CHAPTER 171

Wind Effects on Runup and Overtopping of Coastal Structures

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ABSTRACT

Effects of strong onshore winds on runup and overtopping of coastal revetments were studied in a wave flume with wind-generating capabilities. Runup and overtopping were measured during tests with onshore wind blowing over mechanically-generated waves. The addition of a constant wind over monochromatic waves added substantial energy to the wave field but the energy spectrum remained single peaked if the generated wave period was short (one second). These single-peaked incident spectra of the combined wind/wave tests were then reproduced mechanically using just the mechanical wave generator, with runup or overtopping again being measured. Runup and overtopping were both found to be considerably higher with similar incident spectra under the influence of onshore winds. Results are presented for a range of structure slopes, wind speeds, wave periods, and wave heights. Both smooth and rough revetments were tested.

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I. INTRODUCTION

Design storm conditions for coastal structures typically include strong onshore winds that play an obvious role in transport of splash and spray, and may have a significant effect on wave runup elevations and overtopping rates. Design for runup and overtopping on coastal structures, however, typically ignores wind effects. Traditionally, runup distances and overtopping rates have been calculated from empirical equations determined from series of small-scale physical model tests (e.g., Weggel 1976, Ahrens and Martin 1985, Ahrens and Heimbaugh 1988, de Waal and van der Meer 1992, Ward 1992, Yamamoto and Horikawa 1992, van der Meer and Janssen 1994) that were conducted in the absence of wind. Numerical models currently available for runup and overtopping also neglect effects of onshore winds (e.g., Kobayashi and Wurjanto 1989, Wurjanto and Kobayashi 1991, van der Meer et al. 1992, Kobayashi and Poff 1994).

Because of the importance of accurate estimates of runup heights and overtopping rates, the Coastal Engineering Research Center (CERC) of the US Army Engineer Waterways Experiment Station has initiated a joint research project with Texas A&M University (TAMU) to investigate effects of onshore winds on runup and overtopping of coastal structures. Using a wave flume with wind-generating capabilities at TAMU, a series of tests were conducted on model revetments using a range of structure slopes, incident wave conditions, and wind speeds. Runup elevations or overtopping rates were measured, along with changes in the incident wave spectra due to influence of the wind.

II. TEST FACILITY

The two-dimensional wind/wave flume at TAMU is a glass-walled flume 36.0-m-long by 0.6-m-wide and 0.9-m-deep (Figure 1). Wave generation was by a pair of Seasim Ltd. (presently Commercial Hydraulics) dry-back hinged-flap wavemakers. Wave generation was controlled by an IBM personal computer interfaced to the wavemaker through an analog output card using software developed at TAMU.

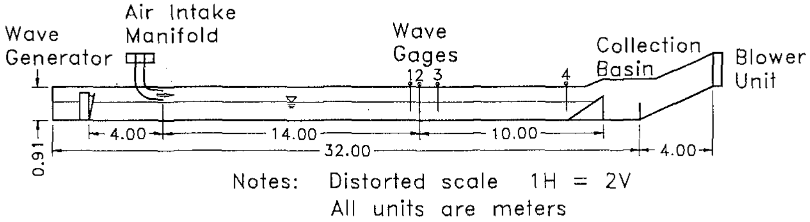

Figure 1. Wind/wave test facility at Texas A&M University

Wind generation was provided by an exhaust blower connected to the end of the flume away from the wavemakers. Air was pulled into the flume through a vertically-adjustable intake manifold equipped with horizontal vanes to help introduce a uniform flow field into the flume.

Runup tests were conducted on plywood test structures with slopes of 1:1.5 (V:H), 1:3, and 1:5. Each slope was tested both as a smooth slope and as a rough slope. Rough slopes replicated riprap revetments and were covered with a filter layer and two-layer-thick riprap armor layer designed in accordance with Engineering Manual EM 1110-2-1614, Design of Coastal Revetments, Seawalls, and Bulkheads (1995).

Data inputs included twin-rod resistance-type wave gauges, resistance-type and capacitance-type runup gauges on the test structures, and a three-cup anemometer for measuring wind speeds. In addition, visual observations of runup elevations were recorded, wind speeds were measured by a pitot-static tube connected to an oil-filled manometer with wind speeds being visually observed, and overtopping rates were determined by measuring water surface elevations in an overtopping basin located behind the test structures at the beginning and end of each test run.

III. TEST PROCEDURE AND RESULTS

A. Determination of Incident Wave Conditions

All tests were conducted with monochromatic waves produced in short bursts such that wave generation would cease before waves reflecting off the test structures could reach the wave board and contaminate the incident wave train. Selection of wave heights was limited by the capabilities of the wavemaker. Wind speeds selected were 50%, 75%, and 100% of blower capacity (providing wind speeds of 6.5 m/s, 12 m/s, and 16 m/s, respectively), as well as the no-wind condition. Tests were conducted at a constant depth of 0.5 m; all wave tests conducted were classified as intermediate waves.

To determine incident wave spectra under the influence of wind, a 1:5 plywood slope was placed in the flume and covered with a wave absorber comprised of several layers of rubber matting ("horse hair") to a thickness of approximately 30 cm near the toe and 23 cm near the crest. A wave gauge placed near the toe of the structure (26 m from the wavemaker) recorded the incident wave train. The method of Goda and Suzuki (1976) was used to examine the recorded signals from a set of wave gauges centered 23 m in front of the wavemaker to separate incident and reflected wave trains and confirm that reflection was minimal. Each of the test conditions was run with the wave-absorbing slope to establish incident wave conditions. Energy spectra showing the effects of wind are given in Figure 2 for generated waves with a 1-sec period and wave heights of 5, 7, and 10 cm.

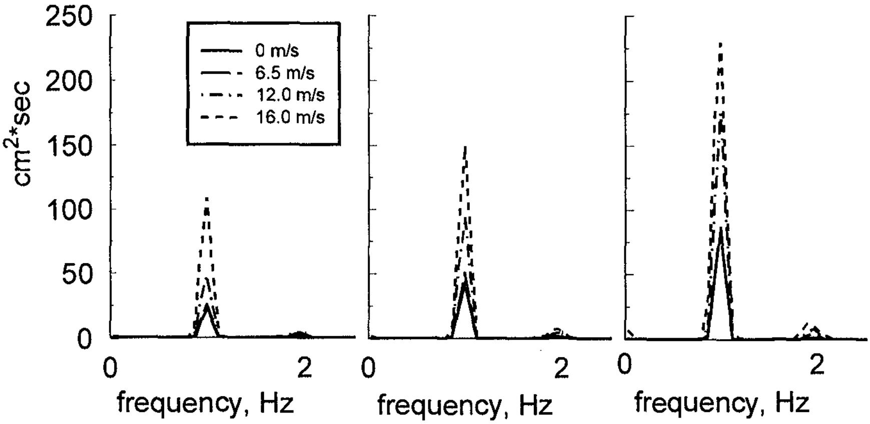

Figure 2. Wave energy growth for 1-sec mechanically-generated monochromatic waves of wave heights (left to right) 5 cm, 7 cm, and 10 cm.

During tests of wind-wave energy growth and tests to establish incident wave conditions for the combined wavemaker/wind generator tests, the amount of wind-induced setup at the revetment was measured. It was found that the wind-induced setup remained constant for each wind velocity, virtually independent of incident wave conditions or structure slope. Observed wind-induced setup elevations were 1 cm, 3 cm, and 5 cm for wind speeds of 6.5 m/s, 12 m/s, and 16 m/s, respectively.

The addition of wind energy to the generated wave train clearly adds energy to the wave spectrum. Earlier tests with mechanically-generated wave periods of 1.75 and 2.5 sec had demonstrated that the majority of the energy increase due to wind produced a second peak in the spectrum at a frequency of about 2 Hz. This second peak is missing in Figure 2 for wave spectra with mechanically-generated wave periods of 1.0 sec, where the additional energy is shown as an increase in the single peak of the mechanically-generated wave. There are two reasons the spectra of the one-second waves remain as a single peak. First, as the wind-wave field developed during the first several meters of fetch, the wind-wave field was characterized by a high-frequency, short wave length wave field. As the steep one-second mechanically-generated waves propagated down the wind-wave flume, high frequency wind waves were blocked at the forward face of the steep mechanical waves and the wind waves were not allowed to form. This phenomenon of capillary/gravity wave blockage was described by Phillips (1984), Shyu and Phillips (1990) and Zhang (1995). Phillips (1984) noted that while this phenomenon is not of great significance in the field, it can significantly affect the wave spectrum in laboratory wind-wave flumes with short fetches.

The second factor restricting development of the second peak in the wave spectra was the significant growth of the mechanically-generated waves due to modulation of the air pressure field. Because the crests of the large mechanically-generated waves were closer to the top of the flume than were the troughs, airflow was constricted by the reduction in cross-sectional area above the crests, resulting in higher local wind velocities at the crests. The opposite, of course, was true at the troughs. This modulation of wind velocities resulted in modulation of the air pressure field according to the Bernoulli equation. The modulated air pressures were in phase with the mechanically-generated waves and led to the growth of the mechanically-generated waves. The modulation of air pressure was not as significant for the longer wave lengths due to the smaller heights used due to limitations of the wave generator.

B. Runup Tests

For the runup tests, the wave-absorbing slope was removed and test slopes of 1:1.5, 1:3, and 1:5 were installed. Each slope was tested both as a smooth slope and built as a typical riprap revetment.

As was seen in Figure 2, the addition of wind to a mechanically-generated wave period of 1 sec remained as a single-peaked spectrum. For these single-peaked cases, it is possible to determine wind effects on runup by mechanically reproducing the combined wind/wave spectra. That is, the stroke of the wave generator can be increased to produce a similar spectrum to that obtained by a lesser stroke under the influence of wind.

Figure 3 plots runup on smooth slopes of 1:1.5, 1:3, and 1:5; Figures 4 plots runup on rough slopes. In both Figures 3 and 4, the abscissa is significant wave height (average of one-third highest waves) recorded near the structure toe, regardless of the height of the mechanically-generated wave. The ordinate is "equivalent" runup, that is, maximum runup adjusted for the increase in still water level due to wind setup. Symbols used in the figures indicate wind velocity used during each test. Figures 3 and 4 clearly illustrate the wind effects: for waves of similar wave height, the runup is considerably greater when the wave height is obtained by a small mechanically-generated wave plus influence of a strong wind, than when the wave height is purely mechanically driven (in the absence of wind).

Overtopping occurred in all tests conducted on the smooth 1:1.5 slope with wind speeds of 12 m/s and 16 m/s, and on the smooth 1:3 slope with wind speeds of 16 m/s and all but one test at 12 m/s. If overtopping occurred, maximum runup is not defined and no data are presented in the figures. On tests with smooth slopes

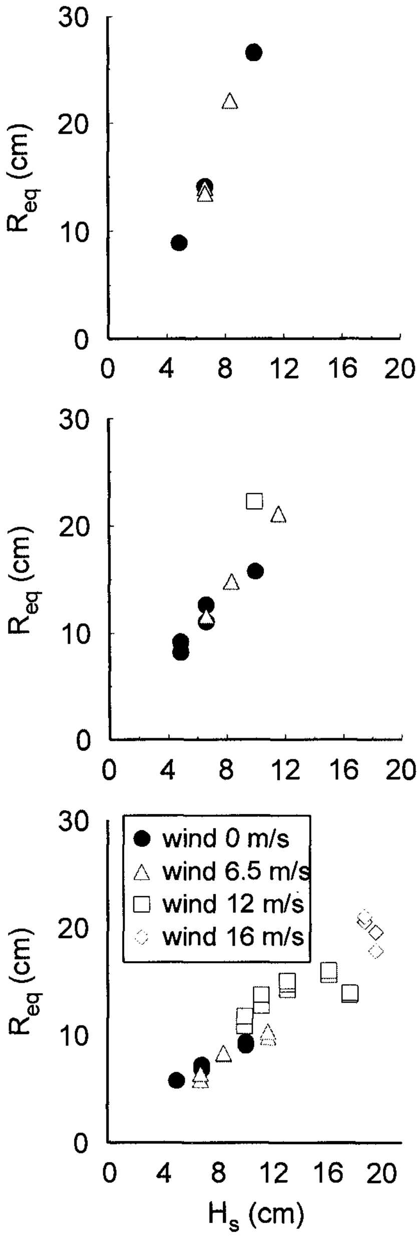

Figure 3. Runup elevations for (top to bottom) 1:1.5, 1:3, and 1:5 smooth slopes.

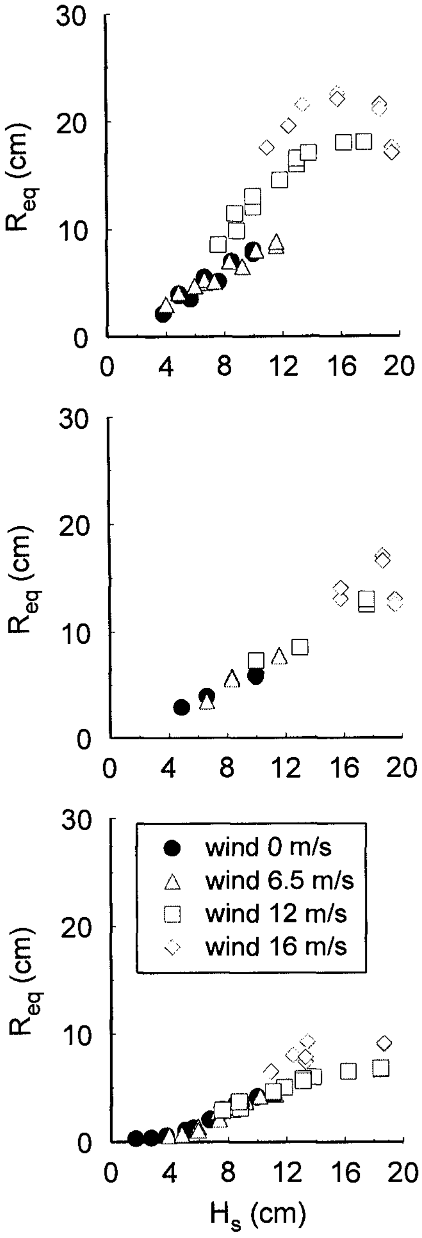

Figure 4. Runup elevations for (top to bottom) 1:1.5, 1:3, and 1:5 rough slopes.

(Figure 3) and rough slopes (Figure 4), the 6.5 m/s wind is seen to have negligible effect on runup elevations. Wind speeds of 12 m/s and 16 m/s cause significant increases in runup elevations on the smooth slopes, and on the rough 1:1.5 slope. For flatter rough slopes, the 12 m/s wind has little effect and only the 16 m/s wind significantly increases runup elevations.

Runup under the influence of the 12 m/sec wind and 16 m/sec wind is seen to increase linearly with incident wave height, then the runup tapers off or even decreases with increasing incident wave height. This is due to wave breaking under the influence of the wind prior to the wave reaching the test structure.

C. Overtopping Tests

In cases where the crest elevation was lower than the wave runup, overtopping was collected and measured in a basin behind the revetment. Different crest elevations on the revetment were tested, therefore a given incident wave condition may appear both in the runup figures (high crest elevation) and in the overtopping data (lower crest elevation).

Figure 5 plots overtopping on smooth slopes of 1:1.5, 1:3, and 1:5. The abscissa is "equivalent" crest elevation (crest elevation adjusted for wind-induced setup) divided by significant wave height measured near the structure toe. Ordinate of the

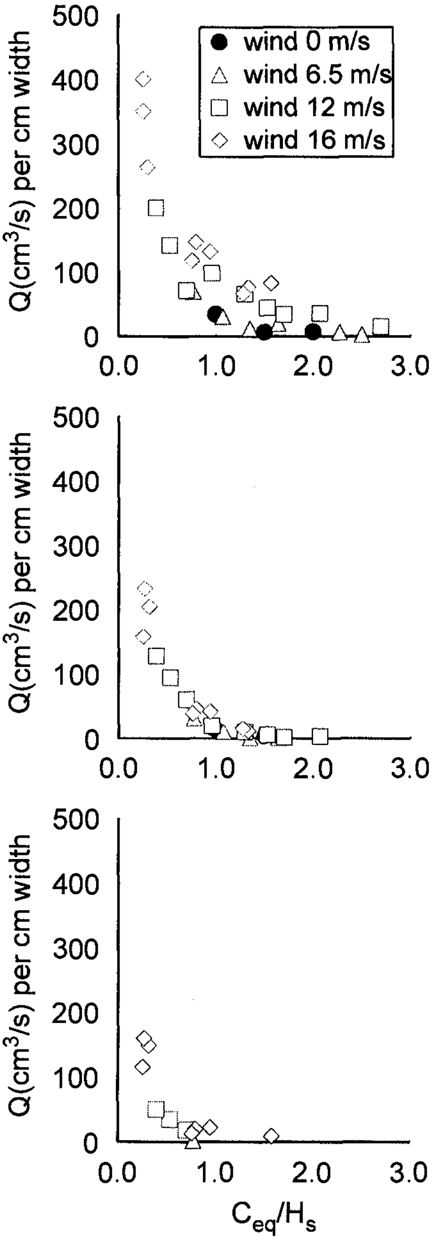

Figure 5. Overtopping tests for (top to bottom) 1:1.5, 1:3, and 1:5 smooth slopes.

figure is overtopping rate per cm of revetment width.

Overtopping results were similar to the runup results: higher wind speeds produced higher overtopping for similar wave heights, and wind effects were more pronounced on steeper slopes.

For no-wind conditions, measurable overtopping was only obtained on the smooth 1:1.5 slope and 1:3 slope. On the smooth 1:1.5 slope, winds of 6.5 m/s are seen to have negligible effect over the no-wind tests, but winds of 12 m/s and 16 m/s produced significant increases in overtopping rates. On the smooth 1:3 slope, winds of 6.5 m/s and 12 m/s appear to have little effect on overtopping rates, and only the 16 m/s winds show an appreciable effect.

IV. DISCUSSION

Physical model studies of prototype locations will typically reproduce certain parameters of a design storm wave environment, but do not reproduce storm winds associated with the design storm. Selected design storm wave heights are reproduced in a wave flume by a mechanical wave generator in the absence of wind. The study reported herein examines the effects on wave runup elevation and overtopping rates of reproducing a given wave height by purely mechanical means and failing to include the associated onshore winds.

Strong onshore winds have been to shown to produce appreciably higher wave runup elevations and overtopping rates for waves of similar heights at the structure toes. Wind speeds of 6.5 m/s (23 km/hr) showed little effect on runup or overtopping, but wind speeds of 12 m/s (43 km/hr) and higher greatly increased both runup and overtopping. The significance of the wind effects, however, requires a consideration of the scaling effects involved.

Wind effects on runup and overtopping include wind energy input into the wave energy spectrum and wind induced setup. Both of these factors have been fully accounted for in the study reported herein. However, mechanically reproducing a wind/wave spectrum does not necessarily reproduce the *shape* of the individual waves. Different wave shapes due to wind forces acting on the waves, and changes in wave breaking due to wind effects, may change the wave kinematics at the structure causing the observed increases in runup and overtopping. Additionally, wind effects on the wave upwash on the structure slope may affect runup not only by helping "push" the upwash up the slope but possibly by reducing the effects of downwash on the subsequent wave. Wind advection of splash and spray has an obvious affect on overtopping rates. Each of these factors is currently being further studied.

V. ACKNOWLEDGEMENT

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