CHAPTER 121

WIND EFFECTS ON RUNUP AND OVERTOPPING

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ABSTRACT

The maximum distance a wave may travel up the face of a coastal structure, or rate of overtopping if runup exceeds structure crest elevation, are critical parameters in planning and design of a coastal structure. Runup and overtopping are usually estimated by empirical equations based on physical model studies that do not include the effects of strong onshore winds that are typically present during design storm conditions. While it is generally assumed that onshore winds will increase runup and overtopping over no-wind conditions, there is currently no means of accurately calculating effects of these winds on runup and overtopping.

A joint research project by US Army Corps of Engineers and Texas A&M University (TAMU) is currently investigating wind effects on runup and overtopping of revetments and vertical walls through a series of physical model studies conducted in a combined wind/wave flume at TAMU. Initial tests measured runup and overtopping rates on a 1:3 smooth revetment for a range of incident monochromatic wave conditions, with wind speeds varying from no wind to maximum blower output. With the addition of wind, large increases in runup and overtopping were recorded over the no wind condition. The combined wind/wave spectrum recorded during tests with wind was then reproduced mechanically. Runup and overtopping were significantly higher during tests with

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wind than during no-wind tests that reproduced the combined wind/wave spectrum.

The tests indicate that runup and overtopping estimates that do not include wind effects are underpredicting runup and overtopping on coastal structures. Continuing efforts in this study are aimed at quantifying prototype wind effects on runup and overtopping based on physical model results.

BACKGROUND

The ability to accurately estimate potential runup and overtopping on a coastal structure is essential to structural and economic design of the structure. Although it may be desirable to construct shore-protecting structures with sufficient crest elevation to prevent overtopping, this is gnerally not economically feasible and overtopping rates must be considered. An analysis of runup heights and overtopping rates is necessary to determine structure crest elevations, design drainage systems, and estimate overtopping-induced damage levels for determining benefit/cost ratios. Typically, runup and overtopping are estimated from empirical equations that were developed from physical model studies (e.g., Weggel 1976, Ahrens and Martin 1985, Ahrens and Heimbaugh 1988, van der Meer 1988, van der Meer and Stam 1991, de Waal and van der Meer 1992, Schulz and Fuhrboter 1992, Ward 1992, Ward and Ahrens 1992, Yamamoto and Horikawa 1992), or determined directly from physical model studies. Numerical models have also been developed to estimate runup and overtopping (e.g., Kobayashi and Wurjanto 1989, Wurjanto and Kobayashi 1991, Kobayashi and Poff 1994); these numerical models are generally calibrated with physical model test results.

The typical design condition for a coastal structure is a severe storm accompanied by strong onshore winds, yet physical model tests on which runup and overtopping rates are based do not include wind effects. The Shore Protection Manual (1984) includes an equation for a wind correction factor that increases wave overtopping rates by up to 55%, but there is no data to support this equation. It is generally agreed that wind speeds greater than 50 km/hr may have a significant effect on runup and overtopping, but little research has been conducted to quantify wind effects (Sibul and Tickner 1956, Weggel 1976).

Resio (1987) divided action of winds on overtopping into two distinct physical processes: (1) increase of runup and overtopping due to wind energy input during the wave runup interval, and (2) advection by wind of water spray and splashing resulting from wave impact on coastal structures. The first process is the major cause for increase in runup and overtopping of mild-slope structures and the second is more important to vertical or steep-slope structures. A third process ignored in the previous studies is that onshore wind may generate onshore surface currents through the work of wind shear stresses and wind-induced wave breaking in the surf zone. This onshore surface current may greatly increase initial runup bore speed on the surface of revetments and consequently may increase runup heights and overtopping rates.

The influence of wind speed on runup and overtopping needs to be determined. Because of very few laboratory and field measurements concerning wind effects on runup and overtopping, our knowledge of how wind may increase runup heights and overtopping rates is far from sufficient. If design wind conditions are found to have a significant effect on runup and overtopping rates, then a method of calculating runup and overtopping that accounts for wind is clearly needed. Funded by U.S. Army Corps of Engineers (USAE), a joint research program is being conducted by USAE Waterways Experiment Station's Coastal Engineering Research Center (CERC) and the Ocean Engineering Program of the Civil Engineering Department at Texas A&M University (TAMU). This paper presents some initial findings from this on-going study.

OBJECTIVES

This study is evaluating effects of wind on runup and overtopping of coastal structures through physical model studies conducted in a combined wind/wave flume at TAMU.

Analysis of the data should lead to a better understanding of the physcis of wind effects on coastal structures. Although it is not possible to fully describe mathematically the processes involved, such as wave breaking or flow through a porous media of randomly shaped, randomly placed armor units, a better understanding is sought of the energy transfers and physical processes involved.

Because of the difficulty of fully describing mathematically the processes involved, empirical equations will be developed to estimate runup and overtopping on coastal structures, including wind effects. This study hopes to provide design guidance for the range of conditions typically encountered in coastal structures design work, within the limitations of the test facility and test conditions.

TEST FACILITY

Physical model tests are being conducted in a 36-m-long by 0.61-m-wide by 0.91-m-deep glass-walled wave flume equipped with a flap-type mechanical wave generator (Figure 1). The electrically-activated wave generator is capable of producing monochromatic wave trains as well as spectral wave trains through a computer-generated signal.

A blower is mounted above and at the far end of the wave flume, away from the wave generator. An intake manifold is located in front of the wave generator, therefore wind is pulled along the length of the flume and exhausts away from the wave generator. The entire flume is covered with removable panels to contain the wind. The blower is capable of producing an average wind velocity in the flume of 16 m/s over a water depth of 50 cm.

A plywood slope followed by a 2-m-long sealed overtopping basin are installed in the end of the flume away from the wave generator. Various extensions allow crest elevation of the slope to be varied. The current slope is set

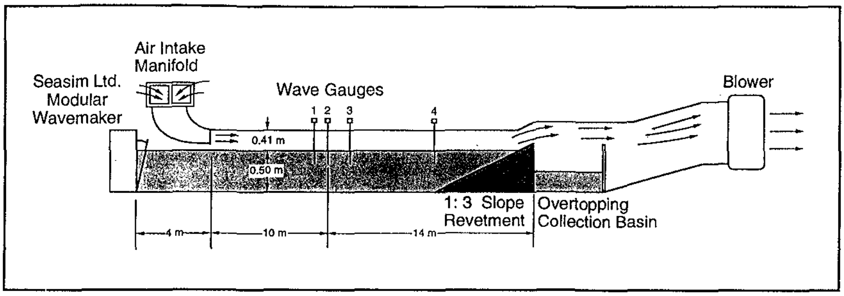

Figure 1. Wave flume test facility at Texas A&M University.

at 1:3 (V:H); other slopes will be installed at the conclusion of testing with the 1:3 slope. Runup on the slope is measured by two resistance gages mounted on the slope face, and by visual observation.

Three resistance wave gages are set in an array approximately mid-way between the wave generator and test slope, and a fourth gage is positioned at the toe of the slope. Gage spacing in the three-gage array is adjusted for different test periods to allow separation of incident and reflected wave trains using the method of Goda and Suzuki (1976).

TEST PARAMETERS

Table 1 lists parameters that will be varied in this study to provide design information covering a range of typical design conditions and to study separately the various effects of wind on runup and overtopping. The current test schedule includes revetment slopes of 1:1.5, 1:3, and 1:5, and of varying crest elevations to study both runup and overtopping rates. Overtopping of a vertical wall will also be studied. Two water depths are being tested, and two or three monochromatic wave heights at each of three wave periods. Greater wave height would have been preferred for the longer wave periods, but were limited by wave generator capability. Each combination of water depth and incident wave conditions will be tested without wind, then at 50%, 75%, and 100% of maximum blower output. Both smooth and rough revetments slopes will be tested, with rough slopes covered with armor stone in accordance with design guidance in the Shore Protection Manual (1984) and Engineering Manual 1110-2-1614, Design of Coastal Revetments, Seawalls, and Bulkheads (1985). At the completion of tests with monochromatic wave conditions, a series of tests will be conducted with irregular waves covering a range of wave heights and periods.

It should be emphasized that the testing program is still in its early phases. This paper presents results obtained only from the 1:3 smooth slope revetment with monochromatic wave conditions and a water depth of 50 cm. Each test was conducted twice; data shown in this paper is the average of the two tests.

Table 1. Ranges of test parameters planned for this study.

Wave Periods(s)	Wave Height(cm)	Revetment Slopes	Structures
1.0	5.0, 7.0, 10.0	1 : 1.5	* Smooth Slope Revetmen
		*1 : 3.0	Rough Slope Revetment
1.75	3.2, 5.4	1 : 5.0	
			Vertical Wall
2.5	2.2, 3.8		

Water Depth(cm)	Wind Speed % of Fan Power	Revetment Heights above SWL (cm)
*50.0	0 (0 m/s)	10.0
	50 (8 m/s)	20.0
	75 (12 m/s)	30.0
	100 (16 m/s)	
65.0	0 (0 m/s)	10.0
	50 (9 m/s)	20.0
	75 (13 m/s)	
	100 (17 m/s)	

* Results Presented

RESULTS AND DISCUSSION

Causes of wind effects on runup and overtopping

Wind affects runup and overtopping of coastal structures in several ways that are not reproduced in a typical wave flume (without wind generating capabilities). Beginning seaward of the structure, local winds may modify incident wave spectra through changes in direction or intensity and affect shoaling of wave trains as they approach shallow water. Wind-induced setup by onshore winds is also observed due to pressure gradients and wind shear at the air/water interface. Higher water levels due to setup result in higher runup both by raising the elevation at which runup begins and by allowing larger waves to reach the structure without breaking. As waves reach shallower water, onshore winds may cause a transfer of potential energy (wave height) to kinetic energy (surface current) through wind-induced wave breaking and through shear effects. Increased kinetic energy may cause higher initial velocities of the runup bore, which would result in greater runup heights. On the structure itself, onshore winds may create a favorable pressure gradient around the wave, and produce shear forces on the wave and runup bore. Finally, waves breaking on a coastal structure create large quantities of spray and on vertical structures may produce large vertical sheets of spray. On prototype structures the onshore winds carry spray over the structure, contributing to overtopping, but in most wave flumes the spray falls back into the flume seaward of the structure and is not measured as overtopping.

Wave runup and overtopping results

A series of tests with monochromatic wave conditions was conducted to compare runup and overtopping rates without wind to runup and overtopping rates when wind of different intensities is added to monochromatic wave conditions. Mechanically-generated waves used in these tests had frequencies of 1.0 Hz, 0.57 Hz, and 0.40 Hz. Waves generated by wind had a frequency of about 2.0 Hz at the toe of the test revetment. Because the mechanically generated waves had a different frequency than waves generated by wind, the result was a bi-modal spectrum comprised of a sharp, low-frequency monochromatic peak for the mechanically generated wave and a broader, high-frequency peak for wind generated waves. In an exaggerated fashion, this is somewhat analogous to ocean swell nearing the coast and being acted upon by local winds.

The figures that follow in this text plot data collected from the wave flume study. The abscissa in all but one of the following figures is wave steepness defined as wave number, k, times wave amplitude, a. Wave number is defined as $2\pi/L$, where L is Airy wavelength determined from flume depth and wave period of the mechanically generated wave. Wave amplitude was determined as one-half the wave height of the mechanically generated wave. To simplify understanding the data these figures, wave steepnesses (ka) used in these tests are given in ascending order in Table 2 along with wave period and wave height. All tests were conducted at a water depth of 50 cm.

Table 2. Wave steepness, period, and height for each set of test conditions presented in this paper.

ka	Wave Period (sec)	Wave Height (cm)
0.013	2.50	2.2
0.023	2.50	3.8
0.029	1.75	3.2
0.049	1.75	5.4
0.104	1.00	5.0
0.146	1.00	7.0
0.208	1.00	10.0

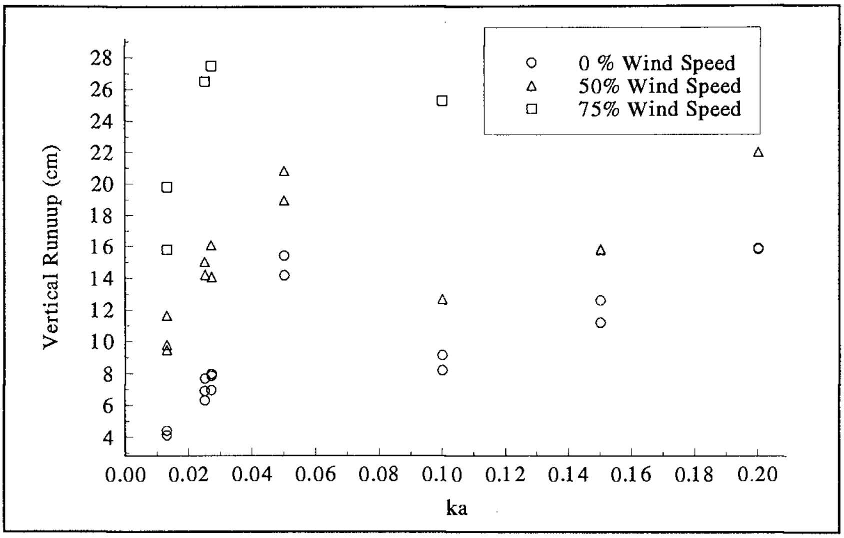

Figure 2. Maximum wave runup for various wind speeds tested.

Figure 2 plots maximum runup versus wave steepness for a range of wind conditions. Because different revetment crest elevations were tested for the overtopping portion of this study, much of the runup data was collected from revetments with more than one crest elevations, which accounts for the paired data points shown in the figure. The ordinate in Figure 2 is maximum runup divided by wave height of the mechanically generated wave without wind effects. Maximum runup was determined visually by observing the runup bore. Small, narrow streams of runup that progressed considerably higher up the test revetment than the bulk of the runup bore were ignored, and an average maximum runup across the middle one-third of the flume was estimated. Wind speeds are presented as a fraction of the maximum blower speed. Average wind speeds for the two depths tested are shown in Table 1.

Figure 2 shows a dramatic increase in runup for tests with wind over tests without wind. This is hardly surprising because wind is introducing more energy into the system. Maximum wave heights occur when crests of a wave from each of the two wave trains coincide, producing a wave amplitude slightly greater than the sum of the individual wave heights (Zhang *et al.* 1992). Because maximum runup elevation is proportional to maximum wave height, increases in maximum runup elevation with addition of wind is expected.

Although crests of a wave from each wave train may coincide to produce a maximum wave height, it is just as likely that a wave trough from one wave train will coincide with a crest from the other wave train. The effect of the wind-generated wave train on overtopping rate, which is time-averaged, is therefore

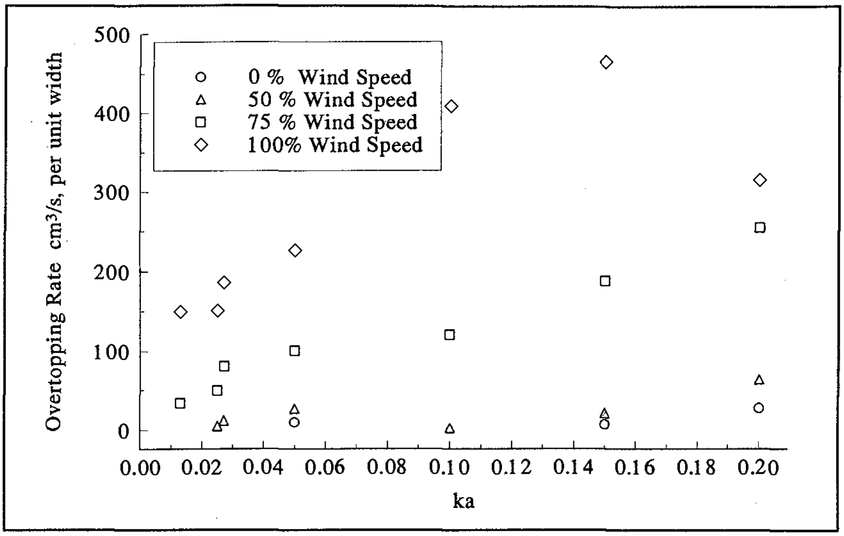

Figure 3. Overtopping rate for different wind speeds tested (revetment height 10 cm above swl).

expected to be less significant than effect of wind on maximum runup. This is illustrated in Figure 3, which shows overtopping rates for a fixed revetment crest elevation of 60 cm (10 cm above swl). The 50% wind speed had little effect on overtopping rate, although larger increases were observed at 75% and 100% wind speeds. The sharp decrease in overtopping rate for maximun wind speed and wave steepness between 0.146 and 0.208 is noteworthy. The mechanically generated wave for $ka = 0.208$ was a 1.0-sec, 10-cm wave (Table 2). At 100% wind speed, the 10-cm waves broke before reaching the revetment.

It is seen in Figure 3 that the increase in overtopping rate with wind is much greater for waves tested with a period of 1.0 sec ($0.10 \leq ka \leq 0.20$) than for tests with wave periods of 1.75 sec or 2.5 sec. An explanation for this may be found in Figure 4.

Figure 4 shows the change in H_{mo} of the mechanically generated wave under the influence of wind. Because the frequency of wind waves (≈2 Hz) differs significantly from frequencies of the 1.75-sec or 2.5-sec waves, wind is seen to have little effect on H_{mo}'s of the longer waves. However, the frequency of the wind waves is relatively close to the frequency of 1.0-sec waves, and wind energy is seen to have a significant effect on the H_{mo} of the 1.0-sec waves.

Mechanically reproducing a wind/wave spectrum

Assuming constant wind conditions, effects of wind on incident waves prior to shoaling may be accounted for by mechanically reproducing a fully developed

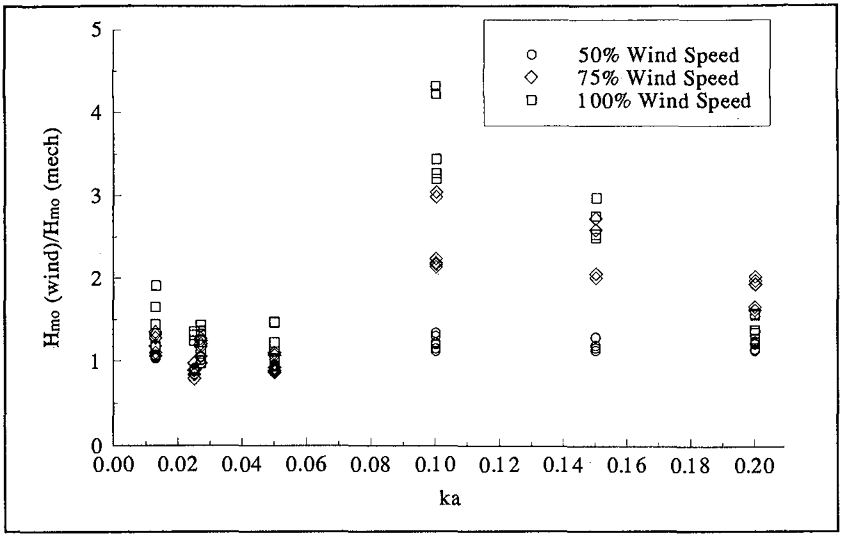

Figure 4. Wind effect on H_{mo} of mechanically-generated wave.

wind spectrum. This is the typical test condition for runup and overtopping in most wave flumes, but fails to account for wind effects during shoaling or wind effects at or near the structure.

To determine effects of wind on runup and overtopping at the structure, an attempt was made to mechanically reproduce the combined wind/wave spectrum. The wave record from the wave gage at the revetment toe (gage 4) taken during tests which included wind blowing over a mechanically-generated wave train was analyzed and the combined spectrum determined. The combined spectrum included a low-frequency wave from the mechanically-generated wave train, and a high-frequency wave generated by wind. Because high-frequency waves travel slower than low-frequency waves, the combined spectrum could be reproduced mechanically by generating a series of high-frequency waves and following with a series of low-frequency waves. When the low-frequency waves catch up with high-frequency waves, the combined spectrum is obtained. Trial and error was used to adjust the H_{mo}'s of the high- and low-frequency mechanically generated waves to match the combined wind/wave spectrum.

The wave generator was unable to reproduce the high frequency of wind waves (≈2 Hz), therefore the frequency used was the highest frequency at which H_{mo} of the 50% wind could be reproduced. The 50% wind was chosen because the wave generator was capable of reproducing the wind wave at a higher frequency than it could reproduce larger wave heights generated by higher wind speeds. Figure 5 shows a mechanically-produced spectrum compared to the wind/wave spectrum. Except for the slightly higher frequency of wind waves, the two spectra are very similar.

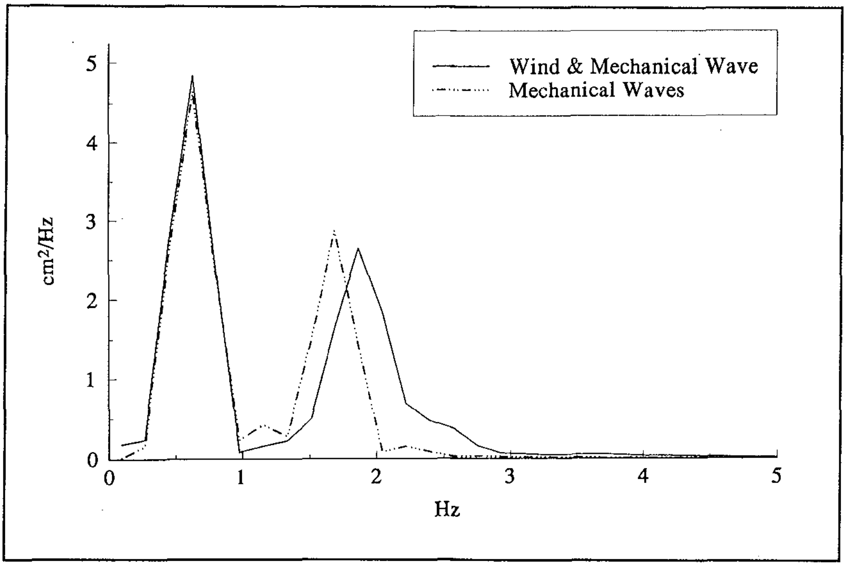

Figure 5. Comparison of energy spectra of wind/wave spectrum and mechanical reproduction of wind/wave spectrum.

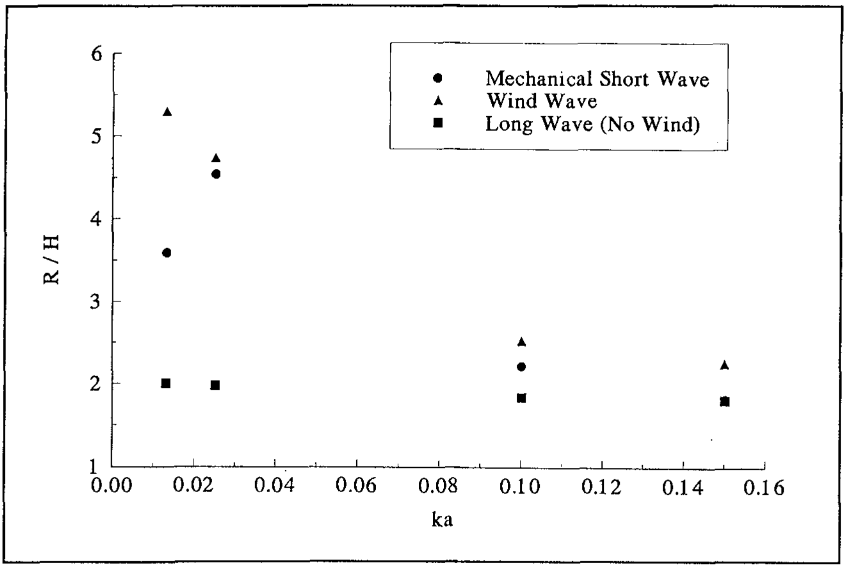

Figure 6. Maximum wave runup for no-wind condition, wind/wave condition, and mechanical reproduction of wind/wave condition (wind speed 50% of maximum).

Figure 6 shows runup information for the four tests reproduced mechanically. Runup data for mechanically-generated, low-frequency wave and for the combined wind/wave spectrum is the same as seen in Figure 2, but Figure 6 also plots runup from mechanically reproduced dual-peaked spectrum. Additional runup observed with wind is attributed to higher surface velocities due to wind-induced breaking and to wind effects on the runup bore.

Figure 6 clearly demonstrates that mechanically simulating wind waves fails to reproduce runup that will occur on prototype structures in the presence of onshore winds, and suggests that current formulae for estimating runup and overtopping of coastal structures therefore underestimate prototype runup and overtopping. However, until scaling relationships for a combined wind/wave experiment have been determined, and until relative effects of wind-induced setup in a wave flume and the prototype have been examined, it is not possible to quantify additional runup and overtopping that will occur on prototype structures.

Final comments

It is clear that wind affects runup and overtopping through a variety of processes and that mechanically reproducing a wind/wave spectrum will only account for some of the wind effects. Additional study is required to separate and quantify effects of wind due to the various processes involved.

In these tests, two key questions need to be answered before a relationship can be determined between model test results and real-world situations. First, the relationship between wind-induced setup in a wave flume and prototype wind-induced setup needs to be determined. Significant setup was observed during physical model tests with wind, which was seen to have an important effect on runup and overtopping. Second, a scaling relationship for runup and overtopping in a combined wind/wave environment needs to be determined. Waves, with gravity as the main restoring force to the inertial forces, are scaled by Froude's law. Wind effects, on the other hand, transfer energy to fluid through shear forces and are scaled by Reynold's law. To satisfy both Froude's law and Reynold's law in a single model requires either a centrifuge to increase gravitational effects in the model, or use of a "super fluid" to change viscous effects in the model. Neither of these options is practical for tests of this size.[5] Scaling relationships need to be explored to allow effects of wind and waves on runup and overtopping to be

[5]A large centrifuge is currently being constucted at WES to be completed in 1995. Test beds for the centrifuge will include a minature wave flume approximately 2 m long equipped with a flap-type wave generator with spectral capabilities and a water-based fluid that can be mixed to obtain a range of kinematic viscosities. Although the centrifuge will be able to create up to 350 g's, the wave flume will be designed only for loads up to about 35 g's. A combined wind/wave environment in the flume could be obtained by redirecting wind created by movement of the wave flume through the air by the centrifuge.

considered separately and then hopefully they may be applied to prototype prototype coastal structures.

ACKNOWLEDGEMENT

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