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Scale Effects Related to Small Physical Modelling of Overtopping of Rubble Mound Breakwaters

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SCALE EFFECTS RELATED TO SMALL SCALE PHYSICAL MODELLING OF OVERTOPPING OF RUBBLE MOUND BREAKWATERS

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By comparison of overtopping discharges recorded in prototype and small scale physical models it was demonstrated in the EU-CLASH project that small scale tests significantly underestimate smaller discharges. Deviations in overtopping are due to model and scale effects. These effects are discussed in the paper and it is explained why it is impossible quantitatively to identify model and scale effects by comparison of the performance of prototype and small scale models. For such identification are needed special dedicated tests. The paper presents such a test which identify the scale effect in the rubble armour on the upper part of the slope. This effect is believed to be the main reason for the found deviations between overtopping in prototype and small scale tests.

INTRODUCTION

Admissible overtopping discharge is a main parameter in breakwater design as it, to a large extent, determines the crest level and the geometry of the crest.

The admissible overtopping of breakwaters protecting roads, berths, sheds and storage areas in the close proximity of the structure, corresponds to small discharges, characterized by average values less than 1 l/sm. Unfortunately there seems to be a significant scale and/or model effects related to small scale model test results as small discharges seem to be underestimated.

This was found in the EU-CLASH project by comparison of measurements in prototype and small scale models [De Rouck et al. (2005)]. An example of such comparisson is shown in Fig. 1 where the dimensionless average overtopping is plotted against the dimensionless freeboard. H_{m0} is the significant wave height calculated from the spectrum, $T_{m-1,0}$ is a wave period calculated from the spectrum, g is the gravity acceleration and A_c is the height of the berm of antifer cubes above mean water level. Despite considerable effort it has not been possible within the CLASH project to separate and quantify scale effects and model effects. Scale effects are due to incorrect reproduction in the model of the prototype ratios between involved forces, wheras model effects are due to incomplete reproduction of the prototype in the model with respect to geometry, wave exposure, methods of recording and data analysis. On this background was performed a detailed study of scale effects with focus on the uprush zone by comparing run-up heights in small scale and large scale models of a cube armoured ramp.

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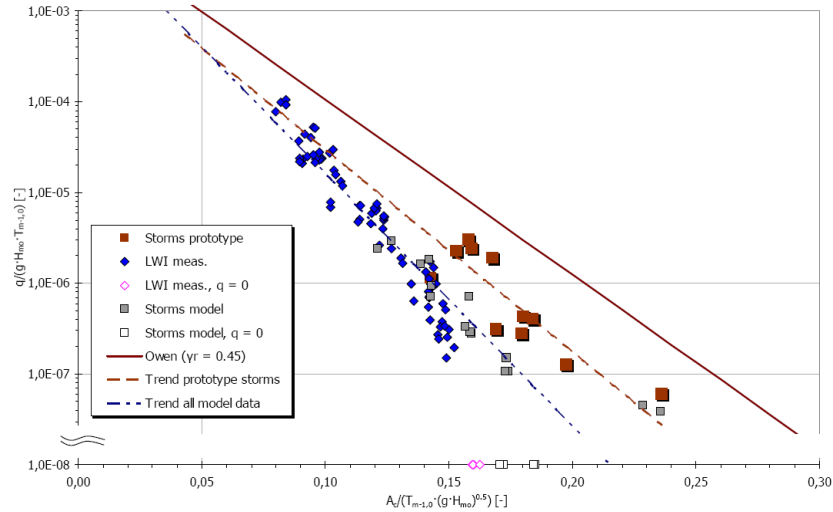
Figure 1. Comparison of model and prototype overtopping for the antifer cube armoured breakwater at Zeebrugge (Geeraerts et al., 2006).

SCALE AND MODEL EFFECTS

Deviations between model and prototype results are due to scale and model effects. Scale effects are due to incorrect reproduction of ratios between forces in the model. Fig. 2 gives an overview of the relevant ratios and the composition of the related scale numbers as well as the phenomenon for which the specific ratio is of importance. All phenomena are present in the interaction between waves and rubble mound structures. However, because we are dealing with surface waves the scaling must be in accordance with the Froude scaling law and the other scaling laws cannot be fulfilled. Consequently there will be scale effects.

Model effects are due to the following differences between prototype and model:

- Deviations in wave kinematics (directionality, wave height distribution, succession of waves, degree of instability);
- Methods in wave recording (pressure gauge, accelerometer buoy, acoustic, staff, etc.);
- Methods of wave analysis;
- Geometrical differences (width of overtopping tanks, sea bed toppography, etc.);
- Lack of wind and currents.

It should be noted that small overtopping discharges (the topic for this paper) are caused by very few waves in a storm. Therefore, it is very important to reproduce these few waves kinematically and statistically correct in the model.

When considering the complex interaction of forces and the difficulties in avoiding model effects it can be concluded that it is impossible to separate and quantify scale and model effects for small overtopping discharges by comparing model and prototype results.
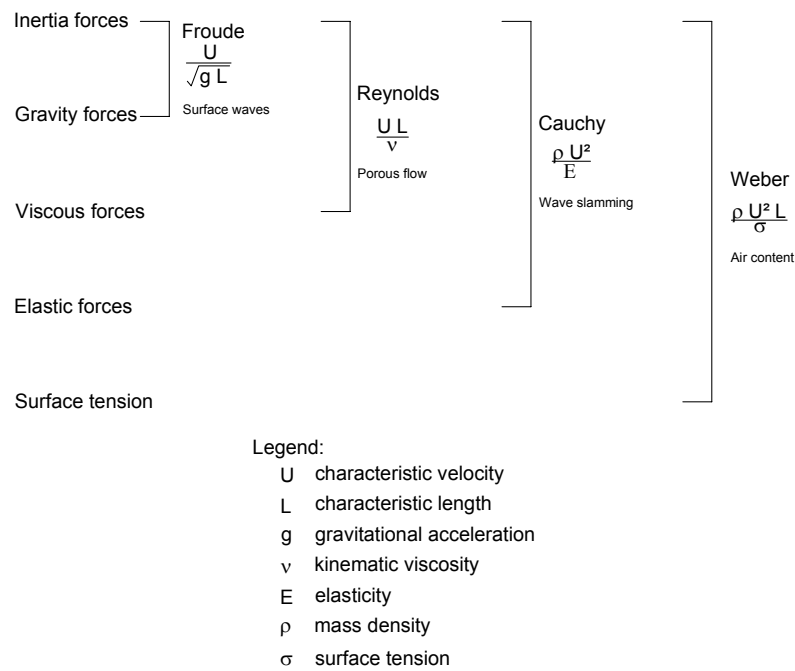
Inertia forces — Froude $\frac{U}{\sqrt{g\,L}}$

Gravity forces — Surface waves

Reynolds $\frac{U\,L}{\nu}$

Porous flow

Cauchy $\frac{\rho\,U^2}{E}$

Wave slamming

Viscous forces

Weber $\frac{\rho\,U^2\,L}{\sigma}$

Air content

Elastic forces

Surface tension

Legend:
- U   characteristic velocity
- L   characteristic length
- g   gravitational acceleration
- ν kinematic viscosity
- E   elasticity
- ρ mass density
- σ surface tension

Figure 2. Ratios of forces and related scale numbers.

FLOW REGIMES

Some scale effects can be studied by comparing small and large scale models because the models can be made absolutely geometrical similar and similar incident waves or flows can be generated due to controlled environments. This is not the case when comparing prototypes with models.

Regimes of scale effects in run-up on rubble mound slopes are shown in Fig. 3.
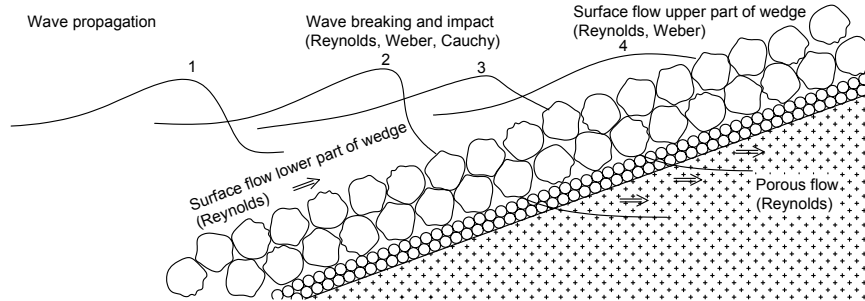
Figure 3. Illustration of surface flow and porous flow domains during run-up (Burcharth, 2004).

The run-up height determines the overtopping. The CLASH project showed bigger overtopping deviations between model and prototype for flatter slopes. This indicates increased flow resistance in the upper part of the run-up wedge. Here the run-up has the characteristics of a flow between obstacles for which drag coefficients can be very dependent on the Reynolds number, thus giving raise to a scale effect.

Reynolds Effect

The larger the drag force on the armour the smaller will be the run-up. The drag coefficient in Morison and Forcheimer equations decreases with increasing Reynolds number in the actual range of fully turbulent flow as schematised in Fig. 4.
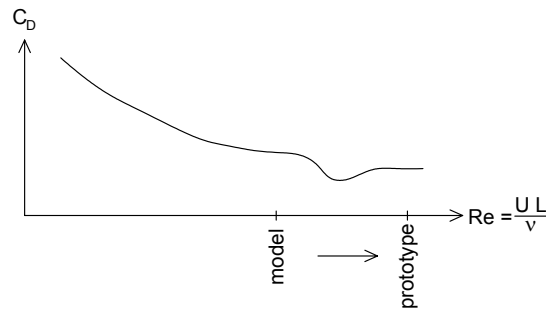

Figure 4. Schematic illustration of drag variation with Reynolds number.

As the reduction in drag coefficients are less for sharp edged objects it was chosen in the experiments to use cubes as armour elements in order to demonstrate a lower limit for the scale impact. Consequently, the scale effects on rock armour are expected to be larger than seen in the present experiments.

Surface Tension Effect

The surface tension is relatively much smaller in large scale models and prototypes than in the small scale models. This cause very different air bubble

structures with many more smaller air bubbles in larger scale models and especially in salt water prototypes (Bullock et al., 2001).

The Reynolds and surface tension scale effects cannot be separated in the tests.

TEST SET-UP

In order to investigate the scale effects on run-up a special test set-up as shown in Fig. 5 was designed. It makes it possible to generate a jet like up-slope flow on the cube armoured impermeable ramp by instant removal of the hatch to the reservoir.
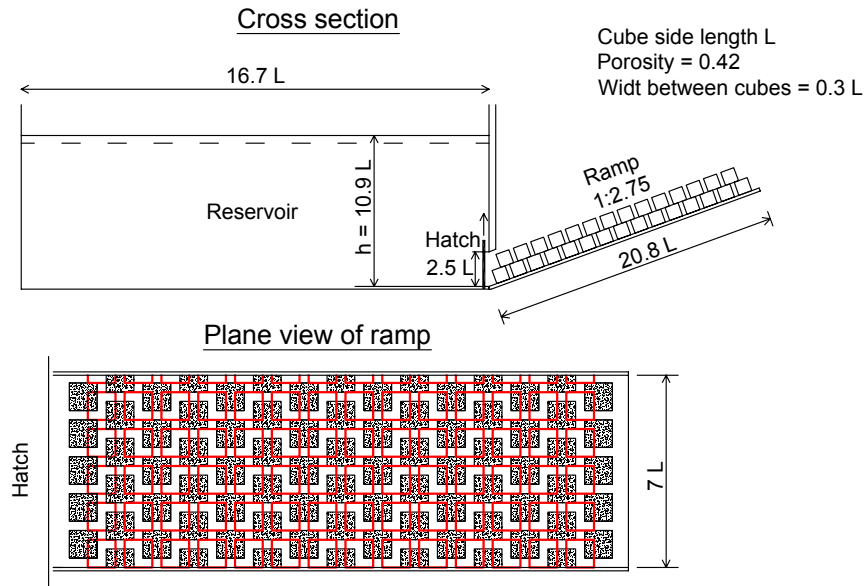

Figure 5. Experimental set-up.

Two geometrically absolute similar models of length ratio 1:5 were used. The cube side length in the two models was:

$$L = \begin{cases} 18.0 \ mm & \text{small scale} \\ 90.0 \ mm & \text{large scale} \end{cases} \tag{1}$$

Determination of Minimum Size of Model

The flow must imitate as closely as possible wave run-up on an armour slope. The minimum size of armour units is usely estimated from the critical Reynolds number for armour stability:

$$\text{Re} = \frac{U \ L}{\nu} \geq app. \ 3.5 \cdot 10^4 \qquad \left(U \approx \sqrt{g \ Hs} \right) \tag{2}$$

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As the outflow velocity from the reservoir is:

$$U \approx \sqrt{2\,g\,h} \qquad (3)$$

it can be calculated that with a small scale cube side length of $L = 18$ mm and $\nu = 10^{-6}$ m^2/s a head h in the reservoir larger than 0.193 m is needed.

Scaling Law for Initial Outflow of Reservoir

Because the model should, in the initial flow phase, imitiate Froude model conditions it must be demonstrated that friction does not play a role. For the instant flow through the sharp edge hatch opening only gravity and inertia forces dominates (Froude model) when, according to Vischer and Hager, 1998, the hatch opening time $t_{0p} \leq 1.25(h/g)^{0.5}$, which corresponds to:

$$t_{op} \leq 1.25\left(h/g\right)^{0.5} = \begin{cases} 0.17 \text{ s} & \text{small scale} \\ 0.39 \text{ s} & \text{large scale} \end{cases} \qquad (4)$$

These conditions were met in the experiments.

RESULTS

Figs. 6 and 7 show by photos a comparison of the run-up processes in the small scale and the large scale models. The differences in time steps in the two models corresponds approximately to Froude scaling, i.e. $\lambda_t = \sqrt{5}$. It is seen that for equivalent time steps the uprush tongue reaches further up the slope in the large scale model compared to the small scale model.
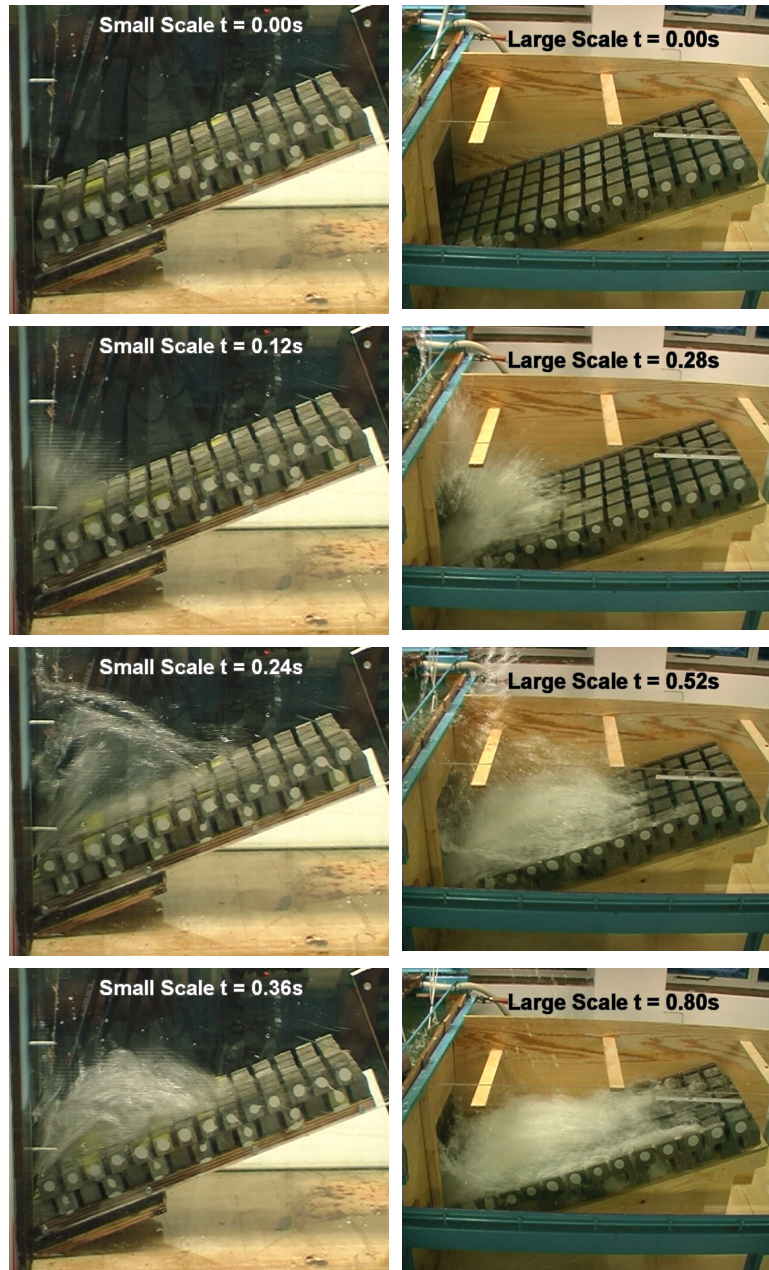
Figure 6. Comparison of the run-up process in small and large scale models.
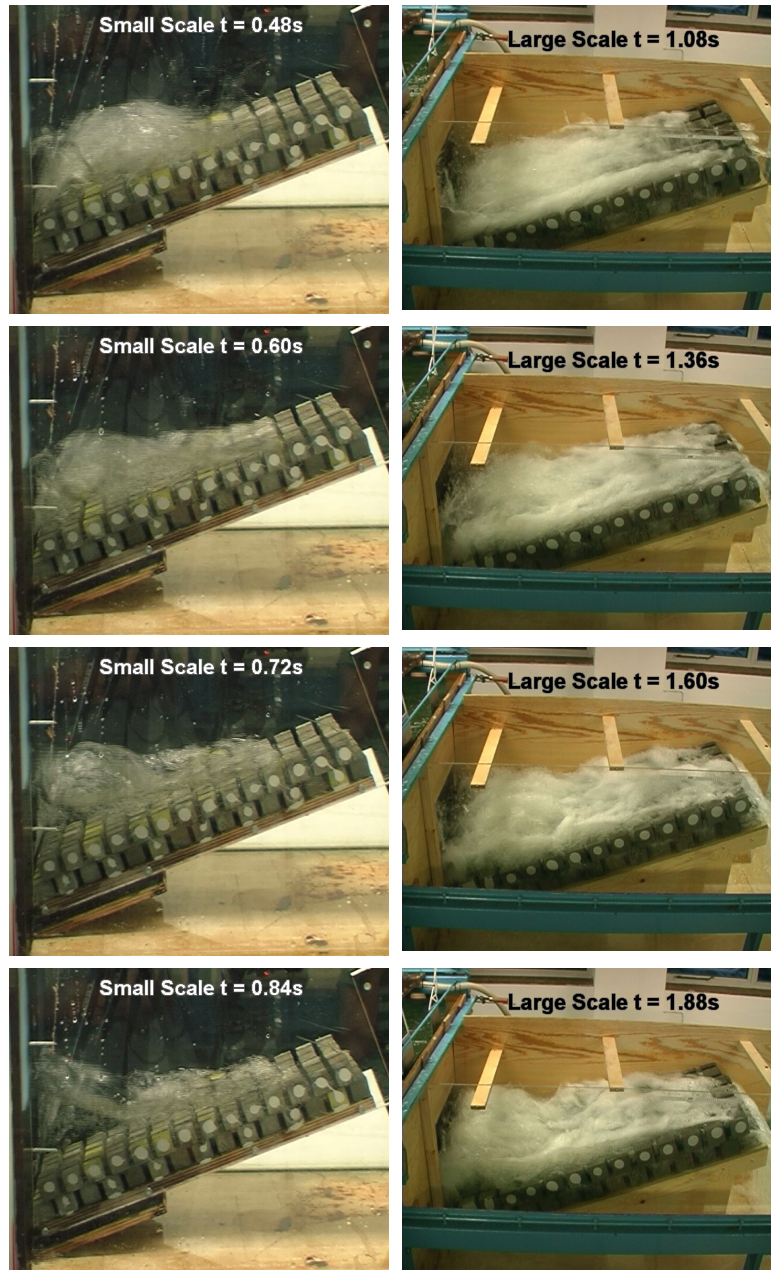
Figure 7. Comparison of the run-up process in small and large scale models.

Fig. 8 shows the maximum run-up level in the two models. It is clearly seen that the run-up along the slope reaches at least three more cubes in the large scale model.
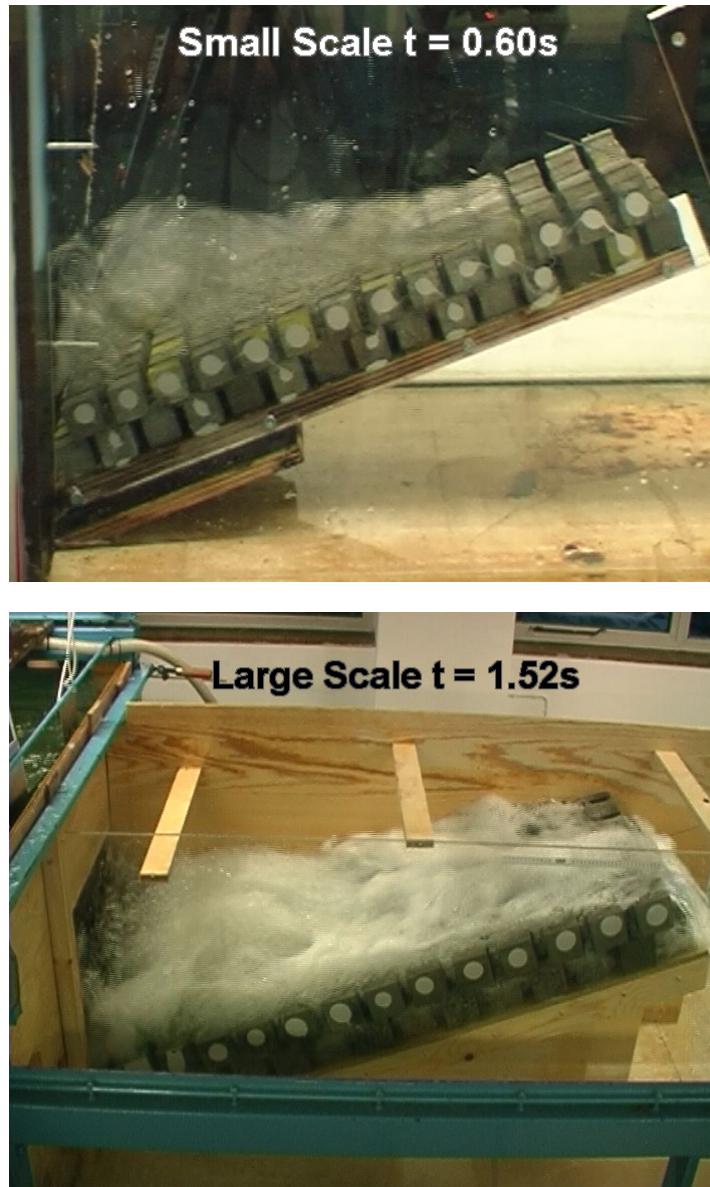

Figure 8. Maximum run-up level for the two models.

CONCLUSIONS

The run-up height on cube armoured impermeable slopes has been studied in two geometrically identical models with length scale ratio 1 to 5.

The imposed flows simulating the wave action were generated accurately in accordance with Froude scaling.

A significant difference in the run-up between the two models was observed. The run-up tongue reaches three cube lengths (approximately 20% of the length of the ramp) further in the large model than in the small model. This corresponds in the actual case to a difference in run-up height of one cube length. Equivalent changes in run-up correspond typically to a factor of approximately 5 to 10 in overtopping discharges.

Because no model effects were present in the experiments it is demonstrated that a significant scale effect exists solely related to run-up in the upper part of the wedge. It explains to a large extent why small scale models underpredicts small overtopping discharges.

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