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

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-342

ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Numerical assessment of the ongoing settlements of the western tower of Terreiro do Paço, in Lisbon, Portugal

Évaluation numérique des affaissements en cours à la tour ouest de Terreiro do Paço, à Lisbonne, Portugal

L. Miranda*, J. Carreto
LNEC, Lisboa, Portugal
**lmiranda@lnec.pt*

ABSTRACT: The development of Terreiro do Paço Square began after the 1755 Lisbon earthquake, with the construction of the eastern side buildings. On the western side, an embankment had to be built first, in an area previously occupied by the river, overlying the existing soft soils. The western tower was constructed later, overlooking the Tagus River, and was not completed until the mid-nineteenth century. In 1941, a Portuguese historian reported that this tower had suffered a settlement of more than 0.5 m. Between 1956 and October 2019, the southeast and northeast corner's settlement increased by 0.15 m and 0.11 m, respectively. Interestingly, no damage was found on the external walls or the arched ceiling of the first storey, indicating a rigid body movement. More recently, the Lisbon Municipality sought to extend the Lisbon Museum by placing one of its modules in the newly vacant western tower. Using the finite elements approach and a three-dimensional numerical model, stress and strain studies were carried out with the purpose of analysing the effect of the rehabilitation works on its safety and functionality. Because of the period since the tower's completion and the permeability of the muddy soils in its foundation, a soft soil constitutive model with creep was used to simulate the ongoing settlements, with satisfactory results. This allowed for a more reliable prediction of future settlements caused by the tower's new usage.

RÉSUMÉ: Le développement de la place du Terreiro do Paço a commencé après le séisme de Lisbonne de 1755, avec la construction des bâtiments du côté est. Du côté ouest, il a fallu d'abord construire un remblai, dans une zone précédemment occupée par la rivière, sur les sols mous existants. La tour ouest a été construite plus tard, surplombant le Tage, et n'a été achevée qu'au milieu du XIXe siècle. En 1941, un historien portugais rapportait que cette tour avait subi un affaissement de plus de 0,5 m. Entre 1956 et octobre 2019, l'affaissement des coins sud-est et nord-est a augmenté respectivement de 0,15 m et 0,11 m. Il est intéressant de noter qu'aucun dommage a été constaté sur les murs extérieurs ou sur le plafond voûté du premier étage, ce qui indique un mouvement rigide du corps. Plus récemment, la Municipalité de Lisbonne a cherché à agrandir le musée de Lisbonne en plaçant un de ses modules dans la tour ouest nouvellement vacante. En utilisant l'approche des éléments finis et un modèle numérique tridimensionnel, des études de contraintes et de déformations ont été réalisées dans le but d'analyser l'effet des travaux de réhabilitation sur sa sécurité et sa fonctionnalité. En raison de la période écoulée depuis l'achèvement de la tour et de la perméabilité des sols boueux de ses fondations, un modèle constitutif de sol mou avec fluage a été utilisé pour simuler les affaissements en cours, avec des résultats satisfaisants. Cela a permis une prévision plus fiable des futurs affaissements provoqués par la nouvelle utilisation de la tour.

Keywords: Settlements; foundation; numerical modelling; historic building.

1 HISTORIC FRAMEWORK

The development of Terreiro do Paço Square began after the 1755 Lisbon earthquake, with the construction of the eastern side buildings. On the western side, an embankment had to be built first, in an area previously occupied by the river, overlying the existing soft soils. The western tower was constructed later, overlooking the Tagus River, and was not completed until the mid-nineteenth century. Its structure consists of exterior walls of stone masonry, a 1st floor supported by stone arcades and vaults, resting in 16 stone columns, being the remaining floors and the roof supported by the exterior walls and four steel pillars, circular and hollow, at the centre of the building. Its foundation comprises a "massive 7 m thick masonry block, resting on a wooden grid" (Castro, 1966), to which pine piles are connected.

Concerning the geological-geotechnical scenario at the tower site, the survey campaign carried out by the Rodio company, in 1965 (Castro, 1966), revealed the presence of heterogeneous landfills, with remains of ancient foundations, to depths of 5 to 10 m. Under the landfill, a layer of clayey mud appears, with increasing thickness towards the river, followed by a layer of sand, also with a slope towards the river and a thickness varying between 5 and 10 m. Then, another mud formation follows, but with a siltier component, and a thickness (under the tower) of around 8 m, which becomes more clayey in contact with the Miocenic formation, which occurs at around 40 m depth (Figure 1). The water table was found at elevation +1.0 m.

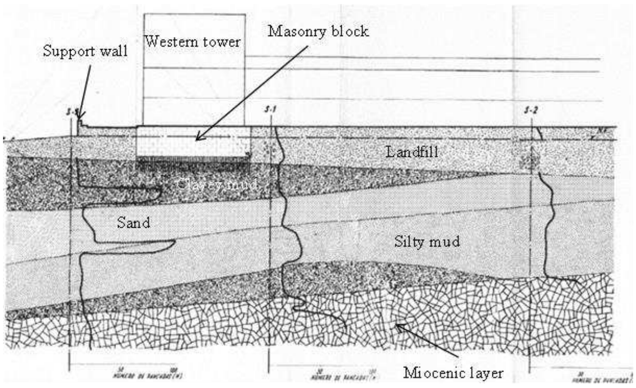

Figure 1. Geological-geotechnical profile at the zone of the western tower, adapted from Castro (1966).

In 1941, a Portuguese historian reported that this tower had suffered a settlement of more than 0.5 m. These significant settlements are explained by the high deformability of the materials in the tower's foundation and its thickness. Regarding the higher settlements of the tower when comparing with the other western wing buildings, this is explained by an increase in the thickness of the muddy soil from north to south, but also by the south area having been gained from the river through the construction of an embankment, after the 1755 earthquake, constituting an additional load on the compressible foundation.

From 1956 onwards, LNEC began measuring the vertical displacements of 8 topographic marks installed in the western wing buildings of Terreiro do Paço. The records are shown in Figures 2 and 3 (Braz, 2019). Between 1956 and 2019, the additional settlement was of 0.153 m, in the southeast corner of the tower (mark N8), and of 0.114 m, in the northeast corner (mark N7). The settlement profile (Figure 2) resembles the deformation of a cantilever beam, fixed at the north end and loaded at the south end. The greatest curvature of the settlement profile was recorded between the N4 and N6 marks, in an area where cracks were identified in the arcade and façade of the Ministry of Agriculture building.

There is an absence of readings between 1989 and 1999. The increase in settlement (66 mm, at the N8 mark) and settlement rate might have been due to an embankment construction, in 1995, as part of the Blue Line of the Lisbon Subway, located at a minimum distance of 35 m from the tower, and due to the TBM passage, from December 1997. In 2009, there was also an increase in the settlement rate, which could be attributed to the construction of a reinforced concrete pile curtain near the south and east façades of the tower. From 2010-2012, the settlement rate reduced at the N6, N7 and N8 marks, remaining practically constant until 2019.

A relevant fact, which is in line with a rigid body type movement of the tower, is the absence of cracks in the exterior walls or in the vaults supporting the 1st floor (Valente and Mesquita, 2017).

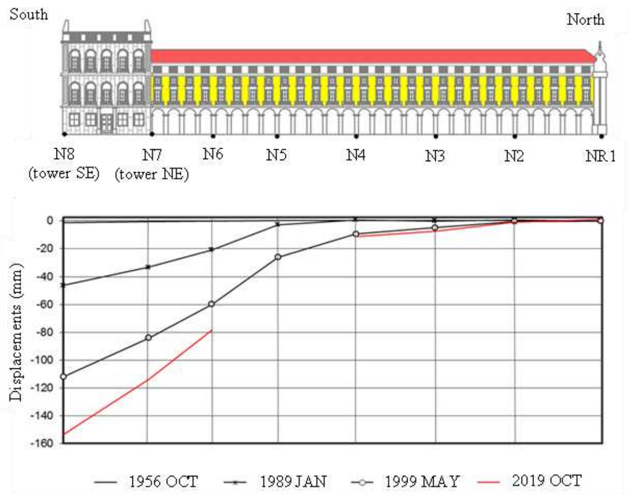

Figure 2. Settlements of the 8 marks installed in the buildings of the western wing of Terreiro do Paço, in October 1956, January 1989, May 1999 and October 2019.

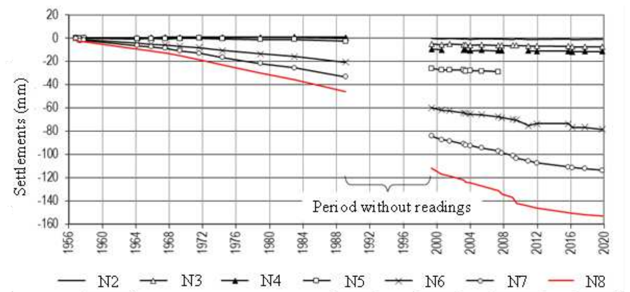

Figure 3. Evolution of the settlements in the marks installed in the buildings of the western wing of Terreiro do Paço.

2 NUMERICAL MODELLING

2.1 Goals

Recently, the Lisbon Municipality sought to extend the Lisbon Museum by placing one of its modules in the newly vacant western tower. Using the finite elements approach and a 3D numerical model, stress and strain studies were carried out with the purpose of analysing the effect of the rehabilitation works on its safety and functionality. In this model, the evolution of the settlements since the tower's construction was simulated, considering: the mechanical and geometric properties of the masonry block foundation; the temporary embankment, built as part of the Lisbon Subway Blue Line construction; and the distribution and magnitude of the permanent and live loads, in the current situation, and after rehabilitation of the tower, to serve the new Museum functions, including the construction of new floors and the removal of the 4 central pillars above the 1st floor.

2.2 Calculation model

2.2.1 Model geometry

The width of the model is equal to the width of the masonry block plus 50 m on each side, to minimize the borders' influence on the results. A depth of 50 m was considered in the z-direction, to reach the Miocenic formation. A support wall, at 16 m distance from the south façade of the tower, was also considered (Figure 4). The tower was assumed to be nearly square in plan, with 24.6 m sides. An extra width of 1.4 m, in the x-direction, and of 1.7 m, in the y-direction, was adopted for the masonry block, with an average depth of 7 m.

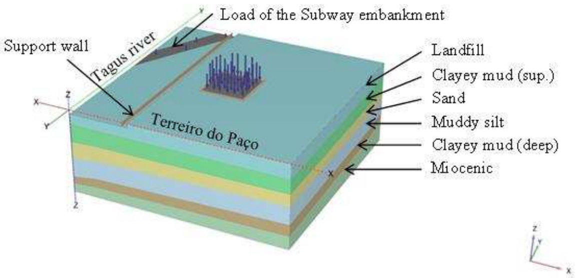

Figure 4. Geometry, geological layers, loads and axes of the calculation model.

The real arrangement of the geological layers is reproduced in Figure 5. Interfaces were introduced between the landfill and the support wall, and between the former and the masonry block, and assigned half the resistance of the adjacent soil. The finite element mesh was generated in *Plaxis 3D* and refined to have a greater density of elements around the masonry block and under the applied loads (Figure 6).

2.2.2 Modelling of the foundation loading

The simulation of the tower's structure, and of the respective permanent and live loads, was carried out through the application of distributed loads at the top of the masonry block, both in the current situation and in the situation of future use. Globally, the tower's requalification project will lead to a 6 % increase on the foundation loading and the removal of the 4 central pillars implies additional loading of the outer walls.

The Lisbon Subway embankment was simulated by a distributed load of 105 kPa, corresponding to a height of 5 m, applied in a width similar to the tunnel diameter.

2.2.3 Foundation materials characterization

A soft soil constitutive model with creep was adopted for the muddy materials, with the aim of integrating the effect of time on their behaviour. Given the period since the construction of the tower and the typical permeability of these soils, it was considered likely that the occurring settlements were due to secondary consolidation of the soil, or creep.

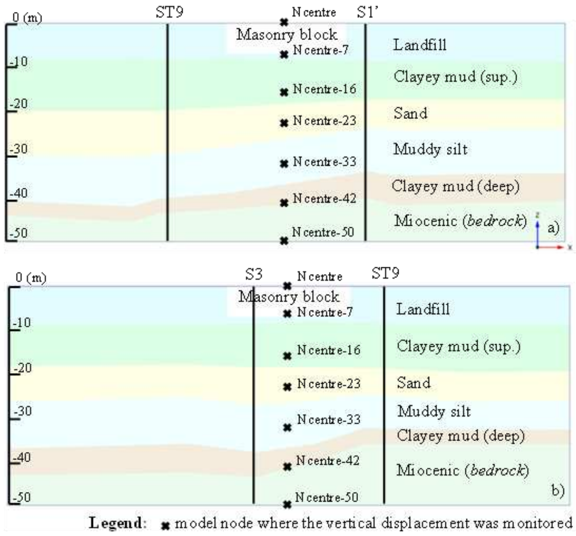

Figure 5. Cross-sections of the geological layers, passing through the centre of the tower: a) x-z and b) y-z.

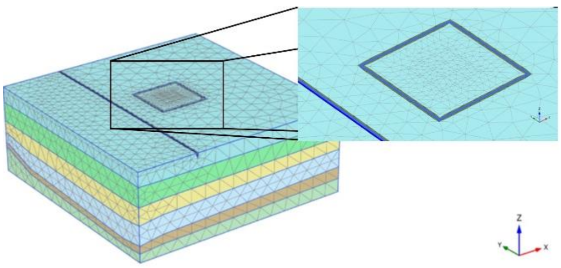

Figure 6. Finite element mesh.

For the remaining materials an elasto-plastic constitutive model with a Mohr-Coulomb failure criterion was implemented, including the muddy silt, since this material presents physical characteristics closer to a silt than to a mud. For the masonry, the linear, single-phase elastic model was adopted, as the voids between masonry blocks were filled with mortar.

In Tables 1 to 3, the parameters that simulate the physical and mechanical properties of the materials are presented. Regarding the muddy materials, the value of the initial void index (e_0) was based on the density of the solid particles, equal to 2.75, and on the water content, obtained from Castro (1966). The modified compressibility, λ^*, and expansibility, k^*, indexes' values were based on LNEC's knowledge of the typical characteristics of these materials in the area. The value of the modified creep index, μ^*, was adjusted to obtain, in the southeast corner of the tower (N8), a similar settlement to the one obtained from 1956 to 2019 (Braz, 2019), while keeping the value in the usual range for organic soils.

The parameters for the remaining materials were defined considering the work of Castro (1966).

2.2.4 Calculation model stages

The calculation model encompassed several phases, namely:

- Initial phase, to establish the initial stresses.
- Phase 1, in which the ground on the south side of the tower was modelled, simulating a fictitious excavation near the river and the construction of the south wall. An elastoplastic analysis was performed, without consideration of consolidation. The displacements at the end of this stage were nullified, so it only influenced the "in situ" stresses.
- Phase 2, in which the masonry foundation block was built and the loads from the tower were applied almost instantly (1 day), allowing the soil to consolidate in the remaining period. This phase went from 1840, when the tower was built, to 1956, when the settlement monitoring campaign began. The calculated values of the settlements are due to the tower's construction.
- Phase 3, which ran from 1956 to 1995. At this stage, only consolidation of the foundation ground occurred.
- Phase 4, which began in 1995, the year when a temporary embankment was placed over the Blue Line tunnel of the Lisbon Subway, and ended in 2007, the year when the embankment was removed. From 1989 to 1999, no geodetic campaigns were carried out by LNEC. With the resumption of measurements, a very significant increase of the tower settlement rate was noted. Thus, this phase was introduced to evaluate the influence of the embankment construction on the behaviour of the tower.
- Phase 5, which began in 2007 and ended in 2021. In this phase, only consolidation of the ground was considered.

To perform a comparative study of the estimated settlements between 2001 and 2100, 3 distinct scenarios were considered, specifically:

- Scenario 6a, in which the current loading situation was maintained.
- Scenario 6b, in which the loading corresponded to the new structure and tower functions.
- Scenario 6c, theoretical situation in which permanent and live loads remained the same until 2100, and 1 m of the masonry block was excavated, reducing its weight and, consequently, the load on the foundation ground. This situation was simulated in the model through reducing the volumetric weight of the masonry from 24 kN/m^3 to 20.6 kN/m^3.

The reinforced concrete pile curtain, built to mitigate the effects of soil liquefaction on the tower, wasn't modelled, as its construction, in 2009, didn't have a significant effect on the settlements of the tower (Figure 3).

Table 1. Parameters adopted for muddy materials.

	Clayey mud (sup.)	**Clayey mud (deep)**
γ *(kN/m^3)*	17.6	19
e_0	1.24	0.96
λ^*	0.0757; 0.15	0.0757; 0.15
κ^*	0.0371	0.0371
μ^*	0.018	0.018
ϕ'*(º)*	20	25
c'(kPa)	0.3	0.3
k (m/day)	0.432x10^{-3}	0.0432 x10^{-3}

γ - saturated soil unit weight; ϕ' – effective friction angle; *c'* – effective cohesion; *k* – permeability coefficient.

Table 2. Parameters adopted for the remaining materials.

	Landfill	**Sand**	**Muddy silt**	**Miocenic layer**
γ *(kN/m^3)*	21	21	19.5	20
E (MPa)	10	14	14	100
ν	0.3	0.3	0.3	0.25
ϕ'*(º)*	30	35	28	30
c'(kPa)	0.3	0.3	0.3	250
k (m/day)	4.64	4.64	0.0864 x10^{-3}	0.0432 x10^{-3}

E – deformability modulus; ν - Poisson's ratio.

Table 3. Parameters adopted for the masonry block.

	γ *(kN/m^3)*	*E (MPa)*	ν
Masonry	24	2000	0.2

2.3 Calculation model results

2.3.1 Model results from construction to 2021

In the model, the vertical displacements are monitored at the 4 corners of the tower (N8, N7, M8, M7) and at its centre: at the surface (Ncentre), at -7 m (Ncentre-7, base of the masonry block), at -16 m (Ncentre-16, shallow clayey mud), at -23 m (Ncentre-23, sand), at -33 m (Ncentre-33, muddy silt), at -42 m (Ncentre-42, deep clayey mud) and at -50 m (Ncentre-50, Miocenic) (Figures 5 and 7).

Figure 7 shows the vertical displacement over time for each of the nodes mentioned above. After the immediate settlement of the layers of sand and muddy silt, there is an initial phase of relatively higher settlement rate, up to approximately 5000 days, which gradually reduces as a result of the primary consolidation of the shallow and deep clayey mud layers. It is estimated that this phase would be almost completed 65 years after the construction of the tower, giving way to the secondary consolidation (through creep) of these layers, with a lower settlement rate and a tendency of stabilization.

The largest settlement occurs in the tower's southwest corner, followed by the southeast corner, which is in accordance with the observations made by Valente and Mesquita (2017). The accumulated settlement at point N8, from 1956 until 2019, attained 153 mm. This value, and the differential settlement between nodes N8 and N7, are in accordance with the accumulated settlements recorded by Braz (2019).

Despite the foundation of the subway embankment having suffered a settlement of 1.15 m, its construction, between 1989 and 1999, seems to have an insignificant effect on the behaviour of the tower.

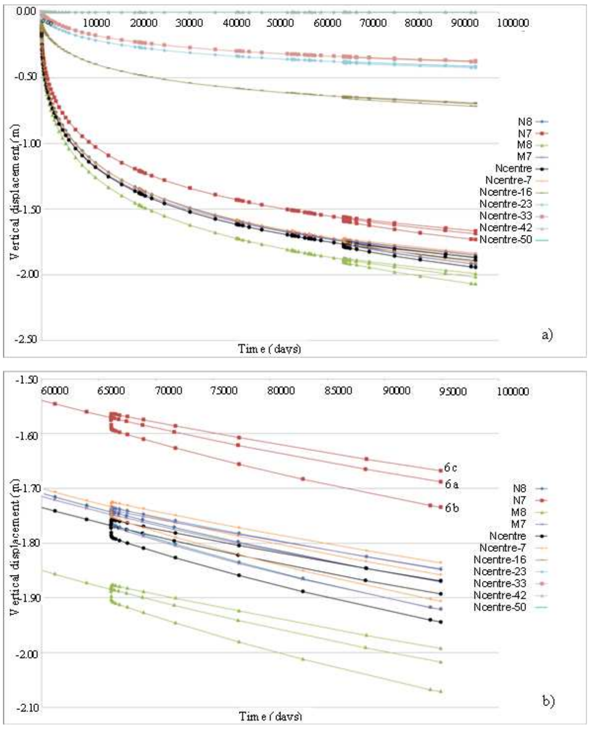

Figure 7. Evolution of the vertical displacement: a) since the beginning of the tower's construction; b) evolution of settlements in phases 6a, 6b and 6c.

Additionally, the vertical displacement at the base of the tower's foundation block (Ncentre-7) is very similar to the one at its top (Ncentre), in accordance with the high stiffness of the block. Moreover, the masonry block rotates like a rigid body, as can be seen in Figure 8.

The vertical displacement of the shallow clayey mud layer is around 33 to 40 % of the settlement of the masonry block and the layers of muddy silt and sand are responsible for around 20 to 25 % of the total settlement of the tower's foundation.

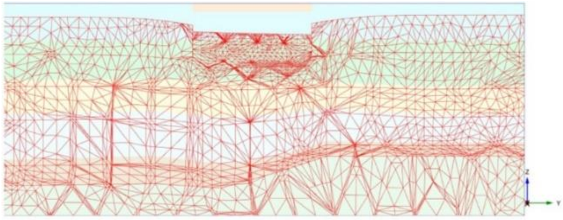
Figure 8. Displacements of the masonry block in 2021 (increased 5 times)

2.3.2 Model results after 2021

The 3 distinct scenarios, from 66078 days (2021) on, are shown in Figure 8: the settlement rate remains the same if the current situation continues (6a); it increases slightly with the increase in loading after the requalification of the tower (6b); and it decreases faintly when 1 m of the masonry block is excavated (6c), after expected bulking from load removal.

Maintaining the current loading, a settlement of 128 mm is obtained in the southeast corner of the tower (N8), between 2021 and 2100, which corresponds to an average rate of 1.6 mm/year (Table 4), a value higher than the rate measured from 2012 onwards (1 mm/year). A differential settlement between N7 and N8 of just 11 mm is calculated with the numerical model.

Table 4. Settlement and average settlement rate, between 2021 and 2100, in N7 / N8, for the current loading situation.

	$\delta_{(2021\text{-}2100)}$ (mm)	$\delta_{(2021\text{-}2100)}/\Delta t$ (mm/year)
N8	128	1.6
N7	117	1.5

$\delta_{(2021\text{-}2100)}$ – settlement; Δt – time period (79 years).

Changing the loading, after requalification of the tower, a settlement of 174 mm is obtained in the southeast corner of the tower (N8), between 2021 and 2100, which corresponds to an average rate of 2.2 mm/year (Table 5). A differential settlement between N7 and N8 of 14 mm is calculated. The increase in the average settlement rate, compared to the previous situation, results from the mud's primary consolidation, due to the increase of load on the foundation (around 6 %).

Considering a 1 m deep excavation of the masonry block, a settlement of 107 mm is obtained in the southeast corner of the tower (N8), between 2021 and 2100, which corresponds to an average rate of 1.4 mm/year (Table 6). A differential settlement between N7 and N8 of 9 mm is estimated.

Table 5. Settlement and average settlement rate, between 2021 and 2100, in N7 / N8, for changing the loading, after requalification of the tower.

	$\delta_{(2021\text{-}2100)}$ (mm)	$\delta_{(2021\text{-}2100)}/\Delta t$ (mm/year)
N8	174	2.2
N7	160	2.0

Table 6. Settlement and average settlement rate, between 2021 and 2100, in N7 / N8, for the situation after a 1 m deep excavation of the masonry block.

	$\delta_{(2021\text{-}2100)}$ (mm)	$\delta_{(2021\text{-}2100)}/\Delta t$ (mm/year)
N8	107	1.4
N7	98	1.2

2.4 Comparative analysis of the modelled cases

Comparing the situation with increased loading, after requalification of the tower, with the current loading situation, there is a difference in the accumulated settlement in 2100, in the southeast corner of the tower (N8), of 46 mm, and, in the northeast corner of the tower (N7),of 42 mm (Table 7). In terms of differential settlement, between N7 and N8, the change in loading leads to a negligible increase of 4 mm.

Comparing the situation of 1 m deep excavation of the masonry block with the current loading situation, there is a reduction in settlement in 2100, in the southeast corner of the tower (N8), of 21 mm, and, in the northeast corner of the tower (N7), of 19 mm (Table 7). The reduction of the differential settlement, between N7 and N8, compared to the current situation, does not exceed 2 mm and is insignificant.

Table 7. Settlement difference in 2100, between scenarios.

	$\Delta\delta_{req\text{-}current\,(2100)}$ (mm)	$\Delta\delta_{exc\text{-}current\,(2100)}$ (mm)
N8	46	-21
N7	42	-19

$\Delta\delta_{req/exc\text{-}current\,(2100)}$ – settlement difference in 2100, between the current situation and after requalification / after a 1 m deep excavation of the masonry block, respectively.

In a nutshell, the excavation of the masonry block has a limited effect on reducing the settlement of the tower in 2100 and has virtually no effect on the differential settlement. This happens because the settlement of the tower, at this stage, is caused by secondary consolidation of the mud layers. The effect of the change in loading, due to requalification, on the differential settlement between N7 and N8 is also reduced, although an increase in accumulated settlement of around 40 mm is expected in 2100, in N7 and N8, in relation to the current loading settlement.

3 CONCLUSIONS

Given the settlement history of the western tower of Terreiro do Paço, and for the purpose of evaluating the consequences of the loading changes on its foundation, three-dimensional stress and strain analyses were carried out, assuming different scenarios.

If the current situation continues, it is expected that the tower will suffer an increase in settlement, in 2100, of 0.12 m in the southeast corner, while the settlement difference between the southeast and northeast corners will only increase by 0.01 m.

With requalification of the tower, load changes will result in an increase in accumulated settlement in the southeast and northeast corners of the tower of around 0.04 m in 2100, in relation to the current scenario, but without significant change in differential settlement.

The possibility of minimizing future settlements of the tower, by removing 1 m in height of the masonry block, has a limited effect, especially with regard to the differential settlements, and requires the reinforcement of the façade and columns foundation. It is, therefore, a complex and low-efficiency solution.

In view of these results, it is considered that the requalification of the tower will not significantly deteriorate its safety and functionality conditions. In fact, after its construction, the tower has already suffered an estimated settlement greater than 0.65 m, with no consequences in terms of its stability.

ACKNOWLEDGEMENTS

The authors are grateful for the support to publish this article, given by the Lisbon City Council.

REFERENCES

Braz, N. (2019). West section of Praça do Comércio. Results of a geodetic survey conducted in October 2019, LNEC, Lisboa, Portugal (in Portuguese).

Castro, G. (1966). Settlements of the west section tower of Praça do Comércio, LNEC, Lisboa, Portugal (in Portuguese).

Valente, R. and Mesquita, C. (2017). West tower building, located in Praça do Comércio, in Lisbon. Preliminary study on the tower's structural and constructive characteristics and on its state of conservation, Oz, Lisboa, Portugal (in Portuguese).