Damage Assessment of *Pombalino* building due to ground movements: Analysis of a Pombalino building in a block at Lisbon's downtown

José Cruz

Instituto Superior Técnico, Universidade de Lisboa

josediascruz1992@gmail.com

October 2017

Abstract

Lisbon´s downtown (*Baixa*) has an unquestionable importance due to its historical and cultural legacy. Known today with the same configuration that was rebuilt after the great catastrophe that occurred in November 1755.

Pombalino buildings represented an important innovation in terms of architecture and urbanism, as well as in terms of anti-seismic resistance. This paper analyzes the reduction of the seismic resistance of a representative *Pombalino* building inserted between two buildings, generated by ground movements registered in downtown Lisbon.

The vertical movements of the ground measured along nearly a 60 years' period was analyzed, as well as 10 years' for the piezometric level in *Baixa*. It was identified the existence of three different rates of ground movement.

The damage level of the building was classified due to recorded differential settlements, using empirical methods.

The response of the building was simulated through numerical models using TREMURI program. The seismic response of the *Pombalino* building was assessed for configurations and amplitudes of differential settlements, by comparing resistant capacity curves. The seismic resistance was significantly affected, when the structure was previously subjected to differential settlements.

Finally, the seismic performance of the building was evaluated using the methodology of the method N2. The building analyzed does not verify the requirements according EC 8, regardless of registering previous settlements in the structure.

Keywords: *Pombalino* building; differential settlements; damage level; resistant capacity curves; TREMURI; method N2.

1 - Introduction

Lisbon's downtown (Baixa) can be considered as the Lisbon's ex libris. Undoubtedly important as regards its historical and cultural legacy, it is known today with the same configuration that was rebuilt after the great catastrophe that occurred in November 1755.

Pombalino buildings represented an important innovation in terms of architecture and urbanism, as well as in terms of anti-seismic resistance.

However, the natural degradation, the interventions and ground movements may have compromised the initial seismic resistance (Mateus, 2005).

The ground movements are due to the application of new loads to the terrain, excavations or alteration of hydrogeological conditions (Renda, 2016).

2 - *Pombalino* buildings

Pombalino buildings are characterized by its homogeneity, simplicity, regularity and by being part from a block of buildings, that taking advantage of the group effect and its constructive regularity, have an increase of seismic resistance.

They are divided by gable walls and normally have five floors: ground floor, noble floor, two upper floors and attic, as shown in Figure 1. The height of the façades was approximately equal to the width of the main streets. They were characteristic of many repeated openings of large size.

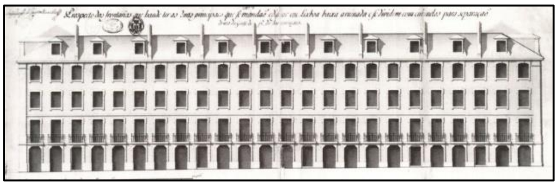

Figure 1: Typical Pombalino building, courtesy of Lisbon Story Center.

The foundations are composed by a system of wooden piles. These are still well preserved today, as they were drilled below the water table, maintaining a permanent moisture level, avoiding wetting and drying cycles.

The stairs were in the center of the building, consisting of stone on the ground floor and wood on the remaining floors.

The outer walls were composed by masonry, which thickness decreased with height. The frontal walls had wooden elements arranged horizontally, vertically and diagonally, connected together to form triangles, known as the crosses of *Santo André* (very resistant to actions in their plane, (Lopes et al, 2005), represented in Figure 2). They improve the resistance to horizontal actions and constitute important elements of energy dissipation.

Figure 2: Crosses of Santo André, courtesy of the Lisbon Story Center.

3 - Empirical method LTSM for assessing damage due to settlements

Boscardin et al. (1989) and Burland (1995) related the parameter of angular distortion with the horizontal strain, for a wall with L / H = 1 and E / G = 2.6, (wall width – L, height – H, Young modulus - E and shear modulus - G) for a single load and a neutral line at the base of the cross-section, as shown in Figure 3. The horizontal strain parameter represents the horizontal differential settlements. Angular distortion parameter represents the vertical differential settlements.

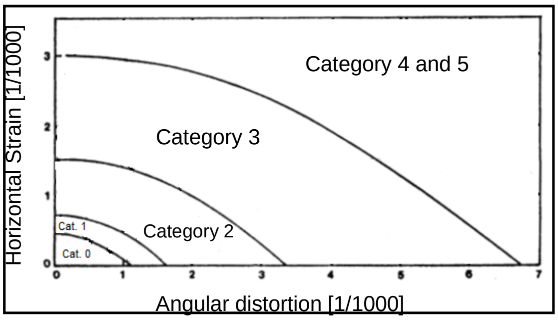

Figure 3: Relationship between horizontal strain and angular distortion for each damage categories, (Boscardin et al., 1989).

4 - Ground movement's analysis of Lisbon's downtown

Figure 4 shows the location of the surface marks, levelling rulers and piezometers in Lisbon´s downtown, which are mainly located in the alluvial zone (inside dashed zone). In Figure 5, there are the 8 measuring points in *Terreiro do Paço*´s western wing.

Based on the analysis of ground movements records measured by: surface marks, levelling rulers and measuring points, three different types of behavior were identified, as shown in Figure 6. Group A showed a stabilized behavior, neither visible settlements nor visible trends of increasing settlement. Group B with a tendency to increasing settlement, but with angular distortion lower than 1/1500, and a group C with an angular distortion rate between 1/700 and 1/400 in approximately 60 years.

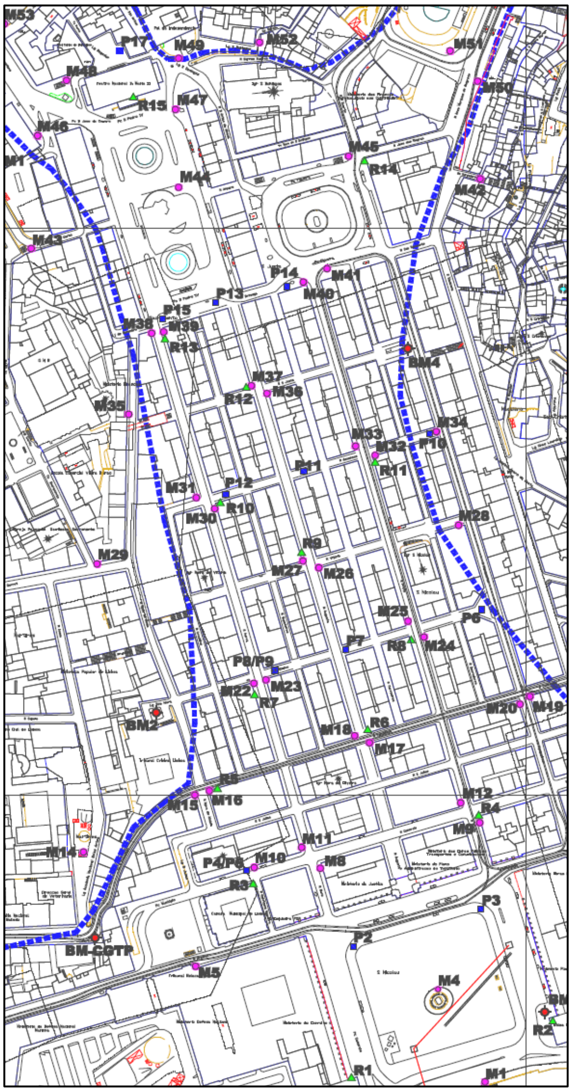

Figure 4: Mapping of piezometers (blue), surface marks (pink) and levelling rulers (green), adapted from CÊGÊ (2004-a).

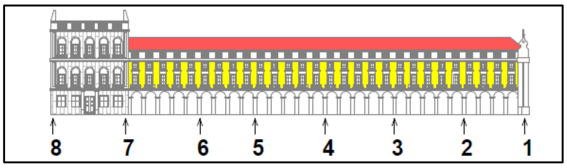

Figure 5: Measuring points located in the façade of the western wing of Terreiro do Paço, (Henriques et al., 2009).

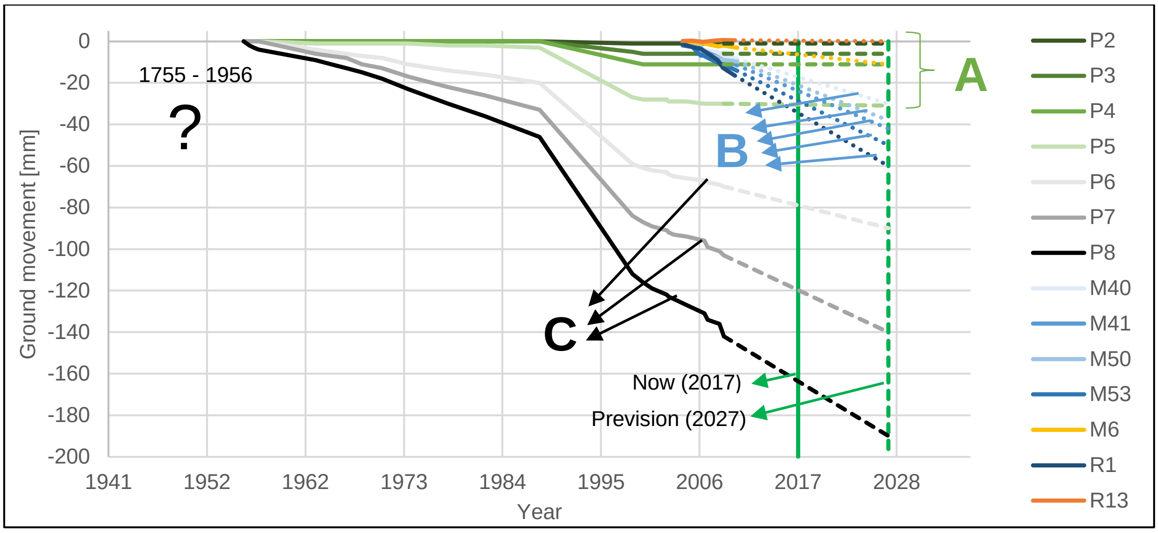

Figure 6: Behaviour of surface markings, levelling rulers and measuring points recorded in downtown Lisbon.

5 – Damage assessment due to differential settlements

5.1 – Empirical method

Figure 7 plots the damage categories on the front and back façade. It is based on the empirical method proposed by Boscardin and Cording (1989) to assess damage due to differential settlements.

For an angular distortion of 1/700, the façade has three categories of damage: 0 (irrelevant), 1 (very slight) and 2 (slight). For an angular distortion of 1/400, the back façade has only one category of damage, 2 (slight) and the front façade has two categories of damage, 2 and 3 (average).

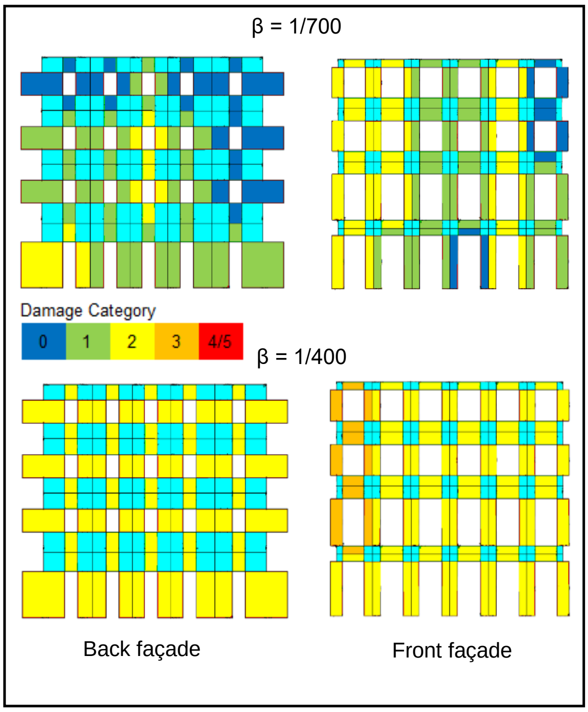

Figure 7: Damage pattern to the back and front façades due to the methodology proposed by Boscardin and Cording for angular distortion of 1/700 (above) and 1/400 (below).

5.2 Damage pattern

In Figure 8, it is shown the damage pattern after differential settlements are imposed to the structure with displacement configuration shown in Figure 11 and obtained with numerical simulation performed with TREMURI program (Lagomarsino et al., 2008).

For an angular distortion, β of 1/700, half of the piers from the upper floors of the back façade suffer shear yielding damage, and one spandrel from third floor, suffers shear collapse.

For an angular distortion of 1/400, only two piers suffer bending yielding damage and spandrels suffer either shear or bending collapse.

The front façade of the building does not have much more damage compared to the situation of imposing dead load to the structure, (β = 0).

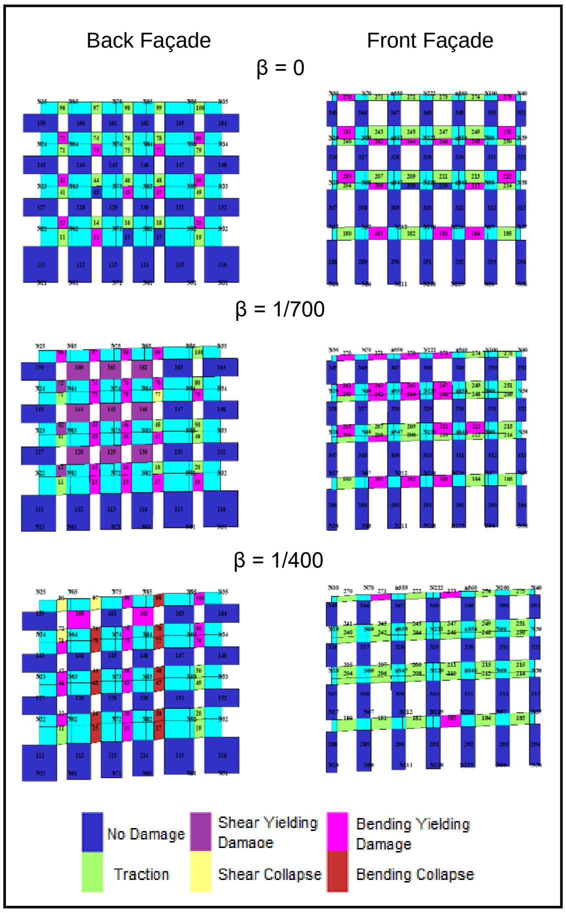

Figure 8: Damage pattern after differential settlements to the back and front façade, for angular distortion, β = (0, 1/700, 1/400).

6 - Seismic assessment

6.1 - Seismic performance of the *Pombalino* building

The *Pombalino* building analysed is shown in Figure 9 and represented in red. It is in the middle of two more *Pombalino* buildings to simulate city block effect.

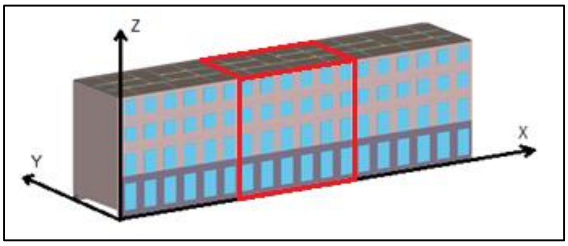

Figure 9: Set of three Pombalino buildings, building under analysis represented in red.

In Table 1, different conditions are imposed for the non-linear static analysis of each set. For instance, the set (X, +, U) corresponds to a nonlinear static analysis with uniform distributed lateral forces, U, acting with the direction X and with the positive orientation, +.

Table 1: Conditions imposed for the pushover analyses performed.

Set	(X, +, U)	(X, +, T)	(Y, +, U)	(Y, +, T)
Direction	X	X	Y	Y
Orientation	Positive	Positive	Positive	Positive
Layout of lateral forces	Uniform	Triangular	Uniform	Triangular

Each set has its resistant capacity curve represented in Figure 10. All curves stop when ultimate displacement is reached. These curves are obtained from pushover analyses with TREMURI program.

The curves (X, +, U) and (X, +, T) present higher ultimate shear force, higher rigidity and bigger ultimate displacements than the curves (Y, +, U) and (Y, +, T). The building is more resistant to a seismic action for the X direction than in Y. This can be explained by its rectangular configuration.

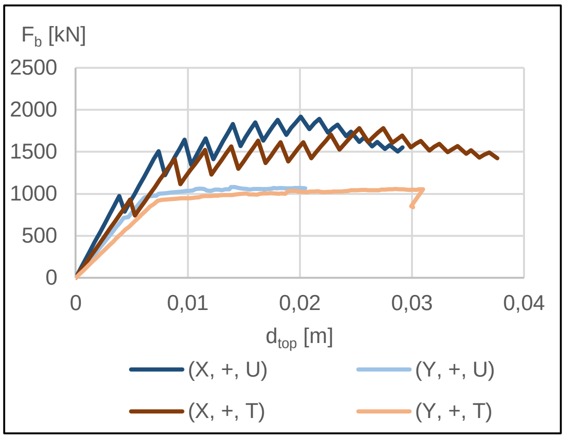

Figure 10: Capacity curves (X, +, U), (Y, +, U), (X, +, T) and (Y, +, T), (all curves stop when du is reached).

In Figure 11, the building as its displacement configuration are represented.

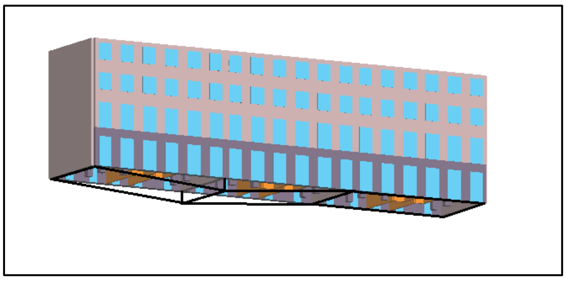

Figure 11: Displacement configuration of the building.

For set (X, +, U), each capacity curve with different angular distortion´s values are also presented in Figure 12.

It is observed for the set (X, +, U) and β = 0, that the curve presents higher ultimate shear force and reaches bigger ultimate displacements. The rigidity of the curves for β = 0 and 1/700 is similar, however, it is decreased for the β = 1/400 curve.

Seismic resistance and ductility are significantly affected when the structure is previously subjected to differential settlements. Especially for 1/400 angular distortion.

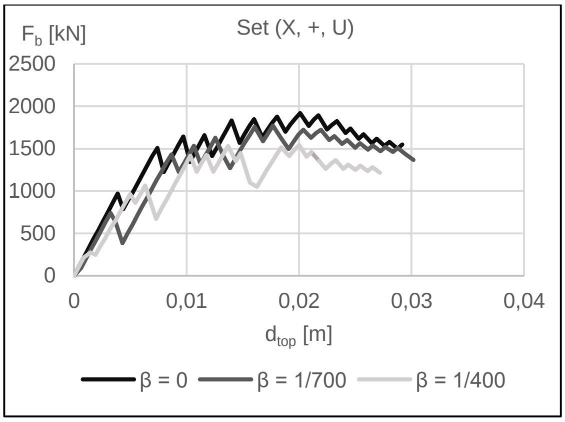

Figure 12: Capacity curves with different angular distortion to the set (X, +, U), (all curves stop when du is reached).

6.2 - Evaluation of the seismic performance of the *Pombalino* building - N2 Method

In Figure 13, it is shown the relation between ultimate displacement, d_u, and target displacement, d_t, for each value of angular distortion and set. The d_t is evaluated according N2 method (CEN, 2010). If the ratio d_u/d_t is lesser than 1, it means the structure does not verify the safety check.

Earthquake type 1 (far-field action) is more demanding than the earthquake type 2 (near-field action) for the structure under study.

For the sets which have (β=0 and 1/700) only one set does not verify the safety, for an angular distortion of 1/400, all sets do not verify the safety.

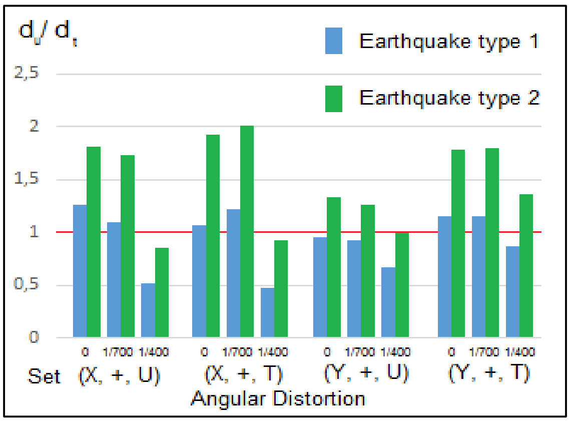

Figure 13: Ratio between the ultimate and target displacement, for earthquakes type 1 and 2 and for each set, as a function of the angular distortion values.

7 - Conclusions

The analysis of the records of ground movement revealed the existence of three different types of movement rate: group A showed no visible trends of settlement increase, group B showed a gentle increase trend, with angular distortion values lower than 1/1500 (10 years´ period) and group C which has a trend to increase settlement and angular distortion values between 1/700 and 1/400 (60 years' period).

Due to the rectangular configuration of the set of three buildings, the building presents greater rigidity and resilient capacity in the X direction (direction of the façades) than in the Y direction. When subjected to a triangular lateral forces configuration, the building exhibits the largest ultimate displacements, although lower base shear force and rigidity than when subjected to a uniform lateral forces configuration. Damage to the elements of the upper floors, as well as the horizontal displacement between the upper floors, are greater for the triangular lateral load configuration.

Seismic resistance and ductility are significantly affected when the structure is previously subjected to differential settlements. Especially for 1/400 angular distortion.

The seismic assessment of the building was performed by means nonlinear static analysis, N2 method, It is observed that the building does not verify the seismic safety criterion according EC8, regardless of whether or not the structure has previous settlements. The earthquake type 1 is more demanding than the earthquake type 2.

References

3Muri Program, S.T.A. Data, versão 2.0.22.

Boscardin, M.D., Cording, E.G., (1989). Building response to excavation-induced settlement. J. Geoptech. Engg., ASCE , 115(1), pp 1-21.

Burland, J.B., (1995). Assessment of risk of damage to buildings due to tunnelling and excavations. Invited special lecture to IS-Tokyo '95; 1st Int. Conf. On Earthquake Geotechn. Engrg.

CÊGÊ. *Monitorização Topográfica de Assentamentos na Baixa Pombalina de Lisboa. Câmara Municipal de Lisboa, Relatórios de Leituras Regulares*: 2004-a (abril de 2004); 2004-b (maio de 2004); 2004-c (junho de 2004); 2004-d (julho de 2004); 2004-e (setembro de 2004); 2004-f (novembro de 2004); 2005-a (janeiro de 2005); 2005-b (abril de 2005); 2005-c (maio de 2005); 2005-d (agosto de 2005);

2005-e (outubro de 2005); 2006-a (maio de 2006); 2006-b (julho de 2006); 2006-c (setembro de 2006); 2006-d (novembro de 2006); 2007-a (janeiro de 2007); 2007-b (março de 2007); 2008-a (outubro de 2008); 2010-a (setembro de 2010) e 2010-b (dezembro de 2010).

CEN., 2010. NP EN 1998-1: *Eurocódigo 8 - Projecto de Estruturas para resistência aos sismos. Parte1: Regras gerais, acções sísmicas e regras para edifícios*. Instituto Português da Qualidade. European Committee for Standardization.

Henriques, M. J., Coelho, J., Vieira, J., Candeias, H., & Catrau, F. (2009). *O sistema para controlo de deslocamentos verticais da ala ocidental do Terreiro do Paço*. 2º Encontro Nacional de Geodesia Aplicada, Laboratório Nacional de Engenharia Civil.

Lagomarsino, S., Galasco, A., Penna, A., & Cattari, S., (2008). TREMURI Program: Seismic Analysis Program for 3D Masonry Buildings - TREMURI User Guide.

Lopes, M., Bento, R., (2005). *A Construção Pombalina*. Curso de Verão "História e Ciência da Catástrofe", Instituto de História Contemporânea.

Mateus, J. M. (2005). *Baixa Pombalina: bases para uma intervenção de salvaguarda*.

Renda, H. (2016). *Danos em edifícios de alvenaria provocados por movimentos do terreno: Análise de um edifício Pombalino da baixa lisboeta*. Master Thesis in Civil Engineer, Instituto Superior Técnico, Universidade Técnica de Lisboa.