Reconstructing The 1755 Tsunami Flood Height In The City Of Cadiz And Its Application To A Tsunami Risk Assessment For A Similar Scenario

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SUMMARY:
This paper is structured in two parts. In part I, detailed analysis of historical documents and a multidisciplinary approach incorporating urban studies and a virtual topographic reconstruction of the city have allowed us to determine 16 flood height indicators for the 1755 tsunami in the city of Cadiz. A 3D reconstruction of the city based on historical evidence of its most likely layout in 1755 have also allowed us to recreate the tsunami flood history in different part of the city. In part II the flood height determined in part I is used to analyse the current vulnerability of the city today following two tsunamis hazard vulnerability methods. The study uses the most likely flood height reached in 1755 to analyse the vulnerability of the city today following two tsunami hazard methods. This work develops a multidisciplinary procedure to determine the 1755 flood heights from historical documents, urban studies, topographical studies and a 3D virtual model of the city.

Keywords: Cadiz, tsunami, 1755 earthquake, urban hazard.

1. THE 1755 TSUNAMI

1.1. Historical Sources

Martínez Solares (2001) published 15 historical sources giving detailed accounts of the 1755 earthquake and tsunami in Cadiz from a nation-wide instruction of King Ferdinand VI. Our research revealed 7 further documents found in the Spanish National Library and the Municipal archives of the city of Cadiz. The city's town hall minutes were also analysed and witness accounts, such as that of Captain Habbard, published in the New York Mercury were also identified.

1.2. Cadiz In 1755

A detailed understanding of the city's layout in 1755 is required to confidently analyse the effects of the tsunami. Maps and historical cartography were found in the Historical Municipal archives (AHM) and the Museum of the Cadiz Courts (MCC) giving a clear understanding of the city's layout in 1755. In particular, engineer Sala's 1734 city map and the municipal nomenclature of 1812 allowed us to determine the city layout and confidently identify street names and city wall features from historical accounts. The MCC also holds coetaneous engineering plans detailing the city walls and port quay heights with datum referencing. The MCC also holds a 1:250 scale model of the city built in 1779.

1.3. Drawing Up The 1755 City Map And Virtual Model

Engineer Sala's 1734 city map was first rasterised and then vectorised with reference to current vector and ordnance survey (hereafter OS) data obtained from the town planning municipal architectural office. This process allowed for an understanding of which parts of the current urban fabric survive from 1755, facilitating the orthographic correction of the 1734 data. Topographical contours were drawn up for the entire city at 1m intervals. The result was a 3D vector map identifying the main urban features of the city as it most likely stood in 1755, as shown in figures 1 and 2. The study of engineering sections revealed considerable detail. The ordnance survey height (OS) of the city quay was established at +4.30m OS thanks to Sala's architectural sections of detailed port renovation works dating from 1734. Albeit, uncertainties remain, in particular the vertical drift of consolidated urban ordnance survey heights, as is to be expected from a city in continuous occupation.

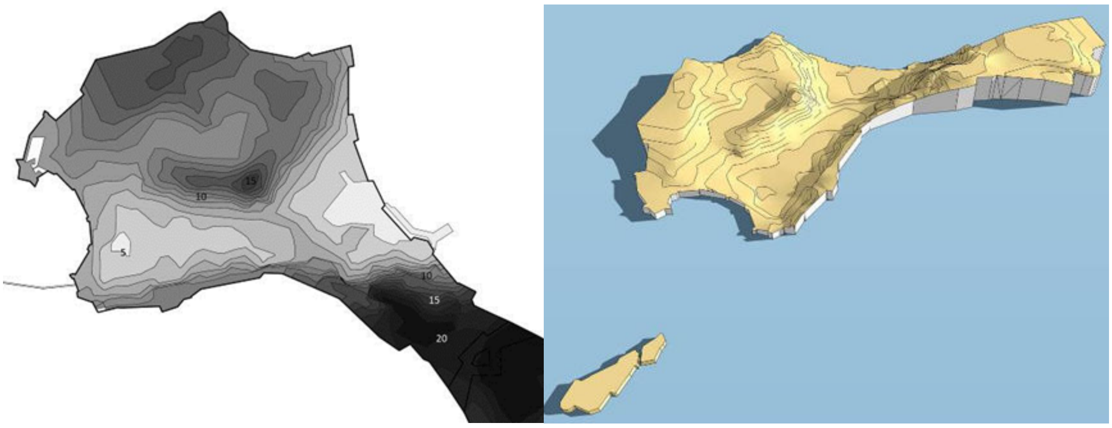

Figure1. Vector and 3D model of the City of Cadiz developed for this work

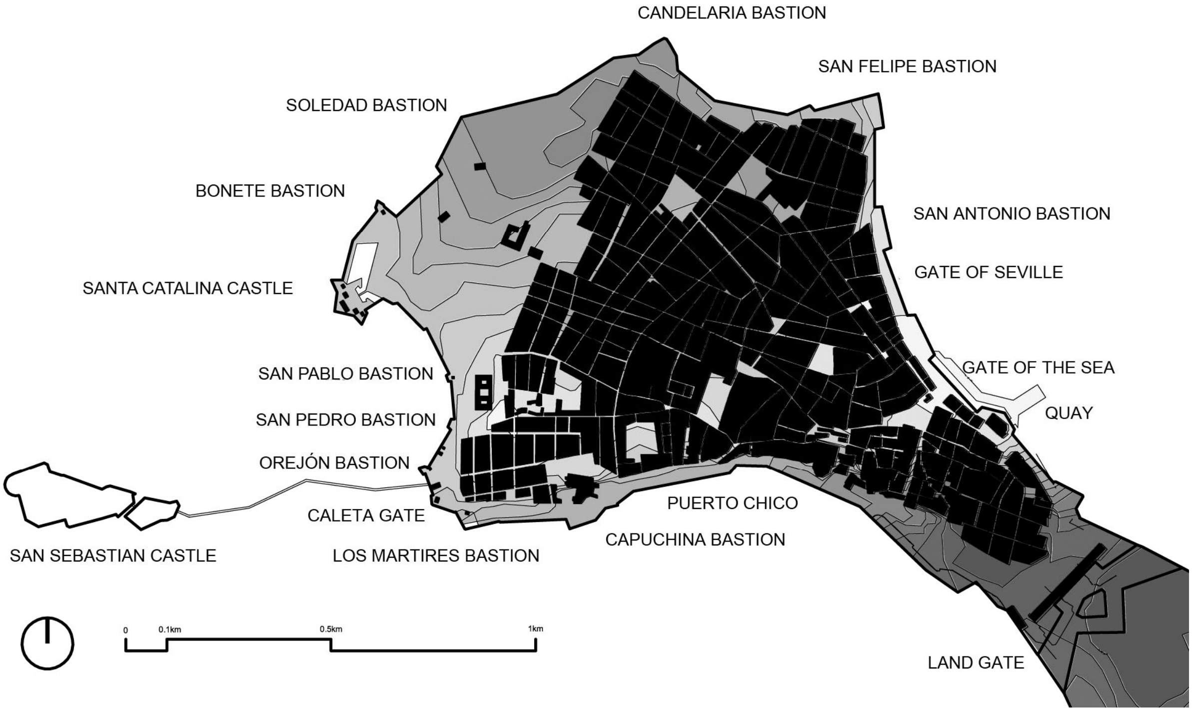

Figure 2. The City of Cadiz as it stood in 1755 with main features from Ignacio Sala's map of 1734

1.4. Flood Indicators From Historical Accounts

Thirty flood indicators were identified from the revision and study of 23 historical accounts of the tsunami and subsequently classified into three quality levels. Q1 was assigned when both planimetric and altimetric confidence could be assigned to a city location affected by the flood. Q2 was assigned if there was either planimetric or altimetric certainty at a location affected by the flood. Q3 was assigned if a location was known to have been flooded, but neither planimetric nor altimetric confidence was possible. Q3 indicators were dismissed and ignored from the study, leaving 14 Q1 indicators and 1 Q2 indicators. A note form summary of the identified flood indicators is shown in table 1.

Table 1. A summary of flood indicators identified for this work. DNN; 221; Situ and LG refer to source authors. OS refers to Ordnance Survey datum. Q refers to Quality Factor.

Nº	OS Height	Source	Text	Commentary	Q
1	+6.06m	DNN	…wooden beams dragged down Cruz Street to the Palma Chapel…	+6.06m at Palma Chapel.	Q1
2	+8.06m	DNN	…Hospice bell dragged a pistol shot inland…	Hospice base +6.52m. (Pistol shot at 25m)	Q1
3	+8.00m	DNN	…Marble base of the cross dragged inland a rifle shot's distance…	Currently Palma Street. (Rifle shot at 100m)	Q1
4	+5.54m	DNN	Beams…floated off to the Pastora Church…	Currently in Sagasta Street at +5.54m.	Q1
5	+7.35m	DNN	…houses near the hospice flooded 2 or 3 *varas*…	Castilian Vara (yard) gives a flood of +7.35m at San Felix street, located today at +4.85m.	Q1
6	+6.00m	DNN	…water emerged from the drain flowing into San Juan and Callejón…	Today San Juan and Callejón lie at +5.95m.	Q1
7	+4.50m	DNN	…Flowed from San Juan de Dios Square into Calle Nueva…	Has to overcome +4.50m to flow into Calle Nueva.	Q1
8	+4.70m	DNN	…gushing into Guanteros Street where it rose half a *vara*…	Today Cristobal Colon Street at +4.26m OS, ponding to +4.70m.	Q1
9	+5.08m	221	…From Seville gate flowing into the Post Office…	Today San Francisco and Rubio y Diaz at +5.08m.	Q1
10	+4.55m	221	…From Recova Drain down half Juan de Andas street…	Today Cristobal Colon Street at +4.55m.	Q1
11	+5.30m +6.85m	In situ	Plaque with water level mark	Level height +6.85m over a +5.30m base.	Q1
12	+6.79m	In situ	Podium of Palma Church	Water didn't penetrate at +6.79m.	Q1
13	+6.50m	LG	…massive block thrown 50 *varas* from the parapet…	Engineer Barnola measured the block at 4.18m x 1.67m 42m from the hospice.	Q1
14	+6.00m	LG	…sea level at 3 *varas* above high tide…	Luis Godin estimates 2.5m water elevation over the port.	Q1
15	+9.50m	Anon	…water reached the King's hospital, those that could, escaped…	Today Manuel de Falla theatre.	Q2

1.5. Tsunami Effects In Cadiz

The 1755 tsunami flooded three areas of the town, shown in figure 3 below.

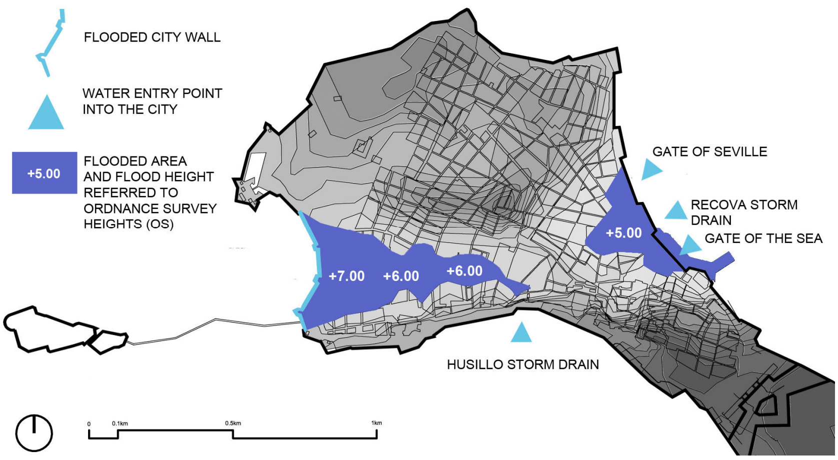

Figure 3. Summary of the city areas flooded in 1755

The flooded areas are referred to in this study as the La Viña, Puerto Chico, and El Puerto. In La Viña the tsunami overflowed the city walls and extensively flooded this neighbourhood of the city. In Puerto Chico the tsunami flooded this area through the sewer system. In El Puerto the tsunami flooded the port facilities outside the city walls and flowed into the town through the city gates. 15 people were drowned in the city according to the deceased registry of the parish of Santa Cruz.

1.6. La Viña

La Viña is a low-lying neighbourhood opening up into a bay arranged in an open jaws fashion. There was violent and destructive flooding with at least three consecutive waves overflowing the city wall. Engineer Barnola left a detailed account step by step of the damage observed to the city walls in this area. Ten of the flood indicators in the city are in this area, shown in Figure 4.

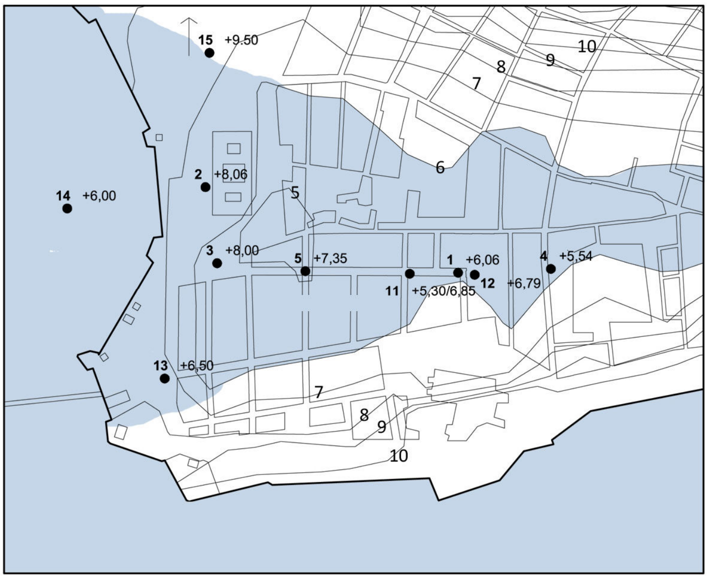

Figure 4. Flood indicators in La Viña. Bold numbers refer to flood indicators summarised in Table 1. Simple numbers refer to contour levels.

We have determined a parapet height of +7.00m OS with a wall platform behind the parapet of +6.30m OS. In La Viña neighbourhood, the height drops quickly to only +4.85m OS. The tsunami demolished the scaffolding of the Hospice building, located at +6.56m OS and dragged the wooden members of the scaffolding 480m inland to Sagasta Street, located at +5.54m OS. In San Felix Street, the waters reached a height of between 2.5m and 3.3m drowning people inside their homes, '…those what with haste could not escape…' The tsunami must have reached a height of at least +7.00m OS to demolish the city wall parapet and execute the damage observed. Within the Viña neighbourhood, there are half a dozen flood indicators of flotsam being carried inland suggesting water ponded at about +6.00m OS. The flood sequence is shown schematically in Figures 5 and 6.

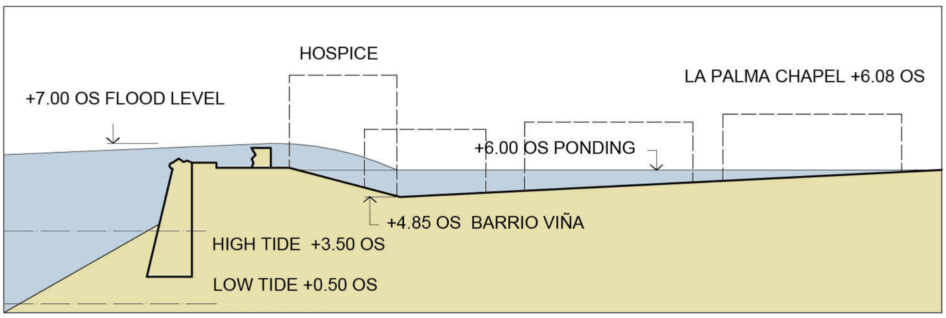

Figure 5. Schematic profile of Viña neighbourhood and flood levels determined in this work

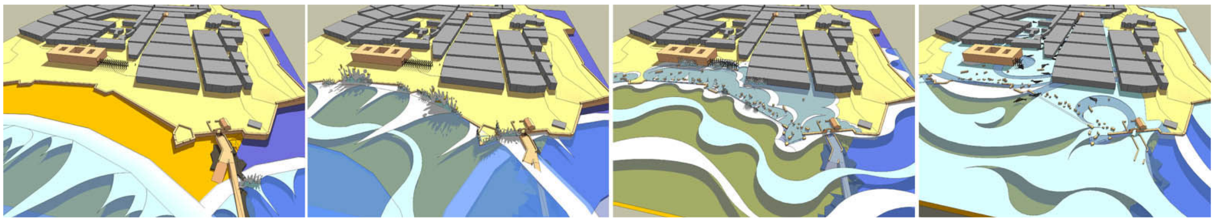

Figure 6. Modelled flood sequence in La Viña from eyewitness accounts and flood indicators. From left to right, Tsunami approach; City wall demolished; hospice trellis dismantled; Flood reaches 580m inland submerging the Viña neighbourhood.

1.7. Puerto Chico

Puerto Chico is a neighbourhood protected by high city walls but flooded by the tsunami through the storm drain in the square. The flooding of Puerto Chico provides an interesting flood indicator as the square and buildings of Puerto Chico remain today. At this location the city walls are high at about +10m OS but Puerto Chico was flooded by water emerging from the drains in the square, situated at +5.95m OS. The water level outside the city walls must have reached or exceeded this height to cause following the principle of communicating vessels. The flood indicator here suggests water ponded at least at level +6.00m OS, affecting a small area of about 6.000m^2. We can use Bernoulli's principle to test the flooding capacity of a hypothetical drain aperture of 1m^2.

$$V = \surd 2 \odot g \odot h$$
$$V = 1.4 m/s$$

Two minutes of sustained sea level at +6.00m OS are required to provoke the flooding observed with about 330m^3 of water through the drain system. The flood sequence is shown in figure 8.

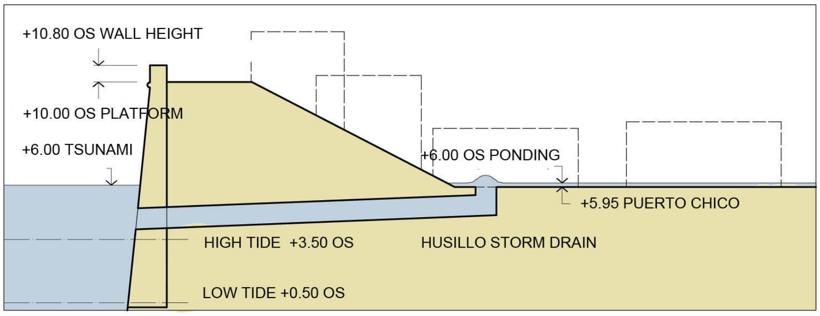

Figure 8. Schematic profile of Puerto Chico square and flooding of this neighbourhood through the storm drain.

1.8. The City Port

In 1755 the port quay was outside the city walls and accessible through the Sea and Seville city gates. The tsunami flooded the quay areas violently, capsizing ships. The tsunami then flowed into the city through the open gates. Water also flowed in through the storm drain of La Recova, in a similar fashion to Puerto Chico. Flood indicators in this part of the city suggest the water reached a height of about +5.00m OS on the land side of the walls, flooding an area of about 43.000m^2 with about 10.750m^3 of sea water. The main features of this area and the flood indicators are shown in figure 9. Because the city is sealed off from the sea by the wall, the flooding here was conditioned by the amount of water that was able to flow in through the city gates. The gate aperture dimensions from the 1734 plans of engineer Sala sum 12.68m in length. We can use Bernoulli's law to check a best fit for the sea level height required to flood this volume of water as follows:

$$V = \surd 2 \odot g \odot h$$
$$V = 5.56 m/s$$

A sustained sea level of about +6.00m OS, coincident with Puerto Chico, would support a flow of 70.5m^3/s and flood this part of the city in about two and a half minutes. See figures 9 and 10 and 11 for this modelled area of the city.

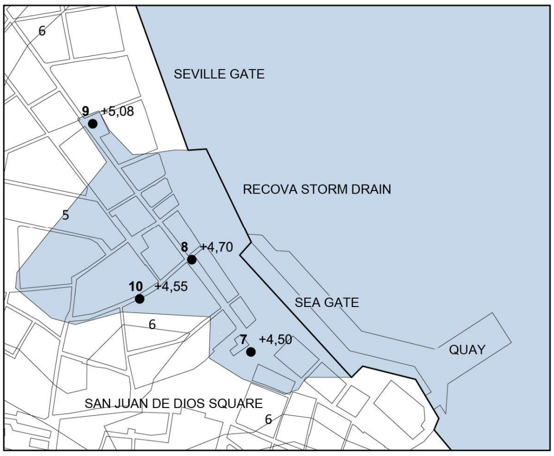

Figure 9. Flood areas and flood indicators referenced in Table 1 for the port area

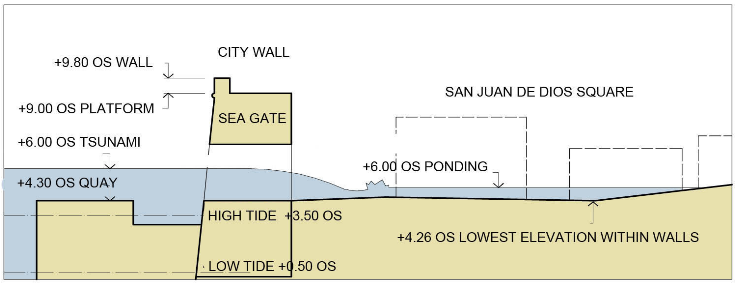

Figure 10. Schematic profile of the Port area and the flooding observed through the city gates

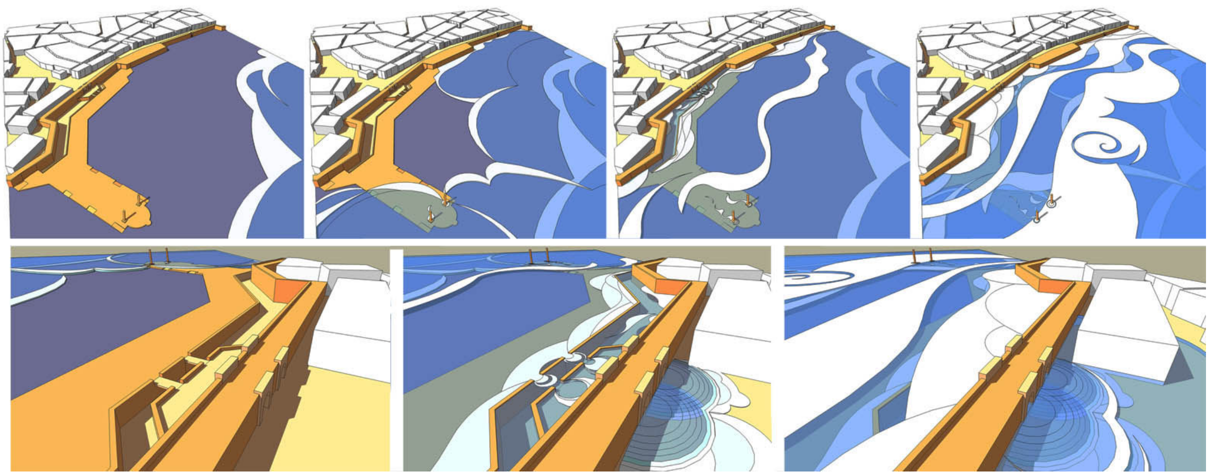

Figure 11. Flooding sequence of the port area. Top left to right; Tsunami arrival; Quay is flooded; Moat fills; Walls retain the flood advance. Bottom left to right; Tsunami arrival; Quay is flooded and moat fills; Water flows into city through the port gates.

1.9. Inferring A Tsunami Crest Height

The analysis of the three areas of the city flooded by the tsunami allows an estimate of the minimum water crest height required to cause the observed flooding. In La Viña, water must have attained a height of +7.00m OS to overflow and demolish the wall parapet levels at that location. In Puerto Chico and the city port, the water must have sustained a minimum level of +6.00m OS for at least two minutes to provoke the observed flooding, although the waters may have been higher. In the case of La Viña, that has a westward-facing open jaws configuration, the higher water level may indicate a case of water convergence or wave amplification as the bay faces the direction of the tsunami arrival.

1.10. Tide Graph Estimate For The 1755 Tsunami In Cadiz

Various authors coincide in reporting the tsunami arrival times, including astronomer Luis Godin who was a direct witness of the event and reports consecutive wave arrivals at 11:10, 11:30, 12:00, 12.35 and 13:15. Godin also concurs with other authors that the tide in Cadiz was in its fifth hour at the arrival of the first wave. Accounts also agree in the fact that the first three waves consecutively flooded the town. In the afternoon, with a waning tide, after the fifth and sixth waves, the most notable phenomenon is the wave trough, which exposes bathymetry never seen before.

From the tide averages at Cadiz published by the oceanographic institute, a tide graph estimate can be drawn up using Godin's time records and adopting the minimum flood OS height of +6.00m for the first three waves from our flood indicator analysis. This first part of the paper concludes the 1755 tsunami in the city of Cadiz had at least an amplitude of 5m (from crest to trough) and sustained a crest height of +6.00m OS, or 2.5m over mean high tide as shown in Figure12.

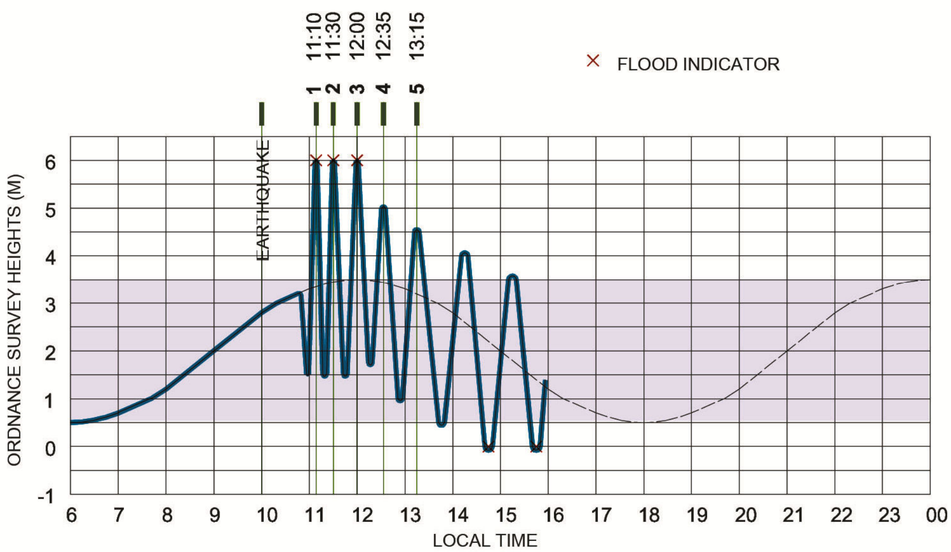

Figure 12. Inferred tide graph from flood indicator levels and arrival times reported by astronomer Luis Godin

2. TSUNAMI RISK STUDY FOR CADIZ FOR A 1755 SCENARIO

2.1. Methods For Estimating Tsunami-generated Damage

Irizarry et. Al. (2008) summarises the most recent methods for estimating tsunami damage losses, notably those developed by Peiris, (2006) Reese, (2007) and Dominey-Howes Papathoma. (2003, 2007) More recent developments include Dall' Osso et. Al. (2009) and the fragility curves based on satellite visual inspection developed by Suppasri et al. (2011)

Peiris (2006) developed vulnerability functions based on the observed damage and research undertaken in Sri Lanka after the Indian Ocean tsunami of 2004. Most of the vulnerability functions developed are based on single storey masonry structures, but wooden frame buildings were also used.

Reese (2007) developed vulnerability functions based on the observed damage and research undertaken after the Java 2006 tsunami. This work proposes four building types, masonry, wood frame, concrete frame, and confined masonry concrete frame. Expected damage is expressed through damage factors that weigh up the cost of repair against the cost of reconstruction. Vulnerability functions for Peiris and Reese are shown in figure 13.

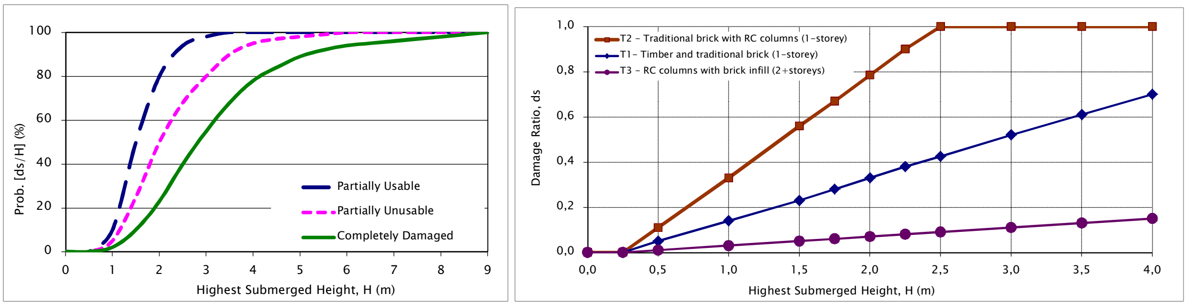

Figure 13. Vulnerability functions of Peiris (left) and Reese (right)

2.2. Method Limitations

The vulnerability curves presented here do not allow discerning between first row buildings with full exposure to flooding and those situated further inland. Consecutive waves or flooding is not considered either. Water speed is not considered and there appears to be no provision for flotsam impact, although being curves based on empirical data, one could argue that these effects are somehow built into the curve composition. These curves do not allow discerning between higher and lower buildings while some authors sustain taller buildings are less vulnerable due to higher loads and stability against lateral flooding (Dissanayake, 2005). There is also a lack of consensus on the number of homeless generated by these curves and as a result no attempt has been made in this work to determine this aspect.

2.3. Damage From A Recurrence Of A 1755 Event Using The Method Of Peiris

In order to apply Peiris' methodology to the case of Cadiz, an estimate of the number of submerged buildings must be made, as well as the flood depth. For this data a tsunami height of +6.00m OS first presented by Murphy (2009) and later refined in the first part of this work has been applied to the modern city of Cadiz. The city has been broken down into boroughs and each function applied to each borough based on the amount of flooding to be expected. Borough 3 is only expected to be flooded in 1% of its extension, while borough 10, the lowest topographically speaking, is expected to be flooded in its totality. For each borough the average water height was calculated based on the same scenario as 1755, that is, a tsunami coincident with high tide. The results are shown in figure 14.

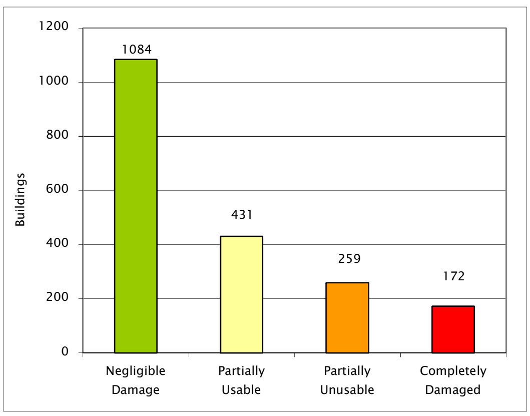

Figure 14. Summary of expected damage to buildings in Cadiz applying vulnerability funcitons of Peiris

With the expected flood heights, about a third of buildings are expected to suffer complete damage, a quarter of them partially damaged while the rest lightly or not damaged. City boroughs 9 and 10 are those that experience most damage, but almost all city boroughs experience some sort of damage. Detailed borough by borough results are shown in figure 18.

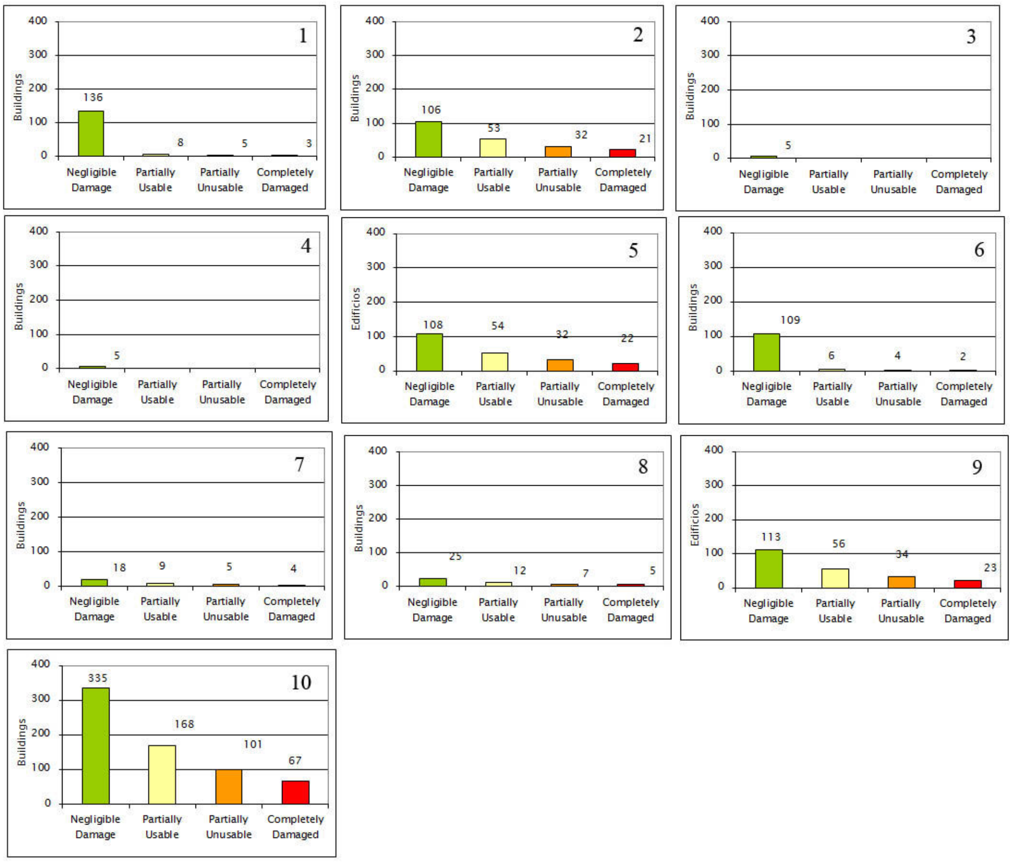

Figure 18. Borough by borough damage in Cadiz applying Peris' vulnerability function

2.1. Damage From A Recurrence Of A 1755 Event Using The Method Of Reese

A correlation must be made for the building types found in the city of Cadiz and the four building types identified by Reese in order to apply vulnerability functions. In order to do this, the building stock of the city was broken down into unreinforced masonry (URM) types and frame buildings (RC) following Murphy's estimate of the city survey in 2009. The URM types were classified as T2 while the RC types were classified as T3. There are uncertainties with this classification due to the fact that Reese develops functions based on the building types of Java, that are not coincident with those found in a European city. In particular, there are no T1 types in Cadiz, corresponding to light wooden frame structures. It is not surprising therefore, that the results of Reese's methodology show considerable less damage than Peiris, with 1815 buildings with moderate damage and no buildings with serious damage.

3. CONCLUSIONS

Damage estimates have been carried out in the city of Cadiz for a 1755 type tsunami scenario based on the flood levels developed by Murphy (2009) for a +6.00m OS water level. Two vulnerability methods, Reese and Peiris have been applied and compared to each other.

Peiris does not consider, for example, different building types and assumes all buildings are equally vulnerable, while Reese develops functions for different construction types based on those found in Java. While these types do not reflect the construction types found in Cadiz, they may serve as an indication to estimate the type of expected damage wrought by a repetition of a 1755 type tsunami. Peiris' methodology identifies almost 2.000 damaged buildings of which 438 would be seriously damaged. Reese's methodology has a more benign result, with 1815 buildings lightly damaged and no serious damage. In both methods, small changes in the flood depth have large result significance. For this reason it is important to conduct these types of studies at smaller scales, where topographical differences can be taken into account in larger detail.

The work shows the extreme exposure of the city of Cadiz to tsunami action, in particular the expansion of the city into the sandy isthmus and outside the city walls. These areas were completely submerged in 1755 but were also uninhabited. Today they are densely occupied. Borough 10 (Cortadura) stands out to be completely submerged with only a flood height of 2.5m over high tide. In addition, the city walls of port area were removed in the early 1900s, and in a repetition of the tsunami, water will flow into the city unhindered by the former city wall.

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