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Design of scaled movable bed experiments using numerical models

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ABSTRACT

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Scaling designs for mobile bed short wave experiments have been analysed using a suite of numerical models to test different sediment scaling configurations. The numerical simulations have revealed that geometrical sediment scaling gives similarity in the boundary layer flow but the sediment transport mode switches from bed-load in the prototype to suspended-load in the model. This is due to the high relation of prototype to model sediment sizes. However, scaling to maintain the relative fall speed allows smaller sediment size relations and closer similarity in the dominant transport processes. A set of corrections have been proposed to minimise the scaling effects in sediment transport rates and bottom evolution.

ADDITIONAL INDEX WORDS: *Bed-load sediment transport scaling, Suspended-load sediment transport scaling, Morphodynamic modeling, Mixing length boundary layer models.*

INTRODUCTION

Scaled movable models are commonly used to study sediment transport, beach evolution and coastal problems. The basic philosophy is to gain a better understanding of the dominant hydraulic/sediment processes, by ensuring that the relative magnitudes of all dominant processes are the same in the model and prototype. However, this is usually an impossible task in scaled models (HUDSON *et al*., 1979).

The design of scaled movable experiments relies therefore, on empiricism. No rigorous methodology to design scaled sediment transport models has been developed (HUGHES, 1993) and consequently results obtained from a scaled physical model may not compare well with reality. Nevertheless, physical modelling remains a useful qualitative tool in understanding the dominant forces and response mechanisms of sediment.

Numerical models provide a low-cost complement to physical modelling, since many design conditions and parameters may be tested in numerical simulations. This is supported by the idea that an experimental model is a simplified version of reality (as are numerical models) where the forcing conditions are controlled within a certain range.

The aim of this study is to introduce numerical techniques to 1) enable improved design of a scaled short wave sediment transport model and 2) to upscale or interpret scaled physical model results.

The present study has been limited to the design of movable bed experiments aimed to study cross-shore morphodynamic beach processes in which incident waves play an important role. The results are therefore applicable for short-wave hydrodynamic models. The numerical techniques are tested using Barceloneta Beach, Spain, as a case study.

REVIEW OF SCALING LAWS IN MOVABLE BED EXPERIMENTS

Short wave hydrodynamic scaling must obey (HUGHES, 1993):
1) The model is geometrically undistorted to correctly simulate wave transformation across the beach profile. Consequently, all lengths are scaled with the geometrical length-scale (n):

$$n_X = n_Y = n_Z = n = \frac{L_p}{L_m} \qquad (1)$$

where n indicates scaling ratio and the sub-indices express the different spatial coordinates. L_p and L_m indicate a length scale in the prototype and in the model, respectively.
2) The Froude number must be similar in the model and prototype, and is given by

$$F_r = \frac{U}{\sqrt{gL}} \qquad (2)$$

where U is velocity, g gravitational acceleration and L the wave length. Froude number similarity implies that the Froude scale must be $n_{Fr} = 1$ and from (2) the time and velocity scales are obtained as,

$$n_T = \sqrt{n} \qquad (3)$$

The time and velocity is then scaled in according to the Froude number.

Sediment transport scaling is a more complex question. It is assumed that perfect similitude in bed-load and suspended load sediment transport may not be achieved. Therefore a compromise between a bed-load or suspended load dominated model must be chosen.

Similarity in sediment transport models is obtained by fulfilling similitude in the following dimensionless parameters (Kamphuis, 1996; Hughes, 1993):

Densimetric Froude number

$$F_* = \frac{\rho u_*^2}{\gamma_i d_{50}} \tag{4}$$

where u_* = bottom shear velocity, ρ = water density, γ_i = submerged sediment specific weight [=$(\rho_s - \rho)g$] d_{50} = medium grain size.

Grain size Reynolds number

$$R_* = \frac{u_* d_{50}}{\nu} \tag{5}$$

where ν is water viscosity. These two parameters make reference to the forcing (F_*) and resting (R_*) forces acting on a sand particle as represented on Shields diagrams. Similarity is also required for the **Relative density of the sediment,** $S_s = \rho_w / \rho_s$ and the **Relative length**, $l_s = A/d_{50}$ must keep similarity, where ρ_w is the water density, ρ_s the sediment density and A is the wave amplitude. Similarity in the **Relative fall speed V_w** should also be maintained:

$$V_w = \frac{w_s}{u_*} \tag{6}$$

where w_s is the settling velocity.

Kamphuis (1996) and Hughes (1993) classified bed-load scale models in terms of the requirements they fulfill. The best bed-load model can maintain similitude in Densimetric Froude number, Relative density of the sediment and Relative length number. Densimetric Froude number similitude results in geometrical scaling of the median, d_{50}, sediment size:

$$n_{d50} = n \tag{7}$$

Several authors have proposed different scaling relations assuming suspended load dominates the transport (see Hughes, 1993 for a comprehensive review). These relations determine the scaling using the sediment settling velocity instead of the sediment size and require similitude in both the relative fall speed and relative density.

BARCELONETA BEACH SCALING

Barceloneta beach is a 1100 m long beach located within Barcelona city facing the Mediterranean Sea on the East side. It is characterised by being in a microtidal environment highly influenced by human activities. It has rigid lateral boundaries formed by the Barcelona port and Port Olympic. Barceloneta is densely populated in summer and multiple activities develop on this beach over the year, with the beach of high importance for the social and economic development of the city. The average beach width is around 38 m, while the typical sediment size is around 0.710 mm, characteristic of reflective beaches along the Catalonian Mediterranean north coast which have a relatively steep slope with gradient of around 0.2.

Barceloneta was created as part of the renewal plan that took place in the city for the 1992 Olympic Games, which included more than 3 km of artificial beaches. However due to a decrease in the input of sediment to the coastal zone, the beaches suffer constant erosion and therefore need constant re-nourishment. Storms from the NE produce major erosion at the northern end. In November 2001, two consecutive NE storms with relatively long return period resulted in strong erosion on Barceloneta beach and significant damage to facilities. In June-July 2002, the Barcelona beaches were nourished with about 110000 m^3, increasing the beach area. However, one and a half years later the beach returned back to its original position.

Following the above review, two mobile bed experimental designs are presented, one based on bed-load modeling and the other based on a suspended-load model. Hydrodynamics conditions are scaled according to Froude scaling. Wave conditions during the November 2001 storms have been selected for simulations, corresponding to a H_{rm0} of 3.5 m and a T_p of 7.0 s. The scale relation is chosen to be 1:5, which gives a model H_{rms0} of 0.7 m and a T_p of 3.3 s from Froude scaling. These model conditions can be generated in many large wave flume facilities.

MODELS AND TESTS DESCRIPTION

Two different numerical models have been used to better design the proposed experiment and to asses the scaling effects in such experiments. One is a coastal area morphodynamic model (Alsina *et al*, 2007), which computes the hydrodynamics, sediment transport and bottom evolution. This model feeds a detailed boundary layer and sediment transport model which computes the vertical, time dependent boundary layer at chosen points across the beach profile.

The coastal area model is composed of the well documented Ref/Dif-1 wave propagation model (Kirby and Dalrymple, 1983), a 2DH circulation model (Cáceres *et al.* 2005) and a sediment transport model (Alsina *et al*, 2007) linked together through a bottom update scheme. The sediment transport computations utilise the Bailard (1981) sediment transport rate formulation which takes into account bed load plus suspended load. Friction factors are computed using the wave current formulation as described in Grant and Madsen (1979).

The detailed sediment transport model computes the vertical time varying boundary layer at selected points on the beach profile. The flow equation reads

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{1}{\rho}\frac{\partial \tau}{\partial z} \tag{8}$$

The near-bed flow is turbulent and the shear stress τ is determined by the turbulent eddy viscosity v_t which is described by the mixing length theory

$$\frac{\tau}{\rho} = l^2 \left|\frac{\partial u}{\partial z}\right| \frac{\partial u}{\partial z} \tag{9}$$

where l is the mixing length taken to be

$$l = \kappa z (1 - z/2D) \tag{10}$$

where D is the water depth and κ the von Karman constant (=0.4). This model enables computation of the sediment transport rates under wave action or under combined wave-current conditions. Sediment transport rates are computed by solving the diffusion sediment equation.

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left(\varepsilon_s \frac{\partial c}{\partial z} + w_s \frac{\partial c}{\partial z} \right) \tag{11}$$

where w_s is the settling velocity of the sediment, and ε_s is the turbulent diffusion coefficient which is assumed to be equal to the eddy viscosity v_t. The near bed concentration condition is taken at the level $z_{ref} = 0.8 d_{50}$ where the concentration c_b is given as a function of the instantaneous shear stress according to Zyserman and Fredsøe (1994). Bed load sediment transport is also computed following Nielsen (1992).

Hydrodynamic numerical simulations (Figure 1) reveal that similarity is maintained for the wave height and return flow velocities, which is expected and ensured by Froude scaling. The effects of non similarity in Reynolds number do not affect these results.

Similitude in suspended load transport models is expected when the relative fall speed V_w is similar in the prototype and the model; therefore settling velocity and shear velocity scales have to be equal. Thus several problems arise when trying to find the correct suspended sediment scaling, since settling velocity depends on many factors (sediment size, flow turbulence and sediment concentration) and it is not straightforward to compute. Moreover the u_* scale may vary when modifying the scaled d_{50} (varying the roughness).

The scale of the shear velocity is then determined. Different authors have defined expressions to compute the friction factor under waves and combined wave-current flows based on experimental data and physical considerations (SWART, 1974; GRANT and MADSEN, 1979). Hence, a theoretical expression can be approximated by:

$$f_w \propto \left(\frac{k_n}{A}\right)^a \tag{12}$$

where A is the free stream amplitude and k_n the roughness length which, since uniform plane bottom is assumed, is taken to be equal to $2.5d_{50}$. FREDSØE and DEIGAARD (1992) suggest the power a value to be equal to 0.25 when $k_n/A < 0.02$, while when $k_n/A > 0.02$ a=0.75 according to experimental data from KAMPHUIS (1975). Therefore the friction factor scale becomes:

$$n_{f_w} = \left(\frac{n_{d_{50}}}{n}\right)^a \tag{13}$$

where n_{d50} is the scale relation between prototype and model sediment size.

The focus of this study is designing scaled experiments and previous information about the sediment fall velocity may not exist. Therefore, a number of formulations have been selected to compute the settling velocity for the given range of d_{50} (HALLERMEIER, 1981; FREDSØE and DEIGAARD, 1992; SOULSBY, 1997). The proposed method proceeds first by computing the prototype settling velocity given the prototype sediment size, then settling velocity in the model is scaled using $n_{ws} = n_{u*}$ (equation (6)) and finally the scaled d_{50} is obtained from the settling velocity formulations used in inverse order. n_{u*} depends on the d_{50} scale, and therefore an iterative process is used until convergence is achieved. The values obtained for the scaled d_{50} range between 0.34 mm (SOULSBY, 1997) and 0.37 mm (HALLERMEIER, 1981) and a near to mean value has been selected, corresponding to 0.35 mm (using FREDSØE and DEIGAARD, 1992).

The d_{50} obtained from this approach is larger than that obtained for the bed-load (geometric) scale model. The immediate implication is that using settling velocity scaling permits models with higher scaling relationships, maintaining the sediment in the experiments in the range for non cohesive sediments.

MOVABLE BED SIMULATIONS

The bed-load model scaling (geometrical scaling) given by (7) gives a scaled d_{50} of 0.142 mm. The suspended sediment model scaling in accordance with the relative settling velocity (6) and using the methodology previously described gives a model d_{50} of 0.35 mm.

Detailed simulations of the boundary layer structure for both sediment sizes have been performed. A cross-shore point corresponding to X/H_0 of around 42 in figure 1 has been selected to perform detailed boundary layer simulations. The resulting eddy viscosity and vertical suspended transport distribution is shown in figure 2. Linear wave theory and current boundary layer interaction is assumed. Figure 2 shows that geometrical scaling leads to similarity between the boundary layers in the model and prototype, with the velocity in the boundary layer scaled by $n^{1/2}$. This has several implications, the most important being that Reynolds number does not affect the scaling of the boundary layer development when the flow is fully rough turbulent (GRANT and MADSEN, 1979; HUGHES, 1993). The simulations assume a plane horizontal bottom and hence scale effects over ripples or a sloping bed may introduce some other scaling effects which are not taken into account in the present study.

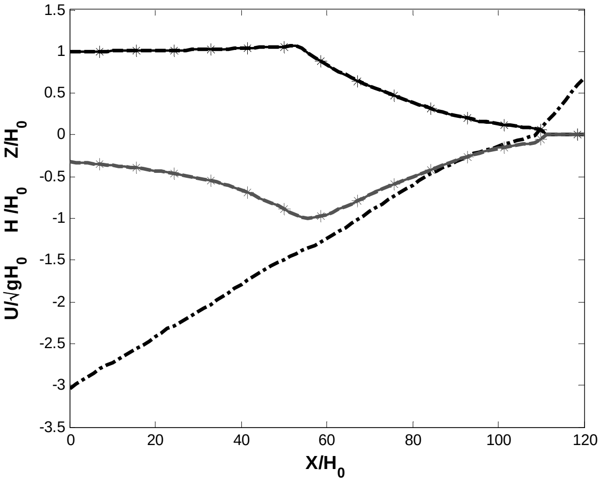

Figure 1. Computed across-shore distribution of dimensionless wave height (black) and return flow (grey) in the prototype (-) and scaled model (-*-). Dimensionless beach profile in dot-dash line.

On the other hand scaling using relative fall speed does not maintain similarity in the boundary layer. Comparatively the roughness is larger and the wave boundary layer thinner. The bed shear stress is therefore higher (higher eddy viscosity and thinner boundary layer).

The vertical distribution of suspended transport (figure 2, right) reveal higher transport rates for the geometrical scaling, a result of the smaller sediment size. The sediment transport from each model is made dimensionless by the relation,

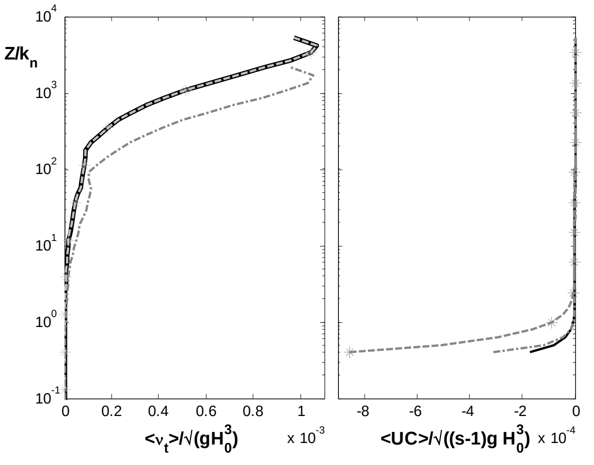

Figure 2. Computed vertical dimensionless eddy viscosity (left) and suspended transport (right). Black line (-), prototype; grey dash line (-*-), bed-load scaling; dashed-point grey line (-.-), suspended load scale model.

$$\Phi = \frac{q_i}{\sqrt{(s-1)gH_0^3}} \tag{14}$$

integrated vertically and compared in figure 3. It is apparent that geometrical scaling gives similitude in the Shields parameter, while initiation of sediment movement is not correctly scaled since similarity in the grain size Reynolds number Re^* is not maintained. Consequently, more sediment is more easily set in movement in the model than in the prototype. In the present simulation, this scale effect has only a small influence on the computed bed-load sediment transport, with bed load transport rates similar in the model and prototype. However, it may be more important with scale relations higher than 1:5. On the other hand, suspended sediment transport is not correctly scaled, which is expected. The suspended transport in the model is much higher than in the prototype.

Suspended-load scaling, in contrast, gives smaller values of the Shields parameter, which means less capacity for setting sediment in suspension. This effect is balanced by the higher diffusion which keeps the sediment in suspension. Therefore, sediment suspension maintains approximate similarity (Figure 3, bottom). Moreover, despite bed load transport inaccuracies, the differences in total transport rates compared to the prototype are less acute than using the geometrical scaling model.

Morphodynamic beach simulations show a similar pattern to the detailed modeling (Figure 4). Shear velocity, Shields parameter and bed-load transport maintain similitude. The prototype test displays similar rates of bed-load and suspended load transport and perhaps bed-load mode is dominating over suspended-load, as a result of the large sediment size (0.710 mm).

In the geometrically scaled model, the finer sediment means that suspended transport dominates, with suspended transport rates three times higher than bed-load transport. In contrast, the suspended sediment scale model shows a better correlation, with suspended load and bed-load of approximately the same order of magnitude. Suspended transport rates are close to similarity, while no large differences appear in bed-load transport. The highest discrepancies appear at the breaking point. Higher bed level changes occur in both the scale models than in the prototype. Compared to the prototype, geometrical scaling displays higher bottom evolution differences than the suspended sediment scaling. All simulations show a general pattern of bar formation close to the breaking point, which is of greater magnitude in the scale models than in the prototype. This tendency is expected to further increase with higher scale relations and higher d_{50} differences between the prototype and model.

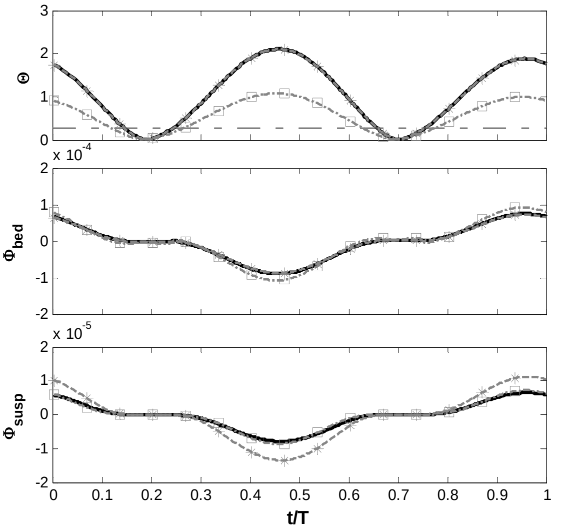

Figure 3. Computed Shields parameter (top plot), dimensionless bed load transport (middle) and suspended transport (bottom). Prototype condition, solid black line (-); geometrical sediment scaling, dashed-stars gray (-*-); relative settling velocity scaling, dash-square gray (-□-).

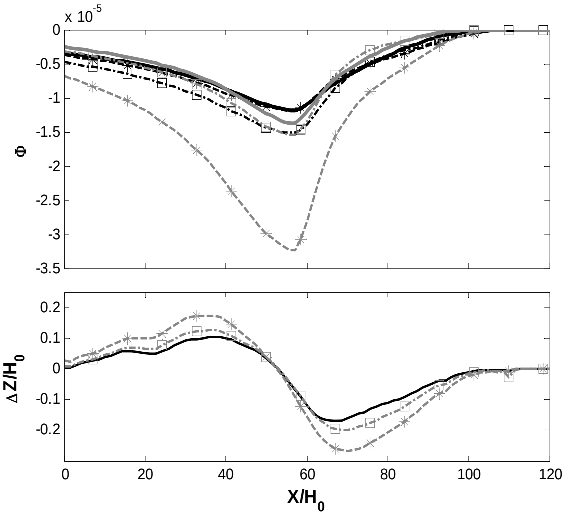

Figure 4. Top figure: computed dimensionless sediment transport rates. Solid line, prototype conditions; dashed line with star symbols, geometrical scaling; dashed-point with squares, relative settling velocity scaling. Black lines indicate bed-load transport rates and grey lines suspended transport rates. Bottom figure: bed level changes after 12 hours of simulation. Solid line, prototype; geometric scale model (-*-); settling velocity scale model (-□-).

DISCUSSION

From the present simulations, geometric scaling is not recommended for sandy beach modeling, since it gives too high prototype-model sediment size relationships and a bias toward suspended load in the model. Therefore, process differences appear, which is not a desired condition when scale modelling. However, geometrical sediment size scaling may be a good choice when the experiments aims to achieve boundary layer similarity, rather than sediment transport scaling, or when bed-load transport is dominant in both model and prototype. Examples of the latter conditions include scouring processes and swash overwash transport on gravel barrier beaches (see Baldock et al., 2005 for a review).

Suspended load scaling provides better similarity in sediment transport rates and bottom evolution. For this scaling, differences still arise from discrepancies in the boundary layer and bed shear stress. Scale corrections are proposed here to overcome this effect. Therefore, taking the suspended sediment model and following the BAILARD (1981) transport formulation where:

$$\begin{gathered} q_{bed} \propto f_w u^3 \\ q_{susp} \propto \frac{f_w}{w_s} u^4 \end{gathered} \tag{15}$$

and assuming n_{fw}=1 and n_{ws}=n_{u*}=n_u then gives the scale for sediment transport to be n_q=$n^{3/2}$. Assuming that all the discrepancies arise from the sediment size relation and introducing equation (12) in (15) a scale correction is suggested, given by:

$$\zeta = \left(\frac{n_{d50}}{n}\right)^a \quad (16)$$

and which is introduced into the scale relations in the form:

$$n_{qbed} = \zeta\, n^{3/2} \quad (17)$$

$$n_{qsusp} = \sqrt{\zeta}\, n^{3/2} \quad (18)$$

$$n_{\Delta Z} = \left(\zeta + \sqrt{\zeta}\right) n \quad (19)$$

Here, n_{qbed} and n_{qsusp} are the scale of the bed-load and suspended load sediment transport and $n_{\Delta z}$ is the scale of the bottom changes. This correction is valid only when the model is scaled using the relative settling velocity eq. (6). The morphodynamic simulation using this correction is illustrated in figure 5, showing significant improvement over the uncorrected simulation shown in figure 4.

CONCLUSION

Bed-load and suspended load scale models for a prototype Mediterranean beach have been evaluated using a suite of numerical models. Hydrodynamic similarity is achieved in both scaling criteria. Simulations have revealed that geometric scaling switches the main sediment transport mechanism from bed-load in the prototype to suspended load in the model despite boundary layer similarity. In this case, suspended sediment scaling appears a better technique to design scaled beach experiments since the transport rate differences are smaller. Correction laws have been suggested to upscale modelled sediment transport rates and bottom evolution from the suspended sediment model. The scaling methodology assumes ideal conditions where sediment sample are uniform and the grain size can be chosen freely. These conditions are rarely found in practical experimentation, where usually scaling considerations have to be made according to the available sediment. The corrections proposed here are useful to evaluate the scale effects in such conditions.

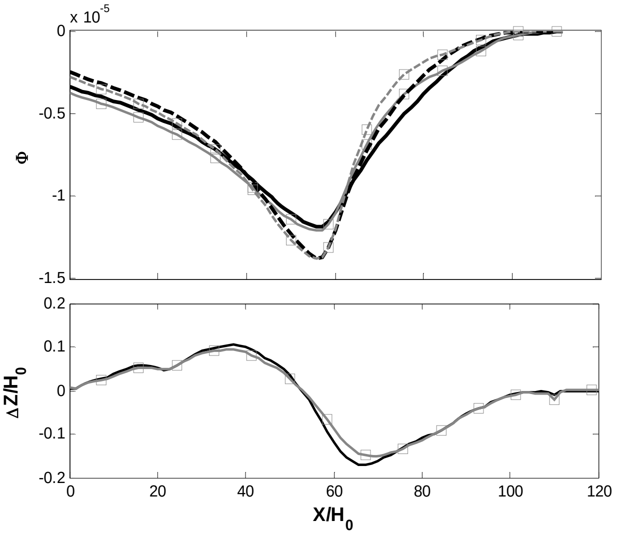

Figure 5. Top figure: computed transport rates corrected by relations (16) - (18); bed-load (-) and suspended transport (--) in the prototype and bed-load (□) suspended transport (-□-) in the scaled model. Bottom figure: bed level changes after 12 hours of simulation corrected by (19), black solid is prototype and gray dashed-square model.

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