Analysis of the wave transformation over a deeply submerged marine structure

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ANALYSIS OF THE WAVE TRANSFORMATION OVER A DEEPLY SUBMERGED MARINE STRUCTURE

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Introduction

In recent years, submerged coastal structures have been extensively used in coastal management projects for protecting shorelines, tunnels, pipelines and submarine outfalls against wave attack. Such structures provide a reduction in wave energy on their lee side by triggering wave energy dissipation over the structure, thus reducing the potential for sediment transport and coastal erosion. Submerged structures are a growing interest due to their relatively low cost compared to conventional breakwaters and their capability of safe-guarding the coastal zone against erosion while maintaining the quality of the coastal environment.

There has been a substantial amount of experimental and numerical research involving low-crested structures whose crests are located at or near the mean water level (Van der Meer & Daemen, 1994, d'Angremond et al., 1996, Seabrook & Hall, 1998, Briganti et al., 2003, etc.). Research into deeply submerged structures is scarce, in spite of an increase in their use. Also, a large part of the research interest on this topic has focused on two-dimensional experimental models or on numerical models. Only a limited amount of research has been conducted in order to investigate the three-dimensional behaviour of such structures, as almost all previous research has consistently focused on the use of uniformly shaped structures with a specific and constant crest elevation.

The novelty of this research project resides in the use of a large-scale, three-dimensional model to study and analyze, both experimentally and numerically, the transformation of waves and wave-induced velocities over a steeply sloped submerged structure, with a varying cross-section and varying submergence depth (Baker, 2007).

Project Description

The Canadian Hydraulics Centre of the National Research Council, in collaboration with the University of Ottawa, performed a physical modelling study to investigate the stability of the armour layer protecting a section of an immersed tunnel. The tunnel is part of an 8.2 kilometre motorway connecting several islands to the mainland. The immersed tunnel is comprised of 18 steel

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elements, with each segment having general dimensions of 180 meters long, by 26.5 meters wide, by 9.75 meters tall. Over most of its length, the tunnel is to be buried below the seabed. However, several of the sections will be positioned at, or above grade. These exposed areas require a protective covering to prevent scouring and undesired structural movements due to hydrodynamic forcing.

Physical Modelling

Stability tests on a 360 meter (prototype scale) section of the immersed tunnel were performed in the Coastal Wave Basin at the Canadian Hydraulics Centre in Ottawa. The basin is 63 meters long, by 14 meters wide, and 1.5 meters deep. The facility is equipped with a computer-controlled wave machine capable of producing irregular long-crested waves with significant wave heights up to approximately 0.35 meters (model scale).

The physical model was constructed at an undistorted length scale of 1:50, a compromise needed in order to minimize scale and boundary effects.

A 7.2 m wide test channel was constructed at the centre of the basin by erecting two parallel solid vertical walls. A concrete bathymetry replicating the actual seabed morphology was further added within the test channel. This bathymetry included a 0.32 meter deep by 6 meter long trench containing fine sand used to simulate the seabed around the submerged structure. The submerged rubble-mound structure had a longitudinally-varying freeboard from approximately half the water depth at the high end, sloping down to just above the seabed at the lower end (see Figure 1).

Figure 1: Layout of the submerged structure in the Coastal Wave Basin, CHC

The time-history of the water surface variation was measured at 10 locations, distributed upwave, downwave and along the crest of the structure using capacitance wire gauges. The magnitude and direction of the currents in the model were measured using two 2-axis electromagnetic current meters (ECM) up and downwave of the structure, and three 3-axis acoustic Doppler velocimeters (ADV) along the crest.

Numerical Modelling

A numerical model (WaveSim) developed at the Canadian Hydraulics Centre (Nwogu 1993, 1996), was used to conduct a series of numerical simulations using input data identical to those used in the physical modelling tests. WaveSim is capable of simulating the propagation and transformation of ocean waves in coastal regions and harbours and is based on a time domain solution of the Boussinesq equations.

The selected computational domain (see Figure 2) was 5.25 meters by 14.4 meters (25 by 245 grid spaces) and was found to be adequate for capturing the details of the submerged structure and the wave transformation occurring in its vicinity. The time step used for the numerical simulations was 0.1 seconds, and the option for incorporating strong nonlinearity was employed.

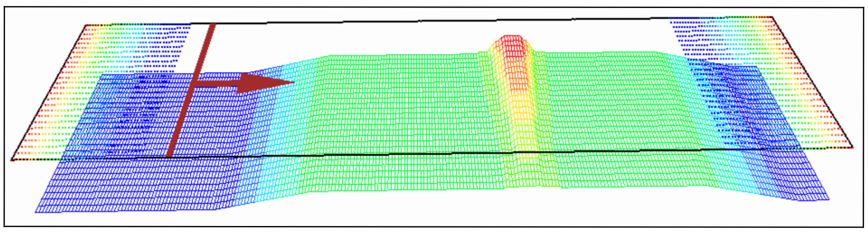

Figure 2: Overview of the computational domain

Data Analysis

A frequency-domain spectral analysis and a time-domain zero crossing analysis were employed to determine a number of different wave characteristics for both the physical and numerical modelling data.

The presence of the structure induces a significant influence on the wave characteristics. Wave energy is partially reflected from the structure, causing the up-wave row of gauges to show significantly higher waves. As expected, the data show that the influence of the structure is larger at the right side, where the tunnel's submergence is lowest. A similar trend was recorded by the gauges located at the structure crest (see Figure 3).

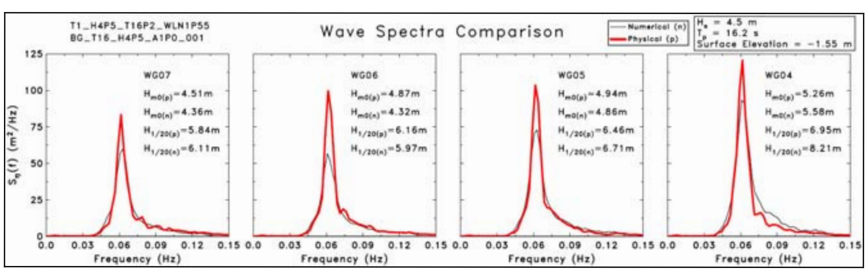

Figure 3: Wave Spectra Analysis

The submerged structures crest forces the approaching waves to shoal as they pass over it. The comparison of the experimental and numerical results of wave spectra indicates good agreement along the entire crest of the submerged structure. The measured and simulated wave-induced velocities were analyzed in order to determine the effects of the submerged structure on the surrounding flow. Comparing the results from the undisturbed case, the influence of the submerged structure can be clearly observed, especially in the ADV readings positioned at the structure's crest. The submerged structure has a greater impact on the wave-induced velocities over the section of least freeboard.

A reflection analysis was also conducted using the numerical model. In the presence of the submerged structure, it was observed that the incident wave trains appear nearly identical along the crest, while the reflected wave trains demonstrate the impact of the submerged structure on the flow. A steady increase in the reflection is observed as the submergence of the structure decreases. A constant reflection coefficient of approximately 35% was observed at the shallowest portion of the submerged structure (see Figure 4).

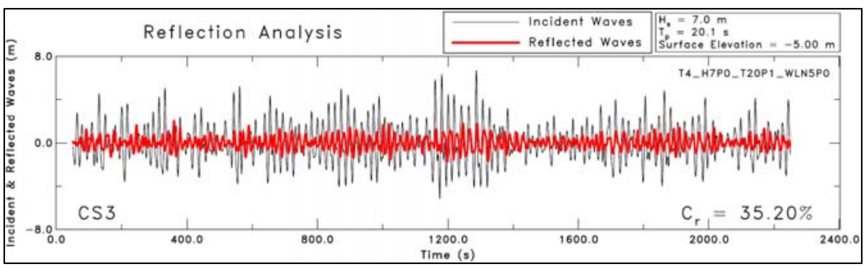

Figure 4: Reflection Analysis

Conclusions

The effects induced by the submerged structure on the wave climate and the wave-induced velocities were satisfactorily simulated with the numerical model. It was observed that the submerged structure analyzed in this research project induced significant changes in the local wave climate and generated a substantial increase in the wave-induced velocities at the crest of the structure. The wave height generally increased over the entire crest of the submerged structure, and the increase was greatest where the submergence depth was the smallest. Wave-induced velocities also increased due to the presence of the structure, and this increase was again maximum where the structure crest was the shallowest. The increase in wave shoaling and the augmentation of the wave-induced velocities were also greater when incident waves were higher. Reflection analysis from the submerged structure displayed a clear trend in the amount of reflected energy in relation to the submergence depth. A reasonable estimate of the expected reflection could be calculated for different submergence depths along the submerged structure.

Large submerged structures represent a viable engineering solution for the protection of critical infrastructure in coastal areas and for further development of new coastal projects. Results of this research advance the understanding of the behavior of large submerged structures and their impact on the coastal environment. This will enable the development of much-needed design guidelines for such structures, which are currently unavailable.

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