Critical flood conditions in two beaches of the Portuguese central west coast

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Abstract: Coastal flooding is expected to be one of the major impacts of climate change in the Portuguese continental territory. In this study beach morphological indicators and hydrodynamic forcings, assessed through field data, allow a comparative analysis of overtopping and flooding conditions in two beaches located in the Portuguese central west coast, Cova-Gala and São Pedro de Moel, during recent events. Results show that for the same hydrodynamic conditions beaches are differently affected. Water level and beach cross-shore profile gradient seem to be the main triggering factors for overtopping occurrence in Cova-Gala. In São Pedro de Moel beach, wave set-up and incoming wave direction can force inland inundation independently of the beach morphological state. These outcomes point out the importance of a comprehensive knowledge of the local factors in adequate flood hazard predictions and mitigation measures development.

Key words: beach typology, coastal flooding, critical flood conditions, Portuguese central west coast.

1. SCOPE AND OBJECTIVE

Worldwide, about 600 million inhabitants live in low elevation coastal zones that are potentially exposed to coastal flooding hazard (Kirezci *et al.*, 2020). As a direct impact of sea level rise, higher and more frequent coastal flooding episodes will have enormous socio-economic impacts in the future (Kulp *et al.*, 2019). Past coastal flooding occurrences impact show the vulnerability of the Portuguese coastline to this hazard (Barros *et al.*, 2020; Santos *et al.*, 2015). Coastal flooding occurs due a temporary increase in sea level. Different factors contribute to this hazard, as meteorological and oceanographic conditions, and territorial coastal zone specificities, such as the geomorphology and the structures presence. The contributing factors for coastal flooding in two beaches located in the Portuguese central west coast during recent events are evaluated in this study.

2. STUDY AREAS

Two beaches vulnerable to coastal flooding and presenting different coastal typologies were chosen (Figure 1): Cova-Gala, located south of the Mondego river mouth south jetty, in Figueira da Foz, and São Pedro de Moel located 4 km further south. Cova-Gala is a sandy beach-dune system with a coastline length of approximately 2 km and a main alignment of 5°N. In the last five decades the beach has been changed due to several human interventions (Freire *et al.*, 2020), presenting nowadays five groynes and a seawall in its southern half sector. For the present study a stretch located in the southern sector of the beach with about 190 m, between two groynes and limited in the backshore by a seawall, was chosen (Figure 1). Seawall average height in this location is 8.5 m above MSL (Mean seal level). Several infrastructures are present on the seawall top as a pedestrian platform with urban furniture. São Pedro de Moel beach is an embedded narrow beach with a coastline with approximately 400 m in length and main alignment of 25°N, limited by an active cliff at both extremes (Figure 1). Backshore, the beach presents a seawall with varying height between 5 and 7 m, and further south an alongshore defence structure with a southwards increasing height. On top of these structures several infrastructures are present as: a road, a square, a pedestrian path, and a view point with urban furniture. At the lower foreshore the beach shows rocky outcrops that are alternately covered and uncovered by sand.

Fig. 1. Location of Cova-Gala and São Pedro de Moel beaches and studied cross-shore profiles (P10 and P11 in the first and P1, P2 and P3 in the second beach, respectively).

3. METHODOLOGY

Between February 2019 and March 2020 the morphological characteristics of the two beaches were monitored, through GNSS surveys using a Topcon Hiper Pro receiver. Data acquisition and treatment details are provided in Freire *et al.* (2020). Several morphological indicators were calculated, based on Carapuço *et al.* (2016), for profiles P10 and P11 at Cova-Gala and profiles P1, P2 and P3 at São Pedro de Moel: beach average width, beach average elevation and beach volume per unit length. Indicators were calculated between the coastline position (beach upper limit, presently corresponding to the defence structure base) and 1 m above MSL. Two overtopping and flooding events that occurred during the survey period were selected: 21/02/2019 and 22/12/2019. Hydrodynamic forcing conditions were characterized based on available data and the water level, measured in Figueira da Foz tide gauge, was provided by the Portuguese Hydrographic Institute (IH). An indicator of surge level was obtained comparing measured data with predicted levels for the same location (available in http://webpages.fc.ul.pt/~cmantunes/hidrografia/hidro_mares.html). Wave conditions were characterized using the Leixões coastal wave buoy data (provided online by the IH - http://www.hidrografico.pt/m.boias) through the following statistical parameters: maximum wave height (Hmax), significant wave height (Hs), peak period (Tp), and wave direction in the peak period (Dir). Meteorological conditions were provided for the Ferrel meteorological station by IH (Figure 1).

4. RESULTS

4.1. Overtopping and flooding events

On 21/02/2019, evidences of Cova-Gala seawall overtopping near profiles P10 and P11, during the first high tide level (04:00), were observed without noticeable impacts. In the afternoon high water level, extensive overwash of the dune located south of the southernmost groyne occurred promoting inland inundation with 30 m incursion (Figure 2). In São Pedro de Moel beach the water reached the seawall in profile P1 surrounding area but no overtopping took place. On 22/12/2019, oral testimonials mention overtopping of the seawall in P10 and P11 Cova-Gala beach profiles, and overflowing between P11 and the goyne. In São Pedro de Moel extensive downtown inundation occurred in profile P1 sector (Figure 2). The inundation took place around 12:00 near high tide level. Flooding impacts included people and vehicles circulation disruption and debris deposition on public roads. Maximum inland water incursion was about 30 m. Oral testimonies indicated this was the worst event affecting the village downtown after 2014 Hercules storm. Water level and wave parameters in the events days and the oceanographic and meteorological conditions during the events are presented in Figure 3 and Table I, respectively. Both events occurred during spring high tide levels. During the February event water level is higher, corresponding to the second highest level of the year measured in Figueira da Foz. The December event was influenced by the storm Fabien that affected Portugal, Spain and France between 21 and 22 December, and was characterised by persistent and intense precipitation, wind from the south quadrant with strong or very strong intensity and energetic wave conditions. Wave climate characterization in front of Cova-Gala (at the position with geographic coordinates 9°00'W and 40°00'N), presented by Oliveira (2016) for the period 1952-2010, shows that significant wave height during the December event reached values above the 99th percentile (Hs>6.5 m correspond to 0.95% of the occurrences).

Fig. 2. Cova-Gala dune overwash on 21/02/2019 (photo above) and São Pedro de Moel inundation on 22/12/2019 (photo below).

4.2. Morphological indicators

Results show that the survey prior to the December event (28/11/2019) corresponds to the less robust situation in Cova-Gala beach profiles P10 and P11. In this survey the three morphological indicators present the lowest values (Figure 4). On 21/02/2019 the beach shows a completely different morphological condition, in both profiles, as beach volume and average elevation is above all survey's average values. In this survey, only the beach width in profile P10 is lower than the average value in that survey. Prior to both events differences in the cross-shore morphology of the two surveys are evident (Figure 5): in November both profiles present lower elevation at the upper limit of the foreshore and profile P10 gradient is lower. The morphological indicators for São Pedro de Moel beach show profile P1 (located in the beach sector where the overtopping and flooding

occurred) presents a smaller beach width in all surveys (Figure 6). Before both February and December events, average beach width shows high values when compared to the other surveys. Also, on November 2019 beach volume is the second highest value observed. In both surveys, elevation of the foreshore upper limit is similar as is the cross-shore morphology, including the profile gradient. One can argue whether the November survey is representative of the beach morphological conditions immediately prior to the December event. Indicators comparison between the 28/11/2019 and 21/01/2020 surveys shows that no relevant changes occurred during this period.

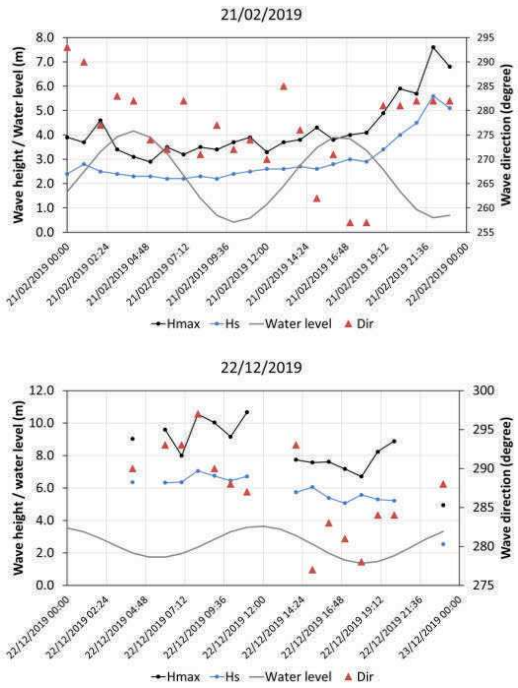

Fig. 3. Water level and wave conditions during the days of the events: 21/02/2019 (above panel) and 22/12/2019 (bellow panel).

*Table I. Oceanographic and meteorological characteristics during the events. * data observed at 11:00 due to equipment failure, ** data not available due to equipment failure.*

	21/02/2019 04:00	22/12/2019 12:00
Water level (m)	4.2	3.6
Surge indicator (m)	0.1	0.3
Hmax (m)	3.1	10.7*
Hs (m)	2.3	6.7*
Tp (s)	17.3	15.4*
Direction (degrees)	282	287*
Hourly wind average/maximum intensity (m/s)/direction (degree)	4.5/5.8/120.5	**
Minimum atmospheric pressure (hPa)	115.9	**

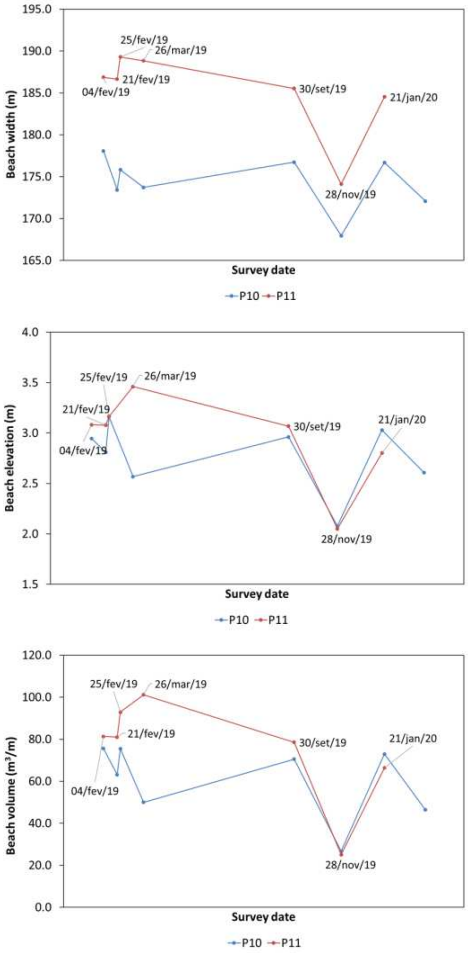

Fig 4. Morphological indicators of Cova-Gala beach: beach width (above), beach elevation (middle) and beach volume (bellow).

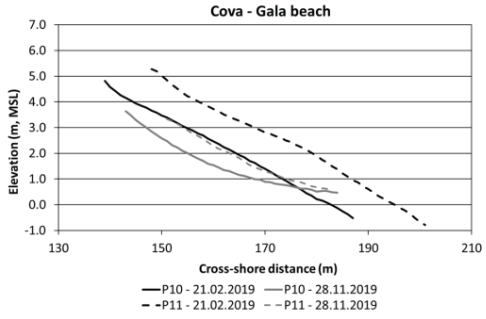

Fig. 5. Cova-Gala cross-shore beach profiles prior to the overtopping and flooding events.

5. DISCUSSION AND CONCLUSIONS

The present analysis aim to identify the critical conditions for overtopping and flooding occurrences in two beaches with different typology. The two studied events had different forcing conditions: in February, high water level was mainly forced by high spring tide, while in December extreme energetic wave conditions adding storm surge (low pressure and strong winds) contributed to high sea levels. Cova-Gala beach is affected in both situations, but beach morphological conditions (lower foreshore and

lower profile gradient) must have contributed for the higher impact of the December event.

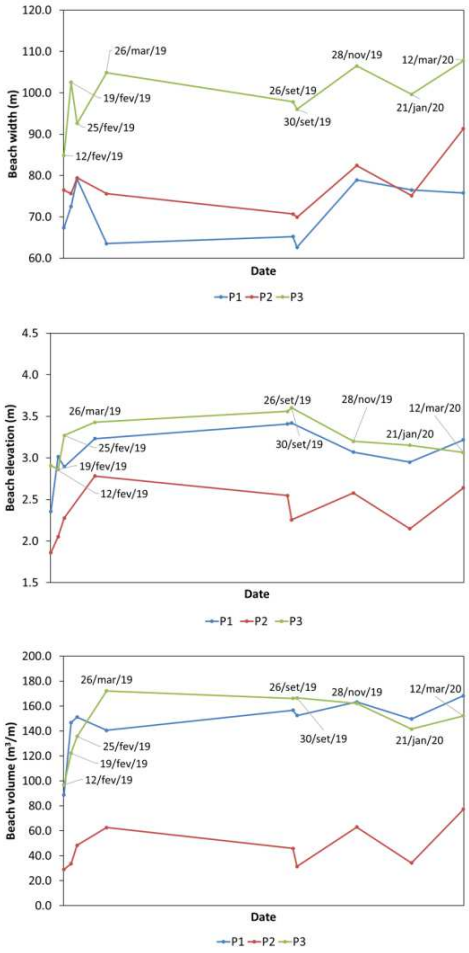

Fig. 6. Morphological indicators of São Pedro de Moel beach: beach width (above), beach elevation (middle) and beach volume (bellow).

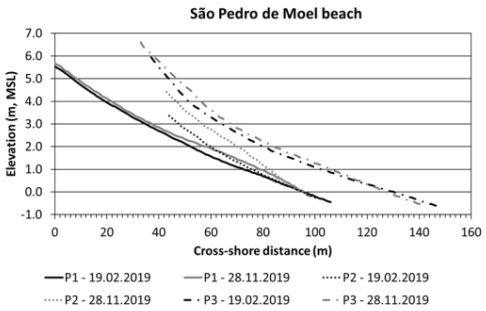

Fig. 7. São Pedro de Moel cross-shore beach profiles prior to the overtopping and flooding events.

São Pedro de Moel beach was only affected by the December event, despite more robust beach morphological condition than in February. Another energetic wave event (Hs>7 m; dir=316º) occurred within the study period, in 14/11/2020, but despite a similar tidal level to the December event, no overtopping occurred due to higher wave obliquity. Results show that the morphological state of the São Pedro de Moel beach is not sufficient to explain flooding occurrences. In this beach wave set-up and incoming wave direction seem to be decisive hazard factors. High wave heights with smaller obliquity reach the beach with more energy, promoting inland inundation. Results show the relevance of local level information in supporting more accurate overtopping and flood hazard predictions.

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REFERENCES

Barros, J.L., Freire, P., Perdiz, L., and Tavares, A. O. (2020). Flooding Occurrences in the Portuguese Continental Coastal Zone: A Database for the Period 1980-2018. *E-proceedings of the 30th European Safety and Reliability Conference and 15th Probabilistic Safety Assessment and Management Conference*, Venice, 7p.

Carapuço, M.M., Taborda, R., Silveira, T.M., Psuty, N.P., Andrade, C., and Freitas, M.C. (2016). Coastal geoindicators: Towards the establishment of a common framework for sandy coastal environments. *Earth-Science Reviews*, 154, 183-190.

Freire, P., Oliveira, F.S.B.F., and Oliveira, J.N. (2020). Coastal flooding process: Comparing different coastal typologies response to extreme hydrodynamic conditions. In: Malvárez, G. and Navas, F. (eds.), *Journal of Coastal Research*, SI 95, 797–802.

Kirezci, E., Young, I.R., Ranasinghe, R., Muis, S., Nicholls, R.J., Lincke, D., and Hinkel, J. (2020). Projections of global scale extreme sea levels and resulting episodic coastal flooding over the 21st. Century. *Scientific Reports*, 10, 11629, 12p.

Kulp, S.A., and Strauss, B.H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications,* 10, 4844, 12p.

Oliveira, J. N. C. (2016). *Modelling the impact of the extension of the north jetty of the Mondego river inlet on the adjacent southern beaches*. Dissertação para obtenção do grau de Mestre em Engenharia Civil. IST, 84p (in Portuguese).

Santos, A., Mendes, S., and Corte-Real, J. (2015). Impacts of storm Hercules in southwestern Europe. *Lecture Notes in Science*, 7, 39-48.