LONG WAVES CLIMBING THE SLOPES OF DIFFERENT ROUGHNESS: RUN-UP HEIGHT AND THE LOAD ON INDIVIDUAL ROUGHNESS ELEMENTS

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A series of experiments at the 300 m length and 3.5 m depth Large Wave Flume (GWK), Hannover, Germany, is conducted to study parameters of the long wave run-up on a plane beach. The main purpose of current series is to investigate the influence of the slope roughness on the wave run-up. Run-up height, dissipation of wave energy, and the force acting on individual roughness elements are analysed.

1. INTRODUCTION

Several catastrophic tsunamis that have occurred during the last decade have pointed out the existing gaps in our scientific knowledge about tsunamis. One gap regards tsunami run-up and its impact on the coast. It has been realized that in many cases tsunami run-up cannot be predicted by existing formulae for wave run-up on a plane beach and hence other parameters, such as realistic topography and bed roughness should be taken into account (Fritz et al., 2007; Okal et al., 2009; Mori et al., 2011).

Studies of the influence of coast roughness on run-up height have numerous applications to tsunami problem. It happens when tsunami propagates over the urban area and houses and coastal structures represent roughness elements (Gayer et al., 2010; Kaiser et al., 2011; Muhari et al., 2011), which help to dissipate wave energy and reduce maximum tsunami inundation and at the same time can break due to tsunami loading (Jianhong et al., 2013; Yeh et al., 2013).

In this paper we focus on this topic from both points of view and study experimentally reduction of wave run-up height due to the bed roughness and corresponding wave loading on roughness elements.

2. EXPERIMENTAL ARRANGEMENTS

Experiments have been performed in a 307 m long, 7 m deep and 5 m wide Large Wave Flume (GWK) at Forschungszentrum Küste, Hannover, Germany on 29 July-9 August 2013 (Fig. 1).

The experimental setup contained a 251 m long section of the constant depth, which was kept at the depth of h = 3.5 m during all tests, and a 1:6 slope section. A total of 16 wave gauges were mounted along the flume to reconstruct the incident wave field and to study its nonlinear deformation. Gauge locations along the flume are 50, 51.9, 55.2, 60, 120, 140, 160, 180, 190, 200, 210, 220, 225, 230, 235, and 245.33 metres from the wave maker. The unperturbed shoreline was located at 272 metres. During the tests, two video cameras and a capacitance probe were used to measure wave run-up on a sloping beach. The capacitance probe consisted of the two isolated copper wires suspended at 5 mm above the slope. A 30 volt 100 kHz signal was applied to the one of the wires. The signal from the other wire was measured by a lock-in amplifier and the amplitude was logged with the sampling frequency of 100 Hz (see Denissenko et al., 2011). The signals from wave gauges were recorded with a sampling frequency of 100 Hz.

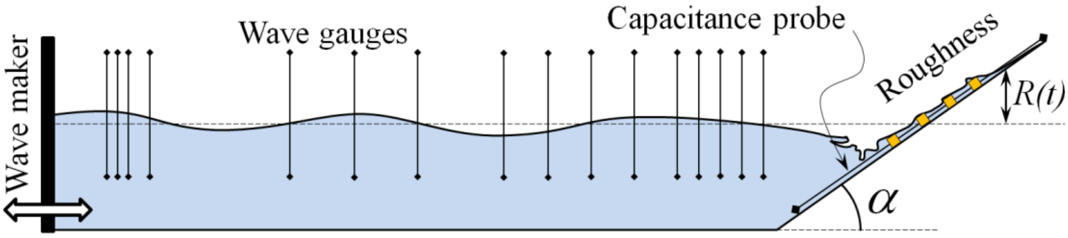

Fig. 1. Experimental setup. Large Wave Flume (GWK) with 16 wave gauges, a capacitance probe, and 1:6 slope with "logs" as roughness elements.

Two cameras were set up to film the surf zone. One video record was used to calibrate the run-up data measured by the capacitance probe. An additional video record was used to determine the shape of the water surface, which was illuminated by a laser sheet along the direction of wave propagation (Fig. 2).

Logs with rectangular 10×10 cm cross-section were used as roughness elements and the force acting on logs were recorded (Fig. 2 right). Two logs were equipped with force transducers; one located at the unperturbed shoreline 272 m and the one located at 276 m mark. Four roughness configurations were considered, with logs every 1 m, 2 m, and 4 m which was compared to the smooth, zero log baseline condition.

The 6000 second series of 20 second waves of growing amplitude were generated to study the initial wave amplitude dependence of the run-up height. The peak-to-trough wave height H was varying from 0.05 m to 0.8 m. The maximum wave elevation above the unperturbed level A was varying from 0.025 m to 0.47 m. To prevent waves reflected from the wave maker panel from interfering with the incident wave field, the wave maker was equipped with the active absorption mechanism. Incident and reflected waves have been reconstructed using linear decomposition techniques as described in Denissenko at al. (2011).

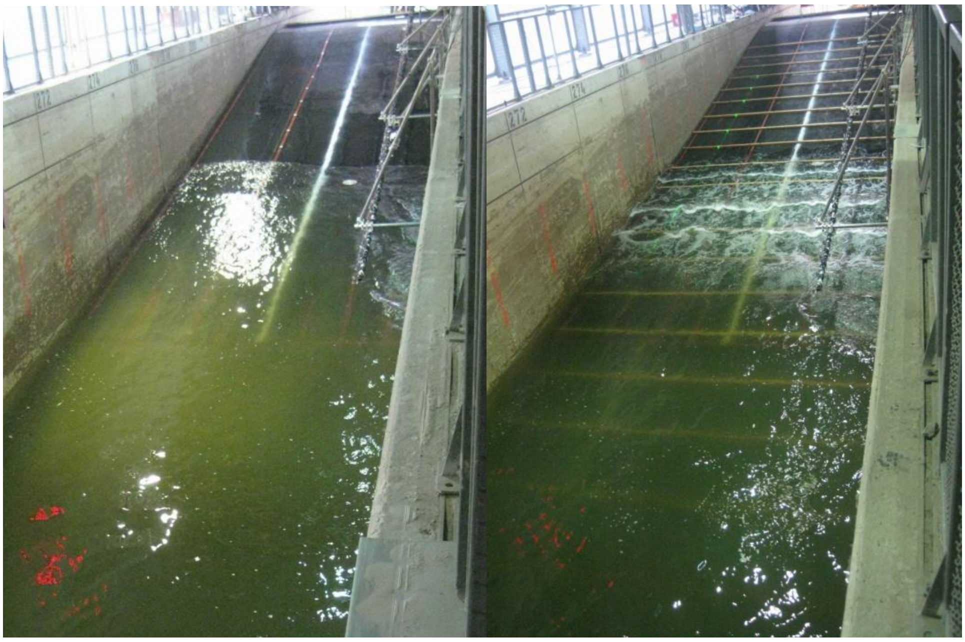

Fig. 2. Wave run-up on the smooth plastic slope (left) and on the rough slope with wooden logs installed at every metre. The wave maker is approximately 250 metres behind the camera.

A set of typical signals is shown in Fig. 3. Note that by the time waves reach the slope, the wave is not perfectly sinusoidal, but exactly the same wave pattern is observed for all conditions, so conclusions of the roughness effect can still be drawn. Time-series from the force transducers (black and magenta) display a clear peak at the time instant the wave strikes the log (note the time delay between the 272 m and 276 m gauges).

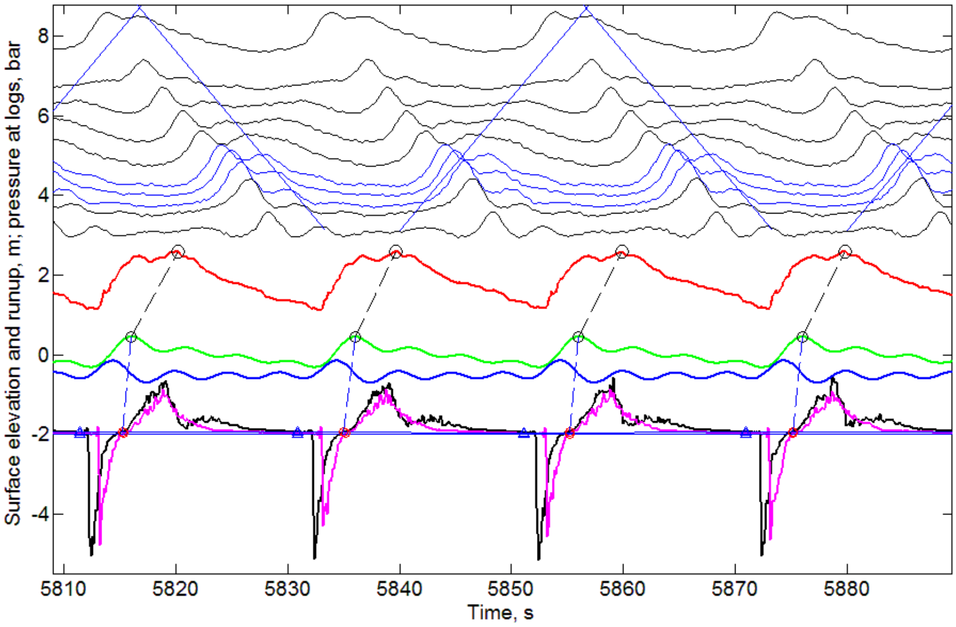

Fig. 3. Typical signals. Red: run-up capacitance probe; Thin lines at the top: wave gauges (slope of straight blue diagonal lines corresponds to the wave shallow water phase speed); Green: incident waveform after reconstruction; blue: time derivative of the incident wave; Black at the bottom: force gauge at the log installed at the unperturbed shoreline mark 272 m; Magenta: force gauge at the log installed at 276 m from the wave maker.

3. RESULTS

To display results, we use the surf similarity parameter, Iribarren number, calculated as

$$\mathrm{Ir} = \tan\alpha \sqrt{\frac{g}{2\pi}\frac{1}{H}} \cdot T_0,$$

where H is the peak-to-trough height, T_0 is the period of incident wave, g is a gravity acceleration. In our experiments, the Iribarren number varied from 4.5 to 30, which all fall into the category of surging waves.

First, we have studied the run-up height versus height of the incident wave at different slope roughness (Fig. 4). Every log in our system obstructs water flow proportionally to its size. It is reasonable to suggest that, decrease of the maximum run-up height is proportional to the flow obstructed by all the roughness elements. This mechanism works only if logs are distributed at a large enough distance from each other so that wakes behind them do not interfere. To illustrate the expected influence of roughness elements, the “total roughness height” is used; which is defined as the sum of heights of the logs covered by the wave plus observed run-up height (plotted by thin lines in Fig. 4). Only the logs located above the unperturbed shoreline are counted. For example, if the running up wave covers 3 logs, then the thin line corresponding to the run-up of 3×10=30 cm higher than that observed is an indicator of the level the wave would reach if not impeded by the logs.

It can be seen from Fig. 4 that small amplitude run-up is only affected by few logs, so that blue and green lines (10 cm logs every 4 and every 2 metres) lie close to the markers corresponding to the observed run-up. At higher wave amplitudes, the difference between the smooth slope and slope with logs become noticeable. When the incident wave is large enough ($A > 0.35$ m), thin lines displaying “predicted” smooth slope run-up based on that observed at the rough slope (thin blue and green lines) nearly coincide with the run-up actually measured at the smooth slope (black markers). This does not work so well when logs are closer to each other (red line, 10 cm logs located every metre). When close, the logs shade each other so the decrease in the run-up height due to the flow obstruction is not as strong. So, at large wave amplitudes and when the roughness elements are well spaced, the total roughness height is a good predictor of the run-up decrease due to the slope roughness.

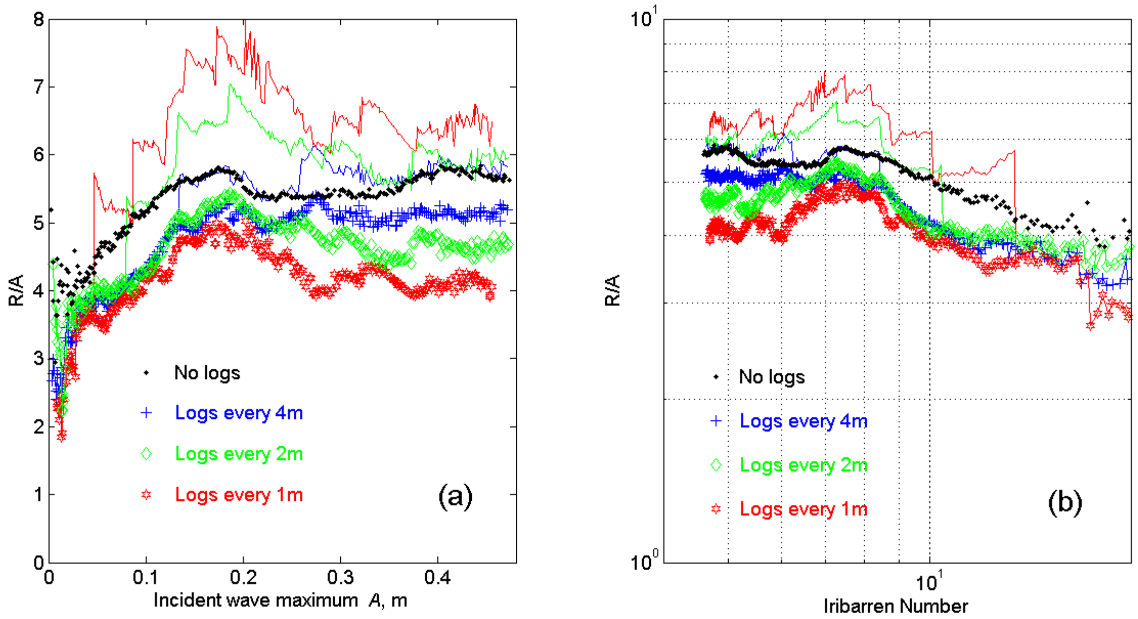

Fig. 4. Run-upheight *R* vs. incident wave amplitude at different slope roughness. The same data is presented with the maximum incident wave amplitude *A* (a) and the Iribarren number (b) on the horizontal axis. Markers correspond to recorded run-up maxima. Solid lines are raised above corresponding marker series by the total sum of heights of the logs the wave encounters on the way up.

To evaluate the influence of the roughness on the overall energy budget, the ratio of the squares of incident and reflected wave heights is plotted as a function of wave height in Fig. 5. It can be seen that up to 60% of the wave energy is dissipated at high amplitudes. Meanwhile, slope roughness has insignificant influence on the amplitude of energy of the reflected wave. However, the tendency, which demonstrates that energy loss increases with an increase of the number of roughness elements is also visible.

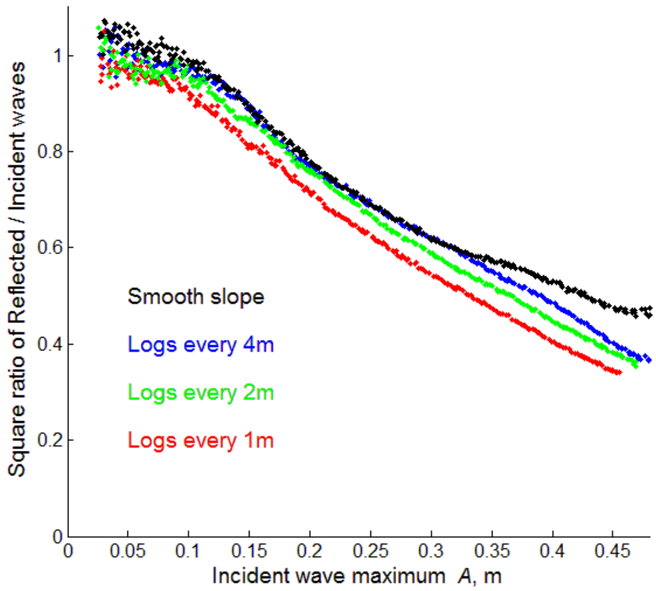

Fig. 5. Energy of reflected wave versus wave amplitude at different roughness.

To further investigate the influence of roughness elements on the run-up height, the total momentum transferred by logs to the flow has been determined by time integration of the force measured by the gauges. Fig. 6 shows results for the two roughness elements (logs) positioned at the unperturbed shoreline level 272 m and at 276 m. Note that below certain amplitude no

force is measured at the 276 m log (lower axis) because no water reaches its location. The pressure at a log (measured force divided by the log frontal area) is integrated over a wave period and normalised by the hydrostatic pressure associated with the wave amplitude times the wave period: $\left(\int P\,dt\right)/\left(\rho\, gAT_o\right)$. The lowest batch of thin lines in Fig. 6 corresponds to the loss of momentum of the incoming wave i.e. the integral of the sharp negative peaks at black and magenta lines in Fig. 3. Observe that the lines nearly collapse, i.e. the momentum reduction by one roughness element is virtually independent of how many other roughness elements are present on the slope. The thin dotted lines in the positive part of graphs show the momentum loss due to the logs of the water receding down the slope. These correspond to the positive peaks at black and magenta lines. Thick lines show the total momentum transferred by logs to the fluid.
It can be seen that for the initial wave amplitude of up to 0.17 m, the total momentum at the shoreline level (272 m) changes slowly oscillating around zero and then starts to grow almost linearly. Similar situation is observed also at the 276 m log. In this case nothing is observed up to the initial wave amplitude of 0.15 m as the wave simply does not reach the log below this value. Then until the initial wave amplitude of 0.2-0.24 m we observe some insignificant changes of total momentum (up to 0.01) and after 0.2-0.24 m the total moment starts to grow linearly.

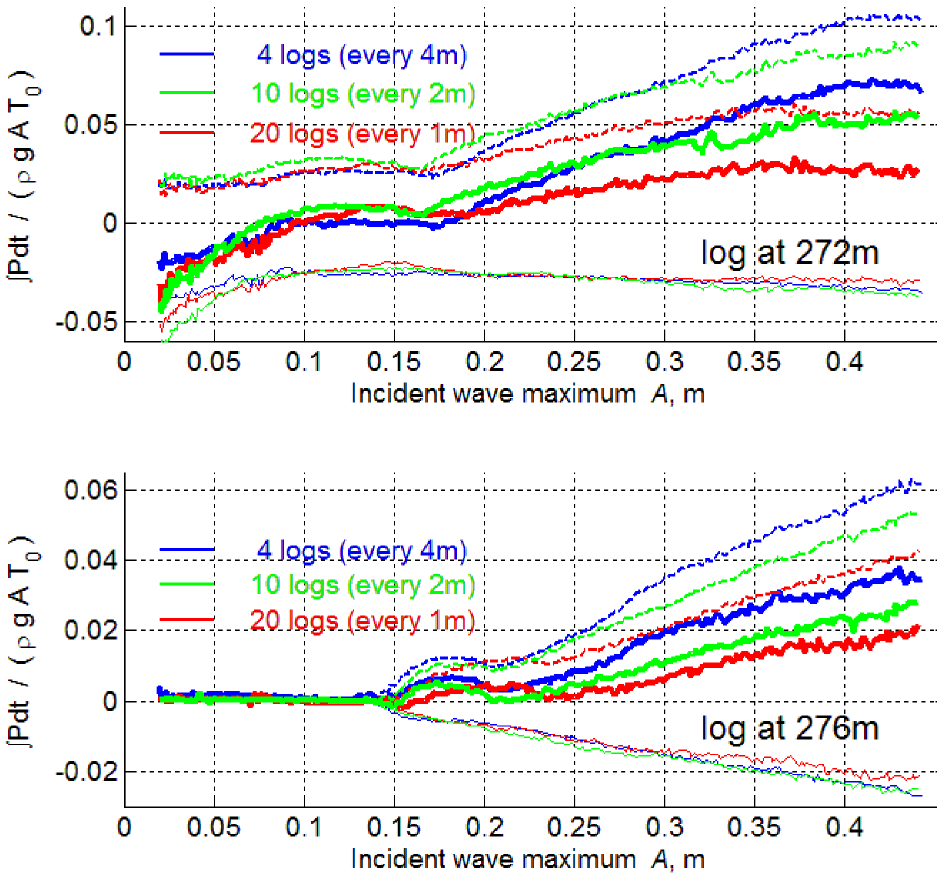

Fig. 6. Momentum loss, associated to the flow up, flow down, and total momentum loss by the fluid vs.amplitude of the incident wave at different slope roughness.Momentum measured at the log located at shoreline (top graph) and 4 metres up the slope (bottom) are shown. Thin lines in the negative part correspond to the momentum extracted by logs from the running up wave. Medium dashed lines at the positive part correspond to the momentum of the opposite sign taken by a log from the receding wave. Thick lines correspond to the total momentum budget.

3. DISCUSSION AND CONCLUSIONS

Run-up height is shown to have a strong non-linear dependence on the amplitude of incident wave and the number of roughness elements (Fig. 4). However, some quantitative predictions can still be made: at higher wave amplitudes, the sum of heights of roughness elements encountered by the wave serves as a reasonable estimator for the reduction of the run-up height due to the obstructions as illustrated in Fig. 4.

It is shown that energy loss during wave run-up on the coast is mostly attributed to the long wave interaction with the slope and is proportional to the field of water contact with the slope and the slope roughness plays insignificant role in it, though there is a clear tendency of increase in the energy loss due to the increase of the number of roughness elements.

Force acting on the roughness elements is related to the amplitude of the incident wave during the run-up phase and is defined by the flowing down near-slope layer when the bulk of the fluid recedes. At higher wave amplitudes, the average force (total momentum) imposed by roughness elements on the fluid is directed up the slope as shown in Fig. 6.

ACKNOWLEDGEMENT

This work has been supported by European Community's Seventh Framework Programme through the grant to the budget of the Integrating Activity HYDRALAB IV within the Transnational Access Activities, Contract no. 261520. ID and AR also thank the support provided by grants ETF8870 and MK-1146.2014.5.

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