3.1.2 Definition of flood exposure indexes for the HR test site

Final Version

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Summary

1. Introduction

1.1 Brief presentation of Activity 3.1

Activity 3.1 within Work Package 3 of PMO-GATE project relates to the assessment of flood exposure in coastal urban areas due to impact of sea level rise. Climate change scenarios are likely to cause the increase of the mean sea level, potentially flooding significant number of objects. Within this activity, a coastal flooding exposure analysis is performed for the particular test site of Kaštel Kambelovac. Furthermore, this activity addresses the main weak points potentially exposed to flooding, which in combination with flood exposure maps are used for flood risk assessment on the particular test site. In addition, existing flood risk management plans are evaluated along with the relevant EU legislation. Finally, a set of actions is defined in order to harmonize local flood risk management plans with EU requirements.

1.2 Description of the test site – Kaštel Kambelovac

Along the Croatian coast, flooding endangers many low-lying coastal areas potentially exposing significant number of objects to flood hazard. Many historical buildings and/or areas are located along the coastline, which are potentially endangered by coastal flooding as well and subject to significant consequences and damage. The City of Kaštela area is endangered by sea flooding due to its low-lying topography and significant number of cultural and household objects located near the coastline. The particular test site in PMO-GATE project is Kaštel Kambelovac, one of the seven settlements that form the City of Kaštela. This area covers around 45000 square meters and includes more than 400 objects.
The benefit of the chosen area reflects through diversity of objects considering construction, architecture and material, built from the 15th century until today. According to Marasović [1] the oldest objects in the area date back to 1467. These buildings were made of stone with a wooden floor construction, and they remained preserved until today with minor modifications over the years. Historical part of the Kaštel Kambelovac is founded in the 16th century around the Tower of Cambi, as well as the church of St. Mihovil and Martin from the 19th century with a bell tower from 1860. This particular area is a mixture of private and public facilities, mostly built as masonry and concrete buildings. Plan view of the selected area is shown in Figure 1, where the green line defines the border of the test site, purple one defines the border of historical part, while the red line shows position of the natural coastline.

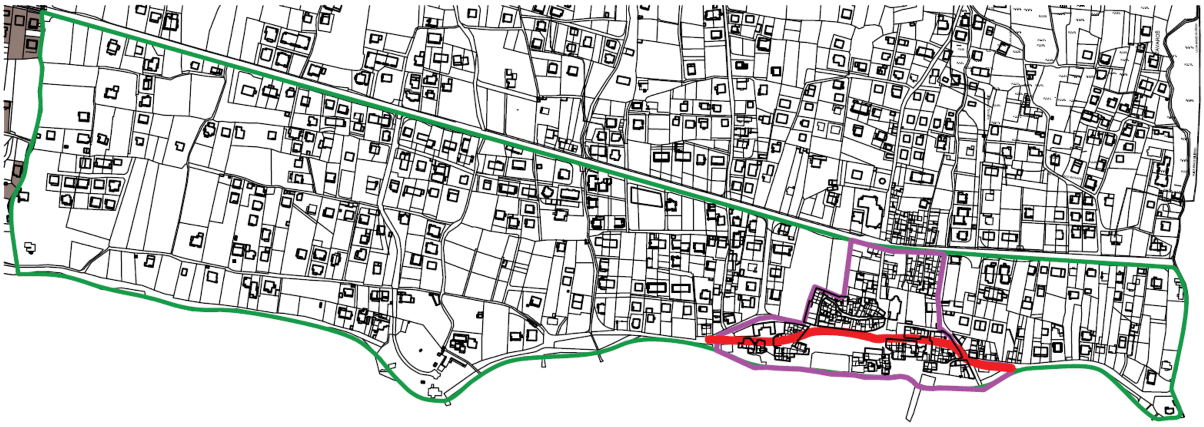

Figure 1. Plan view of the selected area (green line) with the mark of the natural coastline (red line) and the historical part (purple line)

Coastal flooding is considered one of the major threats for coastal urban areas. This is especially related to low-lying coastal areas such as City of Kaštela, where significant part of the city is located near the coastline. High population density in the coastal area of City of Kaštela, together with a large number of buildings and other assets makes this area highly vulnerable. Coastal flooding in the City of Kaštela is becoming more frequent and recent events caused damage to different assets, exposing the weak points within buildings and existing infrastructure.

2. Analysis of sea level oscillations

In the particular area of Kaštel Kambelovac one of the recognized natural hazards is related to coastal flooding due to climate-induced sea level rise. This phenomenon is related not only to climate-change impact, but also to long-term and short-term sea level oscillations. Therefore, the first part of flood exposure analysis is related to identification and characterization of sea level oscillations due to different causes. This part of the analysis is based on the measured tidal data, retrieved from the tide gauging station located at the Institute of Oceanography and Fisheries in Split, 4.5 km from the pilot site (Figure 2) where the sea level oscillations are continuously measured on an hourly basis.

Figure 2. Location of tide gauge station in relation to test site

Available tidal data relates to the period between year 2010 and 2014, and the particular data set used for the analysis is extracted for the period 25.01.2010. - 27.06.2011. Selected data set is transferred to official vertical datum in Croatia (HVRS71) before performing further analyses. This particular data set is chosen due to the fact that within this period the longest available continuous data set is recorded, consisting of 12444 data samples (Figure 3).

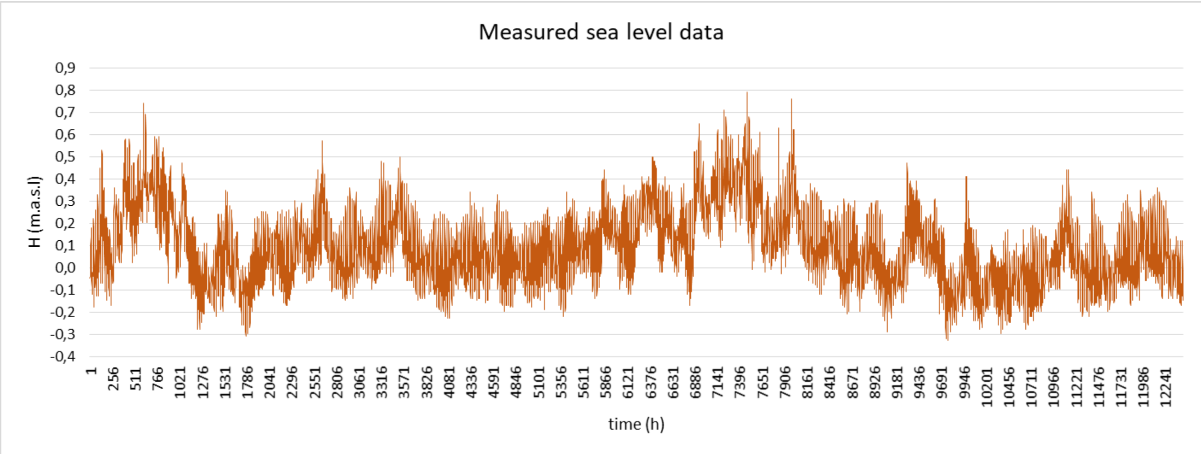

Figure 3. Sea level oscillations data for period between 25.01.2010. – 27.06.2011.

Tidal effect represents the major element causing sea level oscillations, in combination with other natural phenomena. Characterization of the tidal effect within the measured signal is performed with a frequency analysis, resulting with 7 tidal harmonic constituents [2]. Using tidal constituents, the tidal data is simulated and compared with the measured sea level data (Figure 4).

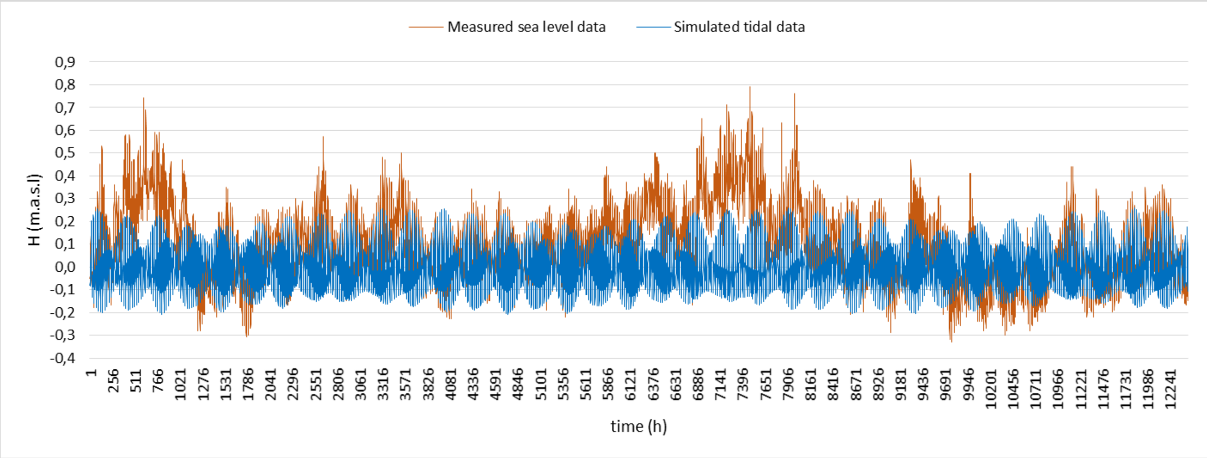

Figure 4. Measured sea level data compared to simulated tidal data

Figure 4 shows the differences between the simulated and measured sea level data, indicating other elements that also have impact on sea level oscillations. The residual sea level, representing the differences between the simulated tidal signal and measured data is presented in Figure 5. It can be assumed that the residual sea level oscillations are mostly caused by the variations of the atmospheric pressure but it can be caused by other elements as well.

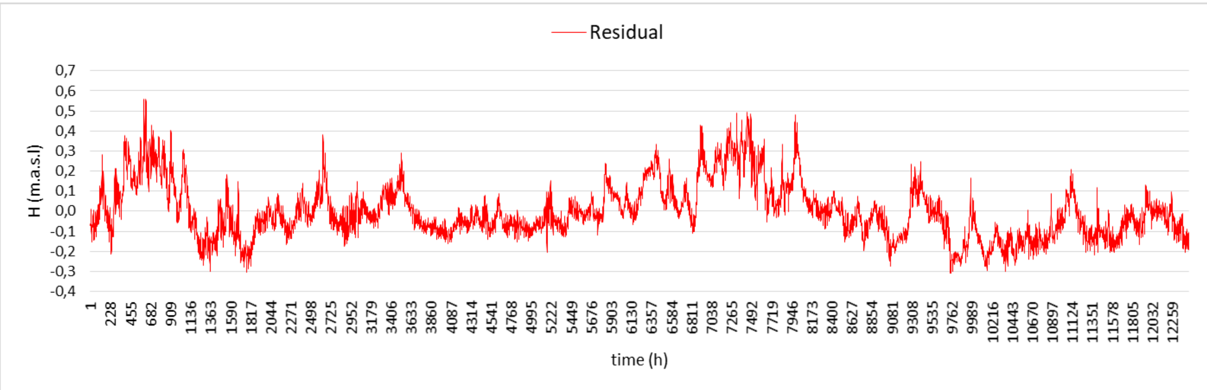

Figure 5. Residual sea level data

According to EU Floods Directive [3], flood exposure maps should be based on scenarios associated with the probability of occurrence:

- floods with a low probability, or extreme event scenarios;

- floods with a medium probability (likely return period ≥ 100 years);
- floods with a high probability, where appropriate.

Probability scenarios are taken into account by representing the residual data (Figure 5.) with a probability density function. Thus, variability of sea level data due to atmospheric pressure and other impacts (residual data) for this particular data set is represented with a normal distribution with parameters μ_{RES} = 0.00 and σ_{RES} = 0.1361867 (Figure 6), which is selected as a reasonable fit.

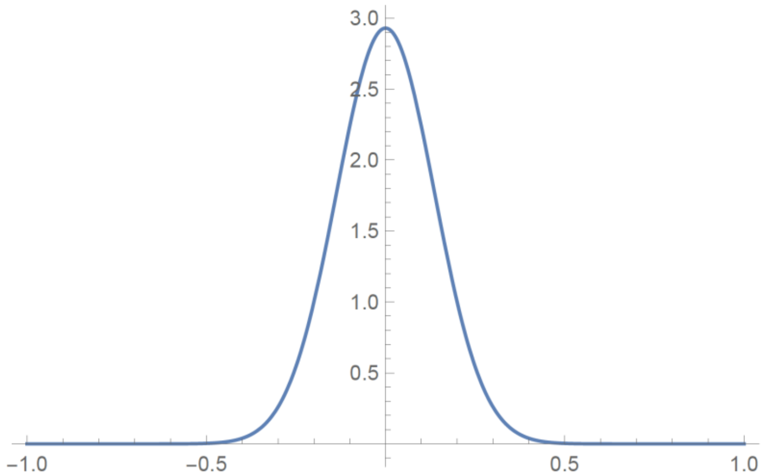

Figure 6. Normal distribution representing residual sea level data

Total sea level values (h_{SEA}) used for flood exposure analysis are estimated based on three different parameters (1): mean sea value (h_{MEAN}), tidal component (h_{TIDE}) and the residual effect (h_{RES}).

$$h_{SEA} = h_{MEAN} + h_{TIDE} + h_{RES} \quad (1)$$

Mean sea level represents the mean value of the measured signal representing all measured sea level values, and it is equal to +0.09 m.a.s.l (meters above sea level). Tidal component is taken as a maximum high tide value, +0.26 m.a.s.l. The residual component is estimated based on selected probabilities. The high probability scenario is estimated as p_{HIGH} = 0.04, corresponding to the return period of 25 years. Moderate probability scenario is equal to p_{MOD} = 0.01, corresponding to the return period of 100 years. Low probability scenario is estimated as p_{LOW} = 0.004, which corresponds to the return period of 250 years.

For the chosen probabilistic scenarios, residual sea level values are estimated from the corresponding normal distribution:

$$h_{RES\ 25} = 0.24 \text{ m.a.s.l}$$

$$h_{RES\ 100} = 0.32 \text{ m.a.s.l}$$

$$h_{RES\ 250} = 0.36 \text{ m.a.s.l}$$

Finally, different scenarios of extreme sea level values are equal to:

$$h_{SEA\ 25} = h_{MEAN} + h_{TIDE} + h_{RES\ 25} = 0.09 + 0.26 + 0.24 = 0.59 \text{ (m.a.s.l)}$$

$$h_{SEA\ 100} = h_{MEAN} + h_{TIDE} + h_{RES\ 100} = 0.09 + 0.26 + 0.32 = 0.67 \text{ (m.a.s.l)}$$

$$h_{SEA\ 250} = h_{MEAN} + h_{TIDE} + h_{RES\ 250} = 0.09 + 0.26 + 0.36 = 0.71 \text{ (m.a.s.l)}$$

3. Coastal flooding exposure assessment due to sea level rise scenarios

One of the major climate change effects is related to expected sea level rise, and this effect is expected to be apparent primarily on the mean sea level. Considering the climate change effect, this analysis is based on the estimations of Intergovernmental Panel on Climate Change (IPCC) and their results of climate change modelling from the IPCC AR5 report [4]. In this report a RCP4.5 scenario is considered, which predicts sea level rise for Croatia between 19 cm and 33 cm in the period between year 2046 and 2065. It should be considered that these scenarios reflect global expectations of sea level rise and should be considered with a degree of uncertainty. Furthermore, these scenarios are considered in Croatian National Strategy for Climate Change Adaptation [5], with additional projection for year 2100 corresponding to 65 cm mean sea level rise.

In this report, rather conservative scenarios are selected for flood exposure analysis (Table 1.). Potential flooding scenarios due to sea level rise are determined based on three major components as well (1), and in accordance to EU Flood Directive considering different occurrence probabilities. The mean sea level is increased for each selected year, while the tidal and residual component remain the same as in the previous chapter.

Table 1. Sea level rise scenarios selected for the analysis [5]

YEAR	SEA LEVEL RISE
2046	19 cm
2065	33 cm
2100	65 cm

3.1 Scenario for year 2046

The first scenario corresponds to the year 2046, for which it is estimated that the mean sea level will rise for additional 19 cm in comparison to the current mean sea level (+ 0.09 m). The tidal component is equal to 0.26 m, and residual components are based on different probabilities and equal to 0.24 m, 0.32

m and 0.36 m, respectively. Taking into account all sea level related parameters, estimated sea level values for year 2046 and each probability scenario are calculated and flood maps for the historical part of Kaštel Kambelovac are presented in Figure 7:

$$h_{SEA\ 25} = h_{MEAN\ 2046} + h_{TIDE} + h_{RES\ 25} = 0.28 + 0.26 + 0.24 = 0.78\ (m.a.s.l)$$

$$h_{SEA\ 100} = h_{MEAN\ 2046} + h_{TIDE} + h_{RES\ 100} = 0.28 + 0.26 + 0.32 = 0.86\ (m.a.s.l)$$

$$h_{SEA\ 250} = h_{MEAN\ 2046} + h_{TIDE} + h_{RES\ 250} = 0.28 + 0.26 + 0.36 = 0.90\ (m.a.s.l)$$

Considering flood exposure of existing building in the historical part of Kaštel Kambelovac, it is visible that only few objects located near the coastline are flooded, even for the low probability scenario. However, most of the public area especially in the historical part is flooded in all scenarios due to low terrain elevation.

a) High probability scenario for 2046

(b) Moderate probability scenario for 2046

(c) Low probability scenario for 2046

Figure 7. Flood maps for year 2046 with respect to different probability scenarios

3.2 Scenario for year 2065

The second scenario corresponds to year 2065, for which it is estimated that the mean sea level will rise for additional 33 cm in comparison to the current mean sea level (+ 0.09 m). The tidal component is equal to 0.26 m, and residual components are based on different probabilities and equal to 0.24 m, 0.32 m and 0.36 m, respectively. Taking into account all sea level related parameters, estimated sea level values for year 2046 and each probability scenario are calculated and flood maps for the historical part of Kaštel Kambelovac are presented in Figure 8:

$$h_{SEA\ 25} = h_{MEAN\ 2065} + h_{TIDE} + h_{RES\ 25} = 0.42 + 0.26 + 0.24 = 0.92\ (m.a.s.l)$$

$$h_{SEA\ 100} = h_{MEAN\ 2065} + h_{TIDE} + h_{RES\ 100} = 0.42 + 0.26 + 0.32 = 1.00\ (m.a.s.l)$$

$$h_{SEA\ 250} = h_{MEAN\ 2065} + h_{TIDE} + h_{RES\ 250} = 0.42 + 0.26 + 0.36 = 1.04\ (m.a.s.l)$$

Comparing to year 2046, a larger number of objects is flooded not only near the coastline. Public objects like the *Rowing Club* and *Public library* are more exposed to flooding in all scenarios, as well as significantly larger public area especially the public square.

(a) High probability scenario for 2065

(b) Moderate probability scenario for 2065

(c) Low probability scenario for 2065

Figure 8. Flood maps for year 2065 with respect to different probability scenarios

3.3 Scenario for year 2100

The third scenario corresponds to the year 2100, for which it is estimated that the mean sea level will rise for additional 65 cm in comparison to the current mean sea level (+ 0.09 m). Tidal and residual components remain the same as for previous scenarios (2046 and 2065) and estimated sea level values for year 2100 and each probability scenario are equal to:

$$h_{SEA\ 25} = h_{MEAN\ 2100} + h_{TIDE} + h_{RES\ 25} = 0.74 + 0.26 + 0.24 = 1.24\ (m.a.s.l)$$

$$h_{SEA\ 100} = h_{MEAN\ 2100} + h_{TIDE} + h_{RES\ 100} = 0.74 + 0.26 + 0.32 = 1.32\ (m.a.s.l)$$

$$h_{SEA\ 250} = h_{MEAN\ 2100} + h_{TIDE} + h_{RES\ 250} = 0.74 + 0.26 + 0.36 = 1.36\ (m.a.s.l)$$

For the year 2100, all scenarios show that a significant number of objects will be flooded (Figure 9.). Flood inundation area has expanded to cultural heritage objects in the historical part, such as *Tower Cambi*. By the year 2100, a large number of public objects and private households will be considered under significant threat from flooding.

a) High probability scenario for 2100

(b) *Moderate probability scenario for 2100*

(c) Low probability scenario for 2100

Figure 9. Flood maps for year 2065 with respect to different probability scenarios

References

[1] Marasović K.; Kaštelanski zbornik, 7, 35-61, 2003.g.

[2] Janeković, Ivica, and M. Kuzmić. 2005. "Numerical Simulation of the Adriatic Sea Principal Tidal Constituents." Annales Geophysicae 23 (10): 3207–18. https://doi.org/10.5194/angeo-23-3207-2005.

[3] DIRECTIVE 2007/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2007 on the assessment and management of flood risks, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007L0060&from=EN

[4] IPCC Fifth Assessment Report (AR5) https://www.ipcc.ch/assessment-report/ar5/

[5] Strategy for climate change adaptation for Republic of Croatia (in Croatian) https://narodne-novine.nn.hr/clanci/sluzbeni/2020_04_46_921.html