Geotechnical characterisation for dating rammed earth architecture. The medieval wall of Seville (Spain)

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ABSTRACT

Rammed earth has been utilized as a construction material in a multitude of heritage sites, as evidenced by the Macarena Wall in Seville, which serves as an exemplary specimen of this construction method. This fortification, constructed using rammed earth caissons, has undergone numerous interventions that could have been enhanced if certain concerns regarding the material composition of the structure had been addressed. In light of this challenge, a research initiative was undertaken in 2019 with the objective of achieving a more precise characterization of the materials comprising the wall. To this end, direct samples were extracted and subjected to both destructive and non-destructive tests, allowing for the determination of their physico-chemical, mineralogical, and granulometric properties. The aim of this work is hence to study the potential origins of the soil used. This approach entailed a meticulous comparison of the sample characteristics with geotechnical data from the surrounding area. This methodology, founded upon comparative criteria and technical analysis, serves as a valuable instrument for the design of future restoration interventions, thereby ensuring the compatibility of the materials utilized. The objective of the present study is twofold: first, to contribute to the enhancement of conservation efforts in the Macarena Wall, and second, to propose a methodology that can be replicated in the context of other heritage assets constructed with earth, thereby facilitating the identification of original materials and promoting a restoration process that is more coherent and respectful of the authenticity of the aforementioned assets.

Keywords:, Seville Wall, Surveys, granulometric properties, heritage, geotechnical study, rammed earth.

INTRODUCTION AND BACKGROUND

The Seville wall has been the subject of numerous restoration interventions, as its state of conservation has been affected over time. However, some of the works carried out have actually contributed to its deterioration rather than improving its condition. In 2019, the Urban Planning Office of Seville commissioned the University of Seville to prepare a report for the study and analysis of the wall (Canivell et al., 2019). This research project come from a scientific collaboration between the Public Urban Planning Management of Seville (*Gerencia de Urbanismo y Medioambiente de Sevilla*, GUMS) and the Research Foundation of the University of Seville (*Fundación para la Investigación de la Universidad de Sevilla*, FIUS). Its purpose was to evaluate the state of conservation and to date the materials and construction elements belonging to the Macarena Wall (Seville). The present research aims to contribute to the characterisation of the physical properties of the wall, providing a basis for future projects or interventions. Although initially developed as an academic work, this study is here presented for the first time in a scientific context, representing an original contribution to the field.

The technical report concluded with responses to the commissioned objectives, as well as with technical recommendations for repair actions, preventive conservation, and maintenance of the rammed-earth structures. Therefore, the various tests carried out served to characterize the wall's construction material. Since the drafting of the report in 2019, restoration works have been undertaken: first on the intramural section (2020-21), later on the extramural section (2022-23), and it is expected that the wall will be accessible to the public in 2025.

CASE OF STUDY: SEVILLE WALL

The ancient city wall of Seville was an impressive defensive construction that surrounded the city since Roman times, later consolidated and expanded during the Islamic domination between the 9th and 11th centuries. Its main function was to protect the city from invasions and attacks, adapting to the military and urban needs of each period.

The wall had an approximate perimeter of 7 kilometres and included 166 towers as well as several access gates. Although parts of the wall were demolished in the 19th century due to urban expansion, significant sections have been preserved, particularly near the Macarena neighbourhood, where restored stretches and the gate of the same name can still be seen. Its architectural and historical legacy provides testimony to Seville's strategic importance and urban development throughout the centuries.

This study focuses on the Macarena section of the wall, a portion that remains standing from the original Seville city wall. The Macarena sector is located in the north-eastern part of the wall.

As shown in Figure 1, the Macarena Wall extends for nearly 700 linear meters. Additionally, due to the city's urban layout, the traces of the ancient Seville city wall are still evident, encompassing much of the historic city centre.

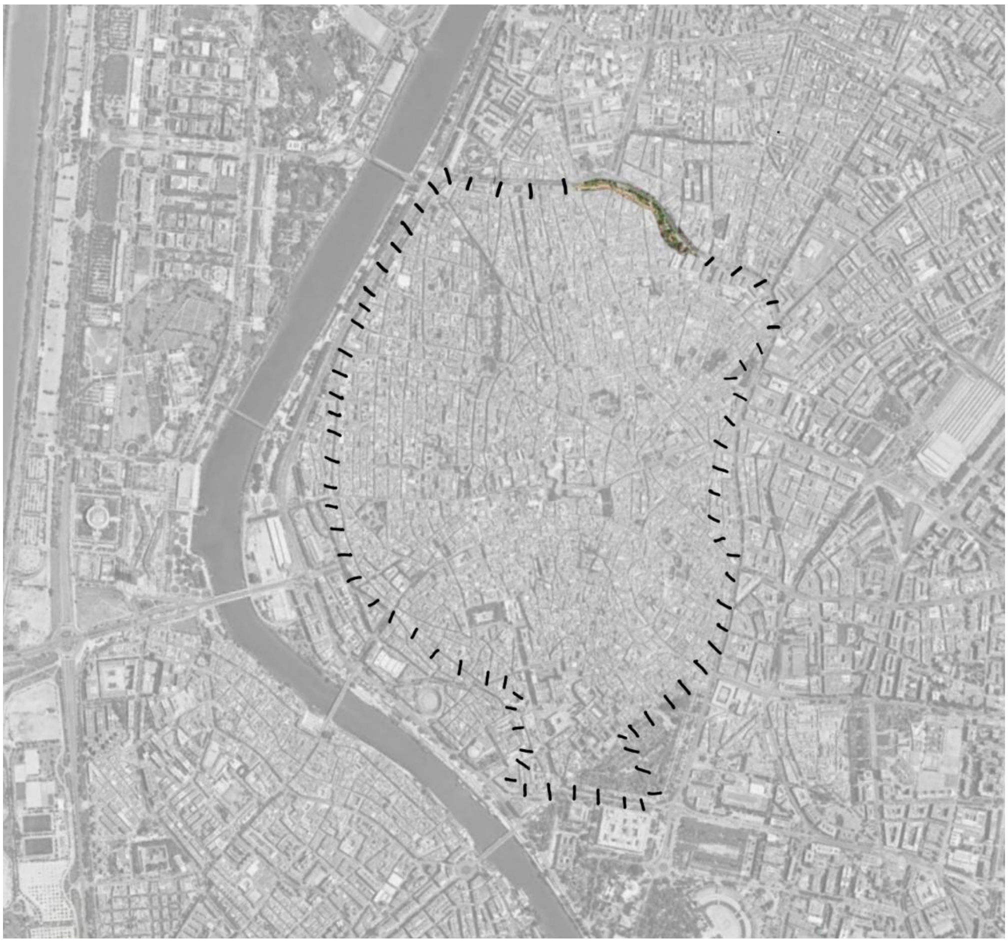

Figure 1. *Aerial black-and-white image with the Macarena Wall sector highlighted in colour and a dashed line tracing the route of the ancient Seville city wall. Source: Own elaboration based on Google Earth image, 2025.*

Tests performed on the rammed earth of the Macarena Wall

Based on the tests carried out for the restoration contract of the Macarena Wall (Canivell et al., 2019) an analysis of the obtained results is presented, which will later be subject to comparison.

Mineralogical Properties

The mineralogical analysis of the samples (Canivell et al., 2019) was one of the main objectives of this test. Analyses were performed using X-ray diffraction (XRD), determining the overall mineralogy through the powder method. Among the possible mineral components identified were calcite, clay minerals, salts, and silicates, among others. Minerals such as quartz and dolomite are present, since they originate from the sand used in the manufacture of the rammed earth. Furthermore, the samples and cores contained feldspars (orthoclase and albite) and phyllosilicates (muscovite). Another mineral detected was gypsum, found in the surface samples.

The quantity of minerals present in the samples and cores highlights the prevalence of quartz, due to the use of siliceous aggregate, with calcite in a lower proportion. This observation appears contradictory, as rammed-earth structures usually present a higher calcite content, since their aggregates are predominantly of calcareous origin (Alejandre Sánchez et al., 2019). The presence of clay minerals, such as muscovite, is minor. Finally, no traces of ettringite were found in the restored samples, which could indicate the addition of cement. However, this does not necessarily imply the absence of cement, as ettringite would only represent approximately 10–15% of the cementing agent, a low concentration relative to the total material that is difficult to detect with the technique used. To compensate for the cohesion typically provided by a cementing agent or fines, the presence of lime mortar could meet this requirement.

Granulometric Properties

The samples extracted from the Macarena wall were analysed through various laboratory tests, among others. Special attention has been given to the granulometry of these samples because, after reviewing previous studies on restorations of rammed-earth walls (Ontiveros et al., 2008; Bellido, 2008; Jové & Guerra, 2011), it is concluded that this is a crucial aspect to consider when seeking similarities with the surrounding soil. To carry out the granulometric test (UNE 103101:1995. Soil particle size analysis by sieving, 1995), samples from the three sectors of the wall were used. Their designation corresponds to the sector where they were taken, for example, M-1_, M-2_, or M-3_, depending on whether they belong to sector "00_SEMU_A_" 1, 2, or 3 (Figure 2). The samples analysed contain approximately 85 to 95% of coarse fraction (gravel and sand). In the samples taken from the original sections of the wall, a high degree of homogeneity is observed in the coarse fraction, including the sand granulometry. Regarding the finer fraction (clay and silt), the percentage is approximately 5 to 15%.

In the table (Table 1) a higher overall composition of gravel and sand can be observed, with clay and silt playing a secondary role. Therefore, considering the proportion of coarse aggregates in the wall, it can be hypothesized that the location from which the material was extracted likely contained layers of gravel and sand in the more superficial areas of the terrain. Over time, in the historic centre, the surface layers from that period may now be found at depths of up to 5 meters.

Table 1. *Composition of sand, gravel and fines from the wall samples*

Sample	Gravel(%)	Sand(%)	Fines (%)	Max	
M-1.1	58,20	28,40	13,40	Gravel	90,3 %
M-1.2	48,30	43	8,70	Sand	53,9%
M-1.3	60,60	23,20	16,20	Fines	16,2%
M-1.4	52,10	33,60	14,30		
M-2.1	72,20	23,90	3,90	**Min**	
M-2.2	68,50	24,60	6,90	Gravel	29,9 %
M-2.3	67,60	25,50	6,90	Sand	4,5 %
M-2.4	78	16,50	5,50	Fines	3,92 %
M-3.1	29,90	53,90	16,20		
M-3.2	47,10	38,50	14,40	**Mean**	
M-3.3	62,70	32,80	4,50	Gravel	63,88 %
M-3.4	90,30	4,50	5,20	Sand	29,38 %
M-3.5	60	36,08	3,92	Fines	6,74 %
M-3.6	67,90	27,30	4,80		

[a] Source: Own elaboration based on Canivell, J., et al., 2019.

The fact that there is a high overall composition of sand and gravel raises the question of whether areas associated with riverbeds are where this type of soil predominates in the more superficial layers. To address this question, attention must be paid not only to the current river courses but also to historical sources that document former river and stream channels. In Seville, the course of the waterways has been modified on numerous occasions, all with the aim of promoting the development of the city and its urban space. However, due to the importance of this topic, it will be addressed in the following chapter.

GEOLOGY AND HYDROGRAPHY OF THE CITY OF SEVILLE

The analysis of the geotechnical conditions of an area must begin with at least a basic understanding of its geology and hydrology. From this knowledge, it becomes possible to understand the relationship between the materials and the factors that influence the geotechnical characteristics of the different types of soil; therefore, special attention is given to hydrology and geology.

Hydrography

The city is located in the centre of a wide fluvial plain formed by the Guadalquivir River. In the middle of this plain lies the city itself, through which the river flows with a meandering course that crosses the entire urban area (Barrios et al., 1997). The hydrography of Seville is of particular importance due to the historical conflict between the city and the river — a constant effort to control its course in order to preserve navigability and protect against flooding (Palomo, 1878). To achieve both objectives, numerous interventions have been carried out on the riverbed. The current urban area of Seville was originally intersected by at least one branch of the river and several streams, of which the most important for the old city was the one referred to as Tagarete, given its location at the foot of a section of the defensive wall (Figure 2). Nevertheless, nowadays all streams have been channelled underground or diverted, and only a fluvial channel remains, situated where the river’s main course has flowed since at least the Middle Ages, although it no longer carries the natural flow of water, which has been diverted to the outskirts of the city. In fact, over the last 200 years, the original length of the Guadalquivir River estuary has been reduced by nearly 40 kilometres (del Moral, 1997).

Seville’s subsoil is relatively homogeneous. However, there are distinctive points corresponding to fluvial areas, such as the sites of former riverbeds of the Guadalquivir and nearby streams like the Tagarete and the Tamarguillo. The uniqueness of the area is due to variations in the ground strata, with a higher proportion of coarse elements (gravel and sand) in the upper layers, resulting in greater soil permeability and sub-alluvial water flow. Another characteristic that distinguishes this location is the presence of blue marls at greater depths, covered by a thicker layer of Quaternary materials. To study the different hypotheses regarding the courses of fluvial elements, their paths were mapped to enable a combined visualization and facilitate the analysis of geotechnical studies located along these courses (Figure 2). The area selected for this study is zone 00_SEMU_A_3.

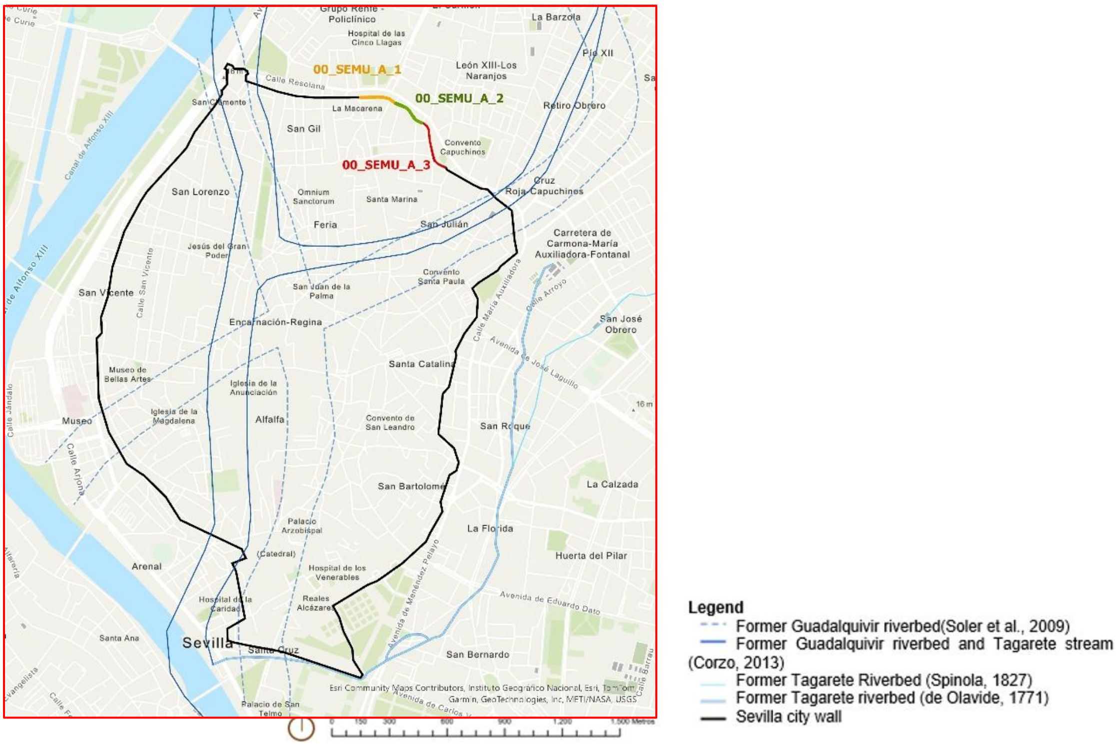

Figure 2. *Different hypotheses of the former courses of the Guadalquivir River and the Tagarete Stream. Source: Own elaboration according to (Soler et al., 2009; Corzo, 2013; Spinola, 1827; de Olavide, 1771).*

The presence of former river channels in the historic centre of Seville, along with the primarily sandy and gravelly strata along their edges, is undeniable. This observation aligns with the mineralogical and grain-size data presented above, and may help explain the locations of the quarries from which the earth used to construct the wall was extracted.

Ground Strata

In order to analyse the soil in different areas of Seville for later comparison with the composition of the samples, the characteristic strata of the city have been examined to understand the general composition of the city's ground. It provides an initial approximation to identify the potential for extracting materials for the construction of rammed earth structures. Seville is located on recent Quaternary materials from the Guadalquivir terrace, which rest upon a marl stratum.

According to local microzoning studies (Soler et al., 2009, Soriano et al., 2024), there are five layers of ground in Seville (Figure 3):

- Layer 0: Manmade fills and brown clays, forming the base of the topsoil layer and mainly consisting of fill material that can reach a thickness of 5–6 m. Quartzite pebbles can also be found.
- Layer A: clays, consisting of clays and silty clays of medium to high plasticity. It occurs at depths ranging from 2 to 8 meters, depending on the specific location.
- Layer B: sands and silts, with a thickness that can reach down to 10 m.
- Layer C: gravel and crushed stone, located above the marls, with medium to high compactness. It is usually found at depths between 8 and 15 m.
- Layer D: marls, corresponding to the blue marls of the Tertiary or Miocene period; their upper boundary varies from 5–6 m in the northern area to about 25 m in the central-western area.
- Water table: Generally, the GWL varies from 2–3 m to 9–10 m, depending on proximity to the Guadalquivir River. The groundwater level rises as the distance to the river decreases.

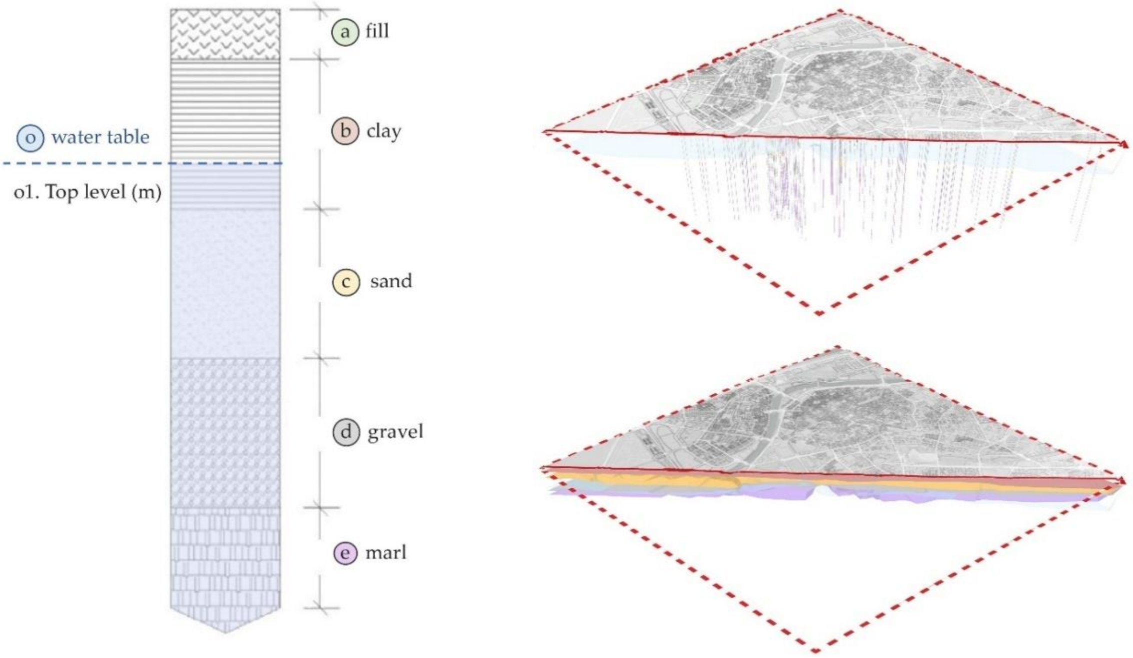

Figure 3. *General stratigraphic layers and soil distribution hypothesis of Seville (Soriano et. al, 2024).*

GEOTECHNICAL STUDY OF DIFFERENT LOCATIONS IN THE VICINITY OF THE SEVILLE WALL

Based on the geotechnical studies database (Mascort & Fuls, 2025), a series of geotechnical studies have been selected according to two mains approaches.

First, those located near the city wall were chosen for their potential relevance. A total of 30 preexisting geotechnical investigations were selected in different areas of Seville close to the former layout of the wall. These 30 geotechnical investigations include, in total, 112 tests analysing the characteristics of the ground. However, boreholes are the key tests, providing valuable information on the composition of the ground strata. Each investigation point is assigned a number representing its code, which will be used for later reference. For the analysis of the tests, ArcGIS Pro software was used to georeferenced them and position them in relation to the former layout of Seville's city wall.

Granulometric Properties

Of the 112 tests, only 58 correspond to boreholes and, therefore, these are the ones that have been analysed in order to identify similarities with the samples from La Macarena. The corresponding data have been collected, and a classification code like S_1 ("S" from boreholes and a number) has been assigned to each borehole. Therefore, in search of data that could confirm the initial hypotheses — that the soil was likely extracted from areas near the city wall, located outside the walls, and possibly from the edges of former riverbeds — the position of each borehole is analysed to determine whether it is located inside or outside the walls, whether it falls within a nearby area defined by an influence zone of 50 m inside the walls and 100 m outside the walls, whether it is close to an old river channel, or whether it presents sand or gravel layers at shallow depths (<10 m). This last aspect mentioned regarding the presence of gravel and sand is crucial, since the Macarena wall is primarily composed of sand and gravel. As a result, out of the initial 58 boreholes, only 48 contain sand and gravel in their uppermost layers which are analysed in Table 2.

Table 2. *Boreholes with sand and gravel layers at depths of less than 10 m*

Recognition points	Geotech . Study	Inside/ Outside walls	Borehole	Area of influence	Old Riverbed	Sand/Gravel
1	01-05	Out	Yes	No	No	Yes
2	01-05	Out	Yes	No	No	Yes
13	13-17	Out	Yes	No	Yes	Yes
14	13-17	Out	Yes	No	Yes	Yes
27	27-29	Out	Yes	No	Yes	Yes
36	36-39	In	Yes	No	Yes	Yes
37	36-39	In	Yes	No	Yes	Yes
44	44-46	In	Yes	Yes	No	Yes
45	44-46	In	Yes	Yes	No	Yes
47	47-50	Out	Yes	No	No	Yes
48	47-50	Out	Yes	No	No	Yes
49	47-50	Out	Yes	No	No	Yes
50	47-50	Out	Yes	No	No	Yes
51	51-53	In	Yes	Yes	No	Yes
52	51-53	In	Yes	Yes	No	Yes
53	51-53	In	Yes	Yes	No	Yes
54	54-57	In	Yes	Yes	Yes	Yes
55	54-57	In	Yes	Yes	Yes	Yes
58	58-60	In	Yes	No	Yes	Yes
61	61-63	In	Yes	Yes	No	Yes
64	64-66	In	Yes	No	Yes	Yes
67	67-72	Out	Yes	No	Yes	Yes
73	73-75	In	Yes	No	Yes	Yes
76	76-78	In	Yes	No	No	Yes
79	79-83	In	Yes	No	Yes	Yes
84	84-90	Out	Yes	No	Yes	Yes
85	84-90	Out	Yes	No	Yes	Yes
86	84-90	Out	Yes	No	No	Yes
87	84-90	Out	Yes	No	No	Yes
91	91-93	Out	Yes	No	No	Yes
92	91-93	Out	Yes	No	No	Yes
94	94-97	Out	Yes	No	No	Yes
95	94-97	Out	Yes	No	No	Yes
96	94-97	Out	Yes	No	No	Yes
97	94-97	Out	Yes	No	No	Yes
98	98-101	In	Yes	No	No	Yes
99	98-101	In	Yes	No	No	Yes
100	98-101	In	Yes	No	No	Yes
101	98-101	In	Yes	No	No	Yes
104	102-104	Out	Yes	Yes	No	Yes
105	105-112	Out	Yes	Yes	No	Yes
106	105-112	Out	Yes	Yes	Yes	Yes
107	105-112	Out	Yes	Yes	Yes	Yes
108	105-112	Out	Yes	Yes	No	Yes
109	105-112	Out	Yes	Yes	No	Yes
110	105-112	Out	Yes	Yes	No	Yes
111	105-112	Out	Yes	Yes	No	Yes
112	105-112	Out	Yes	No	No	Yes

[a] Source: Own elaboration (Aragón, 2025) based on the data cited in (Mascort & Fuls, 2025).

To take into account the situation of each one, it is represented by a point on the plan (Figure 4), thus allowing us to show whether it is close to the wall, near the river or former channels, or simply to locate it and get an idea of its position in case this could lead to another conclusion. For this reason, the layouts of the old channels are marked, and the trace of the former Medieval Wall of Seville is always kept in mind. Furthermore, the points for which granulometry has been studied are highlighted, in order to differentiate, among all those initially considered, the ones that were useful.

On the plan (Figure 4), the granulometric tests of each borehole are represented, sometimes more than one when granulometry was studied at different levels. Therefore, points with nomenclature such as 51_1, 52_1 or 52_2 can be found; all three belong to the same borehole, but the granulometric analysis was carried out at different elevation ranges. Moreover, among the different elevation intervals, three of them are of particular interest as they are found between layers of sand or gravel.

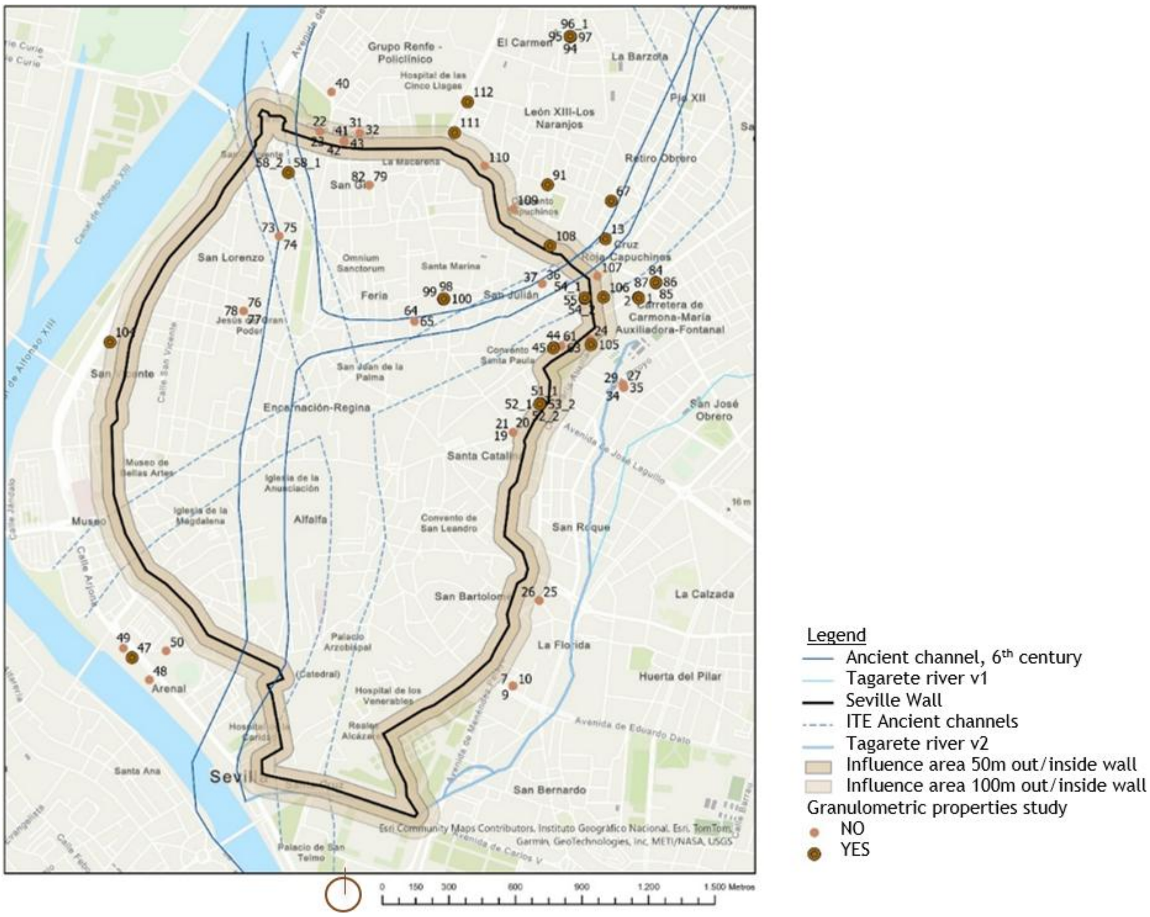

Figure 4. *Location of granulometric tests analysed. Source: Own elaboration (Aragón, 2025) from Mascort & Fuls, 2025.*

Mineralogical Properties

Regarding mineralogy, in the geotechnical studies available, this property is not analysed. However, based on various studies that have been carried out and that generally examine the mineralogy of the city of Seville, this aspect can be characterized. According to Arozamena (2012) in his doctoral thesis, he concludes that the minerals with the highest composition are quartz and calcite, which generally account for 69% and 20%, respectively. As for phyllosilicates, their percentage varies depending on the area, ranging from 5% to 68%. On the other hand, feldspars (2–19%) and dolomite (2–31%) are found in smaller proportions.

COMPARISON BETWEEN GEOTECHNICAL TESTS FROM DIFFERENT LOCATIONS IN THE VICINITY OF THE SEVILLE WALL AND THE SAMPLE FROM THE MACARENA WALL

Granulometric Properties

The methodology adopted consists of comparing the composition of the wall samples with those from the different areas of Seville that have been studied. For this purpose, a data sheet is prepared for each sample, where the results of the comparison and the similarity values between both are also discussed.

These comparisons have made it possible to establish hypotheses, based on specific evidence, regarding the source of the soil used for the construction of the wall. The table presents the percentages of gravel, sand, and fines from survey points that show strong similarity with the wall samples (Table 3).

Table 3. *Composition of sand, gravel and fines from the wall samples.*

Borehole	Gravel(%)	Sand(%)	Fines (%)	Samples that show similarity
S1	67	28	5	M2.2 / M2.3 / M3.6
S2	34	54	12	M3.1
S13	51	42	8	M1.2
S44	56	37	7	M3.5
S45	63	34	3	M3.3 / M3.5
S51_3	69	23	8	M2.2 / M2.3
S52_2	77	18	5	M2.4
S53_2	51	33	16	M1.4
S53_3	61	33	6	M3.3
S67	64	32	5	M3.3
S87	35	57	8	M3.1
S91	59	33	8	M1.1 / M3.3
S94	50	36	14	M1.4 / M3.2
S96_2	52	39	9	M1.4 / M3.2
S97	51	41	8	M1.2 / M3.2
S100	45	38	17	M3.2
S105	28	53	19	M3.1
S111	74	22	4	M2.1
S112	57	38	5	M3.5

[a] Comparison of the soil composition of sample of Macarena Wall with the boreholes of the locations which have been studied. Source: Own elaboration based on the data cited in (Mascort & Fuls, 2025).

In summary, these results support the initial hypotheses, which stated that the materials must have been located close to the rivers due to the percentage of gravel and sand found in the wall samples, and also that, for logistical reasons of the time, they were unlikely to have been situated very far from the wall.

Mineralogical Properties

Regarding the mineralogical properties, as mentioned previously, there is not as much information available as there is for the granulometry (Arozamena, 2012). This is because mineralogy is not analysed in the geotechnical studies considered; therefore, the characteristic mineralogical properties of Seville, of the city in general, are examined (Table 4).

Table 04. *Composition of sand, gravel and fines from the wall samples.*

Quantity	Macarena Wall	Area of Seville
Higher proportion	Quartz and Calcite	Quartz, Calcite, Dolomite and Phyllosilicates
Lower proportion	Gypsum, Orthoclase, Albite, Muscovite, Dolomite, Hornblende and Clinochlore	Illite, Smectites, Kaolinite and Sporadic chlorite

[a] Source: Own elaboration based on the data cited in (Mascort & Fuls, 2025) and (Canivell et al., 2019).

Identified areas

The criteria mentioned above have been combined and represented in Figure 5, which encompasses the areas meeting all or some of the proposed conditions, based on the studies and analyses developed throughout this research.

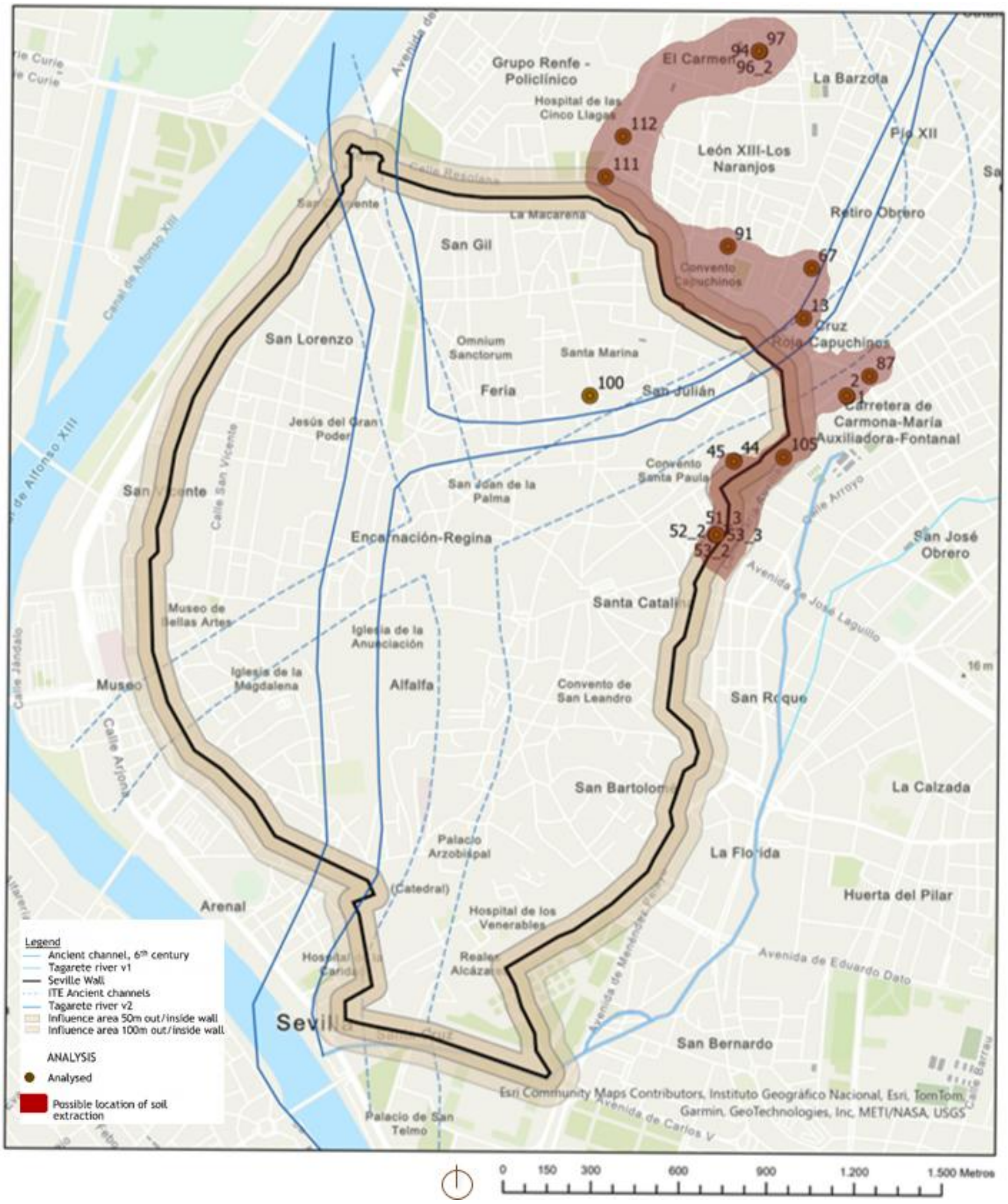

Figure 5. *Hypothesis of the location from which the soil used for the construction of the wall may have been extracted. Source: Aragón, 2025.*

Most of the areas identified as potential sources of the soil used for the wall are located near the Macarena Wall, which supports the proximity principle. However, if remnants of the wall in the southwestern section (the opposite end) were still standing and could be studied, it might be possible that the composition of that part of the wall matched the soil composition of nearby areas.This last hypothesis cannot be verified, since no remains of the Almohad construction survive apart from the Macarena Wall, and the Alcázar Wall belongs to an earlier Islamic period. Therefore, any compositional differences might be attributed to variations in construction techniques typical of that earlier period.

CONCLUSIONS

The granulometric analysis of the Macarena Wall samples allowed for hypotheses regarding the origin of the soil, possibly extracted from former channels of the Guadalquivir River and nearby streams. Boreholes from different areas of Seville enabled more accurate comparisons, showing that gravel and sand layers are closer to the surface in ancient riverbeds.

The use of Geographic Information Systems (GIS) allowed mapping of the results, overlaying borehole locations with ancient river courses, the city layout, and the wall, providing interactive tools for detailed analysis and representation. It was noted that while numerous geotechnical studies with boreholes exist, many are private and difficult to access, highlighting the need for open data to improve understanding of the terrain.

Based on the analyses, three hypotheses were proposed regarding the soil used in the wall construction. Origin from the banks of the Guadalquivir or ancient channels, considering that gravel and sand layers were accessible at the time.

- Proximity to the wall due to logistical constraints of transportation in that period.
- Extraction from areas outside the wall, as the interior was occupied by buildings.
- Most potential source areas are near the Macarena Wall, supporting the proximity hypothesis. Other sections of the wall cannot be verified due to the absence of surviving Almohad remains.

The high percentage of gravel and sand supports the hypothesis that the soil came from the banks of the Guadalquivir River or nearby streams, or from areas where ancient channels once flowed. Seville's soil profile is quite distinctive, with clay layers near the surface and sand and gravel layers deeper down. Considering the technological limitations of the period, it is assumed that excavation was carried out in the shallower layers for ease of extraction. However, over time, the ground level has risen, and strata that were once superficial have become buried beneath anthropogenic fill. In the historic centre of Seville, the ground level may have risen by up to 5 meters since that time. Therefore, the gravel and sand layers considered were those located no deeper than 10 meters.

The fact that many granulometric tests performed near ancient riverbeds or on their banks coincide in composition with the wall samples may be explained by this reasoning. Considering the logistical limitations of the time, it is understood that the extraction of soil took place near the wall. Transportation during that period cannot be compared to today's conditions. Therefore, it is reasonable that most of the boreholes are located very close to the layout of Seville's ancient wall, or at least within its immediate surroundings.

Finally, it should be mentioned that ancient cities were enclosed by walls as a defensive measure against potential attacks. Over time, suburbs developed outside the walls, but most urban life occurred within. The fact that the city was consolidated within the walls suggests that the soil was extracted from outside, since the interior was occupied by buildings. For this reason, most of the boreholes are located outside the wall, supporting this locational criterion.

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