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Implementation of Structures in the CMS: Part I, Rubble Mound

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the mathematical formulation, numerical implementation, and input specifications of rubble mound structures in the Coastal Modeling System (CMS) operated through the Surface-water Modeling System (SMS). A coastal application at Dana Point Harbor, California is provided to illustrate the implementation procedure and demonstrate the model capability.

INTRODUCTION: Rubble mound is typically built as breakwaters, jetties, revetments, and groins for protecting harbors, navigation channels, shoreline, and for controlling flow and sediment transport. The design of rubble mound structures often consists of a core of small to medium size rock or riprap covered with larger rock or riprap to armor against wave energy (Figure 1). In coastal modeling, rubble mound structures are often represented as solid structures, impermeable to both flow and sediment transport. However, some designs with larger riprap in the core may result in sufficient structure porosity to allow flow and fine sediment through and to provide significant sediment storage. Since rubble mound structures are a significant component of hydrodynamic and sediment transport controls in the coastal zone, it is important that the CMS simulates their effects.

Figure 1. (a) Breakwater, Dana Point Harbor, CA, and (b) Groin, Plume Island, MA.

COASTAL MODELING SYSTEM: The CMS, developed by the Coastal Inlets Research Program (CIRP), is an integrated suite of numerical models for simulating water surface elevation, current, waves, sediment transport, and morphology change in coastal and inlet applications. It consists of a hydrodynamic and sediment transport model, CMS-Flow, and a spectral wave model, CMS-Wave (Buttolph et al. 2006; Sanchez et al. 2011a; Sanchez et al. 2011b; Lin et al. 2008).

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CMS-Flow is a two-dimensional (2D) finite-volume model that solves the continuity and shallow-water momentum equations on a non-uniform or quadtree Cartesian grid. It computes the non-equilibrium transport of multiple-sized (non-uniform) total-load sediment and the resulting morphological changes. Wave radiation stresses and wave parameters are calculated by CMS-Wave and supplied to CMS-Flow for the flow and sediment transport calculations. Water level, current, and morphology changes are provided to CMS-Wave at user-specified intervals.

CMS-Wave is a 2D spectral wave transformation model that solves the steady-state wave-action balance equation on a non-uniform Cartesian grid (Lin et al. 2008). The model is designed to simulate wave processes that are significant in coastal inlets and nearshore zones, near jetties and breakwaters, and inside ports and harbors. These processes include wave shoaling, refraction, diffraction, reflection, wave breaking and dissipation, wave-structure and wave-current interactions, and wave generation and growth mechanisms. Additional model features include the grid nesting capability, wave transmission, wave overtopping structures, and wave setup/setdown on a beach slope.

MATHEMATICAL FORMULATION: The Forchheimer equation is used to simulate flow through a permeable rubble mound as

$$I = au + bu^2 \tag{1}$$

where I is the hydraulic gradient, u is the bulk velocity, and a and b are the dimensional coefficients. The first and second terms on the right hand side represent the laminar and turbulent components of flow resistance, respectively. Equation (1) is incorporated into the CMS governing equations as the drag forcing of rubble mound structures. In general, the additional resistance terms are written in the x- and y-direction momentum equations, respectively, as follows:

$$R_x = -ghu(a + b\sqrt{u^2 + v^2}) \tag{2}$$

$$R_y = -ghv(a + b\sqrt{u^2 + v^2}) \tag{3}$$

where g is the acceleration due to gravity, h is the water depth, and u and v are the current velocities in the x- and y-directions.

The adjustable coefficients a and b in the Forchheimer equation have been evaluated in a number of studies. Three sets of formulations, proposed by Ward (1964), Kadlec and Knight (1998), and Sidiropoulou et al. (2007), are included in the CMS to determine the two coefficients. The formulas by Ward (1964) are written as

$$a = \frac{360\nu}{gD^2} \text{ and } b = \frac{10.44}{gD} \tag{4}$$

The formulas of Kadlec and Knight (1998) are

$$a = \frac{255v(1-n)}{gn^{3.7}D^2} \text{ and } b = \frac{2(1-n)}{gn^3 D}, \tag{5}$$

and the formulas of Sidiropoulou et al. (2007) read as

$$a = 0.0033D^{-1.5}n^{0.06} \text{ and } b = 0.194D^{-1.265}n^{-1.14} \tag{6}$$

In Equations (4), (5), and (6), v is the water kinematic viscosity, D is the rock or riprap diameter, and n is the porosity of rubble mound structure.

To simulate the effects of rubble mounds, the porosity, n, is introduced in the continuity equation to account for the rubble mound void space (Reed and Sanchez 2011)

$$n\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \tag{7}$$

and similarly, in the equation of bed change due to the non-equilibrium multiple-sized transport of total-load sediment (Wu 2012)

$$n(1-p'_m)\frac{\partial z_{bk}}{\partial t} = \alpha\omega_{fk}(C_k - C_{*k}) \tag{8}$$

where p'_m is the porosity of bed material, $\partial z_{bk}/\partial t$ is the rate of bed change due to the kth size class of sediment, α is the total-load adaptation coefficient, ω_{fk} is the sediment fall velocity, C_k is the depth-averaged total-load concentration of the kth size class, and C_{*k} is the depth-averaged total-load concentration at the equilibrium state.

NUMERICAL IMPLEMENTATION: The implicit solver of the CMS uses a non-staggered grid for the basis of the numerical solution. The model identifies the cells where the rubble mound structures are located, as shown in Figure 2. The rubble mound resistance formulations are added to the x- and y-direction momentum equations for all the rubble mound cells. The same numerical algorithms are applied to solve the flow and sediment transport equations on the normal cells and rubble mound cells with the modifications made for rubble mound cells in Equations (7) and (8).

INPUT SPECIFICATIONS: Multiple rubble mound structures with different configurations can be specified by identifying the cell IDs (the cell counter on the flow grid) in the CMS. One of the three sets of formulations described previously may be used to determine the coefficients a and b for the nominal riprap or rock diameter and the porosity of each individual structure.

Working with the SMS interface, users can specify rubble mound structures in the CMS by creating datasets for different structure parameters. Five datasets are required for this application. Figure 3 shows the specifications of rubble mound structures in a "*.cmcards" file. Following each card name is the dataset name and then the XMDF file path. The modular format of the advanced cards contains the ID array, the rock diameter, the structure porosity, the base depth of the structure, and the method used to calculate the coefficients a and b, which correspond to the

XMDF files “ID.h5”, “ROCK_D.h5”, “PORO.h5”, “BASE_D.h5”, and “METH.h5”, respectively. For each structure cell, a number greater than zero is assigned in the “ID.h5” file, and the actual rock diameter, the structure porosity, and the base depth are assigned in the “ROCK_D.h5”, “PORO.h5”, and “BASE_D.h5” files, respectively. In the “METH.h5” file, numbers 1, 2, and 3 correspond to three methods used to calculate the coefficients *a* and *b* in the Forchheimer equation.

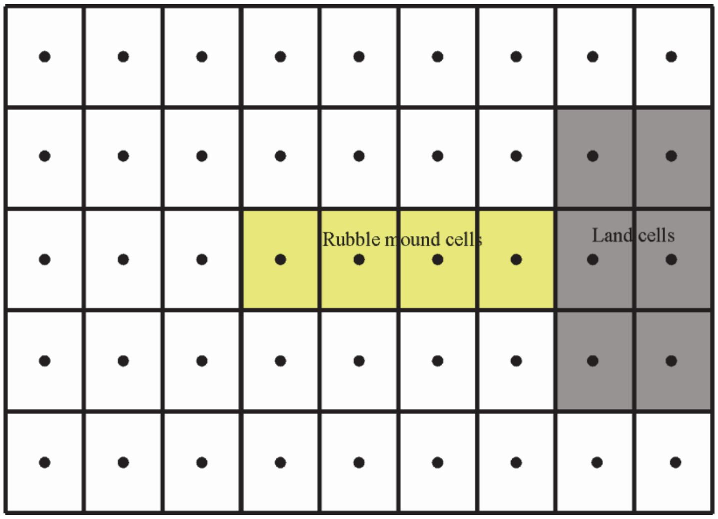
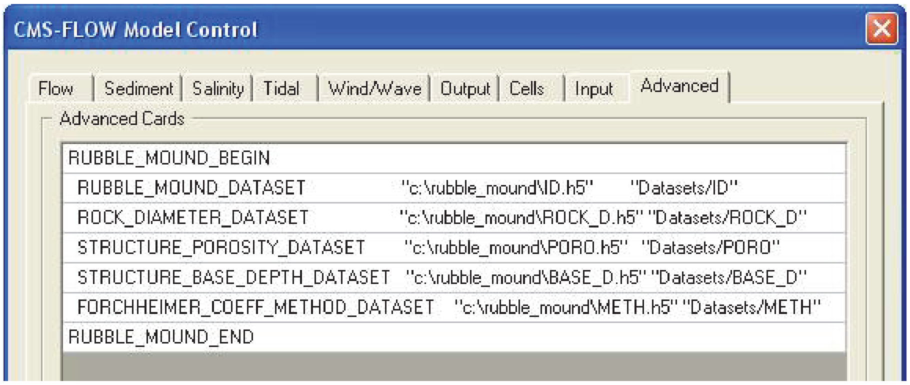


Figure 2. CMS Mesh with Rubble Mound Cells.



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RUBBLE_MOUND_BEGIN
 RUBBLE_MOUND_DATASET              "c:\rubble_mound\ID.h5"     "Datasets/ID"
 ROCK_DIAMETER_DATASET             "c:\rubble_mound\ROCK_D.h5" "Datasets/ROCK_D"
 STRUCTURE_POROSITY_DATASET        "c:\rubble_mound\PORO.h5"   "Datasets/PORO"
 STRUCTURE_BASE_DEPTH_DATASET  "c:\rubble_mound\BASE_D.h5" "Datasets/BASE_D"
 FORCHHEIMER_COEFF_METHOD_DATASET   "c:\rubble_mound\METH.h5" "Datasets/METH"
RUBBLE_MOUND_END
```

Figure 3. Rubble Mound Specifications Using XMDF Datasets.

The rubble mound structure cards start with “RUBBLE_MOUND_BEGIN’ and ends with “RUBBLE_MOUND_END”. A description of the rubble mound datasets is shown in Table 1.

In a demonstration case, consider two rubble mound structures: A and B. Rubble mound A consists of five cells with ID numbers 20, 50, 70, 90, and 110, has a rock diameter of 1.2 m, and the porosity of 0.5. Rubble mound B has four cells with ID numbers 600, 620, 690, and 710, a rock diameter of 1.0 m, and the porosity of 0.45. Both structures have a base depth of 2.0 m. In this case, the ID dataset, ID.h5, contains 9 cell IDs of 20, 50, 70, 90, 110, 600, 620, 690, and 710. Corresponding to the cell IDs, the first 5 elements are 1.2 for rubble mound A and the last 4 elements are 1.0 for rubble mound B in the rock diameter dataset. The first 5 elements of the porosity dataset are 0.5 for rubble mound A and the last 4 elements are 0.45 for rubble mound B.

For the base depth and the method datasets, all 9 elements have a number 2 (m) and 1, respectively, because the two structures have the same base depth and the same formulas by Sidiropoulou et al. (2007) are used to determine the coefficients *a* and *b* for both structures.

Table 1. Rubble mound specifications in the CMS.

Input	Format	Note
ID Dataset	[card=RUBBLE_MOUND_DATASET] [name=IDFile, type=char] [name=IDPath, type=char, default= ”CaseName/Datasets/ID”]	Contain the cell IDs of all rubble mound structures. ID file name and path for the input rubble mound ID dataset
Rock Diameter Dataset	[card=ROCK_DIAMETER_DATASET] [name=RockDiameterFile, type=char] [name=RockDiameterPath, type=char, default= ”CaseName/Datasets/ROCK_D”]	Nominal riprap or rock diameter file name and path for the input dataset of rubble mound structures
Structure Porosity Dataset	[card=STRUCTURE_POROSITY_DATASET] [name=StructurePorosityFile, type=char] [name=StructurePorosityPath, type=char, default= ”CaseName/Datasets/PORO”]	Structure porosity file name and path for the input dataset of rubble mound structure porosity
Structure Base Depth Dataset	[card=STRUCTURE_BASE_DEPTH_DATASET] [name=StructureBaseDepthFile, type=char] [name=StructurebaseDepthPath, type=char, default= ”CaseName/Datasets/BASE_D”]	Structure base depth file name and path for the input base depth dataset of rubble mound structures
Method Dataset	[card=FORCHHEIMER_COEFF_METHOD_DATASET] [name=MethodFile, type=char] [name=MethodPath, type=char, default= ”CaseName/Datasets/METH”]	Method file name and path for the input dataset to determine the coefficients a and b in the Forchheimer equation: 1: Sidiropoulou et al. (2007) 2: Kadlec and Knight (1996) 3: Ward (1964)

Users should refer to Aquaveo (2010) for generating a XMDF dataset (*.h5 file) under the SMS.

RUBBLE MOUND STRUCTURES AT DANA POINT HARBOR: In this CMS application, the permeability of rubble mound structures is simulated at Dana Point Harbor, located on the US Pacific coast, 40 miles southeast of Los Angeles, California (Li et al. 2011; Lu et al. 2013).

Dana Point Harbor is a manmade harbor and is protected from ocean waves by a pair of riprapped breakwaters. The breakwaters, consisting of a long shore-parallel West Breakwater of 5,500 ft and a shore-normal East Breakwater of 2,250 ft (Figure 4), were designed as permeable structures. As these structures can dissipate wave energy and reduce wave reflection, the current and sediment transport can pass through. As a result, fine sands are accumulated inside the West Breakwater and maintenance dredging is required periodically (County of Orange 2009).

The calculations of wave transmission coefficient are based on the formula of d’Angremond et al. (1996) implemented in CMS-Wave (Lin et al. 2011). The seepage of flow and sediment transport was specified in the XMDF datasets (Figure 3). Figure 5 shows the permeable segment of the West Breakwater in this example, which consists of 276 cells. The breakwater has a rock diameter of 1.5 m, the porosity of 0.2, and the base depth of 2.0 m. Sidiropoulou et al.’s (2007) formulas were used to calculate the flow and sediment seepage. The 276 cell IDs and above parameters are specified in their corresponding datasets as listed in Table 1, respectively.

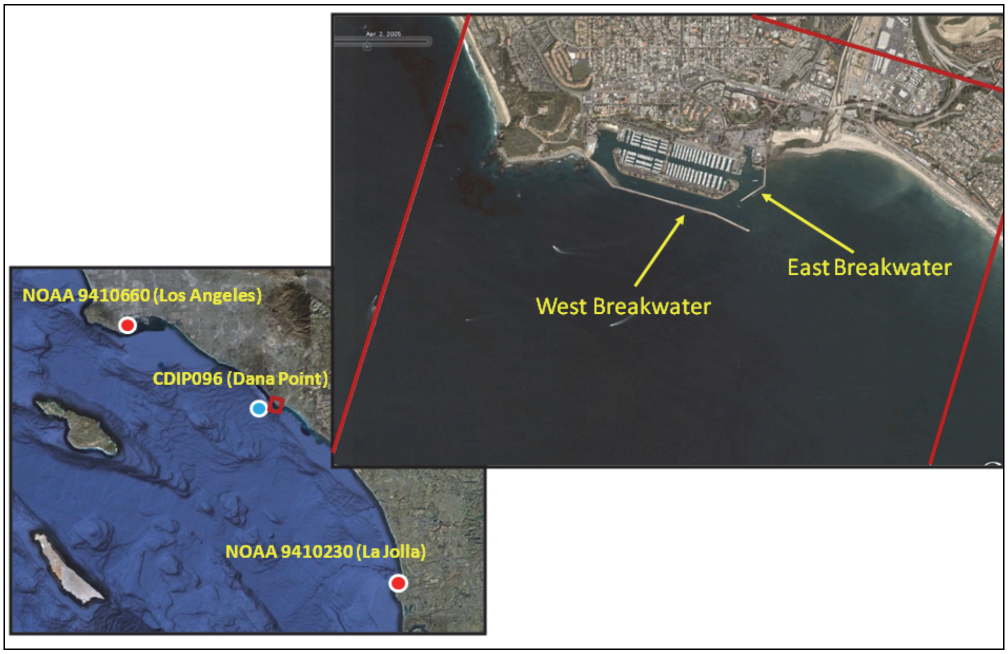

Figure 4. Dana Point Harbor and the surrounding area. The red line denotes the CMS domain.

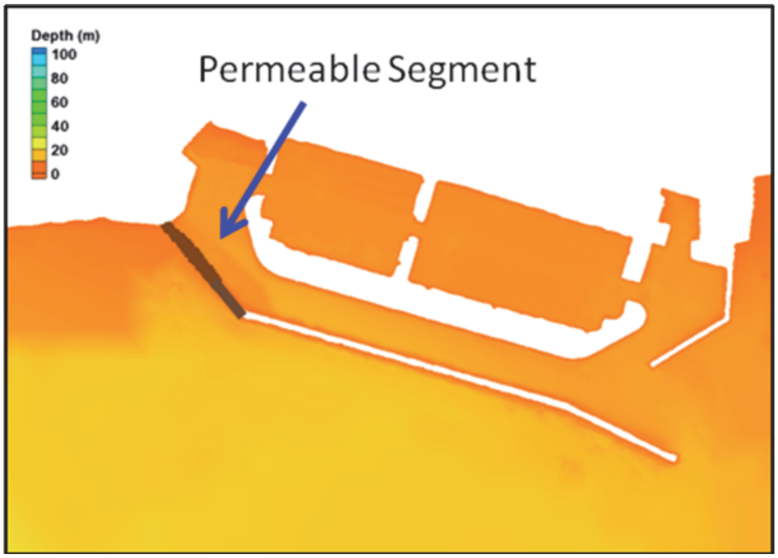

Figure 5. Segment of the West Breakwater specified as Permeable Rubble Mound.

A previous circulation study at Dana Point Harbor (SAIC 2003) showed the evidence of flows through the West Breakwater and impact of the through-flow on the current changes inside the harbor. In this application, a 10-day hydrodynamic and sediment transport simulation was set up. Figure 6 is a snapshot of the current field from the CMS simulation during the peak flow period. With the West Breakwater specified as partially permeable the figure clearly shows that water flows through the structure, and the current speed decreases by approximately 80-90 percent inside the harbor.

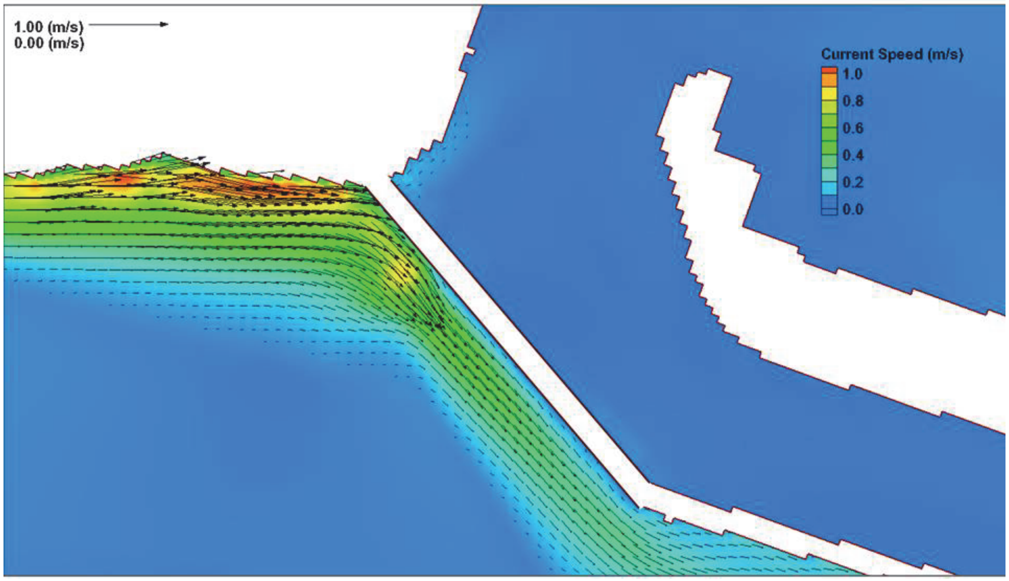

Figure 6. Snapshot of the Current Field during the Peak Flow Period.

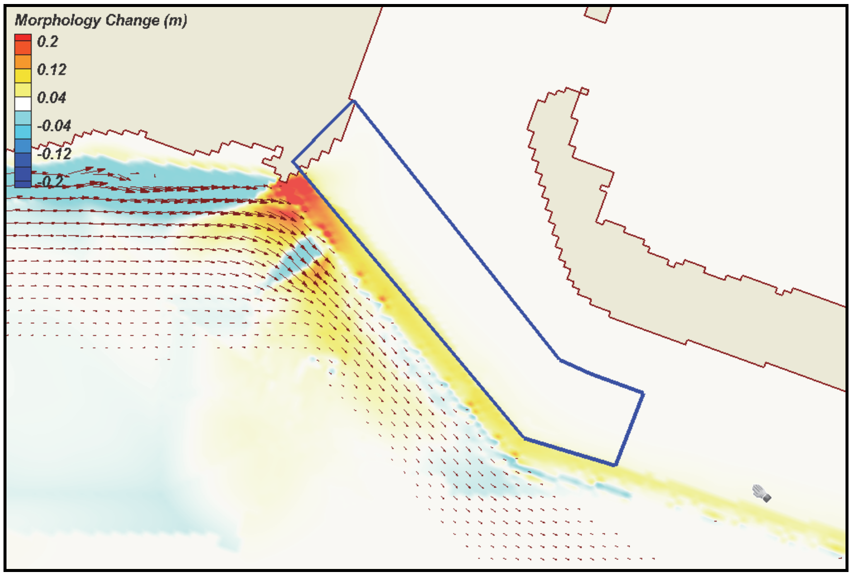

Figure 7. Morphology Change at the End of the 10-day Simulation.

The Google Earth photograph in Figure 4 shows sand penetration through and sand accumulation inside the West Breakwater. Based on the latest dredging information collected in 2009, average annual sediment transport volume is around 5,000-6,000 cy. To estimate the sediment seepage through the West Breakwater, the morphology change was calculated surrounding the west portion of the West Breakwater at the end of the 10-day simulation (Figure 7). Although small, sand accretion can be detected inside the harbor and the distribution pattern of the bed change looks similar to the Google photograph, more accumulation at the northwest end of the breakwater. Transport within a structure cell is greatly reduced by the lower flow speed and lower wave energy, so that large deposition occurs within the breakwater. To estimate the total sediment volume changes related to the sediment seepage through the breakwater, a polygon area is drawn inside the breakwater. The bed volume changes within the area were estimated at the end of the simulation. Time extrapolation of the CMS results presented an approximate annual sediment transport volume of 5,000 cy through the West Breakwater, which is quantitatively comparable to the average annual volumes dredged in 2009.

SUMMARY: Rubble mound structures were incorporated into the CMS and the implementation procedure was described in this note. The application of the algorithms in the CMS was demonstrated and flow and sediment seepage through a permeable breakwater was validated via the volumes from the historical maintenance dredging activities at Dana Point Harbor.

ADDITIONAL INFORMATION: This CHETN was prepared as part of the CIRP and was written by Dr. Honghai Li (Honghai.Li@usace.army.mil, voice: 601-634-2840, fax: 601-634-3080), Alejandro Sanchez of the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Dr. Weiming Wu of University of Mississippi, and Dr. Christopher W. Reed of URS. The CIRP Program Manager, Dr. Julie D. Rosati (Julie.D.Rosati@usace.army.mil), the assistant Program Manager, Dr. Zeki Demirbilek, and the Chief of the Coastal Engineering Branch at CHL, Dr. Jeffrey P. Waters, reviewed this CHETN. Files for the study may be obtained by contacting the author. This CHETN should be cited as follows:

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An electronic copy of this CHETN and I/O files for the example are available from: *http://chl.wes.army.mil/library/publications/chetn/*

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