

CALCULATING WAVE OVERTOPPING VOLUMES THROUGH IMAGE CLUSTERING ANALYSIS

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BACKGROUND AND AIM

In the last decade, the use of video imagery has been increasingly recognised as an efficient technique to model the wave motion (e.g. Buscombe et al., 2020; Stringari et al., 2021) and the wave-structure interaction processes (i.a., Hofland et al., 2015, Den Bieman et al., 2020), overcoming some of the limitations imposed by physical measurements. In the stream of machine-learning techniques for reconstructing quantitative data from video imagery, Formentin et al. (2021) developed a technique based on image clustering analysis to reconstruct the free-surface elevation and the wave overtopping flow characteristics above the crest of coastal dikes. Such methodology was recently extended (Formentin et al., 2023) to estimate also the wave runup at crown walls. Building on this methodology, this paper aims at proposing the videography, and specifically the image-clustering, as effective and accurate technique to estimate also the instantaneous and total wave overtopping volumes.

METHODOLOGY

To the authors' purpose, a new set of small-scale experiments (at 1:50 scale) of wave overtopping at dikes was carried out in the wave flume CIEMito in the the CiemLab of the Universitat Politècnica de Catalunya (UPC) and filmed with a 2 Mpix IDS camera (1900x1080 pixels, 96 PPI, 106 fps). The experiments consisted of focused waves generated starting from the following spectral wave characteristics: $H_{m0}=8\text{cm}$, $T_p=1.6\text{s}$. Waves overtop a smooth 1V:2H dike 8 cm long and 4 cm high, (see Figure 1) installed at the end of a mild foreshore (1V:22.6H) specifically set up to induce the wave breaking before reaching the structure toe. Water depth at the dike toe was 1 cm. The camera was placed to the side of the wave flume in correspondence of the dike so that the camera lens focused exactly on the dike top and on the mid front-section of the structure. The camera filming frame was set up to capture the whole overtopping flow behind the dike.

The video-records of the wave impacts were elaborated with the image clustering technique developed by Formentin et al. (2021). The clustering and all the pre- and post-clustering procedures were re-adapted to fit the scope of the present research. For this purpose, a new procedure was also developed to calculate the areas of the overtopping flow beyond the dike top from the image clustering. Such procedure is meant to be applied to each overtopping event which may last several frames (namely, n frames). The main steps composing such new procedure are illustrated in the following.

i) For each frame, the image clustering is applied. It provides position, extension (pixel) and shape of each object recognized in a frame. The areas of the objects "water" automatically recognized in the frame are noted.

Figure 1 shows in blue the contour of all the objects "water" detected in two consecutive frames selected as examples.

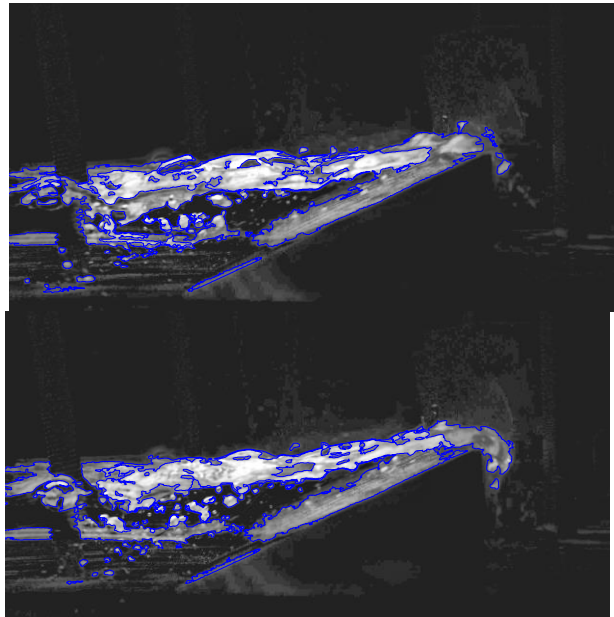


Figure 1- Contour of the overtopping flow (blue) detected with the image clustering for 2 example consecutive frames.

ii) a mask is applied to remove all the elements of "water" before the dike top, in order to isolate the overtopping flow. Then, for each frame the area of the sole overtopping flow is selected among all the areas, and noted. Such area is the individual specific overtopping volume [m^3/m].

iii) The overtopping area of the first frame (namely, "frame 0") is saved as "volume 0". Then, for each couple of consecutive frames of wave overtopping - namely frame 1 and frame 2 -, the image subtraction operation "frame 1 - frame 2" is applied to individuate the difference between the areas of the overtopping flow. Such difference, saved as "volume 1", represents the instantaneous increment of wave overtopping volume (ΔV) occurred between the two consecutive frames. It is important to remark that the image subtraction applies pixel by pixel, i.e. the differences between frames are not calculated between the measures of the areas (scalar operation), but among the matrix of pixels composing the areas of wave overtopping (matrix operation). This way, the shape of the overtopping flow is kept and the calculation of ΔV is meaningful. The result of the operation of image subtraction between the example frames 1 and 2 is provided in false colours in Figure 2, where: the magenta area represents the object "water" at frame 2; the green area would represent the "water" at frame 1 (not visible because it is almost completely covered by the "water" at frame 2); the blue-contoured area

represents the instantaneous ΔV value.

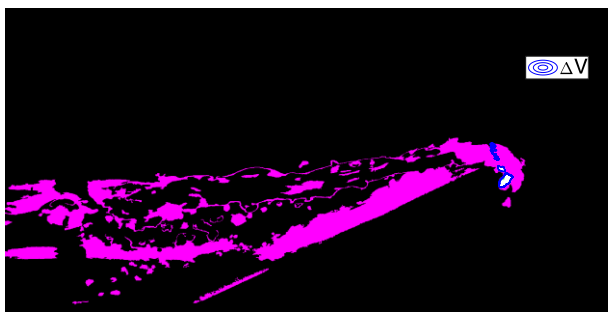


Figure 2 - Area of the overtopping flow calculated from the image subtraction of the 2 consecutive frames selected as example (“volume 1”)

iv) The last volume (“volume n”) is calculated when no more “water” objects are detected beyond the dike top (“frame n”). All the volumes from “volume 0” to “volume n” are summed up and the total volume V associated to the single overtopping event is calculated.

v) The measure of the total volume V is finally converted from pixels to m^3 by means of the conversion law reconstructed from the camera calibration process.

ANALYSIS AND PRELIMINARY RESULTS

The whole methodology was so far applied to the calculation of the overtopping volume associated to one focused wave, with focus phase equal to 90° and focus location $x_f=9.58m$ (measured from the wavemaker at rest). The relative error associated to the conversion from pixel to m was calculated during the camera calibration process and resulted equal to 2.1%. Overall, the overtopping was observed for 16 consecutive frames, for a sampling frequency of 106 Hz. Figure 3a shows the frame-by-frame values of ΔV obtained with the application of the procedure for the calculation of the wave overtopping volumes described above. From this figure, it can be observed that the maximum value of ΔV is $2.91 \cdot 10^{-4} m^3/m$ and that it is reached after 5 frames, i.e. in the first part of the overtopping process. Overall, the total overtopping volume obtained by summing “volume 0” and the subsequent 15 ΔV -values is $1.61 \cdot 10^{-3} m^3/m$. The shape of the function ΔV over time is consistently similar to a wave shape, with a slightly steeper rise phase and a milder decay phase, reflecting the wave steepening process caused by the shoaling during the wave runup. By looking at the profile of the cumulated volumes (Figure 3b), the classic “S-shape” curve is found, where the inflection point corresponds to the frame of maximum overtopping (nr. 5). The average overtopping rate is $1.00 \cdot 10^{-4} m^3/(m \cdot \text{frame})$, which can be considered an average overtopping discharge for the whole duration of the overtopping event.

The uncertainty associated to the measure of the total V obtained from the video-clustering depends on: i) the propagation of the calibration error from a linear to a surface conversion, which can be calculated as $2 \cdot 2.1\% = 4.2\%$; ii) the error due to a wrong estimation of the overtopping areas obtained with the image-clustering, that cannot be quantified exactly; iii) the error associated

to the operation of image subtraction, that it is again hard to quantify. Anyway, a first empirical estimation of the accuracy of the technique is obtained by comparing the total value of V to the corresponding total overtopping volume measured in the lab overtopping tank, which is $1.86 \cdot 10^{-3} m^3/m$, resulting into an error of -16%.

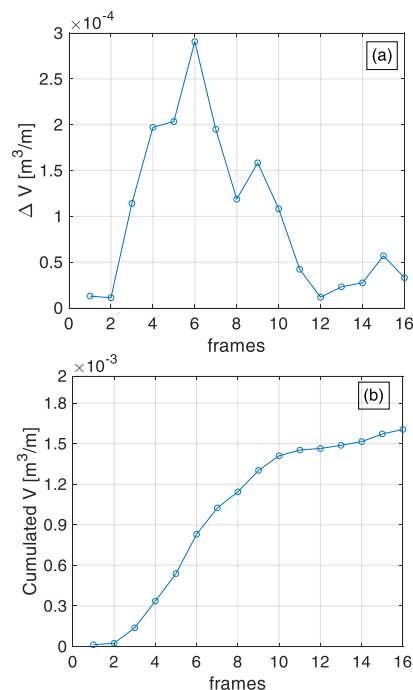


Figure 3. Instantaneous increment of wave overtopping volumes ΔV (panel a) and Cumulated volumes (panel b) from frame 1 to frame 16 for the selected test.

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