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Littoral Hydrodynamics and Sediment Transport Around a Semi-Permeable Breakwater

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Abstract
The increased rate of shoaling in Dana Point Harbor requires a better understanding of hydrodynamics and sediment transport around a permeable breakwater. In this study, an integrated coastal wave, hydrodynamic and sediment transport numerical model was developed to investigate the circulation and sedimentation patterns around the harbor, to address sediment seepage through the permeable West Breakwater, and to assist find solutions to reducing the shoaling inside the harbor. The model calibration and validation were conducted against field measurements of waves, current, and water surface elevation, and a laboratory experiment of low-crested structures (LCS). Comparisons of the calculated results and the measurements indicate that waves are the dominant forcing outside the harbor. Inside the harbor, currents are wind- and tide-driven with small current magnitude of less than 4 cm/sec. The distribution of morphology change shows significant sediment movement and sediment pathways around the West Breakwater. The calculated annual sediment rate in the inner side of the breakwater was comparable to the sediment accumulation rate available from historical dredging records.

Keywords: numerical modelling, hydrodynamics, waves, sediment transport, permeable breakwater.

1. Introduction

The Dana Point Harbor is located in the City of Dana Point, midway between Los Angeles and San Diego, along the southern Orange County Coast of California. The harbor basins and navigation channels are protected by dual breakwaters (East and West Breakwaters). At the time of construction, both breakwaters were designed as a “semi-permeable” structure. Small voids were left intentionally during stone placement to allow currents partially flowing through the breakwaters, thereby promoting better water circulation within the harbor. However, sediment began to seep through the West Breakwater in the 1980’s and, as a result, periodic maintenance dredging has been needed to remove sand material that has accumulated on the lee side of the permeable structure in recent years [3].

The increased rate of shoaling in the harbor requires a better understanding of hydrodynamics and sediment transport around the permeable breakwater. In this study, an integrated coastal wave, hydrodynamic and sediment transport numerical model was developed to investigate the circulation and sedimentation patterns around the harbor, to address sediment seepage through the West Breakwater, and to assist find solutions to reducing the shoaling inside the West Breakwater.

Following the Introduction of this paper, the field data collection and existing data assembly are described in Section 2. Section 3 provides information on modeling methodology. Section 4 presents model results for the calibration and validation simulations, and Section 5 gives the conclusions of the study.

2. Field survey and data assembly

Data are needed to set up a numerical model. Field surveys were conducted to collect bathymetric and hydrodynamic data. Existing data were assembled to develop model forcing.

2.1 Bathymetry

A bathymetric and LiDAR (light detection and ranging) survey was conducted during October 20–24, 2009, to collect basic physical data for the study [7]. The collected LiDAR and sonar data of the breakwaters allow for assessment of the present-day protective structure conditions.

The bathymetric and side-scan sonar data below the water surface and the LiDAR data above the water level were acquired along both sloping faces of East and West Breakwater extending out offshore on the ocean side and in the main navigation channels on the harbor side (Figure 1). In addition to these areas, the primary access channels within the marina basins were also surveyed.

2.2 ADCP measurements

Two Acoustic Doppler Current Profilers (ADCPs) were deployed on both the harbor (inside) and ocean (outside) sides of West Breakwater in Dana Point Harbor from 20 November 2009 to 5 January 2010 (Figure 1). The current data were collected from both ADCPs, and water level and directional wave data were collected on the ocean side. Due to instrument failure, the outside ADCP collected only about six days of data.

Figure 1 Bathymetric and LiDAR survey area. Red dots show the location of two ADCPs.

Measured instantaneous current velocities are typically smaller than 6 cm/sec (0.20 ft/sec) in the main channel and on the order of 10 to 20 cm/sec (0.33 to 0.66 ft/sec) in the seaside area of West Breakwater. It is evident that current flow through the rubble mound structure occurs throughout West Breakwater, consistent with the original design of a semi permeable rubble-mound structure.

2.3 Existing datasets

Besides the harbor bathymetry and ADCP measurements, the offshore bathymetry data were extracted from GEOphysical DAta System (GEODAS) database [11], and waves, water surface elevation, and wind data around Dana Point Harbor were assembled for numerical model.

Wave data were downloaded from the Coastal Data Information Program (CDIP), operated by Scripps Institution of Oceanography (http://cdip.ucsd.edu/, accessed 27 May 2015). Directional wave spectra were retrieved from the Dana Point Buoy CDIP096 and transformed to the model seaward boundary. Wave data analysis shows the predominant waves are from the south-southwest (180-200 deg azimuth) in the summer and the west-northwest (270-280 deg azimuth) directions during the winter month. Extreme large waves are rare as more than 98 percent of the wave population shows a height less than 2 m (6.6 ft). The annual average wave height and peak wave period are 0.95 m (3.1 ft) and 13.7 sec, respectively.

Hourly water surface elevation data were obtained from NOAA tide gage 9410660 (Los Angeles, CA) (http://tidesandcurrents.noaa.gov, accessed 27 May 2015). The time series data indicate a mixed, predominately semi-diurnal tidal regime surrounding the study area. The mean tidal range (mean high water – mean low water) is 1.16 m (3.8 ft) and the maximum tidal range (mean higher high water - mean lower low water) is 1.67 m (5.5 ft).

Wind data were available from NOAA coastal stations at Los Angeles Pier S, CA (9410692) and La Jolla, CA (9410230), and also from the offshore NDBC Buoy 46047 (http://www.ndbc.noaa.gov, accessed 27 May 2015). Local wind observations at Dana Point Harbor (SDDPT) were provided by San Diego Weather Forecast Office, National Weather Service. Comparing to the wind data at the coastal stations, the offshore wind is much stronger. While the wind direction at La Jolla is characterized by the diurnal cycle of the sea breeze signal, the wind at the Dana Point Station does not show a clear pattern due to sheltering effect of the local steep sea cliffs.

Sediment seepage through the West Breakwater has resulted in navigation channel infilling during the last 20–30 years. Since 1990, three maintenance dredges have been conducted to remove fine sand material that passed through and deposited on the harbor side of West Breakwater. The recorded dredged volumes on the harbor side are approximately 19,115 m^3 (25,000 cy), 27,143 m^3 (35,500 cy), and 41,288m^3 (54,000 cy), respectively, in 1990, 1999, and 2009 [2, 3, 4].

3. Method

3.1 Coastal Modeling System

The Coastal Modeling System (CMS), developed by the Coastal Inlets Research Program (CIRP), U.S. Army Corps of Engineers, is selected for this study (http://cirp.usace.army.mil/wiki/CMS, accessed 27 May 2015). The CMS is an integrated suite of numerical models for simulating water surface elevation, current, waves, sediment transport, and morphology change for coastal and inlet applications. The CMS consists of a hydrodynamic model, CMS-Flow, and a spectral wave model, CMS-Wave. CMS-Flow and CMS-Wave are coupled and operated through a Steering Module developed within the Surface-water Modeling System (SMS).

CMS-Flow is a two-dimensional (2D) finite-volume model that solves the depth-integrated mass conservation and shallow-water momentum equations of water motion on a non-uniform Cartesian grid. The wave radiation stress and wave field information calculated by CMS-Wave are supplied to CMS-Flow for the flow and sediment transport calculations. Currents, water level, and morphology changes are feeding to CMS-Wave to increase the accuracy of the wave transformation predictions [12] (Figure 2).

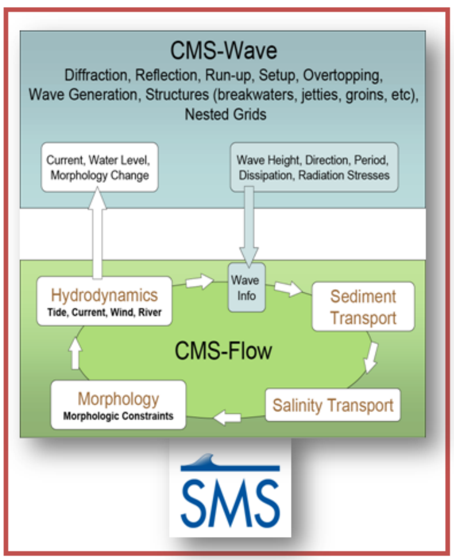

Figure 2 Framework of the Coastal Modeling System.

CMS-Wave is a two-dimensional spectral wave transformation model that solves the steady-state wave-action balance and diffraction equation on a non-uniform Cartesian grid [9]. The model 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. Additional model features include the grid nesting capability, variable rectangle cells, wave run-up on beach face, wave transmission through structures, wave overtopping, and storm wave generation (Figure 2).

For this harbor system, a rectangular grid was adopted for the CMS. Figure 3 shows the CMS grid domain covering Dana Point Harbor and the open ocean region. It extends approximately 5 km alongshore and 4 km offshore. The water depth ranges from 1-2 m above the mean sea level in the harbor to 9 m at the harbor entrance channel, and increases to more than 10 m outside the West Breakwater. The offshore area further deepens to a few hundred meters. The variable rectangular grid system permits much finer local grid resolution to well resolve hydrodynamic and sediment features in areas of high interest such as the harbor and the breakwaters.

3.2 Sediment transport around permeable structure

In the CMS, three sediment transport models are available: (1) equilibrium total load, (2) equilibrium bed load plus advection-diffusion for suspended load, and (3) non-equilibrium total load. The non-equilibrium transport model is used in this study. The near-bed sediment concentration or concentration capacity is calculated with the Lund-CIRP transport formula [1].

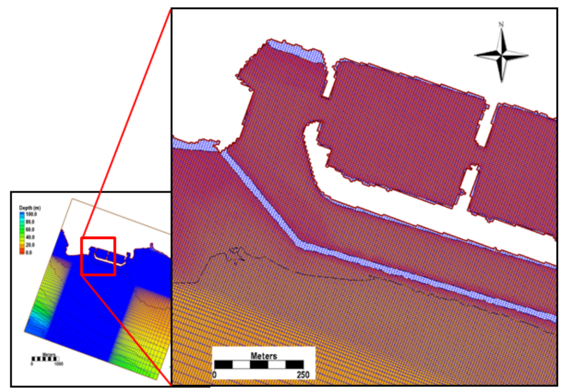

Figure 3. The CMS rectangular grid domain.

Wave transmission through permeable breakwaters is implemented by calculating the transmission coefficient [5]. A unidirectional flow is represented in the momentum equation to simulate flow seepage through porous structures, and corresponding sediment seepage and morphology change are calculated by introducing the structure void space in the equation of conservation of mass [6, 8].

4. Results and discussion

4.1 Model calibration and validation

The CMS was set up to simulate the period of 18 November–17 December, 2009, which covers the initial 7 days of wave and water surface elevation data collection at the outside ADCP location and overlaps with most of the current collection period at the inside ADCP location. The permeability of the breakwaters was specified and the model results were compared with the available measurements at the two ADCP sites.

Figure 4 shows the comparisons of wave parameters between the CMS calculations and ADCP data. On the ocean side, the significant wave height has a 6-day mean value of 0.75 and

0.80 m, respectively, for the CMS results and the observations. The mean peak wave period is 13.5 and 13.1 s, respectively. Both the CMS and data show that the wave directions are from west–southwest, perpendicular to the breakwater.

Waves approaching nearshore experience diffraction, refraction, and reflection from structures, and interact with current, wind and water level. Sensitivity tests were conducted to examine wave propagation mechanisms and wave forcing. It is found that exclusion of wave reflection at the breakwater under-predicts the wave height by as much as 31 %. Therefore, in the wave modeling practice near coastal structures, the focus should be on the proper parameterization and implementation of wave reflection to improve the discrepancy between the calculated and measured wave heights as compared in Figure 4 [10].

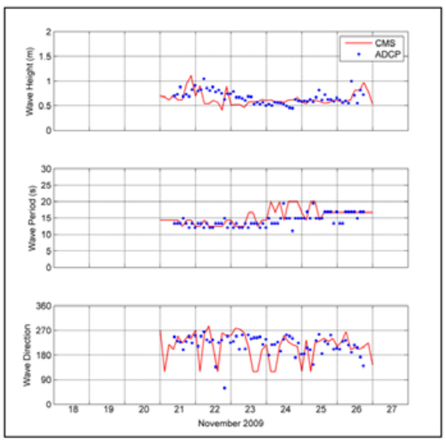

Figure 4. Comparisons of wave parameters between calculations and measurements at the ADCP site outside the West Breakwater.

Figure 5 shows the calculated currents and measurements at the inside ADCP location and the calculated currents at the outside ADCP location for the 30-day simulation from 18 November through 17 December 2009. Two northwest winter storms occurring between 27–28 November and 7–8 December, 2009 caused high currents outside the harbor with a maximum current speed close to 50 cm/sec (1.6 ft/sec) at the outside ADCP gage. Under normal tidal conditions the current speed at the location has a magnitude of 5–10 cm/s (0.16-0.33 ft/sec) with a dominant current direction from west–northwest (along the West Breakwater) toward southeast. Inside the breakwater the current speed is generally smaller than 4 cm/s (0.13 ft/sec), with distinguished flood and ebb tidal current signals. A larger current spike of 8 cm/s (0.26 ft/sec) occurred around 7–8 December, 2009, during the winter storm. Besides wave and wind forcing, tide is also responsible for current changes, as demonstrated by the spring/neap tidal pattern at the inside gage. Comparing to the ADCP data, the CMS well reproduced the tide- and storm-induced currents at the inside ADCP location. The goodness-of-fit parameters indicate an agreement between model and data by a correlation coefficient of 0.73, a root mean square error (RMSE) of 1.1 cm/s (0.04 ft/sec), and a relative RMSE of 9.2 %.

Figure 6 shows the comparison of calculated and measured water surface elevations (WSE) at the outside ADCP site for 18–27 November 2009. During this neap tidal period, the WSE change and current magnitude are small. The CMS results agree with the WSE signals in the 6-day measurements. The goodness-of-fit parameters indicate an agreement between model and data by a correlation coefficient of 0.99, a RMSE of 5.3 cm (0.17 ft), and a relative RMSE of 4.0 %.

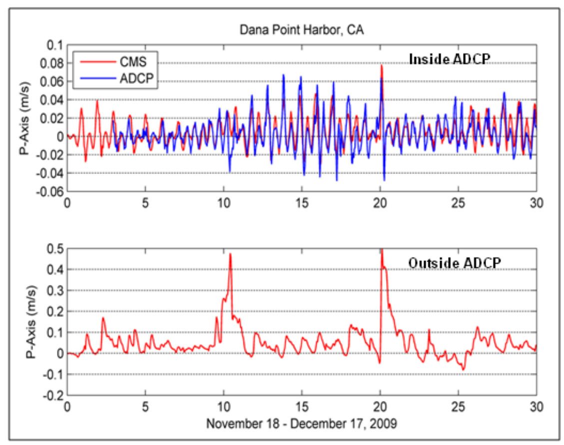

Figure 5. Comparisons of currents between calculations and measurements at the ADCP site inside the West Breakwater.

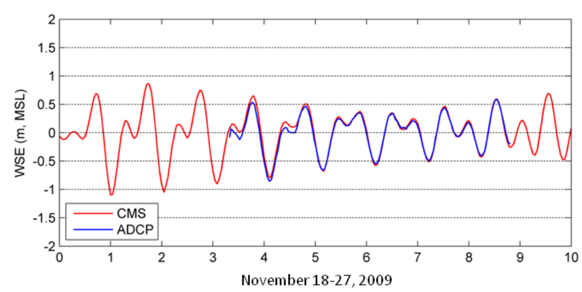

Figure 6. Comparisons of water surface elevations between calculations and measurements at the ADCP site outside the West Breakwater.

To examine annual sediment seepage through the permeable breakwater and compare the results with historical dredging records, a 1-year simulation was conducted from 18 November 2009 to 17 November 2010. The annual sediment accumulation rate on the lee side of the breakwater was estimated using annual morphology and bed volume changes within the harbor. The CMS results show an annual sediment deposition rate of 2600 m^3/year (3400 cy/year).

As mentioned earlier, the observed average annual sand deposition rate is approximately 2676 and 4129 m^3/year (3500 and 5400 cy/year) based on the maintenance dredging record in 2000 and the latest dredging event conducted in the early 2009, respectively. Therefore, the calculated sediment seepage rate is quantitatively comparable to the average annual volume dredged in 2000, but significantly less than that dredged in 2009.

4.2 Waves and current

Figure 7 shows a snapshot of calculated significant wave height field on 20 November 2009 at 09:00 GMT. Waves on the ocean side propagate perpendicular to the breakwater with a significant height of 0.6–0.7 m (2.0–2.3 ft). After transmitting through the structure, significant wave heights reduce to 0.05–0.07 m (0.16–0.23 ft) on the harbor side.

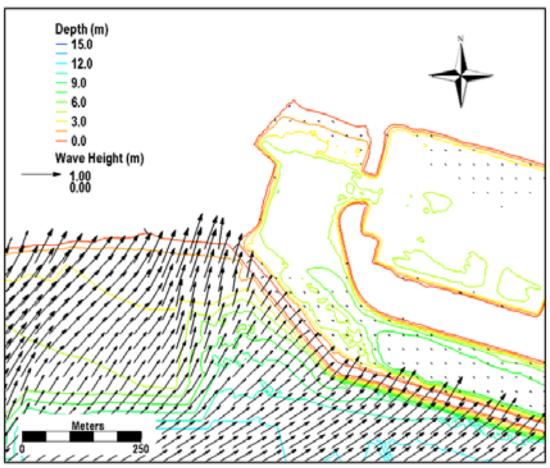

Figure 7. Calculated significant wave height field on 20 November 2009 at 09:00 GMT.

Figure 8 shows a snapshot of the depth-averaged current fields on 20 November 2009 at 08:00 GMT, with relatively large waves propagating from southwest (230° azimuth). Strong currents occur near the landward end of the West Breakwater outside the harbor. The maximum current speed is approximately 0.5–0.7 m/s (1.6–2.3 ft/sec). Inside the harbor, the current is weak with a maximum speed of 3–4 cm/s (0.1–0.13 ft/sec) over the simulation period. The currents around the landward end area of the West Breakwater are seeping through the breakwater with a seepage rate of 2–5 cm/s (0.07–0.16 ft/sec).

4.3 Sediment transport

Figure 9 shows two-hourly snapshots of sediment transport as relatively large waves occur in the area (significant wave height around 1.3 m). The figure indicates significant erosion on the west side of Dana Point, which demonstrates that sediment accreted around the harbor could be due to the Dana Point headland erosion or supplied by the sand material from the erosion from the west side of the headland.

As predominant and large waves propagate from the west–northwest, the longshore current and, therefore, the corresponding sediment transport are moving from the west to the east along the shoreline and from the northwest to the southeast along the West Breakwater. This flow and sediment transport pattern is confirmed by significant sediment movement in the west of the West Breakwater.

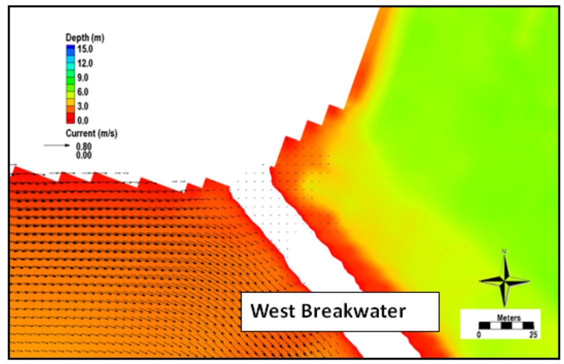

Figure 8. CMS calculated depth-averaged current field surrounding Dana Point Harbor on 20 November 2009 at 08:00 GMT.

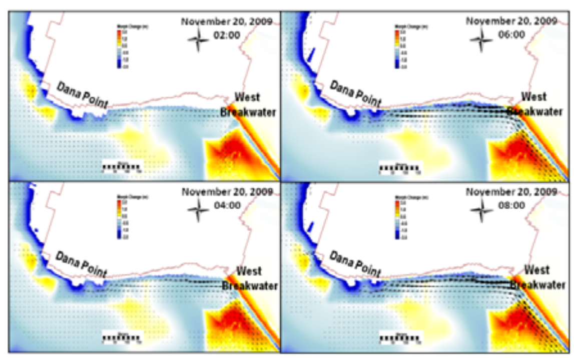

Figure 9. Two-hourly snapshots of sediment transport (vectors) as relatively large waves occurred in the area (significant wave height around 1.3 m). The background color is the morphology changes at the end of the 1-year (18 November 2009 -17 November 2010) simulation.

The Google Earth photographs before the 2009 harbor maintenance dredge show sand penetration through and sand accumulation inside the West Breakwater. Based on the 2009 dredged volume, average sediment accumulation rate in the harbor side is around 3,800-4,600 m^3/year (5,000-6,000 cy/year). To estimate the sediment seepage through the permeable structure, the transport module in the CMS is set up and the structure permeability is specified by adjusting the resistance parameters and the structure void space in the conservation of mass equation. Figure 10 shows the morphology change surrounding the west portion of the West Breakwater at the end of the 30-day simulation. Sand accretion can be detected inside the harbor and the distribution pattern of the bed change looks similar to those shown on the Google Earth photographs. Transport within a structure cell is greatly reduced by the weaker flow speed, lower wave energy, and subsequent smaller bottom stresses. As a result, large deposition occurs within the breakwater. To estimate total sediment volume changes related to the sediment seepage through the breakwater, a polygon is drawn by the breakwater inside the harbor on Figure 10. The morphology and bed volume changes within the polygon are estimated at the end of the simulation. Time extrapolation of the CMS results presents an approximate sediment transport rate of 2600 m^3/year (3,400 cy/year) in the lee of the West Breakwater. The calculated results are quantitatively comparable to the average annual volumes dredged inside of the West Breakwater in 2000, but significantly less than that dredged in 2009.

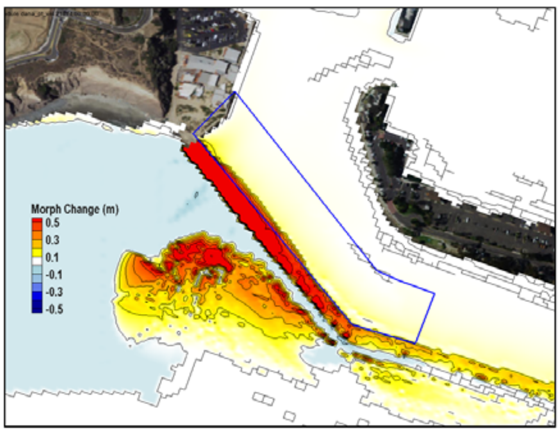

Figure 10. Morphology changes at the end of the 30-day simulation. The blue line denotes the area where bed volume change was estimated.

5. Summary

Wave transmission, and flow and sediment seepage through a porous structure were incorporated into the CMS, a coupled wave, flow and sediment transport numerical modeling system, to investigate wave, hydrodynamic conditions, and sediment transport. The model was calibrated and validated by the measured waves, current, water surface elevation, and the historical dredging information.

The CMS results indicate that the system is tide-dominated with a weak current inside and wave-dominated with a stronger current outside the harbor. By applying and adjusting the parameters of the breakwater porosity and flow resistance, wave transmission, flow seepage, and sediment transport through the permeable structure were properly simulated. The annual sediment transport rate obtained from the CMS simulations was reasonably comparable to the sand accumulation rate obtained from the historical maintenance dredging records.

6. Acknowledgements

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Auckland, New Zealand
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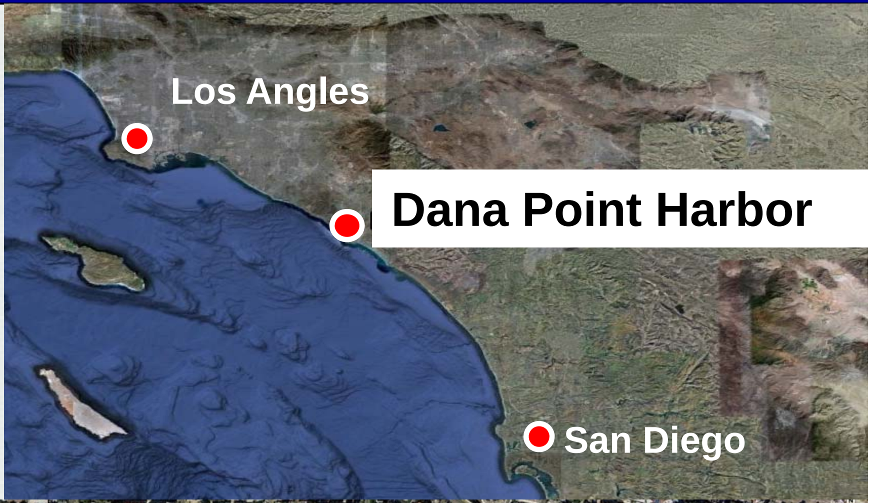
Outline

- Introduction
- Data
- Method
- Results
- Summary

2

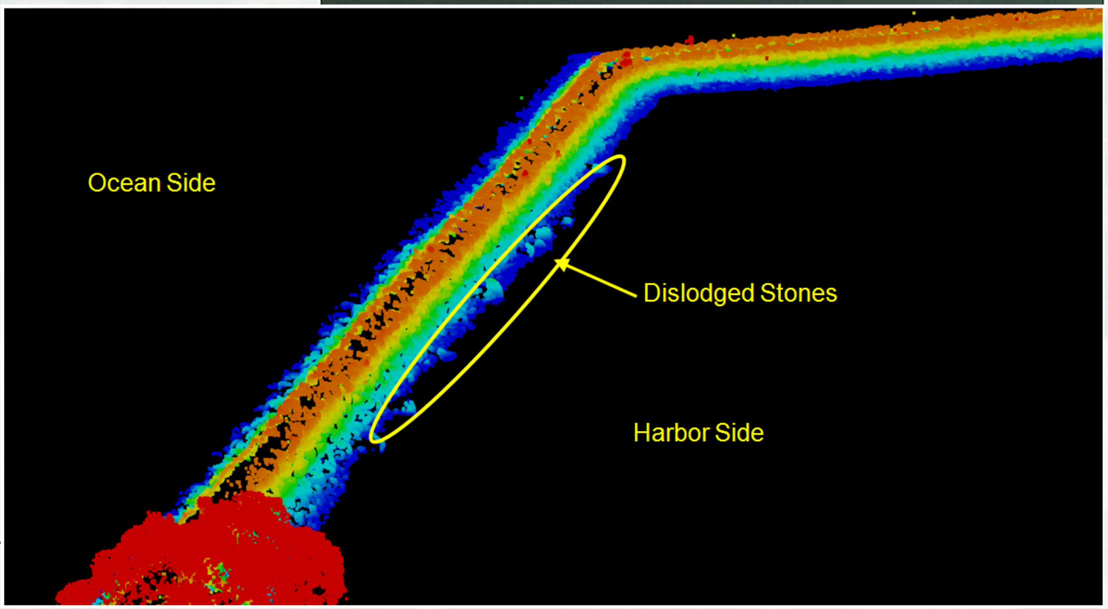
Dana Point Harbor and Present Issues

- Sediment seepage increase through the permeable West Breakwater
- Sediment built up inside the breakwater ~ 3,800 to 4,600 m^3/year
- Dredge required in last two decades (1989, 1999, 2009)
- Needs for circulation and water quality improvement at Harbor



Bathymetry Survey

- Conducted during October 20–24, 2009
- Side-scan sonar: data below the water surface
- LiDAR: data above the water surface
- East and west breakwater extending out approximately 46 m offshore on the ocean side
- Main navigation and primary access channels on the harbor side within the marina basins



ADCP Measurements

Two ADCPs deployed by Noble Consultants

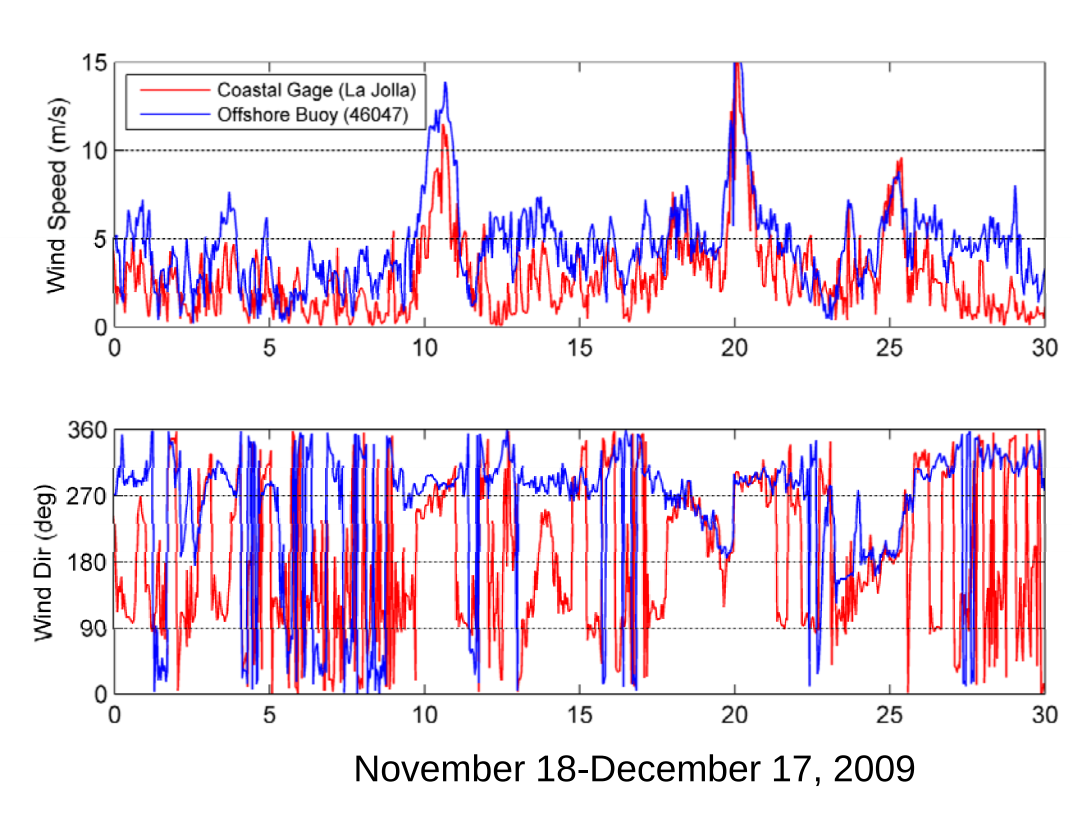
Inside and outside the harbor

Current, water level and directional waves measured

Inside: Depth 7.8 m
11/20/2009-01/15/2010

Outside: Depth 8.4 m
11/20/2009-11/26/2009

CMS-Flow Wind Forcing



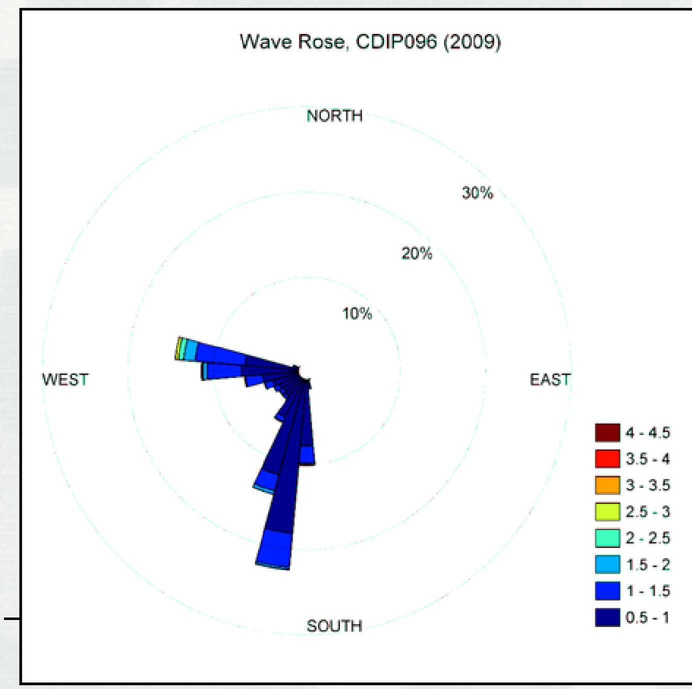
Wind at NOAA's La Jolla Gage, 9410230, and an offshore buoy, 46047

Surface boundary forcing for CMS-Flow

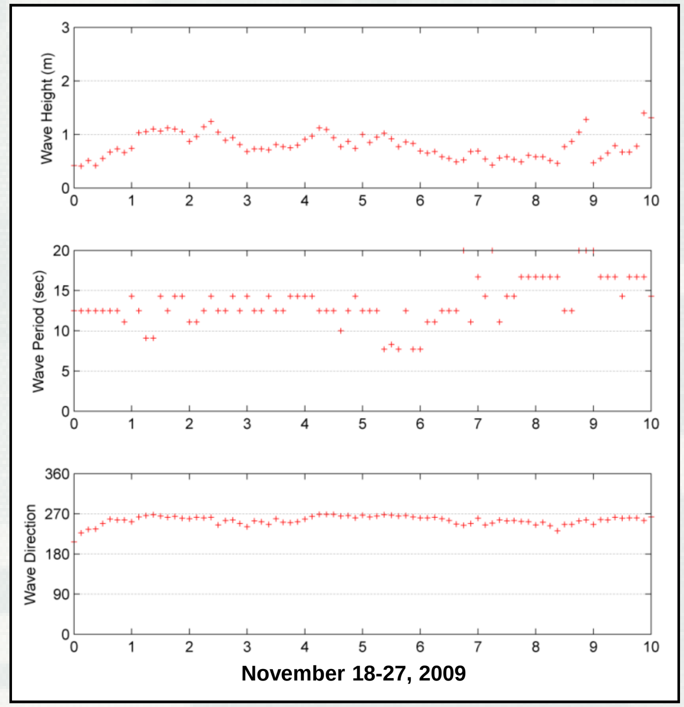
Sea breeze signal

Wind direction: **0° North, 90° East, etc. from which wind blowing**

CMS Wave Forcing



Wave Parameters (CDIP096)



Mean Significant Wave Height: 0.78 m

Mean Wave Period: 13.5 sec

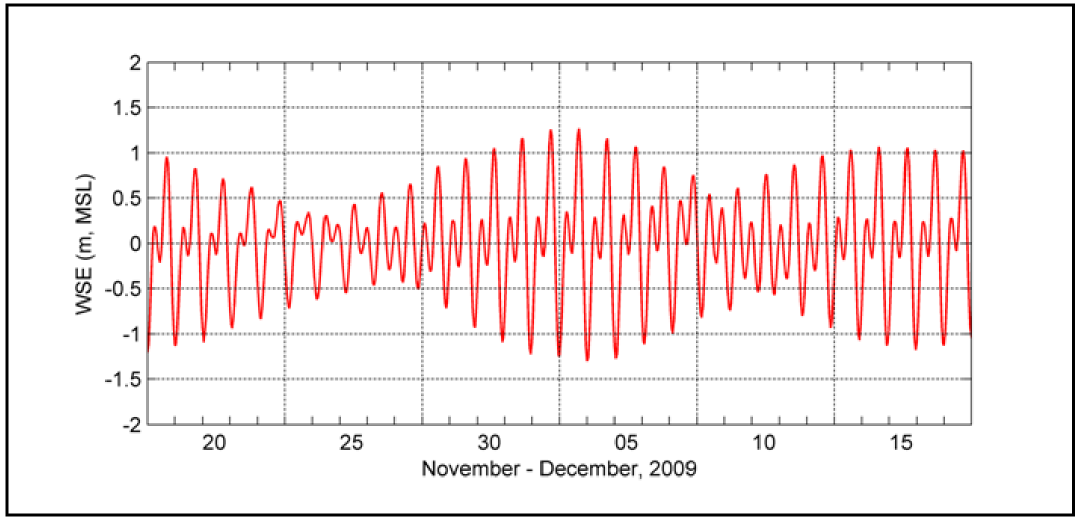
Mean Wave Direction: 255.2°

CMS-Flow Water Level Forcing

Data: Water surface elevation (WSE) at NOAA's Los Angeles Gage, 9410660

Method: Apply WSE along the open boundary

Tide (Los Angeles)



Mixed, predominately semi-diurnal tide

Mean tide range (MHW – MLW): 1.2 m

Calibration period: 18 Nov – 17 Dec 2009

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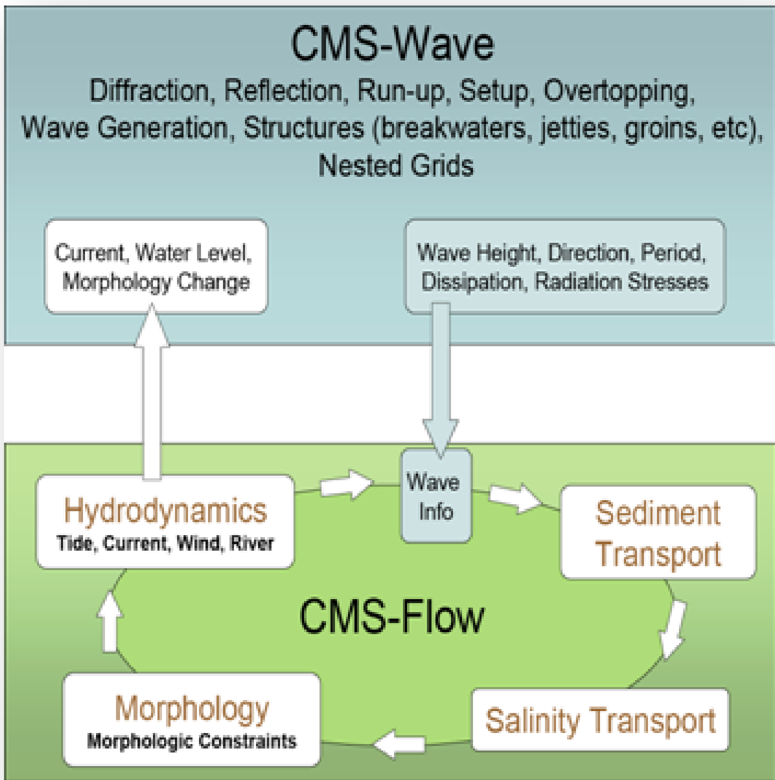
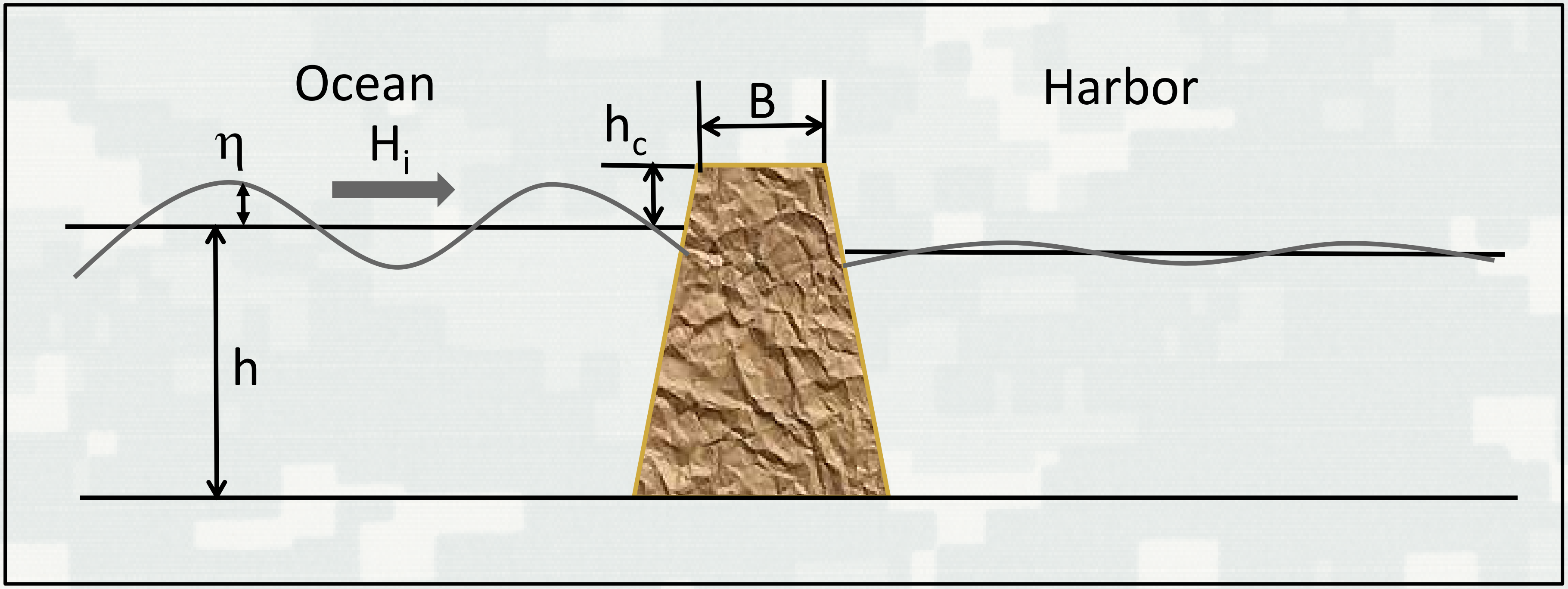
Coastal Modeling System (CMS)



- Developed since 1997 by the Coastal Inlets Research Program (CIRP), U.S. Army Corps of Engineers
- An integrated suite of numerical models for simulating water surface elevation, current, waves, sediment transport, and morphology change for coastal applications
- Consists of a hydrodynamic model, CMS-Flow, and a spectral wave model, CMS-Wave
- Coupled and operated within the Surface-water Modeling System (SMS), a GUI.

Implementation of Breakwater Permeability



CMS-Flow:

Hydraulic Conductivity
Void Factor (Porosity)
Crest Elevation

CMS-Wave:

Porous Breakwater Wave Transmission (Porous Section below MWL)

CMS-Wave Permeable Breakwater

Wave Transmission Calculation
(D'Angremond et al. 1996):

$$K_t = 0.64\,\left(\frac{B}{H_i}\right)^{-0.31}\left[1 - \exp\left(-\frac{\xi}{2}\right)\right] - 0.4\frac{h_c}{H_i}, \quad \text{for } B < 10\,H_i$$

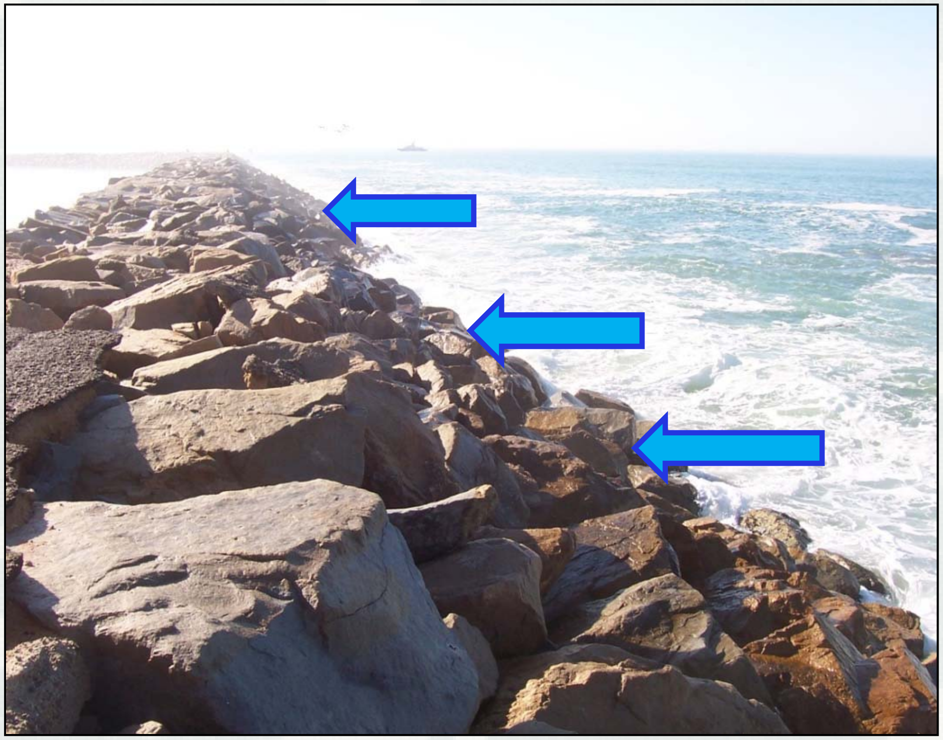
ξ: the Iribarren Parameter – the fore-slope of the breakwater divided by the square-root of the incident wave steepness

CMS-Flow Permeable Breakwater

Equation for laminar and turbulent resistance in porous media (Forchheimer, 1901):

$$I = au + bu^2$$

I :	Hydraulic Gradient
u:	Flow Speed
a, b:	Resistance Coefficients

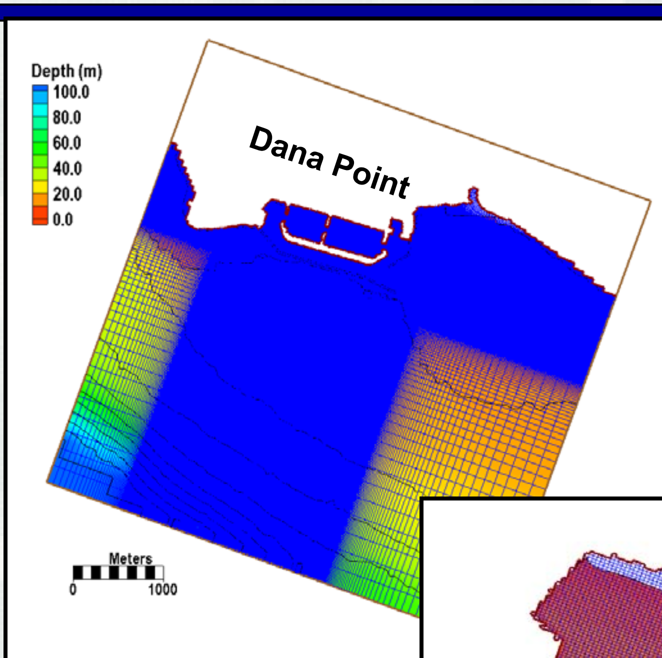


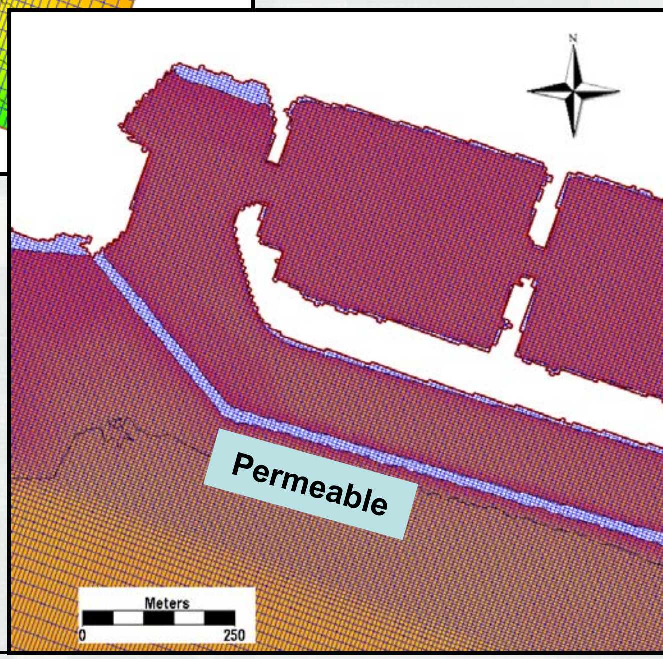
Sidiropoulou et al. (2007)

$$a = 0.003333\, D^{-1.500403}\, n^{0.060350}$$
$$b = 0.194325\, D^{-1.265175}\, n^{-1.141417}$$

D:	Rock Diameter
n:	Void Factor

CMS Grid and Settings





Current, Waves and Sediment Transport Simulation

CMS Domain:

5 x 5 km

Cell Size:

5 to 70 m

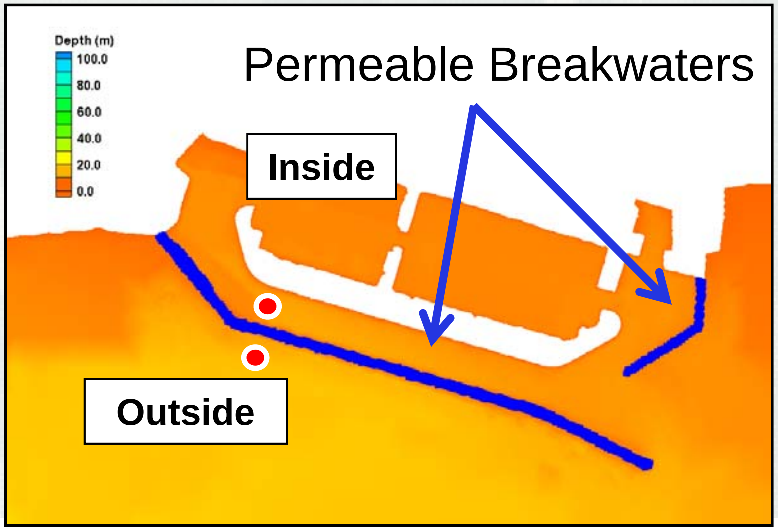
Water Depth:

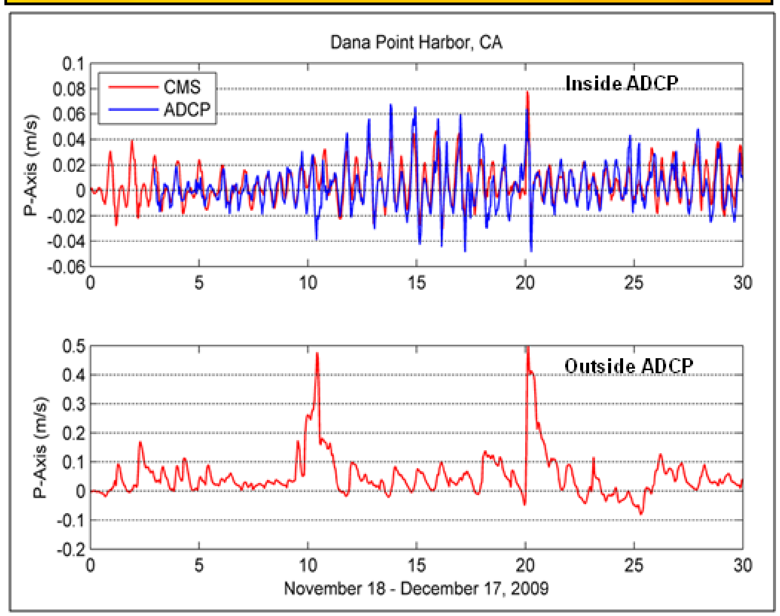
0 to 300 m

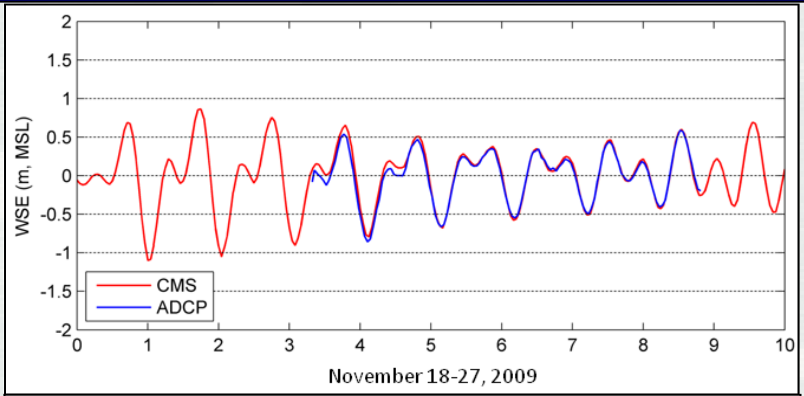
Structure:

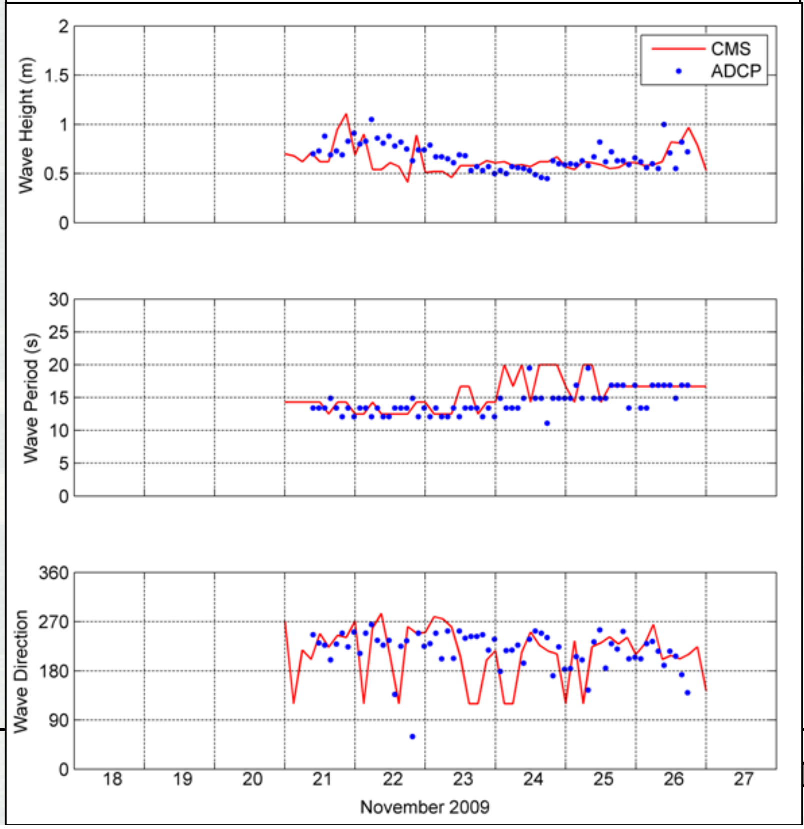
permeable breakwaters

Calculation and Validation





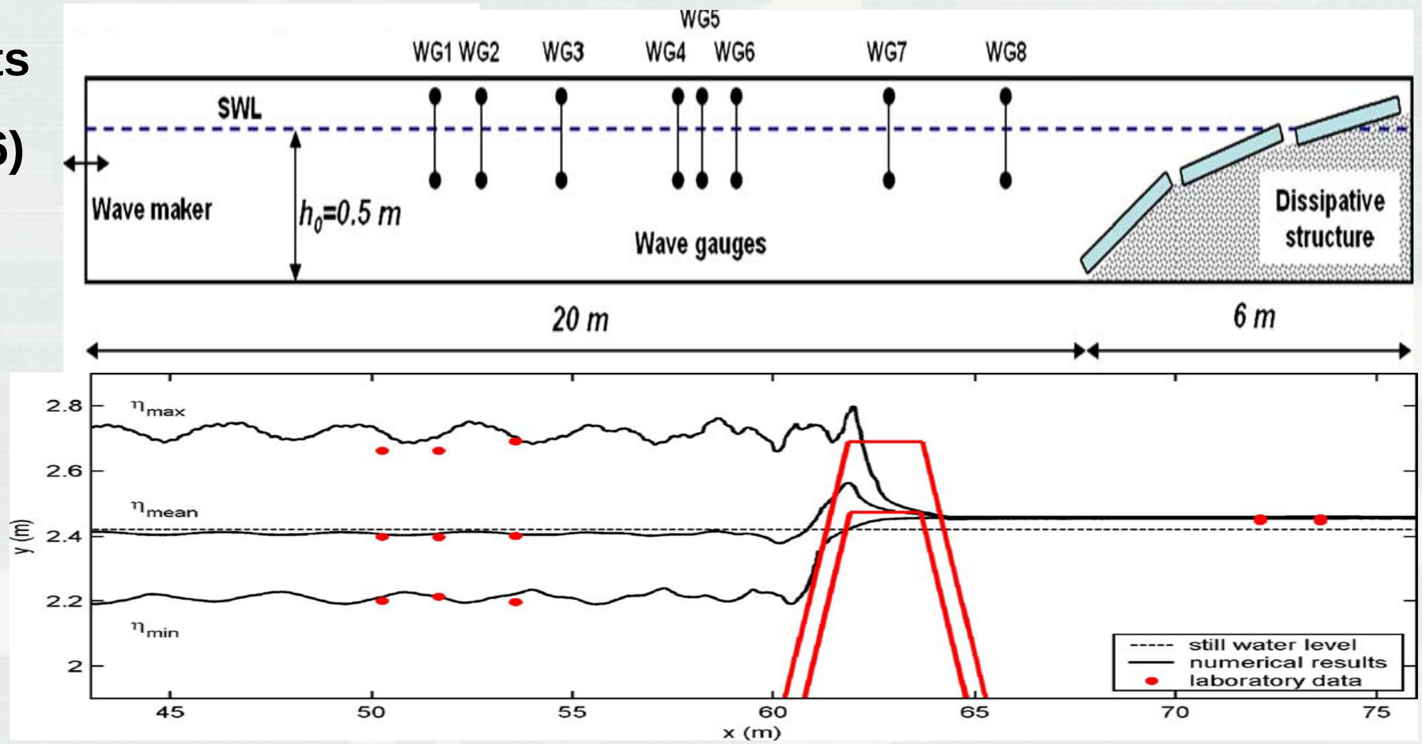




Calculation and Validation

Lab experiments

(Lara et al. 2006)



Experiment	Wave height (m)	Foreslope	Crest width (m)	Crest freeboard (m)
R1F1C2	0.30	1V:2H	1.825	0.07
R1F2C2	0.30	1V:2H	1.825	0.27

Calculation and Validation

Wave height comparison

Experiment	Scenario	Wave Height (m)				
		WG 3	WG 4	WG 5	WG 6	WG 7
R1F1C2	Lab	0.45	0.46	0.51	0.10	0.10
	CMS	0.51	0.51	0.51	0.09	0.09
R1F2C2	Lab	0.47	0.46	0.51	0.01	0.01
	CMS	0.46	0.46	0.46	0.01	0.01

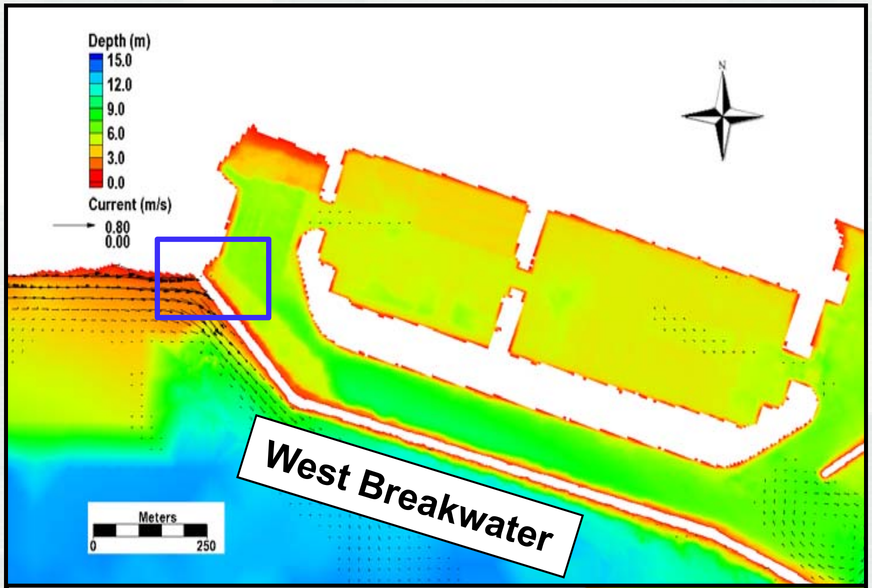
Calculated Current and Waves

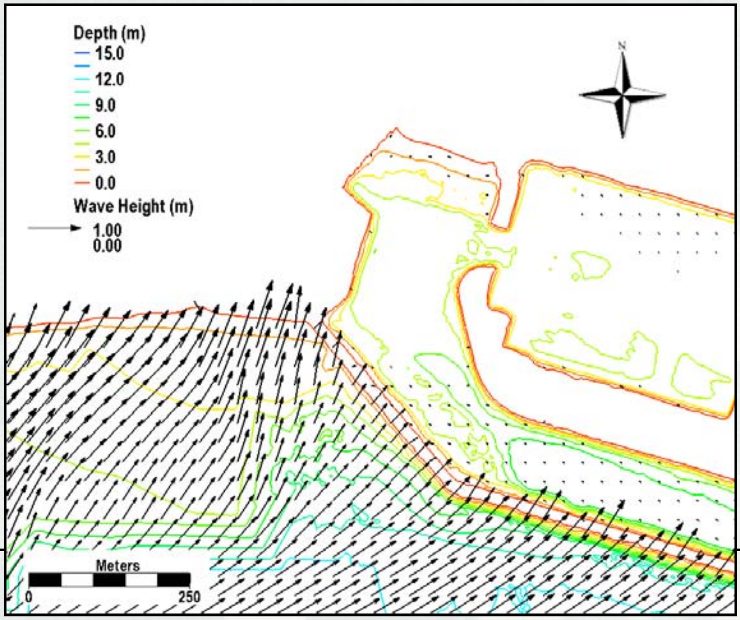
Depth-averaged current:

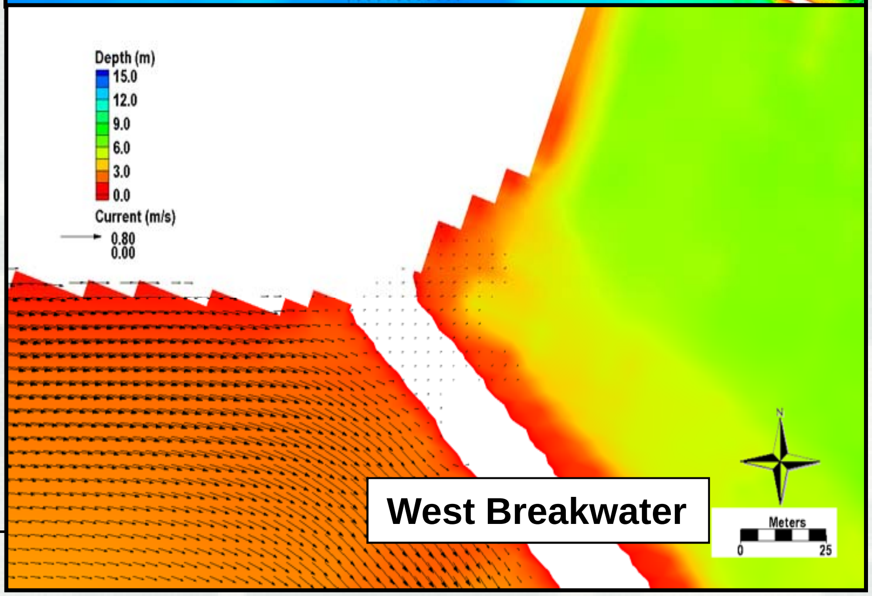
maximum current speed
50–70 cm/s on the ocean side
3–4 cm/s on the harbor side

Waves:

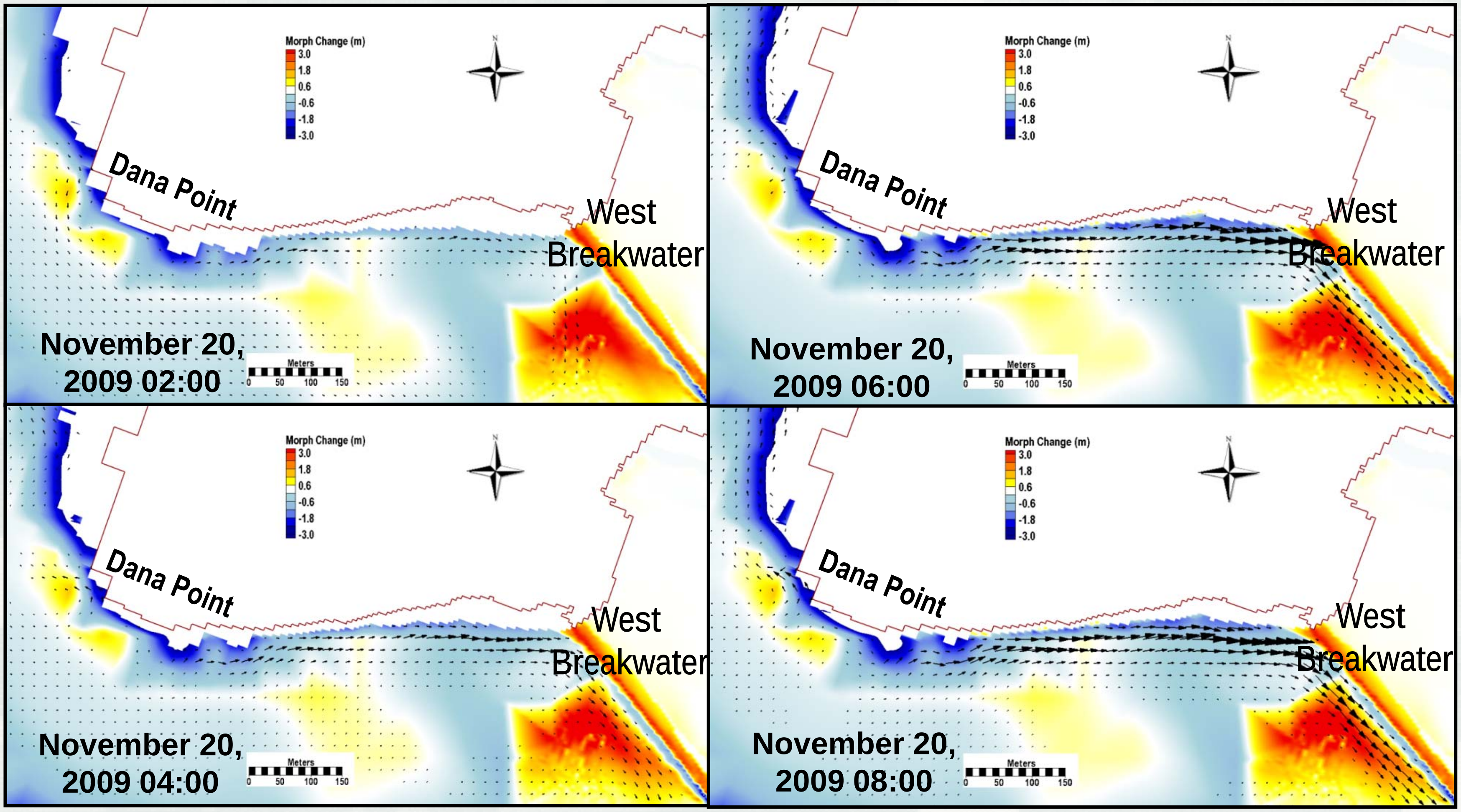
significant height of 0.6–0.7 m.
reduce to 0.05–0.07 m on the harbor side







Calculated Sediment Transport



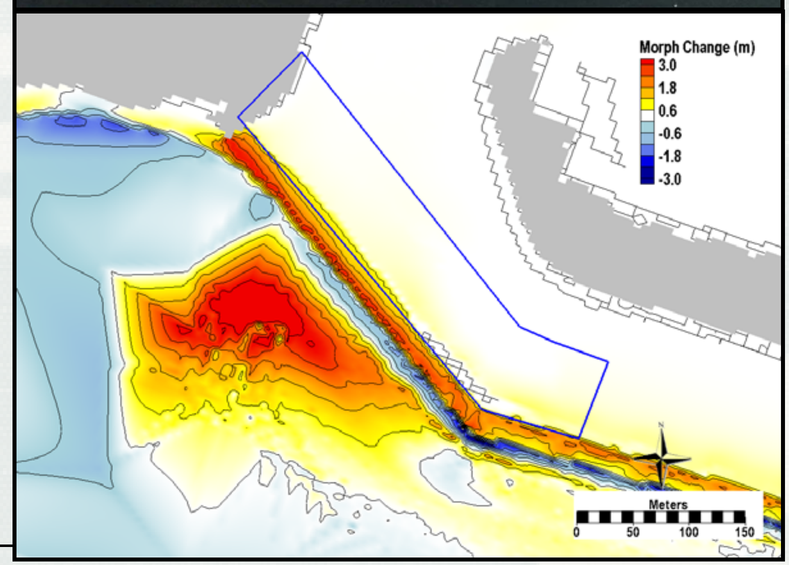
Calculated Sediment Transport

Sediment Transport Through the Structure:

2,600 m^3/year

Based on dredged volumes, average sediment accumulation rate on the harbor side:

3,800-4,600 m^3/year



Summary

- Incorporate calculations of flow and sediment seepage, and wave transmission through a porous structure into CMS to investigate wave, hydrodynamic conditions, and sediment transport.
- The system is tide- and wind-dominated on the harbor side and wave-dominated on the ocean side.
- The calibrated and validated model shows that 4-8% of currents flow and about 10% of wave heights transmits through the structure.
- The annual sediment transport rate obtained from the CMS simulations is reasonably comparable to the sand accumulation rate obtained from the dredging records.

Thank You!

Questions?

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