ANALYSIS OF THE GIRALDA TOWER GEOTECHNICAL PROFILE AND ITS SETTLEMENTS

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ABSTRACT

The preservation of the cultural heritage is a current and challenging issue for the sustainable development of countries, such is the case in the European Union. Seville is a Spanish city located in the southern Iberian Peninsula, and it is well-known for the importance of its cultural heritage. It is one of the main sources for its economic growth, employment and cultural development. The Giralda tower of the Cathedral of Seville is its most representative building. It has been declared as World Heritage Site by the UNESCO due to its patrimonial value. The Giralda was constructed in 1384 as the *Aljama* of the major mosque of Seville. However, it has undergone different construction phases over time. One of the most relevant modifications was the addition of the bell tower designed by the architect Hernán Ruíz in the Renaissance. Moreover, the tower has been affected by several historic earthquakes. The goal of this study is to define the geotechnical profile of the soil under the tower and to analyse its settlements. This study will focus on the several modifications that the building has suffered throughout its history. Moreover, it will properly and exhaustively characterise the foundation, which has not been carried out to date. To do so, the geotechnical profile has been defined accurately with the information of the boreholes drilled at its base. Then, finite elements have been used to model the different load phases, which correspond to the different construction phases. Finally, this analysis has shown a great agreement between the settlements of the tower and its real top displacements.

Keywords: Conservation, Cultural heritage, Finite elements, Foundation, Geotechnical profile, Masonry tower, Soil, Settlements.

1 INTRODUCTION

The preservation of the cultural heritage is a current and challenging issue for the sustainable development of countries. In the European Union (EU), this is an important challenge due to its richness and diversity. Therefore, the regional and local authorities of the EU are committed to safeguard and enhance Europe's cultural heritage through policies and programmes. Such is the case of the Research, Development and Innovation Plan of the *Andalucía* region (PAIDI 2020).

Seville is a Spanish city located in the southern Iberian Peninsula. It is well-known for the importance of its cultural heritage. It affects to its historical and social identity, being one of the bases of the economic and cultural development of the city. The Giralda tower of the Cathedral of Seville is its most representative building. It has been declared as a Word Heritage Site by the UNESCO due to its patrimonial value. Moreover, it has the maximum level of protection: Outstanding Universal Value.

The Giralda tower was built as the *Alminar* of the major mosque of Seville. The mosque was built between 1172 and 1182 during the Islamic period. Its demolition started in 1433, when the Gothic cathedral was being built. However, the tower and the court were saved. The tower was increased in 1184–1198 as the minaret of the major mosque. Furthermore, it has experimented different construction phases over time. The most relevant was the addition of the Renaissance's bell tower designed by Hernán Ruíz in 1568.

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The city of Seville is situated in the centre of a wide river plain formed by the Guadalquivir. Its banks have a different geological constitution. The west bank is a scarp that has a slope of 60–100 m composed by tertiary age materials (Pliocene-Miocene), marl, silt and sands. The east bank has a soft slope with a higher altitude, formed by calcareous cement sand (pipe clay). Hence, the east bank, on which the tower is placed has fluvial sediments of the Guadalquivir river and tributary streams of more than 18 m of thickness.

The main goal of this study is to analyse the settlements of the Giralda tower, in function of several aspects. To do so, the geotechnical profile has been accurately defined according to several works carried out at the base of the tower and in the nearby area [1–3]. Moreover, several modifications that the building has undergone over time have been considered. Next, an exhaustive and proper characterisation of the tower foundation has been carried out. Finally, a finite element model (FEM) has been developed to analyse the foundation movements.

2 METHODOLOGY

First, the information on the geomorphology and geotechnical properties of the soil materials has been gathered. The information has been mainly obtained from the geotechnical campaign executed in 1988, where eight boreholes were executed at the tower base [1]. Then, the geotechnical properties have been compared with other boreholes performed in the area, the Spanish code CTE DB-C [4], the basic geotechnical maps of Seville [5] and the archaeological campaigns (1996–1998) [5, 6].

Four soil profiles have been accurately drawn based on the boreholes. To do so, the commercial software Autodesk Civil3D has been used. The tower foundation has been also included in the model. It has been defined according to different nearby works. In that sense, the first foundation hypothesis was made in 1988 [2], based on the boreholes drilled in the tower's base. It has been completed with the foundation study carried out in 1997 [3] and the archaeology study conducted in 1998 about the tower foundation [6].

Three important construction phases have been defined based on the several modifications that the building has suffered throughout its history. Considering these modifications are

elements, the loads and the boundary conditions. The different construction phases have been defined according to the calculation phases. Each calculation phase corresponds to a particular load or construction phase.

Two models have been considered in the analysis of the foundation settlements. The Mohr-Coulomb model (MC) [8] is an elastic perfect plastic model. It has been taken into account to model the foundation´s behaviour and to obtain a first estimation of the tower's settlement. The computation time is short fast due to the consideration of a constant average stiffness of the soil layer. Later, the Soft Soil (SS) model [7] has been used to obtain a more accurate analysis. This method is used for the analysis of soils like normally consolidated clays, which can be found in the geotechnical profile under the tower.

Finally, the settlements have been compared with the available information of the tower movements.

3 CASE STUDY: THE GIRALDA TOWER

The Giralda tower is the most symbolic building of Seville. It is a great example of the different cultures that have lived in the city throughout its history. Originally, it was built as a minaret for the Islamic main mosque of the city in 1198. The tower has undergone different construction phases and important modifications. The most relevant one is the construction of the bell tower in the Renaissance by Hernán Ruiz in 1568.

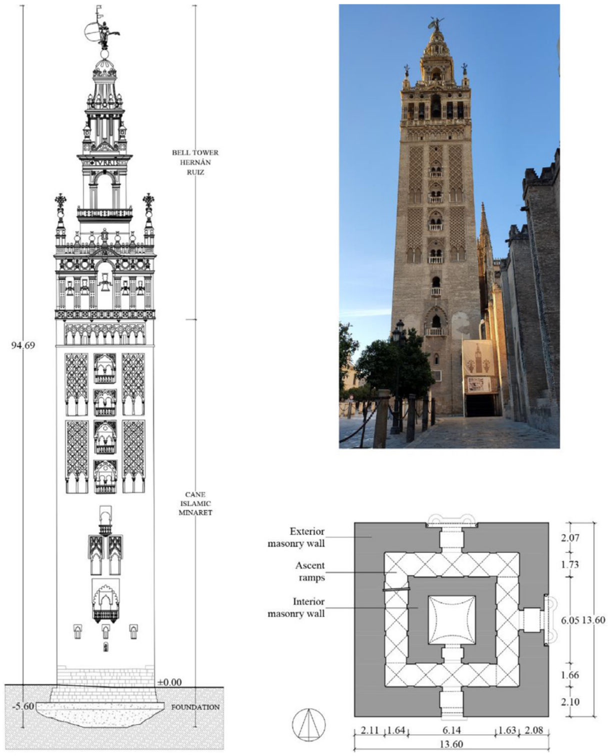

Figure 1: Overview of the tower, elevation and plan.

The cane of the tower, which belongs to the old minaret, was built with two parallel masonry walls. The plan has quadratic dimensions of 13.60 × 13.60 m and the height is 94.69 m (Fig. 1). The masonry walls thickness varies in function of its height (2.00 m-2.08 m-2.30 m). The interior cane has a dimension of 6.00 × 6.00 m, and its masonry walls have a thickness of 1.31 m. In the core of the tower, within the interior walls, there are several vaults. The connection between both canes is made through the ascent ramps. These ramps are composed of solid ceramic bricks (thickness of 0.10 m), compact limestone concrete (thickness of 0.12 and 0.17 m). The total ramps' thickness ranges between 1.10 and 1.40 m. Currently, the tower has a slight inclination towards the southeast corner, which may be caused by the settlements of the foundation or by the irregularities in the construction.

3.1 Foundation of the Giralda Tower

The Giralda tower foundation has been defined according to several previous works carried out in the area. The first hypothesis was complemented with the boreholes carried out in the tower foot in 1988 and the study about its foundation in 1997 [3, 9]. Its definition has been also completed with the archaeological study carried out in the area in 1996 [5] and in the tower foot in 1998 [6]. It is important to highlight that the leaned boreholes, which were carried out in the tower's base in 1988, confirmed that the mortar base has a greater depth in the centre of the tower (up to -5.60 m).

The base of the tower is a foundation slab of 0.80–1.00 m of depth (Fig. 2). However, it has a thickness around 3.00 m in the centre of the tower, reaching -5.60 m deep [3]. The slab

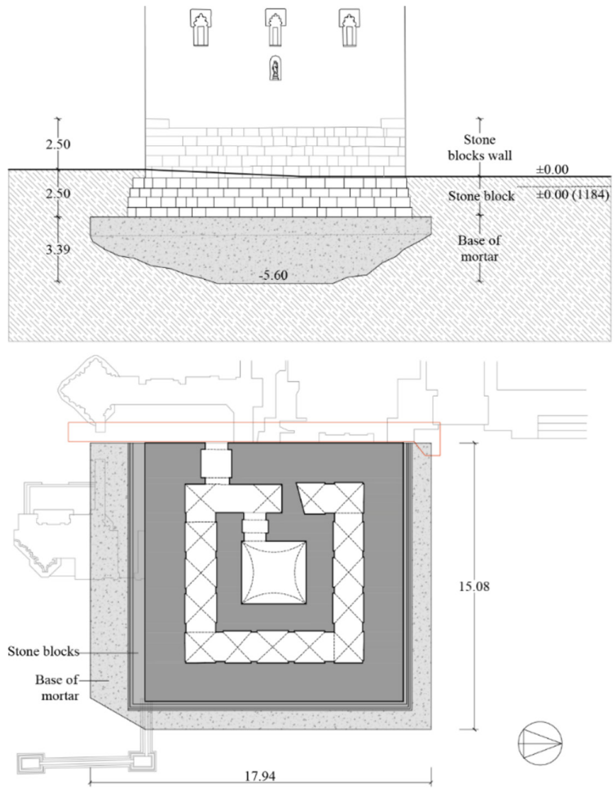

Figure 2: Floor and section of the tower´s foundation.

is composed of mortar made of lime, sand, Islamic and Roman ceramic bricks, fragments of ceramic vessels, fragments of stone blocks, etc. [6]. Moreover, it has been enlarged 1.00 m to the east and to the north and 2.00 m to the south. However, to the west, it has been attached to the pre-existing mosque wall.

The mortar of the footing slab has lost lime due to the presence of a high concentration of organic detritus in the south façade. This is due to the presence of septic tanks and sewer pipes of the XIII and XVIII century [6]. This has caused the loss of cohesion in the mortar of this area.

The excavation has an inverted cone shape, which was made in two phases. The first phase had steeper walls than the second phase. The excavation reached depths up to -3.00 to -3.50 m in the first phase and -5.50 to -6.00 m in the second phase. According to some hypotheses [6], once the excavation was performed, it was filled in by adding mortar up to -2.50 m. This was carried out due to the possible presence of water: superficial water table or a confined aquifer.

The tower foundation is composed of four courses of calcarenite stone blocks, which have a height of 0.48–0.58 m (Fig. 2). The first course stands out 0.70 m with respect to the facades. The other courses widen with the depth around 0.08–0.10 m. The base course reaches a depth of 2.50 m with regards to the current level.

4 GEOTECHNICAL PROFILE

Four geotechnical profiles have been depicted taking into account the boreholes carried out in 1988 (Fig. 3). The profile of each stratum has been plotted through a point cloud, using the

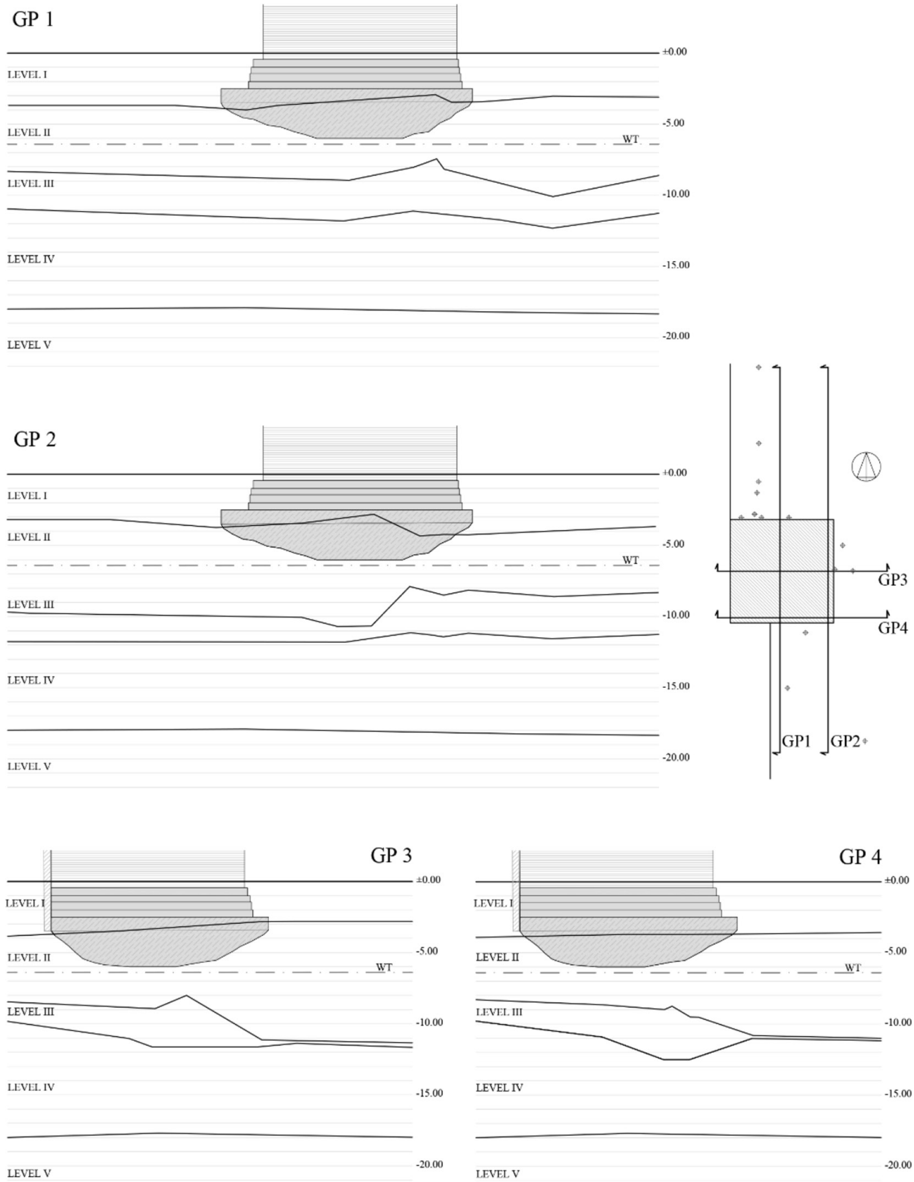

Figure 3: Geotechnical profiles (GP) of the tower.

commercial software Autodesk Civil3D. The tower foundation profile has also been inserted in the FEM.

The underlying soil has been defined accurately. The physical and mechanical properties of the soil layers (Table 1) have been obtained from the boreholes drilled at the tower foot in 1988 [3], other boreholes drilled in the nearby area, the archaeological study carried out in the area in 1996–1998, the Basic geotechnical maps of Seville [10], the IGME and the Spanish code CTE DB-SE-C [4].

Seville is placed on recent alluvial materials from the Quaternary. These were transported by the Guadalquivir river, and they were put on the Guadalquivir blue marls [11]. The geotechnical profile type is composed of infill, sand, clay gravel and marl [10].

The geotechnical profile under the tower has the following layers:

- The level I (0.00 to 2.50–3.00 m) is composed of several layers of infill. Under the pavement, there is a sandy sub-base with gravel of brown tonality. Next, there are several silty marl layers with traces of sand, gravel, ceramic and organic matter.
- The level II (2.00–3.00 to 7.00–9.00 m) is a soft alluvial infill. It is just under the tower foundation, and it is composed of an anthropic fill with ceramic traces, clayey sand and clay with gravel.
- The level III (7.00–9.00 to 11.00–12.00 m) is composed of grey clays with sands and organic and archaeological traces.
- The level IV (11.00–12.00 to 17.90–18.40 m) is an alluvial substrate composed of sandy gravel with traces of silt and clay.
- The level V (17.90–18.50 m / --) is the tertiary substrate, which is composed of the blue Guadalquivir marls.

Table 1: Geotechnical properties of the layers.

	LEVEL I	LEVEL II	LEVEL III	LEVEL IV	LEVEL V
Unit weight, γ (kN/m3)	18.7	19.2	19.1	19	19.2
Satured unit weight, γ_{sat} (kK/m3)	20.7	20.8	19.9	20	19.6
Dry unit weight, γ_d (kN/m3)	17.3	16.2	16.1	-	15.7
Water content (%)	20	28.8	26.8	-	24.9
Compressive strength, q_u (kPa)	155	170.65	227	450	500
Compression index, C_c	0.119	0.153	0.172	-	0.12
Recompression index, C_R	0.0119	0.0153	0.0172	-	0.012
Porosity, e_0	-	0.817	0.852	-	0.82
Effective cohesion, c´ (kPa)	5	29.4	22	10	98
Angle of internal friction ϕ	20°	27°	26°	30°	20°
Elastic modulus E (kPa)	5,000	5,428	6,165	50,000	90,000
Morh-Coulomb model					
Shear modulus G	1,429	1,550	1,761	14,286	25,714
Effective young´s modulus E´(kPa)	3,714	4,032	4,580	37,143	66,858
Effective Poisson’s ratio	0.3	0.3	0.3	0.3	0.3
Soft soil model					
Modified compression index λ*	0.034	0.037	0.040	-	0.029
Modified swelling index k*	0.007	0.007	0.008	-	0.006

It should be noted that the alluvial infill stratum (level II) is 2.00–3.00 m thicker in the south-east corner of the tower. This is a soft stratum, which would have caused a larger settlement in this area.

The water table is 6.00 m deep. However, its depth changes according to the rainy season. Furthermore, the Guadalquivir river level also affects it. Due to that, its depth can change from 2.00–3.00 to 9.00–10.00 m [10].

The tower base is composed of mortar made of lime, sand, ceramic brick, fragments of vessels, fragment of stone blocks, etc. Its geotechnical characteristics (Table 2) have been determined according to other works [12] and the Spanish code CTE-DB-C [4].

5 PHASES AND LOADS

Three relevant phases have been selected for the analysis. These match with historical moments where its weight increased substantially.

1. Construction of the tower´s foundation (-2.50 m) and the base of 2.50 m of stone blocks. It was completed in 1188.
2. Construction of the *Alminar*, which was built with ceramic brick. It was completed in 1198.
3. Construction of the bell tower. It raised the total height of the tower to 94.69 m. It was completed in 1568.

The load of each of the three phases has been determined from the specific weight of each material, which has been obtained from other works and the Spanish code CTE-DB-SE-AE [13]. In addition, due to their relevance, the weight of the bells (24,710 kg), of the *Giraldillo* (1,500 kg) and the four bronze lilies (1,200 kg) have been taken into account.

6 RESULTS

The results obtained from the calculations are shown and analysed in this section. The settlements for each construction phase and the geotechnical profiles (GP) are listed in Table 4.

Table 2: Geotechnical properties of the mortar.

	γ (kN/m^3)	γsat (kK/m^3)	γd (kN/m^3)	w (%)	q_u (kPa)	c´ (kPa)	ϕ	E (kPa)	G	E´ (kPa)
Mortar	16.7	20	15.6	28	5,070	15	40	500,000	228,900	526,470

Table 3: Load of the construction phases considered.

Construction phase	**Year**	**Load (kPa)**	**Total (kPa)**
1 Construction of the foundation and the base of stone blocks	1184–1188	75.30	75.30
2 Construction of Islam minaret	1188–1198	529.5	604.80
3 Construction of the bell tower	1568	47.80	652.60

Furthermore, the results of both analysis (MC and SS) are also presented. The settlements have been measured in three different points, which are located in the middle (point B) and at both ends (A and C) under the foundation (Fig. 4).

As it can be noticed, for Phase 1, the settlements are more uniform than in the other phases. The largest vertical displacements were produced in the phase of the construction of the *Alminar* (Phase 2) due to the increase of the load applied (529,5 kPa). In Phase 3, the settlement increased 5–7 cm. Moreover, the highest differential settlements, which have been measured between points A and C, were located in GP 3 and GP 4 with 5 and 7 cm, respectively. Thus, according to those data, in this direction (west-east), the tower had a greater inclination than

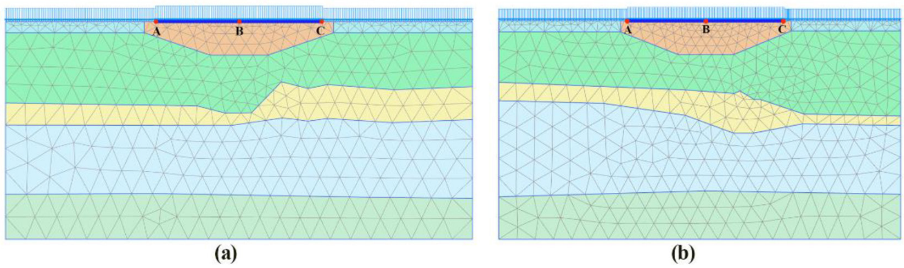

Figure 4: Discretisation and measurement points in GP2 (a) and GP4 (b).

Table 4: Settlement for each construction phases. Dimensions in centimetres.

		PHASE 1			PHASE 2			PHASE 3		
		A	B	C	A	B	C	A	B	C
GP 1	**MC**	-9.10	-9.10	-9.00	-69.80	-69.20	-68.30	-75.80	-75.20	-74.20
	SS	-17.70	-17.80	17.90	-75.80	-76.20	-76.20	-79.40	-79.90	-79.90
GP 2	**MC**	-9.40	-9.20	-9.00	-72.60	-70.60	-68.30	-78.60	-76.70	-74.40
	SS	-17.60	-17.70	-17.70	-76.10	-75.90	-75.40	-79.70	-79.60	-79.00
GP 3	**MC**	-8.10	-8.50	-8.80	-65.30	-67.50	-69.40	-71.20	-73.20	-74.90
	SS	-16.90	-17.50	-18.00	-72.90	-75.20	-77.10	-76.40	-78.80	-80.80
GP 4	**MC**	-8.30	-9.00	-9.70	-66.90	-70.30	-73.20	-72.90	-76.50	-79.50
	SS	-16.90	-17.50	-18.20	-72.00	-75.80	-79.20	-75.50	-79.50	-82.50

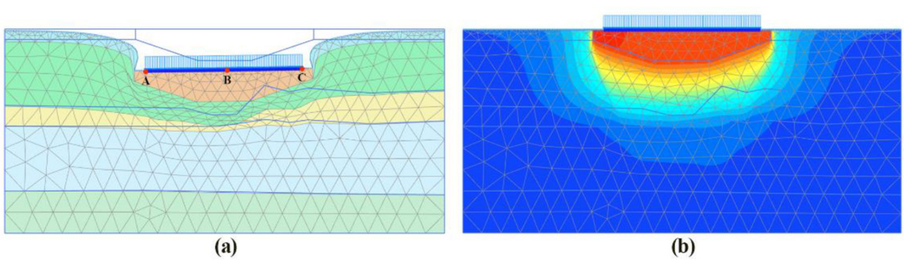

Figure 5: Finite element model. Deformation (a) and total mesh displacement (b) of GP2.

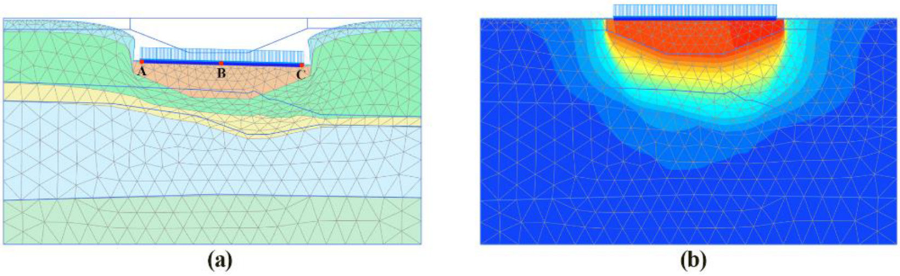

Figure 6: Finite element model. Deformation (a) and total mesh displacement (b) of GP4.

for the south-north one. Finally, for the GP 1 and GP 2, a differential settlement of 2 and 4 cm, respectively, was achieved. In addition, for both geotechnical profiles, more uniform settlements were obtained for the SS models in the three phases, compared to the MC ones.

Figures 5 and 6 show the deformation and the total mesh displacement of the GP2 and GP4, which are located under the east and the south façades, respectively. In these sections, the soft stratum (level II) is thicker, 2.00 and 3.00 m, respectively. Due to this, the differential settlements were higher than in the central profiles (GP1 and GP3). Furthermore, it can be observed that the deformations and displacements under point A were higher than those for point C.

Also, the results of the settlements analysis of the different construction phases, in terms of vertical displacements (u_y) and increased load applied (Σ_{stage}), are presented in Figs. 7–10. The settlement of each point measured (A, B and C) and the different analysis models (MC and SS) have been plotted in these graphics. Generally, the largest settlements were achieved for the Phase 2, while the smallest settlements were obtained for the Phase 3. This fact was due to the increase of the load applied (529 and 47.8 kPa, respectively). Furthermore, the settlements were larger in the SS model than in the MC one. Those results were in accordance with the fact that the SS model is more accurate, and it considers the compression (Cc) and recompression index (C_R) of each stratum.

As it can be observed from Figs. 7 and 8, the differential settlements in GP2 were higher than those for GP1 due to the thickness irregularity of the soft stratum (level II), increasing 2.00 m under the south façade (Point A). In both cases, the settlements were more uniform and higher in the SS model.

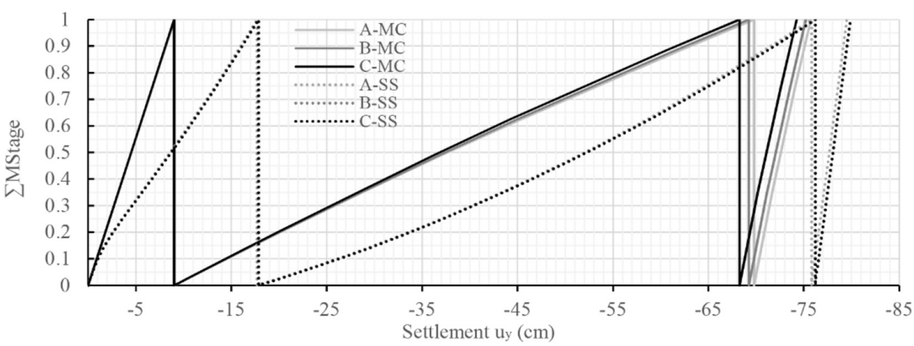

Figure 7: Settlements in GP 1.

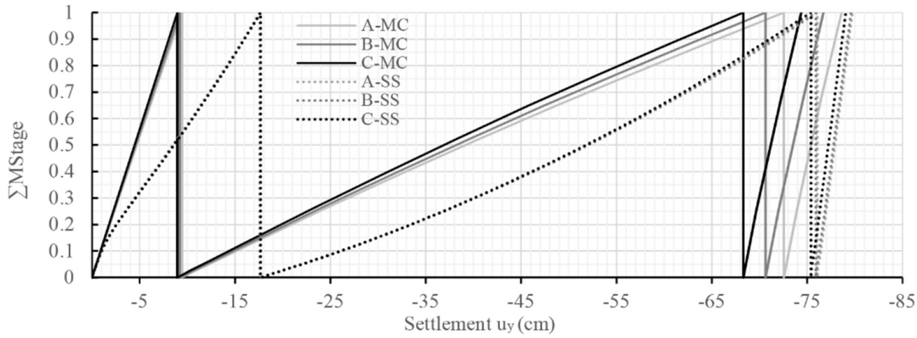

Figure 8: Settlements in GP 2.

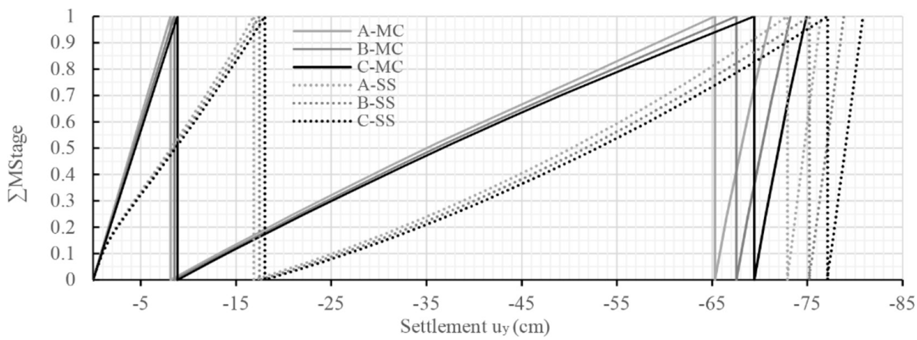

Figure 9: Settlements in GP 3.

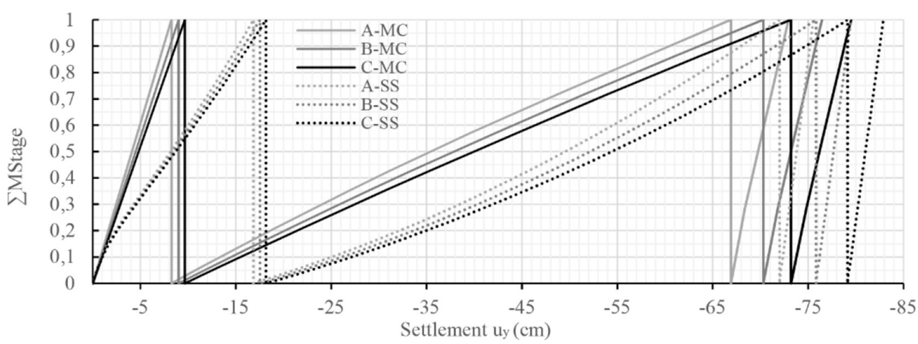

Figure 10: Settlements in GP 4.

To sum up, the differentials settlements in GP3 and GP4 were higher than those for GP1 and GP2, due to the thickness irregularity of the soft stratum (level II), increasing 3 m under the east façade (Point C). Also, it is important to note that the differential settlements appeared since Phase 1 (foundation construction). The major differential settlements were obtained in the GP4, which is under the south façade, where the soft stratum (level II) has the highest irregularity on its junction with the east façade (point C), with a thickness of 7.80 m.

7 CONCLUSION

In this research, the settlements of the Giralda tower, taking into account its different constructions phases, have been studied. For this aim, two calculations models have been carried out (MC and SS) in four geotechnical soil profiles. Thus, the following conclusions were drawn:

The geotechnical profile under the tower presents some irregularity regarding the thickness of the soft stratums (level II and level III). The stratum II increases its depth 2.00 m under the south façade and 3.00 m under the east façade.

The high settlements were due to the soft stratum under the foundation tower, which have a high thickness. These stratums (level II and III) have a very low elastic modulus(E), 5428 and 6165 kPa, respectively. Furthermore, the differential settlements were caused by the irregular depth of the soft stratum (level II), which increases its thickness in 2.00 m for GP2 and in 3.00 m for GP3 and GP4. Due to this fact, the largest differential settlements were obtained in GP2 and GP4, which are near east and south façades, respectively.

Comparing the results for both analyses, it can be observed that, for all calculations, the vertical displacements were always higher in the SS models, compared to those achieved for the Mohr-Coulomb ones (up to 8% in the last phase).

As mentioned earlier, currently, the tower has an inclination in the south-east corner, which could be caused by the differential settlements in the foundation, achieving the highest movements in the profiles near this corner. The differential settlements were greater in west-east direction (GP3 and GP4) than those for the north-south ones (GP1 and GP2). The settlements obtained in these analyses caused a theoretical inclination, which is similar to the real inclination of the tower. On the one hand, the current real top displacements of the tower are 14.7 cm in the north-south direction and 25.5 cm in the west-east one. On the other hand, according to the calculations, for the north-south direction (GP2), a differential settlement of 4.2 cm was obtained, which generated a top displacement of 16.8 cm. In case of the west-east direction (GP4), the differential settlement was 7 cm, which generated a top displacement of 27 cm.

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