CMS: A Coastal Modeling System for Inlets and Navigation Projects

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Abstract

The U.S. Army Engineer Research and Development Center has developed a coastal modeling system (CMS) to address needs of the U.S. Army Corps of Engineers navigation projects. The CMS is a suite of PC-based numerical models to simulate the spectral wave transformation, two-dimensional (2D) and three-dimensional (3D) hydrodynamics, mixed sediment transport, and morphology change. The sediment calculation includes both cohesive and non-cohesive materials based on the non-equilibrium transport mechanism to represent natural processes observed in the field. The recent improvements to CMS are telescoping grids, numerical solution capability for multiple processors and implicit solution scheme for run-time efficiency for PC users. These new features have significantly improved model performance.

Key words: coastal modeling, inlets, hydrodynamics, waves, sediment transport

1. Introduction

Coastal processes are complicated. Natural beaches are always influenced by incoming waves, alongshore and cross-shore currents in the surf zone, wind-driven current outside the surf zone, and constantly changing tides. The shoreline geometry, sediment properties, and bottom characteristics such as rocky bed or coral reef can play important roles in the littoral zone. During a storm, beach and shore are more vulnerable to the high water level and strong wind waves. The nearby inlet and bay entrance or river mouth at the coast may appear as a sediment source or sink to interrupt the littoral transport. All of these factors and physics involved have presented a challenge for coastal engineers to develop a comprehensive numerical model system to simulate the natural beach processes.

The U.S. Army Corps of Engineers (USACE) navigation mission, dating to Federal laws in 1824, is to ensure safe and reliable channels and waterways with minimal impact on the environment. It includes practical applications in navigation channel performance and sediment management for coastal inlets and adjacent beaches to improve the usage of operation and maintenance funds. The Corps dredges nearly 300 million cubic yards of material each year to keep the nation’s waterways navigable. The Coastal Modeling System (CMS), developed since 2006 by the Coastal Inlets Research Program (http://cirp.usace.army.mil/), is designed for accurate and reliable representation of coastal processes affecting operation and maintenance of coastal inlet structures like jetties, breakwaters and earth levees, in navigation projects as well as in risk and reliability assessment of shipping in inlets and harbors. The CMS is an integrated suite of numerical models for simulating flow, waves, sediment transport, and morphology change in coastal areas. It is intended as a research and engineering tool that can be used with efficiency on desk-top computers. Three models are maintained under the CMS: (1) CMS-Flow for flow, sediment, and salinity calculation, (2) CMS-Wave for spectral wave transformation, and (3) CMS-PTM, a particle tracking model. The CMS takes advantage of the Surface-water Modeling System (SMS) interface for grid generation and model setup, as well as plotting and post-processing (Zundel, 2006).

2. System Components

CMS-Flow is a 2D/3D hydrodynamic and sediment transport model capable of simulating depth-averaged circulation, salinity and sediment transport forced by tides, wind, atmospheric pressure gradient, river inflow, and waves (Buttolph et al. 2006). The hydrodynamic model solves the conservative form of the shallow water equations and includes terms for the Coriolis force, wind stress, wave stress, bottom stress, vegetation flow drag, bottom friction, and turbulent diffusion. Three sediment transport formulations are available: a sediment mass balance, an equilibrium advection-diffusion method, and non-equilibrium advection-diffusion transport. The salinity transport is calculated with the standard advection diffusion equation that includes evaporation and precipitation. CMS-Flow applies the finite volume method on a non-uniform Cartesian grid.

CMS-Wave is a spectral wave transformation model that solves the steady-state wave-action balance and diffraction equation on a non-uniform Cartesian grid (Lin et al. 2008). It can simulate important wave processes at coastal inlets including diffraction, refraction, reflection, wave breaking and dissipation mechanisms, wave-wave and wave-current interactions, and wave generation and
growth. The model is a half-plane model so that primary waves can propagate only from the seaward boundary toward the shoreline. If the seaward reflection option is selected, the model will perform a backward marching for the seaward reflection after the forwarding-marching calculation is completed. A specific improvement of CMS-Wave is that the fundamental wave diffraction process is theoretically developed and calculated in the wave-action balance equation (Mase 2001). Additional useful features include the grid nesting capability, variable rectangle cells, wave run-up on beach face, wave transmission through structures, wave overtopping, and assimilation for full-plane wave generation.

CMS-PTM is a particle tracking model capable of introducing and following the trajectory of discrete particles in the flow field (Demirbilek et al. 2008). It computes the paths of sediment particles using the Lagrangian method through a geometric domain as the particles interact with the computational environment. The sediment particle can be of either cohesive (silt, clay) or non-cohesive (sand). The computational environment includes the hydrodynamic flow, wave conditions, sediment property, and land boundary. Therefore, water surface elevations and currents calculated by CMS-Flow and wave information by CMS-Wave drive the CMS-PTM computations in the same CMS domain. The SMS includes tools to generate the necessary information to define the CMS-PTM environment, such as sediment release method and sediment properties.

CMS-Flow and CMS-Wave can be run separately or coupled together. In the coupling mode, the variables passed from CMS-Wave to CMS-Flow are the significant wave height, peak wave period, wave direction, wave breaking dissipation, and radiation stress gradients. CMS-Wave uses the update bathymetry, water levels, and currents from CMS-Flow. The coupling can be operated through the SMS by providing the total simulation period of CMS-Flow with the constant interval of running CMS-Wave. Coupling CMS-Flow and CMS-Wave can simulate many important short-term and long-term processes like the shoreline change, channel infilling, breaching to shore and damage to coastal structure, and storm-induced flooding and erosion. Both models have the nested grid capability as an alternative for circulation, sediment calculation, and wave transformation in the local higher resolution area.

Recent development includes telescoping grid, multiprocessor capability, and implicit solution scheme that intend to increase the efficiency of computer run time. The new features of tidal gates, culverts, and permeable structures for wave transmission, flow and sediment seepage are important to bay and wetland applications. Figure 1 shows the operational flow chart of the CMS.

3. Illustration Examples

The CMS has been widely applied at US to coastal inlets, estuaries, and wetlands, Hawaii islands, and Great Lakes. Recent on-going projects involved several largest US coast-bay system including (1) Grays Harbor, WA, (2) San Francisco Bay and Bar, CA, (3) Galveston Bay, TX, (4) Matagorda Bay, TX, (5) Chesapeake Bay, (6) Cleveland Harbor in Lake Erie, and (7) Rhode Island coast and lagoons. In the present paper, only a set of examples are given for the demonstration purpose owing to the space limit.

Figures 2 to 5 show the CMS telescoping grids and forecast wave/flow fields, respectively, at Humboldt Bay, CA, for the US National Weather Service. Figure 6 shows the CMS telescoping grid at Galveston Bay, TX. Figure 7 shows the calculated morphology change at the Galveston Jetties and Rollover Pass from Hurricane Ike (September 1-14, 2008). Figures 8 and 9 show the pre-Ike and post-Ike calculated bathymetries, respectively, at Rollover Pass.
Cleveland Harbor, OH. The harbor is a major commercial port located on the south shore of Lake Erie. It includes more than five miles of rubble breakwaters and several piers. Winter storms, also known as the northeasters, can create high water level and large waves at the port. The typical storm wave is 3.5 m with a maximum record wave height of 4.2 m. The CMS grid has a coarse resolution of 50 m x 50 m in the offshore and high resolution of 3 m x 6 m at jetties and breakwater. The incident wave condition in the example is 4.1 m and 9.3 sec from N. A constant storm surge level of 1.83 m presenting the 20-year return period is input in the CMS simulation.
Figures 11 shows the calculated sediment (fine sand) concentration field from a normal summer month (August 2008) simulation of a proposed dredged material placement site north of Noyo Bay, located in the north central coast of California. In this simulation, the initial bed outside the dredged material placement area was specified as the artificial hard bottom, where only sediment accretion can occur, to investigate the effect of the discharged material alone. The CMS runs were forced by coastal wind, offshore buoy wave records, and open coast tide data as the northern California coast is well known to have the year-round large ocean waves with consistently strong shore-parallel wind. Figure 12 shows the CMS-PTM result, for August 2008, of a small volume of silt in the scheduled 10-day release (twice a day) of the dredged material in the vertical water column. A good portion of silt in the dredged material release can travel a long distance to south passing Noyo Bay while some silt moves towards the shore to settle or re-suspend in the nearshore.

Figure 13 shows the regional bathymetry grid of Rhode Island south shore with five nested child grids covering the coastal ponds. The regional grid contains a total of 375,000 square cells, each of 200 m x 200 m. The incident wave data as input to this regional grid is from an offshore Coastal Data Information Program (CDIP) Buoy 154 in 48-m depth. Each child grid is generated with variable rectangular cells ranging from larger cells of 50 m x 50 m in the offshore to small local cells of 4 m x 4 m in the pond inlet.
4. Summary

The CMS in the U. S. Army Corps of Engineers Coastal Inlets Research Program is developed for practical applications in navigation channel performance and sediment management to improve the usage of operation and maintenance funds. It is intended as the engineering tool on desk-top computers with accuracy and run-time efficiency. It consists of three main models: (1) a circulation CMS-Flow to compute the unsteady water level, current velocity, density flow, and sediment transport fields on a non-uniform Cartesian grid using the finite volume scheme, (2) a spectral wave transformation model CMS-Wave based on the steady-state wave-action balance and diffraction equation on a non-uniform Cartesian grid with an implicit finite difference scheme, and (3) a particle tracking model CMS-PTM to calculate the paths and mobility of sediment particles in a Lagrangian approach through the CMS computational domain as the particles interact with the hydrodynamics flow, wave conditions, and sediment properties. The CMS considers full coastal processes including wind wave generation and growth, diffraction, reflection, wave-wave and wave-current interactions, wave runup, wave setup, wave transmission and overtopping at structures, breaching barrier islands, storm surge, fate of sediments, shoreline change, and morphology change. The sediment transport formulation solving the suspended-load advection-diffusion equation and the bed-load mass balance in the non-equilibrium sediment transport mode is more realistic as observed and occurred in the field. Wave asymmetry and undertow estimates in CMS are recent new additions in testing for investigation of near and offshore mound movement under strong wave and current environment.

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References


