CHAPTER 157

WAVE RUN-UP AND SEA-CLIFF EROSION

S.-M. Shih[1], P. D. Komar[2], K.J. Tillotson[2],
W.G. McDougal[3] and P. Ruggiero[3]

Abstract

Studies have been undertaken along the Oregon coast to better understand the processes involved in sea cliff erosion in order to develop improved predictions of the susceptibilities of properties to wave attack. A model has been developed that includes evaluations of extreme water elevations measured by tide gauges, calculations of wave run-up levels due to major storms, and a documentation of beach morphology variations that affect the wave run-up and determine the elevation of the junction between the beach and toe of the sea cliff. The occurrence of erosion depends on the combined water levels compared with the beach/cliff junction. All of these factors vary with time and also spatially along the coast. A program has been initiated to measure wave run-up on Oregon beaches ranging from reflective to dissipative in order to test the model predictions.

Introduction

The erosion of sea cliffs backing beaches generally depends on the run-up of large waves generated by a major storm, superimposed on elevated water levels due to tides and other processes that affect water elevations (storm surge, etc.). Critical is the total level achieved by the water compared with the elevation of the junction between the beach and face of the sea cliff. These factors vary with time, tending

[1]Institute of Oceanography, National Taiwan Univ., Taipei, Taiwan
[2]College of Oceanic & Atmos. Sciences, Oregon State Univ., Corvallis, OR 97331
[3]Ocean Engineering, Oregon State Univ., Corvallis, OR 97331

to reach extremes during the winter months so that the susceptibilities of properties to erosion are greatest in that season. The factors can also vary spatially along the length of coast, particularly the morphology of the beach and the degree of protection it offers to the sea cliff from wave attack.

In order to evaluate the susceptibilities of coastal properties on sea cliffs to wave erosion, it is necessary to make quantitative assessments of: (1) potential mean-water elevations due to tides, storm surges, and other processes, (2) the most extreme run-up levels of storm-generated waves, and (3) expected elevations of the beach/cliff junction. The application in this paper is to the Oregon coast, but the techniques can be used on other coastlines, employing wave and water-level data specific to those areas. In this paper we report on analyses of extreme mean-water levels measured by a tide gauge, on calculated wave run-up elevations due to major storms, on a program that has been initiated to measure wave run-up on a variety of Oregon beaches to test the extreme predictions, on efforts to document the beach morphology variations that affect wave run-up and determine beach/cliff junction levels, and on efforts to apply the analyses in coastal-zone management decisions such as the establishment of set-back distances.

Study Site

Erosion has been common along the Oregon coast due to the high energy of the wave climate and the dynamic behavior of its beaches. Much of this erosion has occurred in sea cliffs backing beaches, of concern in that many communities are sited on uplifted marine terraces that are suffering from sea-cliff recession. The erosion has been episodic, associated with the occurrence of extreme storms, but it also has been spatially variable. This spatial variation is due in part to the tectonic setting of Oregon, which has resulted in different rates of coastal uplift (Komar and Shih, 1993). In general, the southern part of the coast and the northern-most part near the Columbia River are rising faster than the present rate of sea level rise, while the north central stretch has minimal uplift and therefore is experiencing a sea-level transgression due to the global rise in sea level. This coast-wide pattern of relative sea-level change is reflected in the degree of sea

cliff erosion. However, there are also more local controls which include the volume of sand on the fronting beach and the corresponding ability of the beach to act as a buffer between the sea cliffs and storm waves (Shih and Komar, 1994). The north-central portion of the Oregon coast, where erosion has been greatest, is segmented into a series of littoral cells by large headlands, which effectively isolate the stretches of beach within each cell. Sources and losses of sand to the series of littoral cells are highly variable, and this has controlled the amount of sand on the beach and the elevation of the beach/cliff junction. As a result, there tends to be differences in susceptibilities of properties to erosion between the series of littoral cells. It is this high spatial as well as temporal variation in the susceptibilities of properties to erosion that has made it important to develop analysis techniques that can assist in rationally evaluating those susceptibilities.

Model Development and Process Evaluations

The Basic Model

The model is illustrated in Figure 1. The probability of water reaching the base of a sea cliff backing the beach is dependent on water-elevation factors which include:

1. The tide level within its predicted harmonic cycle;
2. Processes such as storm surge, water temperatures, and the occurrence of an El Niño that produce departures of the mean water level from the predicted tidal elevations;
3. Set-up induced by waves breaking on the beach;
4. The frequency and elevations achieved by the run-up of individual waves above the mean set-up level.

Important to the induced erosion of sea cliffs is the comparison between elevations achieved by the water due to these combined processes ($H_T + \overline{\eta} + R$ in Figure 1), and the elevation of the junction of the beach face with the sea cliff (H_J). Wave-induced property erosion will not occur unless the elevation of the water exceeds the elevation of the beach/cliff junction ($H_T + \overline{\eta} + R > H_J$). Implementation of the model to evaluate the susceptibilities of sea cliffs and associated properties to erosion depends on the ability to quantitatively evaluate the processes that govern water and beach elevations.

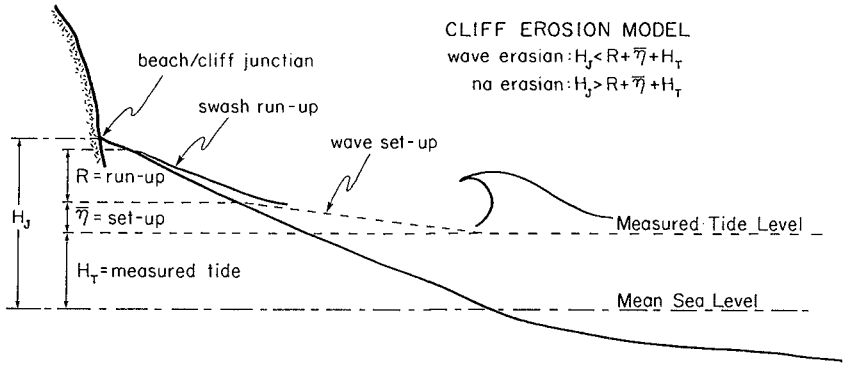

Figure 1: The basic model for the quantitative assessment of the susceptibilities of sea cliffs to wave-induced erosion.

Extreme Water Levels

From the above list of water-level factors, it is apparent that tides are generally an important process controlling water elevations on the beach and thus the probability of waves reaching the toe of the cliff. Water-level elevations resulting solely from tide-generating forces are predictable, but there can be significant departures from those predictions due to a number of oceanic and atmospheric processes. The analyses presented here are based on the tide-gauge records from Yaquina Bay on the central Oregon coast. Measurements from that gauge span a sufficient number of years for projections of extreme water-elevations expected within a 100-year time frame.

The yearly extreme high tides recorded at the Yaquina Bay tide gauge have been analyzed to construct the probability curves of extreme water levels shown in Figure 2. The measurements were modeled by the General Extreme Value distribution (Shih, 1992). The results are expressed in terms of recurrence intervals of the water-level elevations, but can also be expressed as the probability of occurrence of a specified level during a given year. Based on the measured water levels, the projected 100-year elevation is about 2.5 meters above mean sea level (MSL). A similar analysis of the predicted yearly extreme tides yields a curve that is displaced well

below that based on measured tides, Figure 2, and yields a projected 100-year predicted tidal elevation of about 2.0 meters, some 50 cm lower than that based on the measured extreme tides.

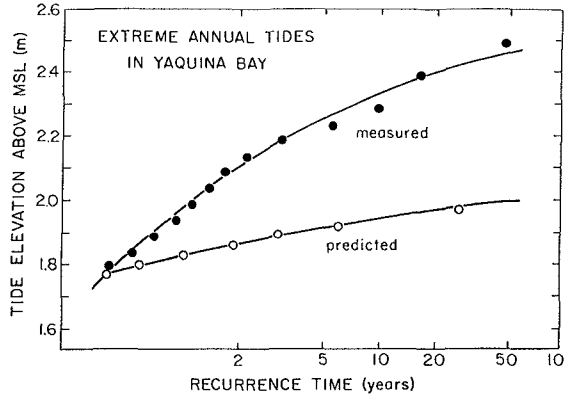

Figure 2: Analyses of extreme predicted and measured tides based on the yearly maximum elevations recorded on the tide gauge in Yaquina Bay on the central Oregon coast.

The results demonstrate that there are significant differences between predicted and observed extreme tides, with the measured elevations typically being 10's of centimeters higher. This demonstrates the importance of the oceanic and atmospheric processes such as storm surge, water temperatures, etc., that can raise water levels well above predicted tidal elevations. It is important to account for the causes of the differences between the measured versus predicted tides in order to improve our basic understanding of the processes. Detailed analyses of these processes are still underway, but the broad seasonal variations are apparent. Higher water levels occur during the winter off the Oregon coast due to the generally warmer water temperatures (upwelling during the summer makes the water colder and denser, depressing the water-surface level); typically, mean-water elevations are about 20 cm higher during the winter than in the summer (Huyer et al., 1983). A particularly important phenomenon affecting extreme water levels is the occurrence of an El Niño; for example, the 1982-83 El Niño raised water levels by approximately 15 cm above the previously measured high levels for the winter months, on the

order of 35 cm above the average measured levels for those months (Huyer et al., 1983; Pittock et al., 1982).

There can also be daily fluctuations in mean water elevations such as those due to a storm surge as low-pressure fronts cross the coast. This factor has been investigated for only a few specific storms that resulted in property erosion along the Oregon coast (McKinney, 1976). In those few cases the maximum increases in water elevations attributable to storm surge were less than 20 cm. This small magnitude, compared with other coastal areas, results because the storms either crossed the coast too fast to develop a sizable wind set-up of the water, or the extreme waves of the storm were generated by a large fetch but not by extreme winds. More study of storm surge on the Oregon coast is needed, since it still exerts an important control on the total elevation of the water, and thus on the occurrence of sea cliff erosion; furthermore, there may be circumstances when storms do give rise to more significant storm surges on the Oregon coast.

Storm Waves and Run-up Levels

The second component in the cliff-erosion model is the evaluation of wave run-up associated with major storms. An assessment of this factor requires a good documentation of the deep-water wave climate and a capacity to calculate wave run-up elevations on beaches for those wave conditions.

A variety of wave-data sources is available for the Oregon coast upon which to base projections of extreme-wave parameters, which in turn can be used to calculate extreme run-up elevations. The data sources include the deep-water buoy data of the Coastal Data Information Program (CDIP) of the Scripps Institution of Oceanography, and from the National Data Buoy Program (NDBP) of NOAA. Those buoy-measurement programs began only in the 1980s, and in themselves do not provide a sufficiently long record upon which to base extreme-wave projections. Important in this respect are wave data derived from the microseismometer system operated by Oregon State University at the Marine Science Center in Newport. This system has been in operation since 1971, yielding measurements of significant wave heights and periods four times each day. Direct comparisons between buoy and microseismometer measurements demonstrate that the seis-

mometer yields good data for significant wave heights, while the periods are systematically too large (Tillotson, 1995; Tillotson and Komar, in review). Wave data are also available for the 20-year period from 1956 to 1975, derived from the daily wave hindcasts of the Wave Information Study (WIS) of the U.S. Army Corps of Engineers. Unfortunately, the WIS wave heights are systematically 30% too high in comparison with the direct measurements. An attempt was made to recalibrate the WIS data in order to make it more compatible with the wave climate based on the direct measurements, but the results then yielded too few storm-wave conditions based on a threshold of the significant wave height being greater than 6 meters, the limit used in the extreme-wave analyses. Therefore, the extreme-wave analyses had to rely on the combined measurements of the deep-water buoys (specifically the CDIP buoy offshore from Bandon, Oregon), and the wave data derived from the microseismometer system (Tillotson, 1995; Tillotson and Komar, in review). The data base thereby consists of 23 years of daily wave measurements, during which 24 storms were identified as having deep-water significant wave heights equal to or greater than 6 meters. The largest measured deep-water significant wave height was 7.3 meters, while extreme-wave analyses yielded a wave height of 7.8 meters for the 50-year projection, and a less reliable value of 8.2 meters for the 100-year projection. If a 5-meter wave height is used to define "storms" rather than 6 meters, then the projected 50-year and 100-year wave heights are respectively 8.2 and 8.8 meters.

This established deep-water wave climate has been used to calculate extreme run-up elevations on Oregon beaches backed by sea cliffs. There is a considerable literature derived from studies of wave run-up on structures such as jetties and on natural beaches; Douglass (1990) provides a recent review, and van der Meer and Stam (1992) have undertaken a synthesis of the extensive laboratory results. The analysis approach used here is based mainly on the field measurements of Holman and Sallenger (1985) at the Field Research Facility, Duck, North Carolina, and in particular on the results of Holman (1986) derived from his reanalysis of the data to evaluate extreme run-up elevations. Holman analyzed run-up in terms of the mean run-up level, the significant level (elevation of the

highest one-third), the 2% exceedence elevation, and the absolute maximum run-up elevation achieved during a 20-minute measurement record. In our predictions, we have used the 2% exceedence, denoted by $R_{2\%}$. Similar to earlier studies, Holman (1986) found that this run-up elevation can be predicted by the relationship

$$\frac{R_{2\%}}{H_s} = C\xi \qquad (1)$$

where H_S is the deep-water significant wave height, C = 0.90 is an empirical constant established by the measurements, and ξ is the dimensionless Iribarren number defined as

$$\xi = \frac{S}{(H_s/L_o)^{1/2}} \qquad (2)$$

where S is the slope of the beach face and L_o is the deep-water wave length given by $L_o = (g/2\pi)T^2$ where g is the acceleration of gravity and T is the wave period. Combining the above equations yields

$$R_{2\%} = CS(H_s L_o)^{1/2} = C\left(\frac{g}{2\pi}\right)^{1/2} SH_s^{1/2}T \qquad (3)$$

for the run-up elevation as a function of the deep-water significant wave height and period, and of the beach slope. Equation (3) accounts for the total run-up elevation due to the presence of waves, that is, it combines the wave-induced set-up which raises the elevation of the mean shoreline, and the swash elevation of individual waves beyond that mean shoreline. If analyzed independently, the set-up and swash elevations both have predictive equations like the above relationships, but the coefficients in equation (3) are respectively C = 0.35 and 0.55, which sum to the 0.90 coefficient.

Equation (3) has been used to calculate expected run-up elevations associated with the 24 storms during the past 23 years. Here the calculation depends on the wave period during the storms, as well as the wave heights. This emphasizes the importance of storms in that, as is commonly found, there is a broad positive correlation between significant wave heights and periods (Tillotson, 1995; Tillotson and Komar, in review), which combine in equation (3) to yield the most extreme run-up elevations on Oregon beaches during the past 23 years. Those calculated $R_{2\%}$ values for the 24 storms have been subjected to an extreme-value analysis using the Automated

Coastal Engineering System (ACES) developed by the U.S. Army Corps of Engineers. Assuming a beach-face slope of S = 0.03, an approximate average for the Oregon coast, the projected 50-year run-up level is 1.87 ± 0.15 meters, while the less reliable 100-year projection is 1.97 ± 0.17 meters (Tillotson, 1995). These magnitudes for the extreme wave run-up are comparable to the total tidal excursion on the Oregon coast, and are much larger than water-level enhancements resulting from storm surge, etc. The calculations, therefore, reconfirm the importance of run-up during storms being a major factor in causing sea-cliff erosion.

Beach Morphology and Elevations

The elevation of the beach/cliff junction, H_J (Fig. 1), can vary from one beach to another due to the total quantities of sand within the littoral cells, and with the grain size of the beach sediment. The grain-size dependence has been demonstrated by Shih and Komar (1994) in a study of the Lincoln City littoral cell on the central Oregon coast. This cell is unusual in that there is a pronounced and systematic longshore variation in sediment grain sizes and thus in the beach morphology, ranging from dissipative to reflective systems. The coarser-sand reflective beaches have higher beach/cliff junction elevations, probably resulting from the higher levels that can be achieved by run-up during storms due to the slope dependence S in the run-up relationships. Furthermore, the coarser-sand beaches undergo larger profile changes through the seasons, and also experience greater profile shifts during individual storms as compared with the finer-sand beaches. Rip currents on the coarser-sand beaches tend to erode larger and deeper embayments into the berm, and this in particular can lower the elevation of the beach/cliff junction, thereby locally and temporally increasing the susceptibility of the property to erosion.

The analyses have established that a critical component to the development of cliff erosion models is the determination of the beach/cliff junction elevation and how it depends on the total quantities of sand on the beach, the coarseness of the sediment, and on factors such as the occurrence of a rip-current embayment that locally lowers the elevation. This

component has been particularly important to the occurrence of cliff erosion episodes along the Oregon coast.

Measurements of Wave Run-up

In order to test the model that combines water elevations with calculated wave run-up levels, and to better understand the processes involved in sea-cliff erosion, we have begun a program to measure wave run-up on a number of beaches. Swash run-up is measured using the video techniques developed by Holman and Sallenger (1985). This includes beach profile surveys of the swash zone, and the video recording of the run-up signal during high tides, with markers placed on the beach for geometric transformations. The time series of vertical run-up signals were then extracted from the two-dimensional video intensity signal using the beach profile elevations and known geometric positions of the markers. The highest run-up levels achieved during 50-second time intervals were sub-sampled from a 70-minute run-up time series digitized at 1 Hz, giving a total of 82 data points of run-up maxima; a long sampling interval and time series were necessary due to the strong infragravity component in the run-up. The run-up maxima were then analyzed to determine the maximum run-up (R_{max}) achieved during the 70-minute measurement interval, the 2% exceedence statistic ($R_{2\%}$), the 33% "significant" exceedence ($R_{1/3}$), and the mean run-up elevation ($\overline{R}$); all of these measurements include the set-up elevation.

Thus far, three sites along the Oregon coast have been included in the measurement program, representing different degrees of beach sand volumes and buffering capacities, and different beach sand grain sizes and morphologies ranging from strongly dissipative to reflective. The results from the three beaches are given in Figure 3, where all elevations are with respect to mean sea level as established by surveying from nearby bench marks. The tide levels shown are for the times of run-up measurements. At Beverly Beach the maximum run-up exceeded the beach/cliff junction elevation, and the extreme swash was observed to surge up the face of the cliff. Beverly Beach is located within a littoral cell that is deficient in sand volume, and this in part is reflected in the low level of its beach/cliff junction elevation (4.1 meters, MSL) compared

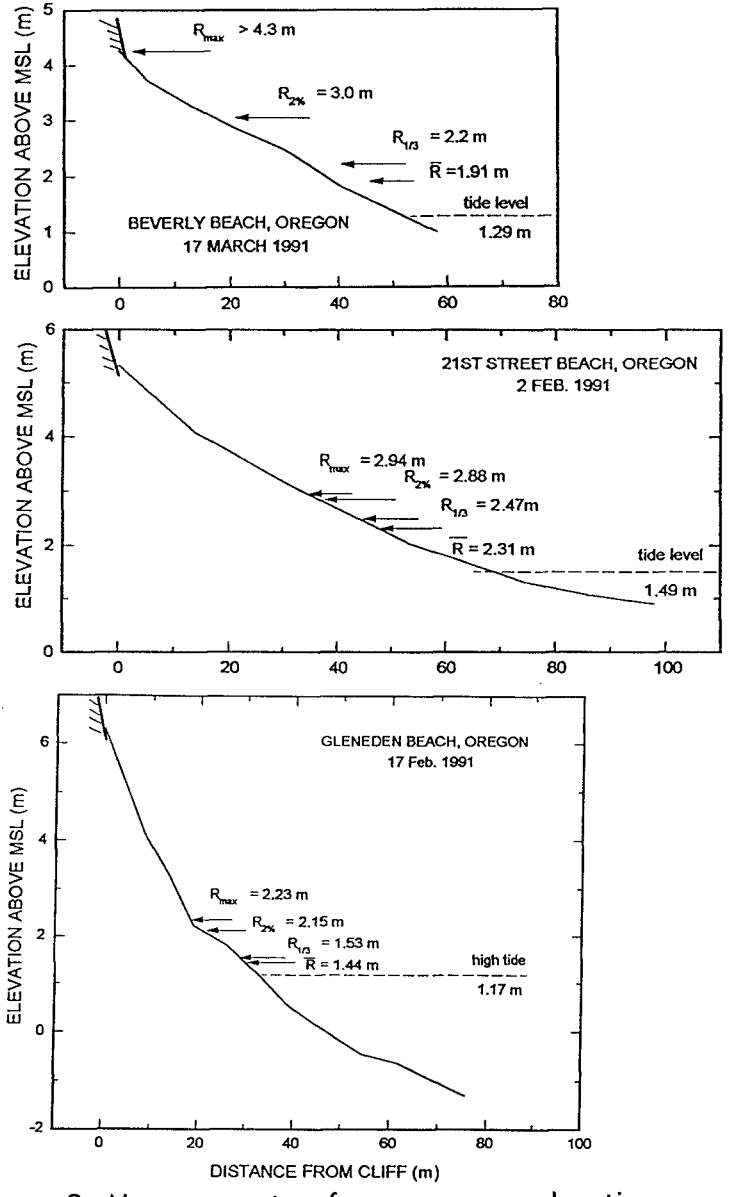

Figure 3: Measurements of wave run-up elevations on three beaches along the Oregon coast, where all elevations are referenced to mean sea level (NGVD).

with the other two beach locations included in Figure 3 (elevations of 6.2 and 5.3 meters, MSL). This difference in part also results from the contrasting grain sizes of the sediments on these three beaches. The lower beach/cliff junction elevation at Beverly Beach, has resulted in a high frequency of wave run-up reaching the toe of the cliff, and in substantially greater erosion compared with most other locations on the Oregon coast.

The other two beach locations included in the run-up measurements, Gleneden Beach and 21st Street Beach, are within the Lincoln City littoral cell (Shih and Komar, 1994). Gleneden Beach is coarser grained and has the steeper slope so it is reflective (summer) to intermediate (winter), while the beach at 21st Street is composed of fine sand and is always dissipative. During the times of run-up measurements, Figure 3, the swash did not reach the beach/cliff junctions at either location, and this is generally the case as cliff erosion is a relatively rare event within the Lincoln City littoral cell due to the large quantities of sand on the beaches. In that cell, rip currents play a particularly important role in locally reducing the beach/cliff junction elevation, H_J, during the occasions of episodic erosion.

The run-up measurements can be analyzed to test the model predictions, specifically the predicted elevation achieved by the calculated $R_{2\%}$ run-up level superimposed on the measured tide, compared with the measured results. Although the measurements thus far have not included extreme-storm conditions, the comparisons can still provide a test of the model. The comparisons for the three data sets of Figure 3 are given in Table 1.

Table 1: Model and Measurement Comparisons

Location	Date	Tide (MSL) (meters)	H_S (m)	T (sec)	$R_{2\%}$ + Tide	
					Calc.	Meas.
Gleneden	2/2/91	1.17	1.56	13.1	2.04	2.15
21st Street	2/17/91	1.49	2.76	13.1	2.31	2.88
Beverly Beach	3/17/91	1.29	3.47	14.2	2.47	3.00

In each comparison in Table 1, the predicted water elevation is lower than the measured elevation, the difference ranging from about 10 to 50 cm. This difference results from the calculated $R_{2\%}$ using equation (3), versus the measured run-up elevation, since the measured tidal elevation is the same in both calculated and measured total water levels in Table 1. This suggests that equations (1) and (3) based mainly on the measurements of Holman and Sallenger (1985) and Holman (1986) at the Field Research Facility, Duck, North Carolina, will need to be revised for the present application to run-up on Oregon beaches. Such a revision at this stage is premature, as we presently have only the three measurement sets shown in Figure 3. A primary objective of our ongoing research is to obtain more run-up data on a greater variety of beaches, at which time refinements in the model calculations can be made.

Summary and Discussion

The application of the sea-cliff erosion model to the Oregon coast has shown that the predicted tides, elevations of mean water levels due to a variety of processes, and wave run-up during major storms can all be contributing factors to the erosion. Also important is the morphology of the beach, and in particular the elevation of the beach/cliff junction. In some littoral cells on the Oregon coast, this junction elevation is low due to the paucity of sand on the beach, allowing elevated water levels to frequently reach the toe of the sea cliff, resulting in more rapid erosion. In other littoral cells there are sufficient volumes of sand on the beach that it generally can act as a buffer between the water and sea cliff. In those cells rip currents at times cut embayments into the beach and locally lower the beach/cliff junction elevation so that cliff erosion results; the erosion is therefore extremely episodic and spatially variable.

Although the model thus far has been useful in a broad examination of sea-cliff erosion variability along the Oregon coast and in accounting for the susceptibilities of properties to erosion in the various littoral cells, refinements based on additional field data are needed. This is the objective of our on-going research. In particular we are focusing on the video collection of more run-up data on a greater variety of beaches in order to re-calibrate the run-up equations so that they

provide improved predictions. The measurements are also being analyzed to determine the proportions of infragravity versus incident-wave energy so as to provide a better understanding of the dynamics of wave run-up. In that connection, our continuing research is expanding to obtain measurements of water depths and celerities of the bores leading up to the swash, as well as properties of the resulting run-up. The measurements will be used to test and refine models of run-up dynamics and elevation predictions, and to improve the design of shore-protection structures used to reduce sea-cliff erosion.

Acknowledgments

This work is a result of research supported by the NOAA Office of Sea Grant, Department of Commerce, under Grant # NA81AA-D000086, Project R/CP-24.

References

Douglass, S.L.(1990) *Estimating runup on beaches: A review of the state of the art*: C.R. CERC-90-3, U.S. Army Engr. Waterways Experiment Station, Vicksburg, Miss.

Holman, R.A. (1986) Extreme value statistics for wave run-up on a natural beach: *Coastal Engineering*, 9: 527-544.

Holman, R.A., and A.H. Sallenger (1985) Set-up and swash on a natural beach: *Journal of Geophysical Research*, 90 (C1): 945-953.

Huyer, A., W.E. Gilbert, and H.L. Pittock (1983) Anomalous sea levels at Newport, Oregon, during the 1982-83 El Niño: *Coastal Oceanography and Climatology News*, 5: 37-39.

Komar, P.D., and S.-M. Shih (1993) Cliff erosion along the Oregon coast: A tectonic — sea level imprint plus local controls by beach processes: *Journal of Coastal Research*, 9: 747-765.

McKinney, B.A. (1976) *The spring 1976 erosion of Siletz Spit, Oregon, with an analysis of the causative wave and tide conditions*: M.S. thesis, Oceanography, Oregon State University, Corvallis, 66 pp.

Pittock, H.L., W.E. Gilbert, A. Huyer, and R. Smith (1982) *Observation of sea level, wind and atmospheric pressure at Newport, Oregon, 1967-1980*: Data Report 98, College of Oceanography, Oregon State University, Corvallis.

Shih, S.-M. (1992) *Sea-Cliff Erosion on the Oregon Coast: From Neotectonics to Wave Run-up*: Ph.D. thesis, Oregon State University, Corvallis, 135 pp.

Shih, S.-M., and P.D. Komar (1994) Sediments, beach morphology and sea cliff erosion within an Oregon coast littoral cell: *Journal of Coastal Research*, 10: 144-157.

Tillotson, K.J. (1995) *Wave Climate and Storm Systems on the Pacific Northwest Coast*: M.S. thesis, Oceanography, Oregon State Univ., Corvallis.

Tillotson, K.J., and P.D. Komar (in review) The wave climate of the Pacific Northwest (Oregon & Washington): A comparison of data sources: *Journal of Coastal Research*.

van der Meer, J.W., and C.-J. M. Stam (1992) Wave runup on smooth and rock slopes of coastal structures: *Jour. of Waterway, Port, Coastal and Ocean Engineering*, Amer. Soc. Civil Engrs., 118: 534-550.