# A NUMERICAL MODEL OF WAVE/BREAKWATER INTERACTIONS

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## Abstract

A numerical model has been developed to simulate breakwater response to wave impacts with special reference to armor unit behavior and breakwater stability. The model uses a finite difference hydrodynamic code to follow the wave impacts and determine wave forces upon the breakwater components. A discrete element code models the breakwater response and motions. The model rationale and numerical basis are followed by three examples used in this, the concept validation, stage of model development.

## 1. Introduction

Failures of rubble-mound breakwaters, particularly those built with artificial armor units, have been occurring over the last decade. The much publicized major breakwater failure at Sines, Portugal (Edge and Magoon, 1979) has highlighted the problem. Damage assessment of the Sines event (PSID, 1979) funded by the National Science Foundation demonstrated that the design methods and philosophies which were used may have been inadequate. These methods have included use of the empirical Hudson's stability formula which links the slope of the breakwater face with the weight and stability coefficient of the armor units.

With introduction of artificial breakwater armor shapes, in particular the dolos unit (Merrifield and Zwamborn, 1966), much lighter armor units than the equivalent quarried rock armor have been used. The artificial units have dramatically increased interlocking abilities and hence larger stability coefficients. Thus, for a given design wave, Hudson's formula predicts a lighter unit than if a low stability coefficient typical of natural rock had been used. However, recent studies have concluded that artificial armor units are particularly susceptible to dynamic motions imparted by the inertial and drag forces of waves impinging upon a breakwater structure. Specification of artificial armor units for breakwater design demands better understanding of the structural loading phenomena on individual elements and the limitations imposed by the concrete and reinforcing properties.

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This paper presents a numerical technique for studying both the behavior and overall breakwater stability under a variety of wave loadings and the behavior of individual armor units. A discussion of the numerical approach is followed by examples using simplified armor unit shapes and breakwater geometries. While the ultimate aim of this line of research is to be able to model, in three dimensions, breakwaters constructed using both existing and proposed armor units, the object of this paper is to show the feasibility of the adopted approach using two-dimensional examples. The computer model is structured in a modular fashion which allows additions and enhancements to be included as they are developed.

## 2. Numerical Approach

Consider a generalized breakwater cross section consisting of a wave breaking on a multilayered armored breakwater (Figure 1). The wave breaking process is highly non-linear, consisting of inertial and viscosity induced forces. A complex energy dissipation and force reversal process follows in the armor unit, filter layer and core regions. The armor units are designed to resist the forces but they will rock and possibly break if overstressed or improperly positioned. Such breakages aid or initiate larger failures.

Rather than attempt to model the complete wave/breakwater interaction with one computer code, an approach has been adopted which is believed will allow both theoretical and numerical developments in wave breaking analysis to be incorporated with a minimum of program restructuring. The wave/breakwater interaction is modeled by two distinct codes, one describing the wave action and forces, the second describing the armor unit behavior. At this stage of concept development, it is being assumed that the interactions can be decoupled for time periods on the order of the time between subsequent wave impacts. This assumption implies that the short term response of the armor units does not significantly alter the wave force field within these intervals. For non-catastrophic failure, the assumption is valid as armor movement is on the order of centimeters. In failure situations, the assumption is no longer valid. However, the decoupling assumption reduced computation time considerably during this concept validation stage of the model development. As model development progresses, full coupling will be introduced.

In formulating an numerical approximation to the physical system it was realized that a complete description of the wave forces does not exist. However, simplified numerical approximations to the wave breaking process can be made. The classical equations describing stress within a structural unit are well known and have been applied in a number of studies of breakwater armor units (e.g., Lillevang and Nichola, 1976).

### 2.1 Wave Forces

The wave forces resulting from impacts upon a breakwater type structure are calculated using a version of the finite difference

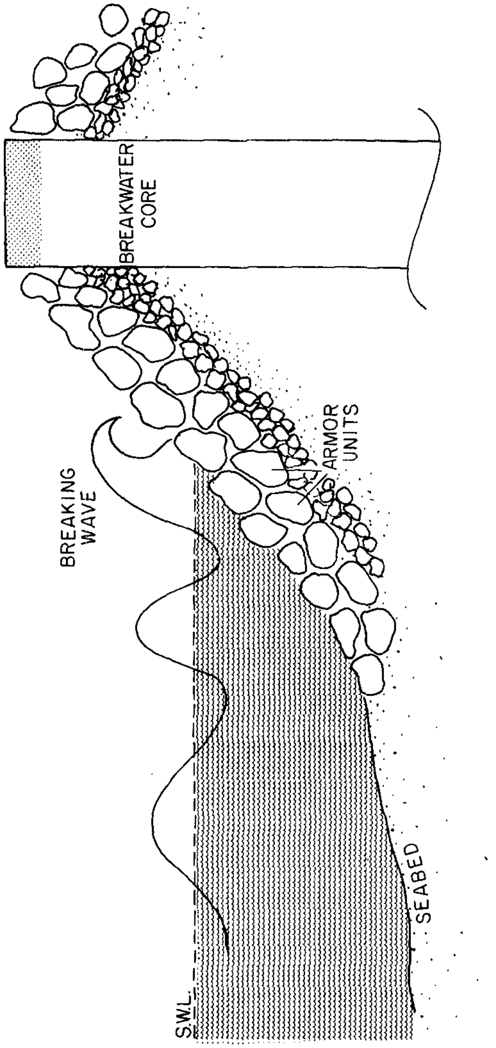


FIGURE I.
GENERALIZED BREAKWATER CROSS-SECTION

computer code, SOLA-VOF, developed at Los Alamos Scientific Laboratories for solving transient fluid flow problems with multiple free boundaries (Nicholas et al., 1980). The constitutive equations used in the code are the Navier-Stokes equations and a form of the continuity equation which includes limited fluid compressibility (Figure 2). The feature of the program which makes it particularly useful in this application is the concept of the fractional volume of fluid (VOF). The "F" equation (see Figure 2) is used to describe the existence and position of a free surface within a finite difference cell. The value of F is zero in an empty cell and one in a full cell. A cell with a value between these limits indicates that a free surface (or boundary surface) exists in that cell. Because the free surface is defined in a cell by cell manner, multiple free surfaces can exist within a modeled region. As no a priori assumptions are necessary regarding the position of the free surfaces as it varies spatially or temporally, free surfaces can pass over or through a mound of obstacles.

At the current stage of development, obstacles to the water movement such as armor units are included as rigid zones within the modeling area. For non-failure conditions this approximation is reasonable. However in order to study the effects of rocking and failure, a more general movable description of the obstacles will be necessary. Forces on the obstacles are calculated by integrating the pressures around an obstacle. This method allows inertial effects to be included directly.

Wave loadings can be specified by a number of methods. In the examples to be shown, an initial water surface was defined with and without initial velocities. Alternatively, a pressure field can be used to initiate a wave response or a full description of internal velocities and surface elevations could be input. A random sea could be defined by the last method.

A simplified diagram of the program's operation is shown on Figure 3. The finite difference approximations to the momentum equations are first solved using the previous timestep values of velocity and pressure in the appropriate terms. After application of the boundary conditions, the continuity equation is solved in an iterative manner to obtain the new timestep values of velocity and pressure. Finally the F equation is solved for all cells. More explicit details of the scheme have been published previously (Nicholas et al., 1980).

## 2.2 Armor Units

The response and behavior of the breakwater armor units are modeled using a discrete element model originally developed for simulating jointed rock behavior (Cundall, 1980; Dames & Moore, 1981). The model calculates the individual armor unit (i.e., element) response to both the applied fores and the constraints of the surrounding units. The internal block stresses and inter-block fluid pressures can be calculated at each step in the armor unit

Navier-Stokes

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + g_x + \nu\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right]$$

Continuity

$$\frac{1}{\rho c^2}\frac{\partial p}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Volume of Fluid

$$\frac{\partial F}{\partial t} + u\frac{\partial F}{\partial x} + v\frac{\partial F}{\partial y} = 0$$

FIGURE 2. EQUATIONS USED IN FLUID CODE

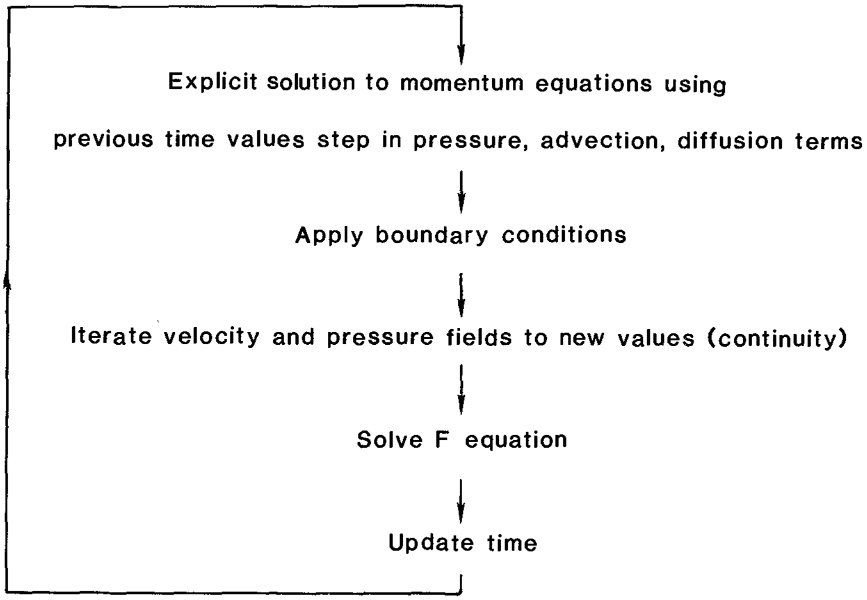


FIGURE 3. SIMPLIFIED CALCULATION CYCLE: SOLA-VOF

code. Joints between the units and corner-to-edge or corner-to-corner contacts are treated as boundary conditions between the units. Therefore the corner locking and frictional forces associated with breakwater unit interactions can be modeled correctly. By including fracturing and splitting within the discrete elements, failure of the armor units and/or the overall breakwater can simulated. The code uses a fully dynamic explicit scheme to solve the equations of motion thus allowing the true response of the units and the interactions to be followed. The basis calculation cycle is shown on Figure 4.

At the present stage of program development, armor unit shapes from discs to rectangles can be modeled. The discs are simulated by increasing the corner rounding, which is used to prevent elements "locking up", until a disc results. Further developments of the jointing or shaping aspects of the program, by which joints and hence blocks are defined, will allow more sophisticated armor shapes to be modeled.

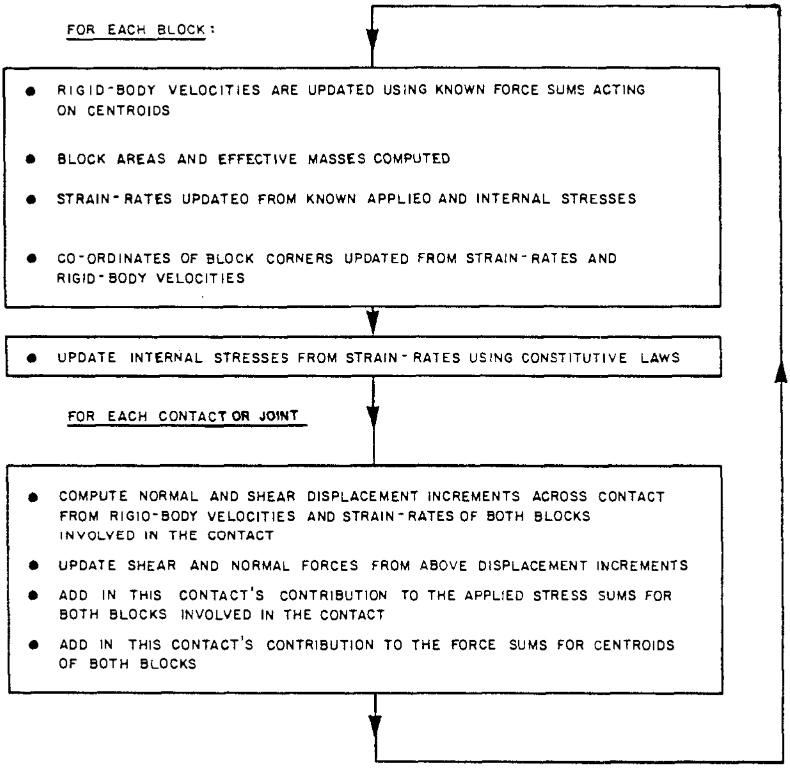
## 3. Examples

Three examples of the current program configuration follow. The first two are essential revetment problems as a fully reflective boundary is assumed at the centerline of the "breakwater". In the third example, a breakwater is constructed by adding a "harbor" side to the revetment grid. In all cases, artificial spacing of the armor blocks in the fluid program is required to allow forces to develop around the blocks. The space is the result of modeling a three-dimensional problem in two dimensions. The breakwater geometries are extremely simplified - more so than the programs will allow - as these examples were aimed at concept validation rather than quantitative validation.

### 3.1 Revetment Example

The grid used in the fluid modeling is shown on Figure 5. The armor blocks are defined as rigid obstacles as is the revetment core. The armor units are 1.6 meters square. A wave loading is approximately by a 2.6-meter high "block" of water released in a manner similar to a dam break. One of the many verification cases of the fluid code included the reproduction of a laboratory dam break test. A no-flow boundary condition is used on all boundaries. As previously mentioned, the armor units are separated to allow fluid flow between the blocks. Snapshots of the fluid behavior are shown on Figure 6. This figure shows the initial block of water collapsing to form a "surging" wave.

The forces on the armor blocks developed during the wave impact and reversal are shown on Figure 7. Comparison of the force histories on Blocks 1 and 2 shows the expected force reduction on the second layer block afforded by the first layer block. A similar pattern can be seen in the force histories of Blocks 3 and 4. Blocks 1 through 4 show a smooth increase and decrease of forces as would be expected from submerged blocks. Blocks 5 through 7 show



FOR EACH BLOCK:

- RIGID-BODY VELOCITIES ARE UPDATED USING KNOWN FORCE SUMS ACTING ON CENTROIDS
- BLOCK AREAS AND EFFECTIVE MASSES COMPUTED
- STRAIN-RATES UPDATED FROM KNOWN APPLIED AND INTERNAL STRESSES
- CO-ORDINATES OF BLOCK CORNERS UPDATED FROM STRAIN-RATES AND RIGID-BODY VELOCITIES

- UPDATE INTERNAL STRESSES FROM STRAIN-RATES USING CONSTITUTIVE LAWS

FOR EACH CONTACT OR JOINT

- COMPUTE NORMAL AND SHEAR DISPLACEMENT INCREMENTS ACROSS CONTACT FROM RIGID-BODY VELOCITIES AND STRAIN-RATES OF BOTH BLOCKS INVOLVED IN THE CONTACT
- UPDATE SHEAR AND NORMAL FORCES FROM ABOVE DISPLACEMENT INCREMENTS
- ADD IN THIS CONTACT'S CONTRIBUTION TO THE APPLIED STRESS SUMS FOR BOTH BLOCKS INVOLVED IN THE CONTACT
- ADD IN THIS CONTACT'S CONTRIBUTION TO THE FORCE SUMS FOR CENTROIDS OF BOTH BLOCKS

FIGURE 4. SIMPLIFIED CALCULATION CYCLE: RAGE

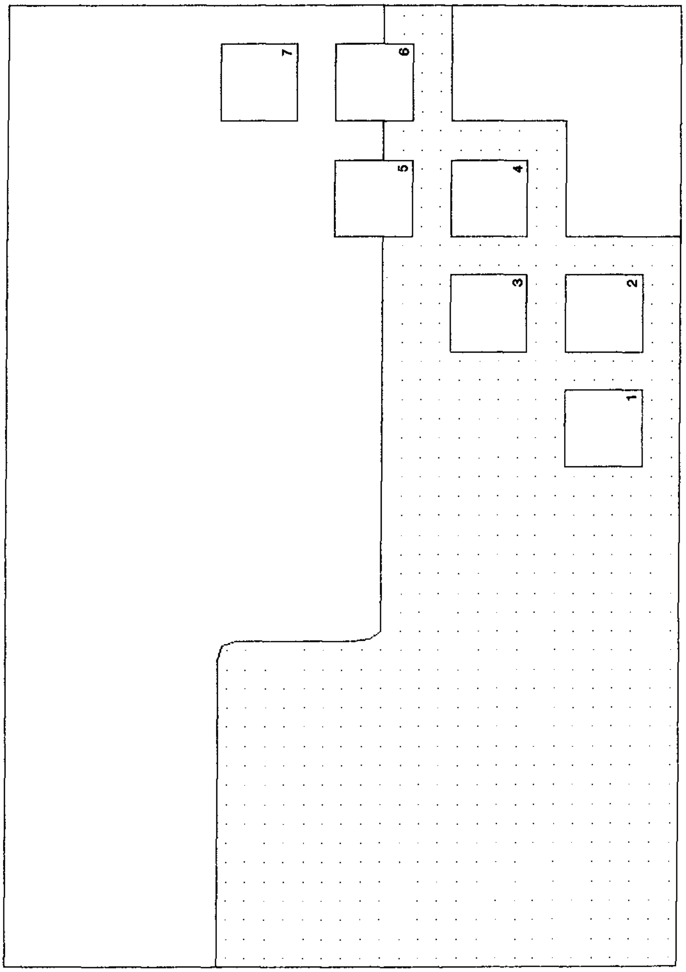


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FIGURE 5. EXAMPLE 1: INITIAL WATER SURFACE

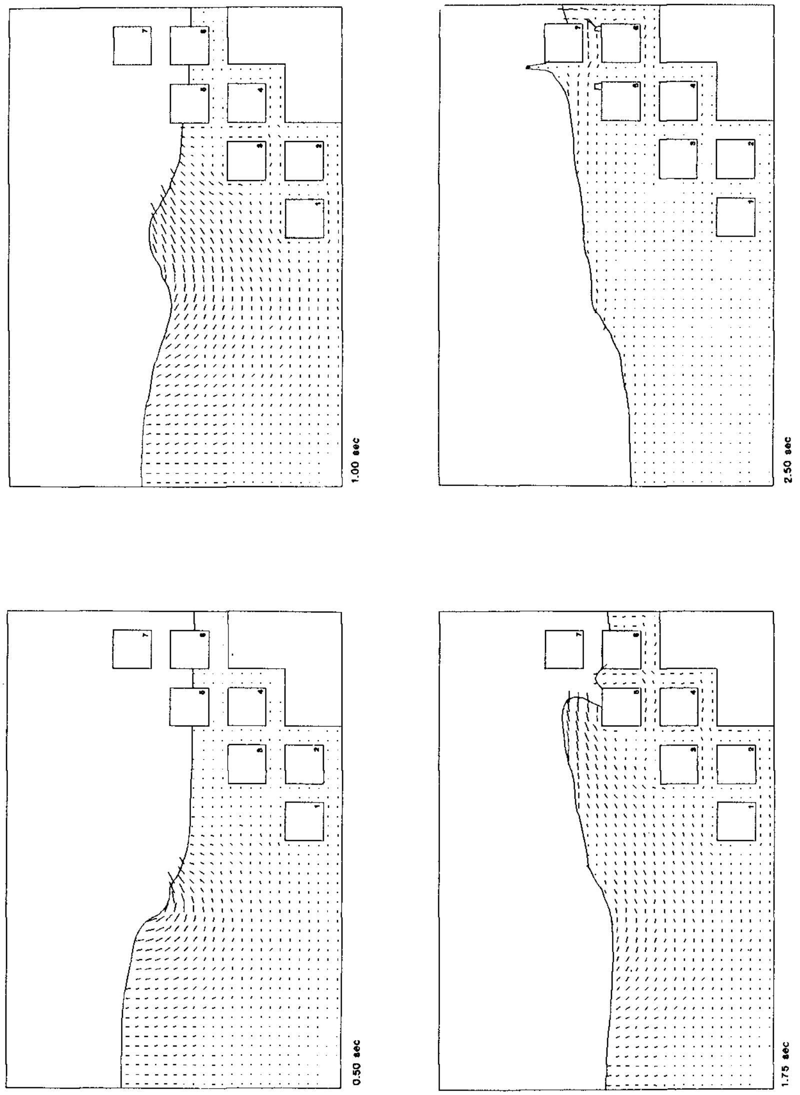


FIGURE 6. EXAMPLE 1: WAVE IMPACT

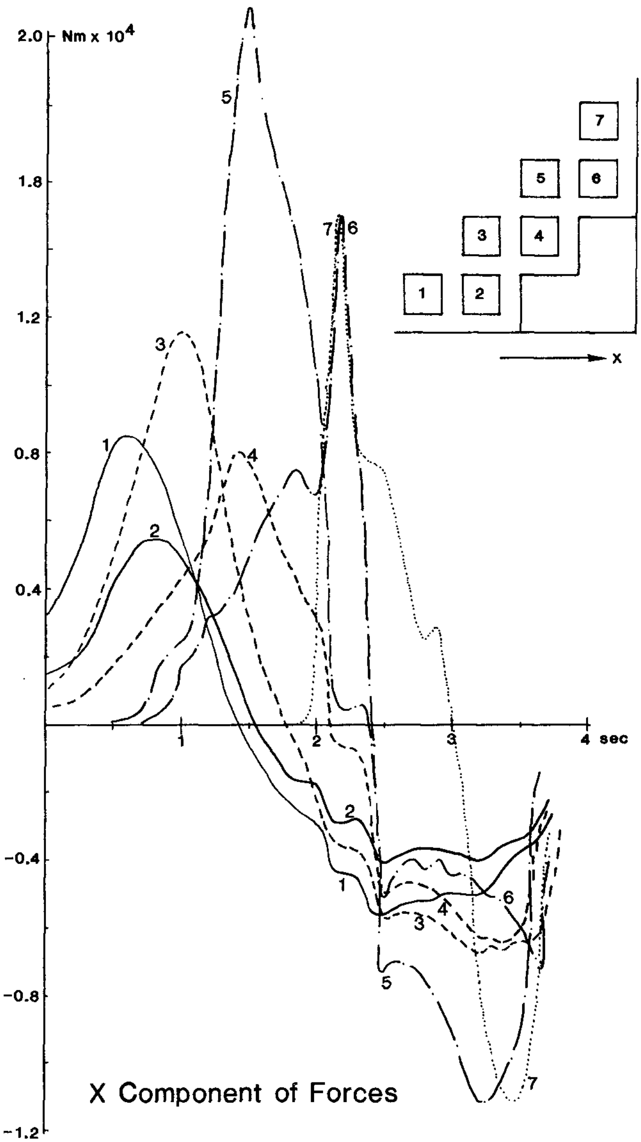


FIGURE 7. EXAMPLE 1: FORCES ON BLOCKS

much sharper peaks resulting from impacts upon the semi-submerged and free blocks. Block 5 shadows Block 6 as in the case of the submerged blocks.

The discrete element block model setup is shown on Figure 8.a. As the forces are applied at the block centers, no artificial spacing between the blocks is required or could be maintained as the blocks are free to move and are subjected to gravitational accelerations. The block movements resulting when the force histories are used is shown on Figures 8.a through 8.e. The displacements are exaggerated as the actual movements are very small (on the order of millimeters). The incoming wave (Figures 8.a, 8.b) has very little effect while the backwash (Figures 8.c, 8.d) causes the blocks to rock and hence the toe block to move outwards. Figures 8.e and 8.f show the return rocking of the blocks and the final pattern when the forces are removed. Reapplication of the same force history to the displaced blocks caused retightning during the incoming wave portion of the force history and redisplacing during the backwash. Repeated applications of the wave history did not cause a failure.

### 3.2 Revetment Modifications Example

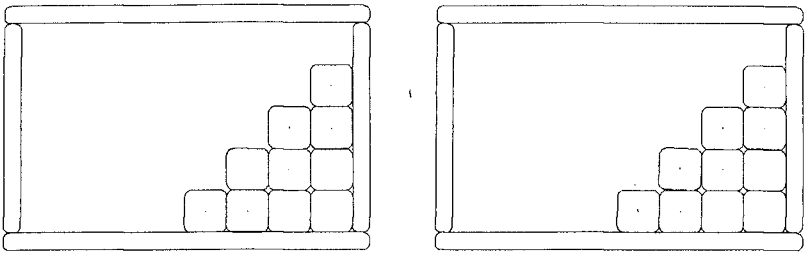
The fluid grid was modified to include a "filter layer" of smaller blocks and four cases were run modifying the spacing between the blocks and the wave loading. Case 1 is the above "surging wave" example run again with the new grid, Case 2 is the same grid with the interblock spacing reduced from two grid cells to one grid cell. In the second two cases, a wave shaped block of water was defined with an initial velocity to form a "plunging" wave. Again, interblock spacings of two and one cells were used.

The histories of forces acting upon the small filter block marked with an X on Figure 9 are shown on Figure 10. As expected, the surging wave produces less force on the filter unit than the plunging wave. The larger spacings allow greater forces to develop in the interior of the breakwater.

### 3.3 Breakwater Example

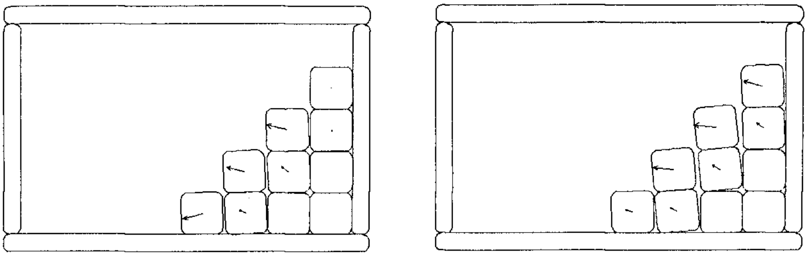
To investigate the effect of replacing the revetment in the first example with a true breakwater, the grid was extended as shown on Figure 11. The figure shows snapshots of the wave passing through and over the breakwater. It is interesting to note that jetting through the breakwater (Figure 11.c) induces waves on the harbor side (right) of the breakwater. This jetting has been observed in real breakwaters.

In this example a "surging" type of wave was applied as in the first example. The x component of forces on two blocks are compared with the forces on the equivalent two blocks in the previous example, Case 2. Figure 12 shows the forces histories on the exposed Blocks 3 and 5. Block 3 is a submerged block, while Block 5 is initially only partially submerged. The impact histories for the blocks are identical with the exception that in the breakwater case



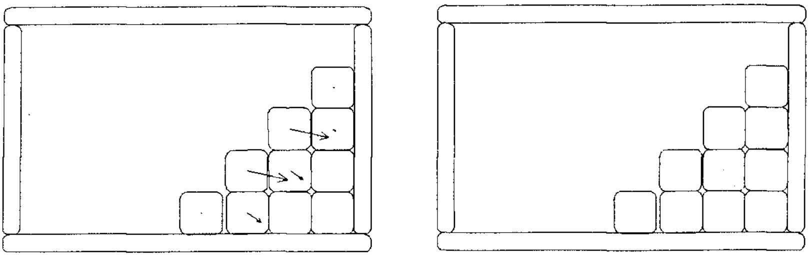
a. T=0.37 sec

b. T=1.50 sec



c. T=3.09 sec

d. T=3.89 sec



e. FORCES REMOVED

f. FINAL POSITION

FIGURE 8. EXAMPLE 1: BLOCK MOVEMENTS

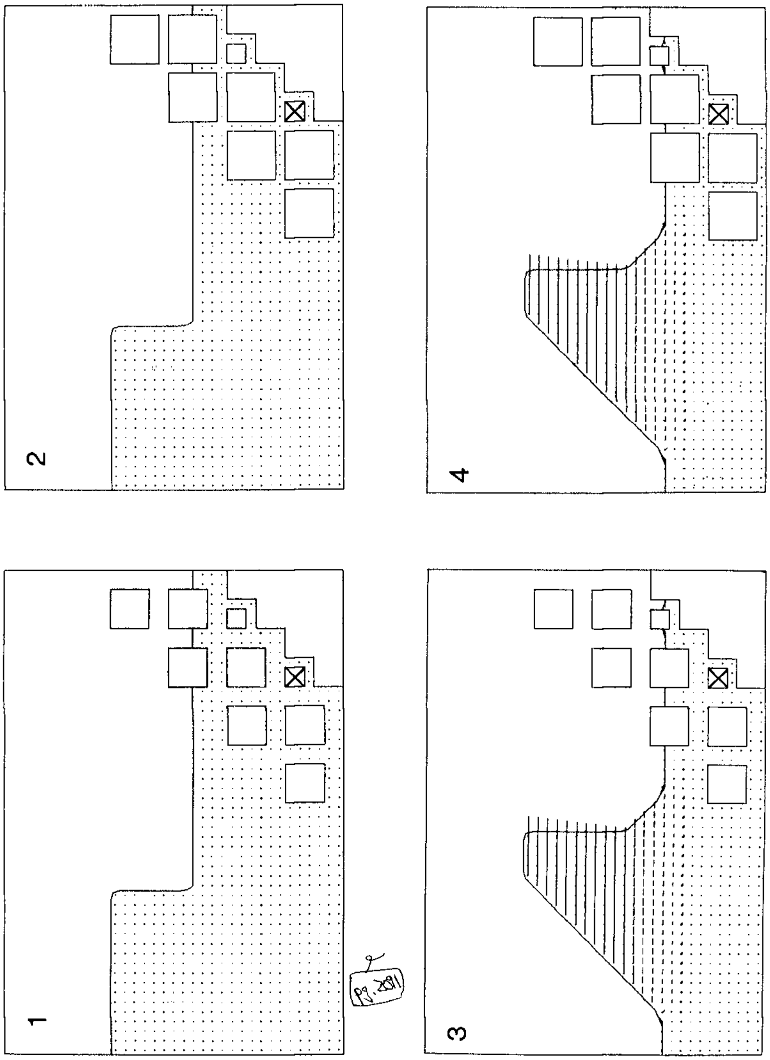


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FIGURE 9. EXAMPLE 2: CASE DEFINITION

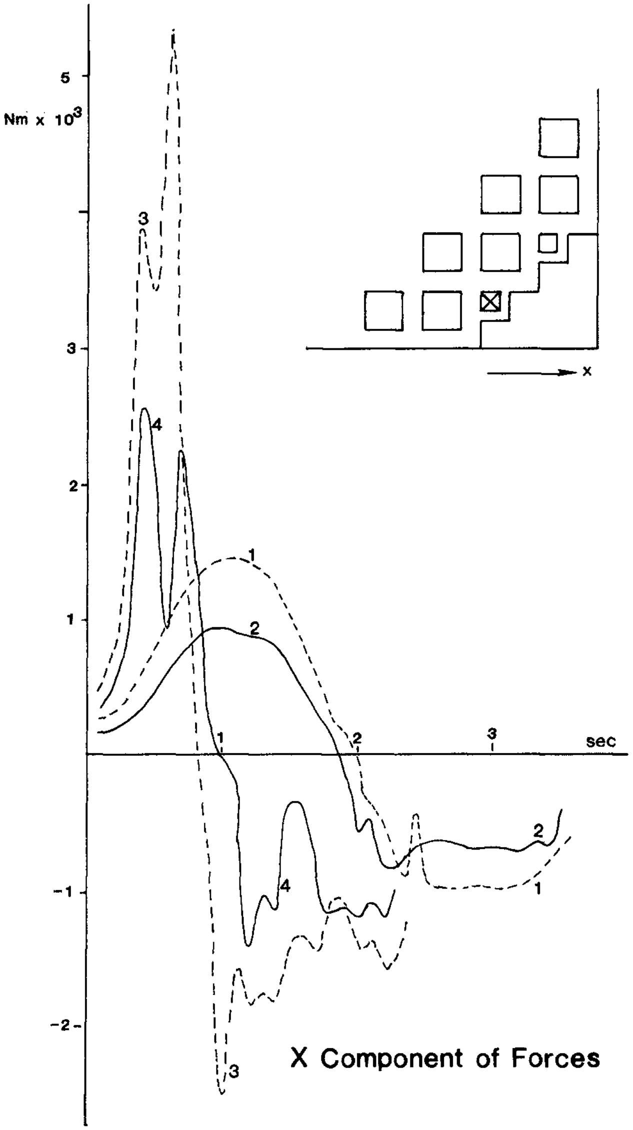

FIGURE 10. EXAMPLE 2: FORCES ON FILTER BLOCK

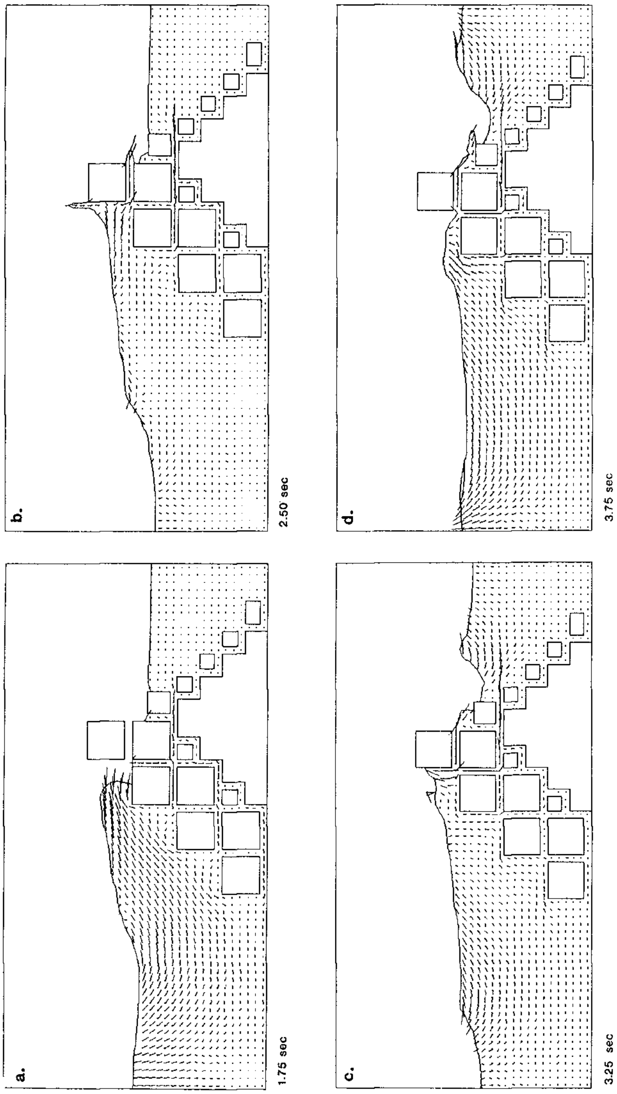

FIGURE 11. WAVE IMPACT ON BREAKWATER

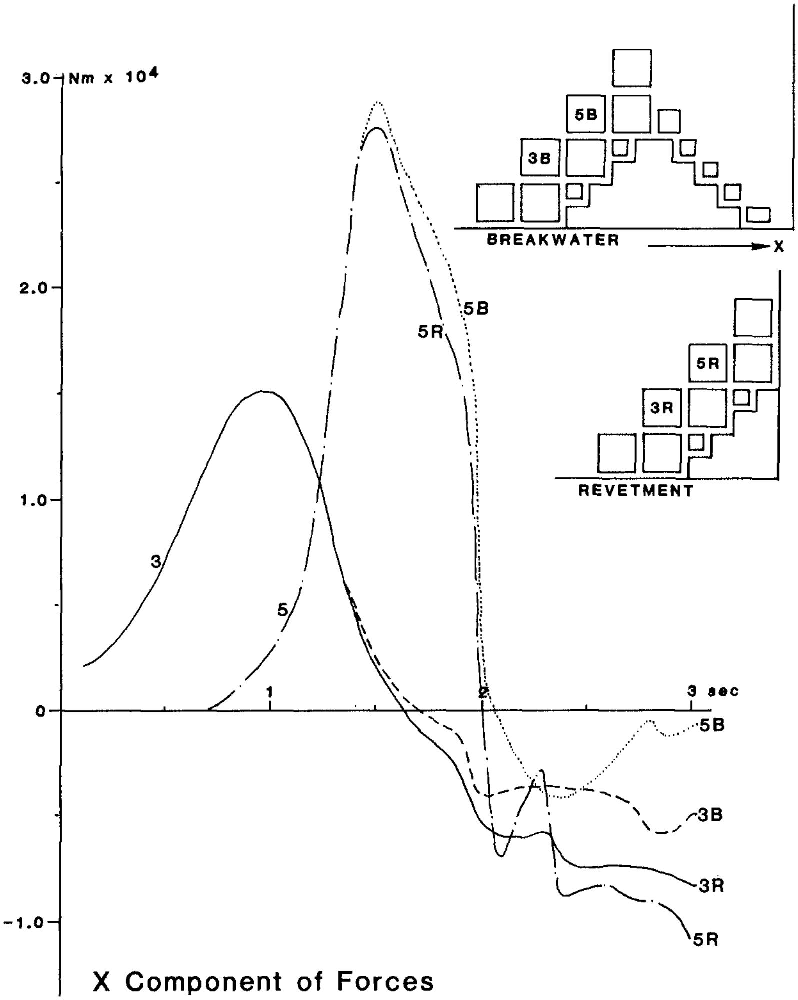

FIGURE 12. EXAMPLE 3: FORCES ON BLOCKS

a slightly greater maximum force is experienced on Block 5. This may be due to a reduction in the amount of water traveling up through the gap between Block 5 and its neighbor to the right in the breakwater case because of jetting through the breakwater. Consequently, an increase in the net impact force acting on the front face will result.

The backwash forces on both blocks are less in the breakwater case than those in the revetment case due to the flow through the breakwater. Block 5 shows a breater reduction than Block 3. This is probably because the backwash experienced by Block 5 in the revetment case is primarily due to wave runup caused by the revetment wall. The backwash experienced by the submerged Block 3 is due in greater part to the effects of the blocks to its right.

## 4. Conclusions

The results described above are encouraging and indicate the feasibility of the adopted approach. Considerable work needs to be done, such as introducing movement to units in the fluid program and conduting calibration tests, before the model can be used as a predictive tool. However, even in this relatively crude form, useful calculations can be made. Eventually, random placing of units matching that used in breakwater construction will be achieved by simulating the placing and settling processes.

Although the present model is two-dimensional, it is envisioned that in this form the model will provide a useful function in the design and stability analyses of present and future breakwaters. The jump from the current two-dimensional model to the three-dimensional model will eventually be made though at this time the additonal costs and complexity are not justifiable.

## Acknowledgments

The authors are grateful for the help of Tony Hirt, Peter Cundall and Peter Carpenter in coaxing the model to its present state.

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