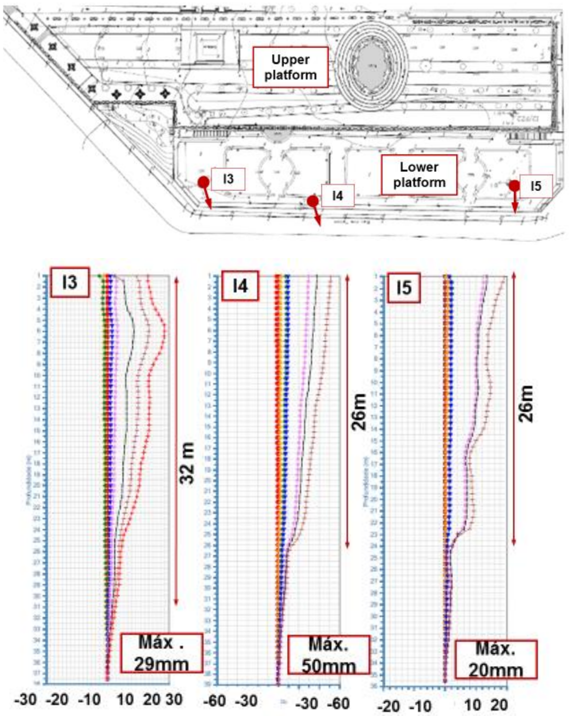

Figure 3. Record of accumulated movements in inclinometers installed in 2011 on the lower platform.

3 MAIN RESTRAINTS

As main restraints that would affect the stabilization solutions adopted, can be pointed out:

a) Geological and hydrogeological conditions, with three geotechnical zones: ZG3 - heterogeneous landfills, composed mainly by clayey sands; ZG2 – soft Miocene layers, consisting essentially of silty and sandy clays; ZG1 - stiff Miocene layers, with mainly hard silty clays (Table 1).

b) Very sensitive neighborhood conditions: the solution to be implemented should minimize the occurrence of any deformations in neighboring structures and infrastructures.

c) Conditions of accessibility and car traffic in the surroundings: advising the use of solutions that minimize the volume of earth works, as well as noise and vibrations.

d) Conditions associated with the landscaping: the garden at the lower platform should be dismantled and reinstalled.

The main objectives of the stability solution would be to improve the overall stability of the slope as well as the respective drainage conditions.

Table 1. Geotechnical zones and parameters

Geotechnical Zone	Description	γ (kN/m³)	Ø' (º)	c' (kPa)	Es (MPa)
ZG1	Landfill: sands and clays	18	28	0-10	5-15
ZG2-1	Miocene: Silty clays, silty sands	20	32	20-60	30-60
ZG2-2	Miocene: marls and weathered sandstones	21	34	20-60	30-60
ZG3	Miocene: marls and sandstones	22	40	60-100	60-100

4 ADOPTED SOLUTIONS

The adopted stabilization solution consisted on the execution, at the SPA view point inferior platform level, of bored piles walls, Ø1000mm, spaced 0.8m, with reinforced concrete (long) or plain concrete (short), forming several rectangular buttresses, with 5m wide. The piles were capped by reinforce concrete capping beams and cover by a lightweight aggregates (LWA) fill, allowing to increase the global slope stability conditions (Figures 4, 5 and 6).

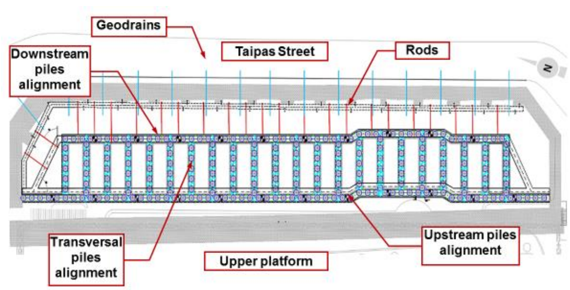

Figure 4. Plan of the adopted solutions.

The longer reinforced concrete piles intersect the previously identified sliding surfaces. The shorter plain concrete piles allow to increase the shallow and less compact ground confinement.

The piles accommodate a significant part of the earth pressures, relieving the existing retaining walls, as well as contributing to increase their local stability

The length of the piles was defined with the aim of ensuring not only that they will rest on a competent layer (ZG1), but also in such a way that they could intersect the previously identified sliding surfaces, based on the inclinometer´s readings. For a better control of the deformations of the lower wall between the lower platform and Taipas Street, the outside piles were connected by steel tie rods to a reinforced concrete distribution beam, nailed to the wall the buttresses through sub-vertical permanent nails, Gewi Ø32mm. For a better deformation control the rods, spaced by 2m in plan, were pre-stressed.

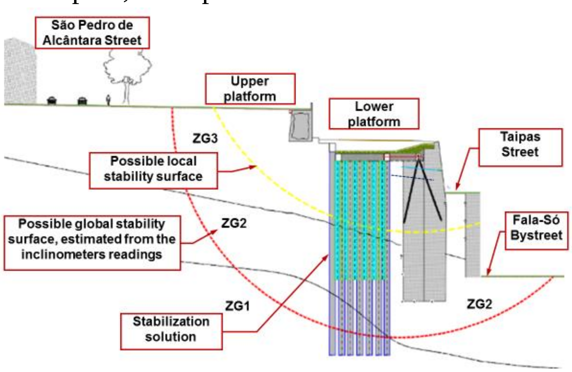

Figure 5. Cross-section of the adopted solutions.

The piles were cover by the LWA fill, expanded clay 10-20mm size, properly confined by geotextile blankets. The use of this type of material allowed either the weight reduction at the unstable zone, increasing the safety factor of the overall slope stability, decrease of the earth pressures over the existing walls, resulting in greater control on the deformations of this structure. The use of LWA fills also allowed to increase the overall shallow drainage conditions.

In order to allow to increase the deep drainage conditions, sub-horizontal geodrains, Ø 50mm PVC pierced pipes wrapped in geotextile, were also installed in the lower wall, facing the Taipas Street.

Complementary to the slope stabilization works, additional rehabilitation works were also carried out at the lower masonry wall. The most important were: cracks sealing using cement mortars as well as the rehabilitation of the wall face wall, including a new coating after the removal of the existing vegetation.

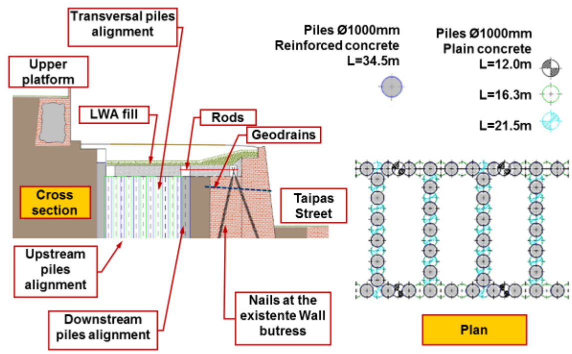

Figure 6. Details of the adopted solutions.

5 DESIGN

The initial design phase comprised a back analysis of both the platforms and retaining structures, assessing the overall the slope overall stability. The analysis was performed using the PLAXIS 2D finite element software. The calibration of the geological and geotechnical model was performed in order to try to reproduce the horizontal displacements recorded by the inclinometer’s readings. The magnitude of the observed displacements, coincident with a calculation approach under static conditions, led to the formation of the sliding surfaces, which are indicated in Figure 7, corresponding to an overall safety factor of 1.12. The behavior of the slope was also analyzed for the seismic action, leading to a global safety factor inferior to 1.0, confirming the need to design a slope stabilization solution.

After the numerical model calibration through back analysis, it was used to design the stabilization solution. Table 2 presents, comparatively, the values related to safety to overall stability before and after the intervention.

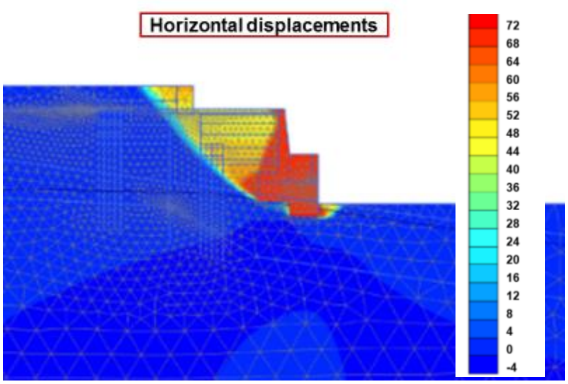

Figure 7. Numerical analysis for the evaluation of global stability to static actions [FS=1.12], horizontal displacements (cm).

According to the numerical analysis it was possible to conclude that the stabilization solution will lead to an important increase of the slope overall stability for both static and seismic actions.

Table 2. Summary of pre and post intervention overall stability safety factors

Situation	Static	Dynamics
Before Interventions	1.12	<1,00
After Intervention	1.70	1.25

6 SITE WORKS

The stabilization and drainage works were conditioned by the small space at the lower and working platform, mainly for the bored piles execution, leading for a very demanding organization and activities planning. The works began with the execution of the bored piles, for both the stabilization solution, using guide walls, and for the crane foundations.

During the execution of the piles, soft materials were intersected, as well as the remains of old constructions, which determined the need to use various drilling techniques, from temporary casing to soil and rock augers (Figure 8).

Figure 8. View of the piles works.

Following the execution of the bored piles, the remaining work was carried out with lower restraints, mainly the capping beams, the rods and the nails (Figures 9 and 10).

Figure 9. View of the excavation works.

Figure 10. View of the nail’s execution.

At the end the LWA was installed (Figure 11) over a waterproofing membrane, in order to drive the water to the drainage systems, mainly longitudinal drains and geodrains. At this moment, only the garden reinstallation is missing, leading to the installation of a vegetal soil layer, over the LWA fill, necessary for the replanting of the vegetation.

Figure 11. View of the lightweight aggregates

The last structural intervention was the cleaning and rehabilitation of the lower wall, facing the Taipas Street, including the repair of existing cracks.

7 MONITORING AND SURVEY

As already stated, during and after the execution of the stabilization works, several devices have been installed and reinstalled allowing the monitoring and survey of the SPA viewpoint slope and walls, confirming as fundamental risk management tools. After the stabilization works conclusion, the monitoring system includes topographic targets installed at the walls, as well as a inclinometers and piezometers.

The inclinometers and piezometers allowed to evaluate the lateral deformations in depth and the measurement the ground water level. On the other hand, the topographic devices allow the measurement of 3D displacements, at the original walls.

According to the monitoring results, about 1.5 years after the completion of the stabilizations and drainage works it was possible to confirm the stable behavior of the SPA viewpoint slope (Figure 12).

Figure 12. View of the final works

8 FINAL REMARKS

Following previous and similar works (Pinto, 2007 and Pinto, 2016) in this paper it was described a case study where the importance of both the geological and geotechnical information, as well as the monitoring and survey works, were key issues in order manage the geotechnical risk, allowing to predict and to anticipate the execution of stabilization and drainage works of a slope located at one of the most sensitives places of the Lisbon Historical Center.

In spite of the complex works, the deadline and the budget for most of the works were fulfilled.

9 ACKNOWLEDGEMENTS

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