CHAPTER 111

Armour Displacements on Reshaping Breakwaters

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Abstract

A computer simulation model for the reshaping of dynamically stable breakwaters under normally incident, monochromatic waves has been developed. The proposed model is used to simulate initial reshaping as well as transport on the developed profile. Preliminary validation of the model has been carried out by comparison with data obtained from experimental tests on a berm breakwater.

Introduction

The concept of reshaping breakwaters has recently received a significant amount of attention although such structures have been in existence for many years. Potential design problems associated with reshaping breakwaters concern the extent of initial profile reshaping and the implications of rock degradation on overall structural integrity. Rock durability has been the subject of a number of investigations including the work of Latham (1988) and more recently Magoon (1992) although there is no model relating incident wave conditions to stone mobility on the seaward slope.

Van der Meer (1990) developed a computational model, based on empirical equations, which can be used to

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predict profile changes. The need for more detailed information, without physical model testing, has led to the development of a numerical model which includes some representation of individual elements of the structure.

A reshaping simulation model has been developed by combining a numerical description of both wave loading and the particulate structure of a breakwater armour layer. A one-dimensional model is used to describe wave-induced velocities on the seaward slope. Rock armour units within the armour layer are represented by equivalent spherical particles. A force model is used to assess armour stability and initiate displacements on the slope. With a good calibration procedure it is possible to simulate rock displacements resulting from exposure to given wave conditions.

Particulate Structure

The armour layer of a breakwater is numerically represented by a random assembly of spherical particles. From a specified grading curve for the rock material, the equivalent spherical diameter is calculated for each stone class. The proportion of each size of spheres is also determined followed by random selection and finally placement within the packing volume. The structure is built-up in a series of horizontal layers of variable thickness to form the required initial profile.

Placement involves a vertical drop, from an appropriate location in the horizontal plane, followed by a rolling sequence until a statically stable position of minimum energy is found. If necessary, it is possible to achieve increased packing density by using a more selective placement procedure. For static stability, the centre of gravity of the object sphere must lie within the triangle formed by the three contact points in the horizontal plane. The following geometric equations must be simultaneously satisfied for the object sphere to be in contact with three supporting spheres,

$$(x_o - x_1)^2 + (y_o - y_1)^2 + (z_o - z_1)^2 = (r_o + r_1)^2 \tag{1}$$

$$(x_o - x_2)^2 + (y_o - y_2)^2 + (z_o - z_2)^2 = (r_o + r_2)^2 \tag{2}$$

$$(x_o - x_3)^2 + (y_o - y_3)^2 + (z_o - z_3)^2 = (r_o + r_3)^2 \tag{3}$$

in which x, y and z are the co-ordinates of the sphere centre, r is the radius and the subscript o indicates the object sphere whilst the subscripts 1, 2, 3 identify the three supporting spheres. Longitudinal and transverse sections through the numerically constructed armour layer of the berm breakwater are illustrated in figure 1. There are approximately 3000 spherical particles in total. The transverse section shows the structure width to be 0.3m (or $9D_{n50}$ where $D_{n50}=(M_{50}/\rho_a)^{1/3}$ in which M_{50} is the average stone mass and ρ_a is the mass density of the stone) which is sufficient to minimize the influence of the side-wall boundaries. Above the berm it can be seen that there are two layers of spheres which correspond to two layers of rock in the physical model. This layer is extended beyond the crest level of the physical model as the numerical wave model is not able to simulate overtopping by waves.

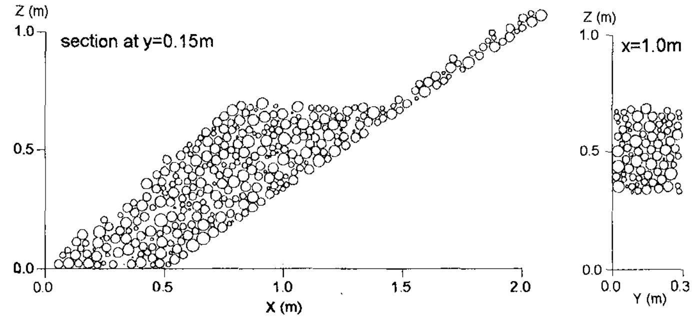

Figure 1. Numerically Constructed Armour Layer

Wave Loading

A mathematical wave model is used to calculate the water particle velocities and accelerations on the seaward slope. Figure 2 provides a definition sketch for the wave model.

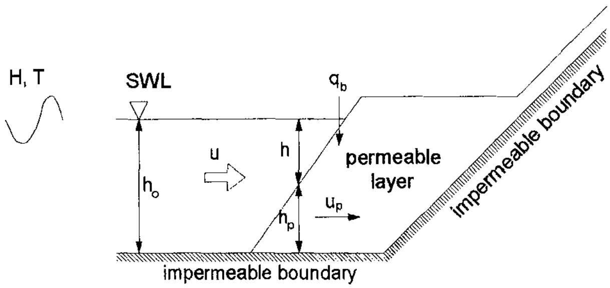

Figure 2. Definition Sketch

The governing differential equations, as derived by Kobayashi (1990), for the flow on and within a *permeable* slope are given for:
(i) *external flow:*

$$\frac{\partial h}{\partial t}+\frac{\partial(hu)}{\partial x}=-q_b \tag{4}$$

$$\frac{\partial(hu)}{\partial t}+\frac{\partial(hu^2)}{\partial x}=-gh\frac{\partial\eta}{\partial x}-\frac{1}{2}f_w u|u|-u_b q_b \tag{5}$$

in which h is the water depth, u is the depth-averaged velocity, g is gravitational acceleration, f_w is a wave friction factor, q_b is the discharge into permeable layer and u_b is the horizontal discharge velocity at interface
(ii) *internal flow:*

$$\frac{\partial(h_p u_p)}{\partial x}=q_b \tag{6}$$

$$\frac{\partial(h_p u_p)}{\partial t}+\frac{1}{n}\frac{\partial(hu_p^2)}{\partial x}-u_b q_b=-gnh_p\frac{\partial\eta}{\partial x}-gnh_p(a+b|u_p|)u_p \tag{7}$$

in which h_p is the depth of permeable layer, u_p is the discharge velocity in permeable layer, n is the porosity of armour layer, ν is the kinematic viscosity of fluid and further:

$$a=\frac{\alpha(1-n)^3\nu}{n^2 g D_{n50}} \qquad b=\frac{\beta(1-n)}{n^3 g D_{n50}^2} \tag{8}$$

A preliminary verification of the permeable slope wave model has been carried out with velocity measurements on the seaward slope of a reshaped berm breakwater.

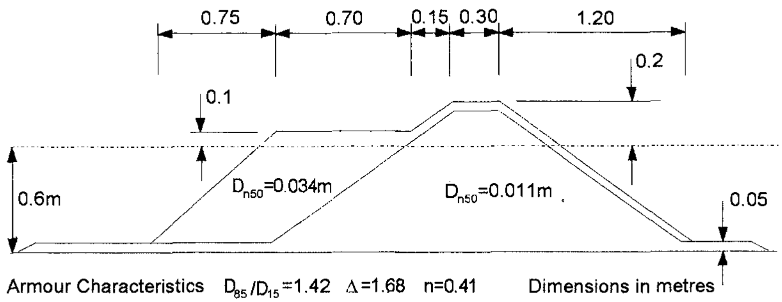

Figure 3. Model Berm Breakwater

The initial profile of the berm breakwater is illustrated in figure 3. The berm breakwater was reshaped using 4000 irregular waves from a Pierson-Moskowitz type spectrum with a significant wave height, H_s=0.180m and mean period, T_M=1.93s.

Maximum uprush (positive) and downrush (negative) velocities, measured using a MINILAB ultrasonic current meter, can be compared with calculated values in figure 4 for the specified regular wave conditions. The velocities are measured at mid-depth and the calculated values are depth-averaged values. Calculated maximum downrush velocities appear to be in relatively good agreement with measured values although the calculated velocities are consistently greater. There are more significant differences observed with the uprush velocities. The measured uprush velocities are much lower than expected and are not considered reliable due to poor performance of the current meter in highly aerated flows as observed during the uprush phase.

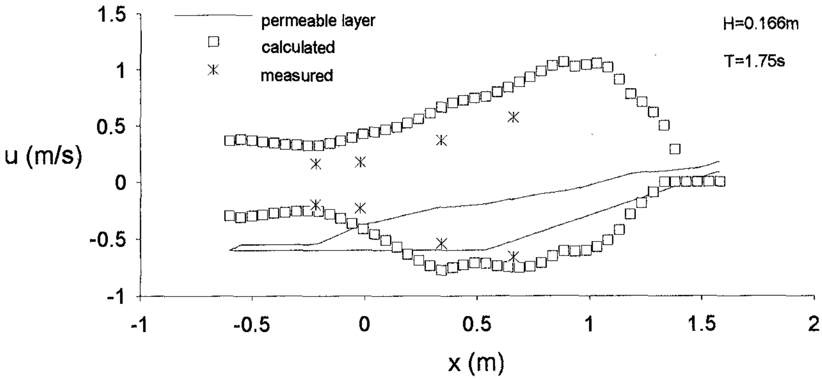

Figure 4. Measured and Calculated Maximum Velocities

The wave model requires the estimation of three input parameters which may be adjusted for calibration purposes. Some guidance for the selection of a suitable wave friction factor, f_w in equation 5, can be given by the formula developed by Madsen (1975) although a value of f_w=0.3 was adopted after calibrating the model against observed maximum run-up levels. For the internal flow resistance, the laminar and turbulent flow coefficients, α and β in equation 8, must be specified for the rock material. Values of α=8000 and β=2.4 were selected based on the results of experimental investigations by Burcharth (1991).

Armour Initiation

To assess the stability of individual elements on the surface layer of the seaward slope, a failure mode must first be assumed. The most common displacement mechanism for single stones can be observed in the laboratory to be of a rotational nature. Den Breeker (1985) found that almost 90% of rock armour displacements could be characterized by a rolling motion as opposed to sliding or lifting. For initiation it is thus appropriate to consider disturbing and restoring moments acting about a possible point or axis of rotation.

Disturbing forces resulting from the hydrodynamic wave loading are determined using a Morison-type equation including drag, F_D, inertia, F_I, and lift, F_L, force components given as:

$$F_D = 0.5\rho_w C_D (C_{SD}\frac{\pi}{4})D^2 u|u| \tag{9}$$

$$F_I = \rho_w C_M (C_{SI}\frac{\pi}{6})D^3 \frac{du}{dt} \tag{10}$$

$$F_L = 0.5\rho_w C_L (C_{SL}\frac{\pi}{4})D^2 u^2 \tag{11}$$

in which ρ_w is the mass density of water and D is the particle diameter. The values selected for the force coefficients are based on the results obtained by Tørum with a drag coefficient, C_D=0.35 and an inertia coefficient, C_M=0.20. For the lift coefficient, C_L=0.15 is chosen although there is no guidance on suitable values. The resultant in-line force, F_X (=F_D+F_I), is assumed to act through the centre of gravity of the projected area which is exposed to the surface flow. The vertical component of force, F_Z (=F_L) perpendicular to the direction of the flow is assumed to act through the centre of gravity of the body.

The coefficients, C_{SD}, C_{SI} and C_{SL} are included to take into account the influence of partial submergence which may be necessary for particle locations between the maximum run-up and run-down levels. The submergence coefficients, C_{SD} and C_{SL} represent the reduction in projected area in the vertical and horizontal planes respectively, whilst C_{SI} is associated with the reduced volume.

In addition to the hydrodynamic loading, the buoyancy force resulting from the displaced fluid must also be considered. The buoyancy force, F_B, acts through the centre of gravity of the body in a direction perpendicular to gradient of the local, instantaneous free-surface as previously considered by Brandtzaeg (1966). The magnitude of the force can be calculated using the following expression:

$$F_B = \rho_w g (C_{SI} \frac{\pi}{6}) D^3 \tag{12}$$

The buoyancy force is separated from the particle weight as information concerning the gradient of the free surface is available from the wave model. The force is normally assumed to act vertically upwards. Restoring forces resisting movement comprise of the weight of the body:

$$W = \rho_a g \frac{\pi}{6} D^3 \tag{13}$$

as well as friction and interlocking forces.

Previous research by Wang (1990) indicates that friction and possibly interlocking forces can be directly related to the weight of the particle. In an attempt to include the combined influence of friction and interlocking, a coefficient, C_{FI}, is introduced. The selection of suitable values for C_{FI} is discussed further in the section describing the reshaping simulation model. The following condition must be satisfied during the specified duration to ensure initiation of movement:

$$e_1 F_{ZX} > e_2 (C_{FI} W) - e_3 F_B \tag{14}$$

in which F_{ZX} is the resultant wave force ($F_{ZX} = \sqrt{F_X^2 + F_Z^2}$) e_1, e_2 and e_3 are the moment arms for the wave loading, effective particle weight and buoyancy force respectively. The moment arm for each component of force is found by calculating the perpendicular distance from the line of action of the applied force to the point or axis of rotation. A diagram of the system of forces, for a simplified particle geometry, considered for initiation is given in figure 5.

The wave loading is calculated for each particle and during a single wave cycle, based on calculated local depth-averaged velocities and accelerations. If the disturbing moments exceed the restoring moments for a specified minimum duration, t_{MIN}, then movement is initiated in the direction under consideration. Usually, three possible directions of movement are considered which are defined by the relative position of the supporting particles.

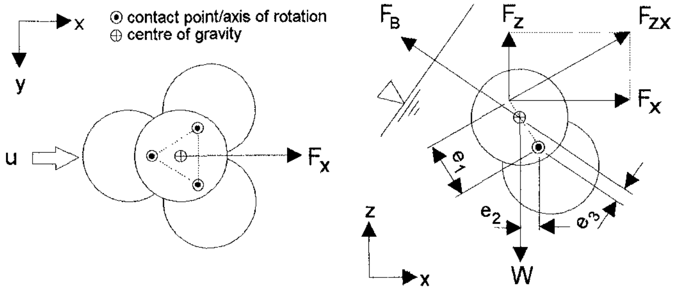

Figure 5. Forces Applied to Single Particle

For the purposes of predicting forces on individual particles it is more appropriate to consider a velocity outside the boundary layer. This is consistent with the measurements made by Tørum (1992) in which velocities and forces were measured on a berm breakwater slope from which force coefficients have been derived.

Reshaping Simulation

The reshaping simulation involves the application of two separate models which are linked by an iterative procedure. Initially, the surface of the armour layer is numerically profiled and an average profile is obtained from three longitudinal sections with measurements at intervals of D_{n50}. To provide input to the wave model, a greater resolution of profile measurements will be required. Additional data is obtained by linear interpolation between points of the average measured profile.

Once a converged solution has been obtained from the wave model, temporal variations of water depth, velocity, acceleration and gradient of the free surface during a complete wave cycle are stored for 25 *sampling stations* along the slope.

One limitation of the displacement model is that only surface particles which are exposed to the external flow are considered to be potentially mobile. These particles are identified by having contact with only three supporting particles.

The stability of each surface particle is considered in turn commencing with particles nearest the toe of the slope. The wave-induced horizontal and vertical components of force are calculated using the data from the wave model. Velocities and accelerations at the precise particle location are obtained by interpolation of data stored for the two nearest sampling stations.

The magnitude of the discrete displacement, d_{MIN}, must be small enough to provide a good resolution of particle displacements but sufficiently large to minimize computational times. For the simulations carried out, $d_{MIN}=5D_{n50}$ was found to be adequate.

If threshold conditions are obtained, the particle is given a discrete displacement of length d_{MIN} in the direction selected as the path of least resistance. This is the direction which is associated with the maximum ratio of disturbing to restoring moments. Periodic boundary conditions are applied; thus if a particle passes through the sides of the computational domain, it is re-introduced at the opposite side. By this means any sidewall effects are eliminated. After displacement, a rolling sequence is used until the particle is relocated in a statically stable position.

After all surface particles are considered and displaced if hydrodynamically unstable, the process is repeated a further four times. The adjusted slope is then re-profiled for new input to the wave model followed by further displacement of surface particles. The complete iterative procedure described is repeated until there is negligible profile change from two successive particle relocation operations although there may be oscillatory displacements on the slope.

The process of particle *nesting,* particularly with berm breakwaters, has been observed in the laboratory whereby smaller material fills voids within the berm resulting in a highly interlocked layer and increased stability. This process has, to some extent, been incorporated into the simulation model by checking the location of surrounding elements after a particle is relocated on the slope. If the particle is sheltered from the surface layer from the external flow, an increased coefficient of $2C_R$ is applied to the particle weight which generally prevents further movement. If the surrounding elements are subsequently moved, the coefficient reverts back to its normal value and further displacement is possible. Particle nesting of undersize material was not found to be a dominant factor for stability of the reshaped slope which may be attributed to the relatively narrow material grading (D_{85}/D_{15}=1.42).

Application to Berm Breakwater

The berm breakwater illustrated in figure 3 was reshaped with the irregular wave conditions previously described. The numerically constructed breakwater was reshaped by regular waves with the same waveheight and period as the irregular wave parameters, H_S and T_M, therefore H=0.18m and T=1.93s. The damage was expected to be more extensive with the regular wave conditions as there will be few waves greater than H_S in the irregular wave series.

The main calibration factor required by the reshaping simulation model is the combined friction-interlocking coefficient, C_{FI}. An artificially high value of C_{FI}=5.0 results in an almost statically stable structure whereas a low value, C_{FI}=0.5 produces a highly mobile structure for which all particles are unstable. In the absence of suitable data relating to the rock material, a trial and error procedure is required in order to determine a suitable value for which the predicted profile matches the experimental profile. Once established, reshaping under other wave conditions can be studied as the value of C_{FI} is also expected to be a property of the packed material and independent of the wave conditions. The value of C_{FI} is expected to be a function of the structure slope although the chosen constant value of C_{FI}=1.6 was found to be adequate for the simulation presented.

Results from the reshaping simulation, for the initial structure, are presented as an average reshaped profile. A measured and predicted reshaped profiles are shown in figure 6. An intermediate profile is also included although the simulation is not time-dependent and only included to provide an illustration of how the profile evolves.

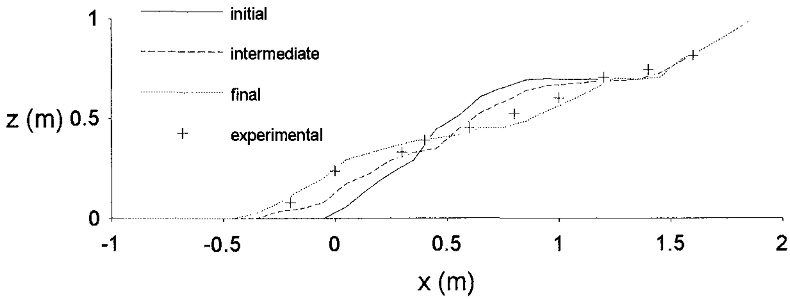

Figure 6. Measured and Predicted Average Profiles

The predicted profile shows an increased degree of erosion from the upper part of the slope with a corresponding increased amount of accretion below SWL. The toe of the reshaped profile does not consist of material at its natural angle of repose but there is still some influence of the hydrodynamics which produces a relatively smooth transition to the horizontal bed. A section through the numerically reshaped structure is presented in figure 7.

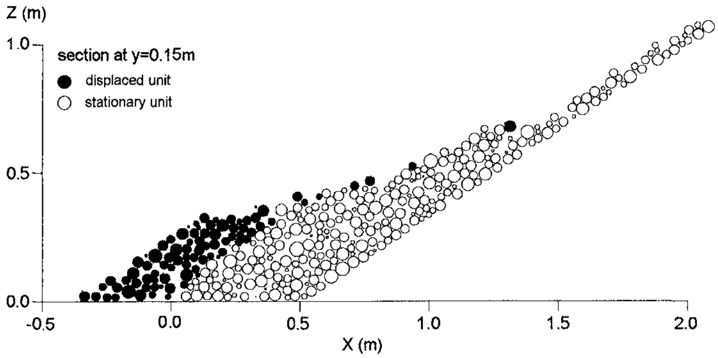

Figure 7. Section Through Reshaped Berm Breakwater

After initial reshaping of the model breakwater, further tests were carried out in which individual stone displacements were observed as described by Tomasicchio (1992). By painting the reshaped profile in zones across the width of the flume, damage to the surface layer defined by the number of displaced stones was determined. Wave conditions with progressively increasing stability number, N_s ($N_s = H/\Delta D_{n50}$, where $\Delta = (\rho_a - \rho_w)/\rho_w$), but constant wave steepness, were used and an assessment of the cumulative damage made after each test. Most of these tests were conducted with irregular waves although some data is available for displacements under regular waves. Due to the differences in the measured and predicted profiles, quantitative results from physical and numerical experiments are not compared. Figure 8 shows results from a typical simulation of displacements on the reshaped slope presented as a plan view of surface particles before and after exposure to regular waves with H=0.166m and T=1.86s. The particles are shaded according to their position on the reshaped slope before displacement.

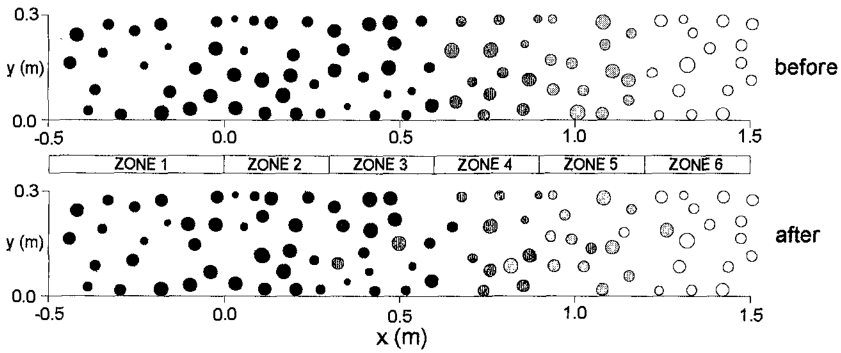

Figure. 8 Surface Particle Displacements

Conclusions

A reshaping simulation model, using a deterministic approach, which includes detail of individual armour displacements is shown to provide a qualitatively good prediction of profile development. Predictions of transport on the reshaped profile can also be made with the calibrated model although the results have not been validated against experimental data.

The influence of variability within the random structure of the armour layer can be investigated by repeating the numerical experiments on a modified structure. A different structure, with the same material grading and initial profile, can be numerically constructed by providing different seed values to the random number generator used to select particles for placement.

Modifications towards a more probabilistic model should include the variability of particle shape. This would require a distribution of projected area/volume, wave force and friction-interlocking coefficients rather than applying a single value as used in the present model.

Further improvements to the component models are possible although the associated increase in computational time should be taken into consideration. The simulation of initial reshaping with the present model can take up to 8 hours on a 50MHz 486 machine.

Acknowledgements

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