Journal of Coastal Research | 12 | 3 | 691–701 | Fort Lauderdale, Florida | Summer 1996

The Effects of Seawalls on the Beach: Part I, An Updated Literature Review

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ABSTRACT

KRAUS, N.C. and McDOUGAL, W.G., 1996. The Effects of Seawalls on the Beach: Part I, An Updated Literature Review. *Journal of Coastal Research*, 12(3), 691–701. Fort Lauderdale (Florida), ISSN 0749-0208.

A previous review by the first author of the literature on the effects of seawalls on the beach is extended to cover the period 1988 to the present. The review synthesizes knowledge on beach profile change, longshore sand transport, and scour in the vicinity of seawalls. Remarkable progress has been made since 1988, with new phenomena and observations reported, such as on longshore transport processes at walls. Some previous results and conclusions of the 1988 review have been cast into doubt, with example new results being that (1) wave reflection at walls may not be a significant contributor to profile change, and (2) scour at seawalls in the field may be more a product of longshore transport and return of overtopping water than a result of direct cross-shore wave action. The validity or usefulness of small-scale physical model tests is questioned. Conclusions and recommendations for future work are given. This paper is the first of a companion set of papers that investigate the effects of seawalls on the beach. The second paper presents a numerical model of cross-shore transport and beach profile change at seawalls that includes wave reflection, and it compares predictions to measurements made at the SUPERTANK project and to recent results found in the literature on scour at walls.

ADDITIONAL KEY WORDS: *Seawalls, beaches, scour, erosion, shore protection, physical models, literature review.*

INTRODUCTION

The textbook *Coastal Environments, An Introduction to the Physical, Ecological, and Cultural Systems of Coastlines* written by R.W.G. "Bill" Carter (1988) is unique in its coverage of the scientific, engineering, and managerial aspects of the coast. The breadth and rigor of the book are a legacy from a career cut short at its peak. Bill's keen interest in the seawall and beach interaction are evident, and for this commemorative volume of the *Journal of Coastal Research* the authors wish to extend the theme by compiling new information and by examining recent physical and numerical modeling results on beach profile change at seawalls. This exercise brings surprising conclusions.

At the time Bill was writing on the interaction of seawalls and beaches, substantial debate was taking place on the effectiveness and functioning of seawalls. As a result, the Coastal Sediments '87 Conference (Kraus 1987a) held in New Orleans, Louisiana, had as a sub-theme "The Effects of Seawalls on the Coast." Papers on the physical processes of beaches and seawalls were presented in two sessions, and a panel session was convened to discuss the subject at a plenary session attended by the approximately 300 participants of the conference representing the fields of coastal engineering, geology, and geomorphology. Subsequently, a special issue of the *Journal of Coastal Research*, edited by Kraus and Pilkey (1988) was published that contains eight papers further exploring seawalls and the beach. Numerous research activities have been undertaken as a result of the intense focus on seawalls and beaches in the mid 1980s, including field data collection as compiled in another special issue of the *Journal of Coastal Research* edited by Finkl and Pilkey (1991).

In this paper, we update the literature reviews of Kraus (1987b, 1988) by analyzing approximately 40 recent papers dealing with the seawall and beach interaction. The 1988 review contains approximately 100 citations to the literature with extensive discussion and synthesis that will not be reproduced here, but which underlie several of the presented topics. In a companion paper (McDougal, Kraus, and Ajiwibowo this issue, referred to here as PART II), we examine profile change observed in front of vertical walls in tests made at the large-scale SUPERTANK Laboratory Data Collection Project (Kraus, Smith, and Sollitt 1992; Kraus and Smith 1994; Smith and Kraus, 1995). PART II also develops a numerical simulation model for wave reflection, cross-shore transport, and beach profile change in the presence of seawalls (McDougal, Kraus, and Ajiwibowo 1994), and the model is applied to examine scour at seawalls to produce new results and to critically examine previous laboratory test and prediction formulas.

95139 received 10 August 1994; accepted in revision 9 April 1995.

BACKGROUND

In this section, information is summarized on the interaction of seawalls and beaches published concurrent with or after the review of KRAUS (1988). In that review, several questions on the interaction were raised and answered based on information in the literature available at that time. These questions concerned the following morphologic and sediment-transport processes associated with seawalls and the beach:

- Maximum depth of scour (scour is defined as a local lowering of the profile below ambient level due to wave and current interaction with a structure)
- Beach profile shape and change
- Beach plan-form shape and change
- Beach erosion and recovery
- Waves and water level
- Horizontal and vertical circulation patterns

All of these topics are touched upon in the present paper, often from a new perspective in light of developments reported in the recent literature and in a companion paper (PART II).

Although seawall design and construction are not dealt with here, for the interested reader we mention the manual by VERHAGEN (1993) for a comprehensive treatment and the paper by FRANCO and TOMASICCHIO (1992) concerning historical seawall designs and modern innovations for protecting the Venice Lagoon, Italy. MAGOON *et al.* (1988) describe qualitatively seawalls that have successfully functioned for 25 years along the coast of southern California from the standpoint of structural integrity. VAN DE GRAFF and BIJKER (1988) give an integrated approach based on their experience for deciding whether seawalls will be effective or ineffective with regard to erosion and long-term shore protection (*cf.* DEAN 1986; KRAUS 1987b, 1988; GRIGGS and FULTON-BENNETT 1988). BASCO, DOLAN, and SINCLAIR (1992b) present a case study of potential legal obligations associated with seawall failure.

A seawall is a shore-parallel structure constructed to prevent landward retreat of the shoreline and inundation or loss of the upland by flooding and wave action. In this review, we include revetments and bulkheads under the heading of "seawalls," although their main function is to prevent erosion but not necessarily prevent flooding. Seawalls are usually built on coasts experiencing chronic erosion or in danger of inundation, and where further shoreline recession and flooding must be prevented. PILARCZYK (1992) discusses the extreme situation of the Netherlands and its many locations at which no erosion or flooding can be tolerated (see also KUNZ (1993) for a similar situation at Nordeney, one of the East Frisian Islands of Germany). A seawall constructed on a beach with ample width and sediment supply, such as occurred on north Padre Island, Texas (MORTON 1988), can introduce unnecessary problems by interrupting longshore sediment transport during times of high water and by preventing natural excursions of the beach in transformation between summer (swell) and winter (storm) wave conditions. On the other hand, there are situations where seawalls have intermittently functioned during long-term cycles of erosion and become inactive and even buried during times of sediment abundance (*cf.* KRAUS 1988).

Much of the controversy and confusion about the potential harmful action of seawalls on the beach can probably be attributed to lack of distinguishing between what PILKEY and WRIGHT (1988) have called "passive" erosion and "active" erosion (see also, discussion by GRIGGS *et al.* 1991, 1994). They refer to passive erosion as being ". . .due to tendencies which existed before the wall was in place," and active erosion as being ". . .due to the interaction of the wall with local coastal processes." Engineers usually do not consider passive erosion in evaluating whether "seawalls cause erosion," because the purpose of the wall is to prevent further erosion, and the structure cannot be faulted for fulfilling its intended function. The sediment locked up by the seawall is, however, considered by engineers and planners in forming sediment budgets and in regional planning. Passive erosion is a concern in management and engineering considerations of the long-term evolution and usage of the coast. The main emphasis of most technically oriented engineering studies on beach processes has been on understanding whether and how seawalls alter the beach profile and change the neighboring shore.

An important and, perhaps, self-evident property of seawalls is that they may prevent long-term recovery or building of the back beach by prohibiting berm formation by wave uprush and dune formation by wind (CARTER 1988; MORTON 1988). WEGGEL (1988) classified the action of seawalls on the beach and identified three major variables that control cross-shore processes and profile change due to the presence of walls (he also considered longshore processes). Of these, the *location* of the beach with respect to the shoreline is a key parameter which he used to define six types or evolutionary stages of seawall-beach interaction. WEGGEL's Type 1, a seawall located above maximum runup during maximum storm surge, was stated to have no effect on beach processes. Because WEGGEL considered only waterborne sediment transport, the beach-building effect of wind was omitted and restricts his conclusion. Seawalls have been buried by wave- and wind-transported sand (*e.g.*, BERRIGAN 1985a, 1985b), showing that elevation of the seawall enters in the assessment. HEADLAND (1992) describes the design of a combined dune and seawall system for protecting a military facility, in which the seawall was proposed to be buried in a dune emplaced in the beach nourishment operation and which would become active only if the dune erodes during an extreme storm.

DEAN (1986) proposed an "approximate principle" that relates the volume of toe scour at a wall to the volume that might be potentially scoured in the absence of the wall: "In a two-dimensional situation in nature with wave and sediment conditions conducive to formation of a longshore bar, the additional volumetric scour immediately fronting the armoring will be less than or equal to that volume that would have been provided through erosion by that portion of the profile upland of the armoring if that armoring were not present." This principle has been verified in physical model tests by BARNETT (1987; see also, BARNETT and WANG 1988), HUGHES and FOWLER (1990), MISELIS (1994). These studies are discussed below.

FIELD STUDIES

Long-term field observations of the seawall and beach interaction have been conducted at two locations in the United States, one on the east coast (Virginia Beach and Sandbridge, Virginia) by BASCO and colleagues and the other along Monterey Bay, California, by GRIGGS and colleagues. In addition, some storm assessments have become available since 1988.

Long-Term Monitoring

BASCO and colleagues (BASCO 1990; BASCO, BELLOMO, and POLLOCK 1992a) have performed beach profile surveying along the extensively walled Sandbridge Beach, Virginia, since August 1990. Survey data are available from 1980. In contrast to the long-term stable beach at Monterey Bay, California, studied by GRIGGS and colleagues, the sandy beach at Sandbridge is eroding at a long-term average rate 1.1 to 2.9 m/year (BASCO *et al.* 1992a). In agreement with the studies of GRIGGS and colleagues, BASCO *et al.* (1992a) found the rate of berm lowering in front of seawalls to be slightly higher at seawalled sections, as compared to neighboring beach and dune sections not backed by walls. Preliminary results after 4 years of monitoring showed that volume loss rates seaward of walls computed using a weighted-averaging method was greater at the adjacent dune and beach reaches than at the approximately 7 km of wall along Sandbridge.

Seaward Boundary Condition

BASCO (1990) emphasizes what he calls the "seaward boundary condition"—the offshore bathymetry and resulting longshore variations in wave height and direction that can produce divergent nodal points in longshore transport and similar factors that contribute to passive or background erosion not related to the presence or absence of a seawall.

Statistical Procedures

BASCO, BELLOMO, and POLLOCK (1992a) emphasize the use of statistical procedures in analysis of their data. They conclude, based on analysis of 12 years of profile survey data and under the assumption that longshore transport rates are in balance over the study site, that ". . .there is no strong statistical evidence to support the claim that seawalls have caused higher shoreline recession at Sandbridge."

GRIGGS, TAIT, and SCOTT (1990), GRIGGS *et al.* (1991, 1994), and TAIT and GRIGGS (1990) describe results of an eight-year long ongoing monitoring program at both vertical and sloping seawalls of different structural characteristics. The study sites are along a wide sandy beach backed by cliffs. The strength of the program is in its continued weekly to monthly beach profile surveys to wading depth, yielding more than 2,000 lines for analysis, and the study includes beach sections adjacent to the walls. Passive erosion is stated not to be a concern, allowing the study to focus on possible active erosion. Summer beach width at the walls are so great that "memory" of the wall in short-term sediment transport processes was erased. Selected results of the studies of GRIGGS and colleagues are as follows:

Beach Berm and Foreshore

During the transition from summer to winter, the berm at walls typically cut back sooner relative to adjacent control beaches. The berm was lost sooner at walls located closer to the shoreline. A flatter profile was thus obtained at the walls. GRIGGS *et al.* (1991) speculated that the accelerated berm removal at the walls might be caused by (1) wave reflection at high tide, (2) increased sediment suspension due to turbulence (created by reflection from the wall), and (3) elevated beach water table (whether due to presence of the wall or to natural causes is not stated). GRIGGS *et al.* (1991) found there was no consistent difference in the beach profile at vertical impermeable walls and at permeable sloping walls, a result that contradicts conventional paradigms.

Summer Beach Recovery

By late spring or early summer, berm height and width were the same on walled and unwalled beaches. The study site was a beach at the foot of high cliffs, so dunes would not be expected to form. MOODY (1996) found recovery to be essentially the same on walled and unwalled beaches in his physical model experiment.

Scour

In the seven years of surveying summarized to date by GRIGGS *et al.* (1994), including one year of surveys made before and after major storms, a surprising result (to the present authors) was that a scour trough was never observed in front of any of the seawalls studied. A caveat was given that wave and storm conditions were considered milder as compared to more severe storms that occurred off California in the 1980s. However, storm waves did impact the walls frequently during the monitoring period.

End Effects

Reflection of waves at the ends of walls was observed to cause local erosion and arcuate indentations that extended 50 to 150 m alongshore, an expected result (*cf.* WALTON and SENSABAUGH 1979; MCDOUGAL, STURTEVANT, and KOMAR 1987; TOUE and WANG 1990).

In a study associated with the monitoring project of GRIGGS and colleagues, PLANT (1990) and PLANT and GRIGGS (1992) attempted to observe both the processes (water-seawall-beach interaction) and resultant response of the beach profile. PLANT draws attention to the reduced water permeability in the beach in front of a wall for the water that has flanked and entered behind it. Water temporarily held behind a rock revetment above beach level can add to the backwash. Other interesting and potentially important considerations on the local water table at walls are discussed. PLANT shows that a seawall alters the swash uprush and backwash amplitude, velocity, and duration, and he points to several areas requiring research on the coastal sediment processes at seawalls. The present authors agree with PLANT (1990) and PLANT and GRIGGS (1992) that more process-oriented field studies should be pursued.

Storm Assessments

Documentation of impacts of powerful hurricanes on the beach, including some beaches backed by seawalls and revetments, are compiled in a special journal issue entitled "Impacts of Hurricane Hugo: September 10–22, 1989" (FINKL and PILKEY 1991). Two papers in the special issue contain profile surveys and discussion of beach profile change on beaches with and without walls.

BIRKEMEIER *et al.* (1991) provide pre- and post-storm profile comparison plots for Myrtle Beach and Debidue Beach, South Carolina. Many of the walls were submerged during the hurricane surge, producing substantial loss of dunes behind them due to overwash. An impression gained from the plots is that the profile in front of walls was typically lowered in a manner consistent with Dean's "approximate principle" (DEAN 1986). In front of one wall at Debidue Beach, the profile dropped 1.5 m. At the time of the post-storm profile survey (about one week after the storm), the beaches in front of walls showed signs of formation of a recovery berm.

NELSON (1991) performed 12 beach profile surveys at Myrtle Beach, South Carolina, about the day before arrival of Hurricane Hugo. Seventy-eight profile lines otherwise surveyed during March and April, 1989, were available for comparison with post-storm surveys (if the survey bench marks survived the storm!). The total data set contained survey lines at seawalls and adjacent to seawalls. NELSON states that all beaches in northern South Carolina suffered erosion, and that the erosion extended "upward and inland behind the beach to elevations of 4 to 5 m above mean sea level." Further, "The landward movement of the high tide (shoreline) position in Garden City averaged 12.2 m with great variability along the beach." An interesting observation was that the pre-storm waves produced beach accretion, attributed to buildup of the dunes by landward wind, arrival of the long-period storm forerunner swell, and higher than normal spring tide. Within the framework of extensive erosion produced by Hurricane Hugo, NELSON concluded that "Erosion was not increased in front of seawalls or riprap revetments." In more detail, erosion of the upper interdidal supratidal beach profile was found to be less between seawall segments than at areas without structures, attributed to reduction of erosive forces by the adjacent beach-front structures. On the interdidal portion of the beach profile, NELSON states "it did not appear that the presence or absence of tall wide buildings or gaps in seawalls had any effect on the intertidal beach profile." However, erosion troughs were observed at many riprap armored beaches within the study area.

MOSSA and NAKASHIMA (1989) monitored a concrete-bag seawall and adjacent unwalled beaches at Fourchon, Louisiana. Monitoring occurred from seawall placement starting in late 1985 through 1988, subsequent to impact by a major hurricane, Gilbert, in September 1988. This study is interesting in the number of phenomena considered, ranging from deltaic processes and subsidence consolidation to overwash and obstruction of longshore transport by obstacles along the wall. In general terms, observed storm erosion and subsequent recovery at the wall two months after Hurricane Gilbert were intermediate in value relative to the adjacent natural beaches located to the east and west.

UDA (1989) inspected scour at seawalls and revetments along the coast of Japan and concluded that scour and structure failure were not produced solely by cross-shore processes. He posited that sand was removed from the beach in front of structures by longshore transport to first lower the profile over time (one mechanism of passive or background erosion). Subsequent combined longshore and cross-shore transport processes, including wave overtopping and scour, then resulted in structure failure.

The paper of JOHNSON (1992) primarily concerns longshore processes at seawalls. It is interesting and unique in tracking the longshore movement of large individual slugs of fine sand and slugs of gravel that were originally emplaced in three separate operations to mitigate erosion downdrift (south) of St. Joseph Harbor, Michigan, on the southeast shore of Lake Michigan. Johnson observed the fine sand to be carried ". . .past the many seawalls within the first 4 miles downdrift. . ." The fine sand has moved faster than the gravel, and ". . . the gravel consumes itself building beaches over every seawall it encounters, hence moves very slowly downdrift." JOHNSON explains the difference in transport between the two widely differing sediment particle grain sizes in that the fine sand is suspended and does not necessarily come to shore where it would be slowed in movement, whereas the gravel tends to accumulate on the shore "in high steep prisms," even in front of seawalls.

Sand slugs and gravel slugs originating from different fills as identified by JOHNSON (1992) move in identifiable units that preserve identity in a type of collective longshore sand wave motion recently studied by THEVENOT and KRAUS (1995). Such sand bodies move at different rates than would be predicted for individual sediment particles and represent an interesting complication to longshore transport processes on beaches with and without shore-protection structures.

FITZGERALD, VAN HERTEREN, and MONTELLO (1994) describe beach change and severe damage along Massachusetts Bay associated with the Halloween storm of 1991, a long-duration, powerful storm that struck the northeast coast over several tidal cycles, resulting in a long period of high water levels. Numerous seawalls exist along the study area that contain many reaches of chronic erosion and limited sediment supply. Hurricane Bob had struck the area only six weeks before, leaving the coast in a weakened state with many beach berms and dunes depleted of sediments. FITZGERALD *et al.* found that all beaches (seawalled and non-seawalled, sand, and gravel) experienced erosion as a result of the storm, and that ". . . beaches with wide berms or where adjacent dunes were scarped and mined of their sand exhibited less overall change than sandy beaches backed by seawalls or revetments." Presumably, on walled beaches, sand removed from the upper beach by Hurricane Bob that remained on the profile provided a source to reduce the erosion capacity of the Halloween storm. Along the northern half of Nantucket Beach, the most extensive damage coincided with gravel ridges and the absence of seawalls, indicating that the walls provided some level of damage protection to the upland, serving their intended purpose.

It is difficult to capture details of the coastal sediment processes in field studies. Therefore, appeal is made to physical modeling or laboratory studies, discussed next.

LABORATORY STUDIES

We start this section with comments about movable-bed laboratory experiments conducted at relatively small scale. Although scaling is a complex subject (*e.g.*, see WANG, TOUE and DETTE (1990), HUGHES and FOWLER (1990), HUGHES (1993), and OUMERACI (1993) for recent approaches to scaling beach profile change), for purpose of discussion here, "small scale" will refer to experiments conducted with waves of height less than 15 cm on models composed of fine to very fine sand. Concern abounds regarding scale distortion in physical model studies. The inability to preserve all hydrodynamic and sediment transport laws in the laboratory may result in different sediment transport and morphologic change as compared to the field. Incorrect scaling might enter, for example, as: 1) dominance of threshold of sediment motion in the laboratory, which could alter the direction and magnitude of bed load sediment transport; 2) presence of ripples in laboratory surf zones, which do not exist in the field and which can obscure trends in profile change; 3) differences in sediment transport mode as suspended load or bed load between the laboratory and field; and 4) inability to scale simultaneously both bedload and suspended load, which may be particularly troublesome for experiments involving both cross-shore and longshore transport, and different Reynolds numbers and turbulence intensity which in turn affect sediment transport mode and magnitude.

In reviews of scour at seawalls, KRAUS (1987b, 1988) found that either deposition or scour at walls occurred in small-scale laboratory tests aimed at producing scour and attributed this apparent discrepancy to scale mismatches between sediment size and wave length. Physical model experiments that include both longshore and cross-shore transport are rare and important for their realism, but they may also produce greater spurious results than two-dimensional (cross-shore only) experiments because of greater limitations on generating wave height and period in basins, as well as because of the presence of artificial circulation in the basin.

A paper omitted from previous reviews by KRAUS (1987b, 1988), but which may have bearing in understanding scour at seawalls is that by NISHIMURA, WATANABE, and HORIKAWA (1978). They studied scour at a seawall produced by an incident tsunami simulated in a 25-m long tank. Variables investigated were face slope of the wall, slope of the backland, beach slope, water depth at the toe of the wall, crown height of the wall, bed material (mesalite, fine sand, coarse sand), and incident tsunami height (0.35, 0.30, and 0.25 m, which the authors consider as substantial for a model). For the modeled conditions, the amount of scour found at the wall due to overtopping by the tsunami was found to be mainly controlled by two parameters: 1) the rate of return flow from the water that had flooded the backland, and 2) the thickness of the water layer receiving the return flow (water depth at the toe due to all sources). KADIB (1963) had previously studied scour produced by overtopping short-period waves, but the results were not conclusive.

BARNETT and WANG (1988) summarize results of the study of BARNETT (1987) previously reviewed in KRAUS (1988). However, because several of the conclusions of these well-conducted two-dimensional laboratory tests have bearing on the SUPERTANK test results and conclusions described in PART II, selected results from BARNETT and WANG are included here. The tank used was 37 m long, 1.2 m high, and partitioned along its axis to produce an effective beach and profile width of 0.87 m. The 0.15-mm sand beach (median fall speed of 1.77 cm/sec) was 17 m long, and the tests were begun with the beach profile formed in the shape given by $A\ x^{2/3}$ where $A = 0.075\ m^{1/3}$ and x is distance offshore. Near the shoreline, this profile was joined at the point of tangency with a 1V:5H beach face slope for tests without a seawall. In different tests, a vertical wall was placed at three locations around the still-water shoreline (at the shoreline, and +/− 0.3 m from the shoreline). Wave heights and periods in the horizontal section of the tank of depth 0.46 m ranged from 4.00 to 11.75 cm and 1.30 to 1.81 sec. Comparable tests with and without a seawall were conducted to distinguish the influence of the seawall on the profile.

With the caveat that these tests were done at small scale and are therefore suspect, selected results reported by BARNETT and WANG (1988) are summarized as follows:

(1) "For all cases tested, profile configurations with and without a seawall were remarkably similar in overall plan form; this suggests that the major transport process is not significantly influenced by the presence of the seawall."
(2) Under storm waves, seawalls accentuated the erosion trough in the surf zone into a scour hole at the toe of the walls instead of spanning over the swash zone.
(3) Local scour at the walls, was stated to be "severe" in many cases. However, ". . . the volume of sand retained upland of the structure (which would otherwise be eroded under identical wave conditions without a seawall (DEAN 1986)) was found experimentally to be approximately 60% greater than the additional volume eroded at the toe of the structure." In other words, less sand volume was removed from the scour trough than removed from a beach unprotected by a wall.
(4) "Wave reflection, often considered to be a major adverse influence on scour in front of a seawall, did not appear to play a significant role" (in beach profile development).
(5) Beaches with walls recovered with greater sand volumes than the corresponding test cases without walls. BARNETT and WANG state that this result should not be taken to indicate that seawalls promote beach recovery after storms, but that such recovery can occur at beaches fronted by walls. The present authors note that because the beaches in the tests with seawalls did not erode as much as those without walls, it is probable that recovery proceeded more efficiently for the tests with walls.

HUGHES and FOWLER (1990) conducted what were termed "midscale" physical model tests for profile change on beaches with and without a seawall. To the present authors, the word "midscale" indicates wave parameters, sediment size or fall speed, and geometric dimensions of the facility (mainly length and slope of beach, and water depth) that are intermediate between customary small-scale laboratory models and the average conditions that exist at beaches in nature. Midscale represents the lower limit of wave energy and beach geometric conditions that can exist in nature for which the hydrodynamic and sediment transport processes, hence beach morphology change, do not differ significantly from those associated with average wave and beach conditions found in nature. Fourteen tests were conducted using regular and irregular waves (with several tests aimed at reproducing profile change generated in large-scale laboratory tests, referred to as the "prototype" by HUGHES and FOWLER) performed in Germany (DETTE and ULICZKA 1987) in which the wave height was 1.5 m and the wave period was 6 sec. Much of the prototype data are unpublished, and the reader is referred to HUGHES and FOWLER (1990) for further information. The HUGHES and FOWLER report is comprehensive, and only selected results are reviewed here.

Scaling Guidance

Scaling guidance for cross-shore transport and beach profile change was comprehensively and critically reviewed. HUGHES and FOWLER concluded that preservation of the similitude of two parameters would enable (scale) modeling of prototype conditions. The parameters are (1) the dimensionless fall speed number $N = H/wT$, where H is wave height, w is sediment fall speed in quiescent water, and T is wave period, and (2) the Froude number for shallow-water waves. The concentration of sediment suspended by breaking waves can be related to the number N (KRAUS, LARSON, and KRIEBEL 1991), and introduces a (known) scaling distortion for midscale models under the assumption that profile change is mainly controlled by suspended sediment transport. The (undistorted) Froude number is believed to represent the major surf zone hydrodynamic processes. The midscale tests of HUGHES and FOWLER were successful in reproducing beach profile change generated in the prototype with and without a seawall. For simplicity, based on experience the authors suggest that midscale beach profile physical modeling refer to tests with wave heights greater than 15 cm for very fine and fine-grained sand and wave-formed beach profiles. (The prototype tests modeled by HUGHES and FOWLER started from a planar slope and thus tended to violate modeling of natural beaches.)

Impact of Seawall

Although successful in reproducing profile change produced in large-scale physical model tests, the prototype tests used for the comparison were unrepresentative of most sandy beaches in that the movable sand layer resided on an immobile fixed plane-sloping bottom. Thus scour could not strictly occur, as the movable bed could only erode to the fixed planar slope. Plots of beach profile evolution at the seawall show a general lowering or deflation of the profile without scour. The concept that the volume of additional erosion from a beach in front of a wall will be equal to that from an equivalent beach without a wall was found to be approximately correct for the one comparison test performed (also concluded by BARNETT and WANG 1988).

HUGHES and FOWLER (1991) performed physical model tests to validate their theoretical description for predicting scour at vertical walls produced by normally-incident, non-breaking irregular waves. Maximum scour depth was substantially less under irregular than regular (monochromatic) waves, and the authors concluded that the phenomenon may not be of significance for design, and that "... prediction methods for the majority of scour problems experienced at coastal structures are still lacking." They also speculate that, in situations involving both cross-shore and longshore (or wall-lateral) water motion, lateral currents may increase scour, a point discussed further below.

TOUE and WANG (1990) placed a 3-m long seawall with 1-m return walls at the still-water shoreline on a sandy beach (grain size not given, but it is believed that fine sand was used) in a 28 m × 28 m × 1-m deep basin to examine the seawall and beach interaction alongshore and across shore. Three pairs of tests (with and without a seawall) were performed for incident wave conditions with offshore wave angles of 0°, 5°, and 10° for offshore waves 11 cm high with 1.74-sec period. The initial beach configuration was an equilibrium profile as used by BARNETT and WANG (1988). TOUE and WANG found less erosion for cases with the wall in place than for the corresponding case without a structure. For the two oblique wave cases, because of impoundment of longshore transport by the wall, the downdrift beach eroded for a longshore length of three to four times the wall length. The authors do not interpret their results in the context of similar studies available in the literature (*e.g.*, WALTON and SENSABAUGH 1979; MCDOUGAL *et al.* 1987). Also, although the authors state as a working hypothesis that "...the longshore current together with reflected wave energy (from a seawall) trapped in the trough (of the profile) will remove sand from in front of seawall and transport them (*sic*) to down drift location," the hypothesis was not directly addressed.

KAMPHUIS, RACHET, and JUI (1992) studied the beach and seawall interaction in five tests conducted with a sophisticated three-dimensional movable-bed model using obliquely incident random waves of significant height between 5 and 9 cm, period of 1.15 sec, and offshore angle of 10° (beach was aligned 10° to the wave generator). The longshore transport of the 0.12-mm sand used and beach profile change were monitored in addition to the hydrodynamics. The beach was first molded to an equilibrium form under wave action starting from a 1V:10H slope, after which the vertical wall was emplaced. Selected results are described here, again with a caveat that the tests were conducted at small scale.

MISELIS (1994) studied the beach profile and seawall interaction, including scour, produced by severe storm conditions simulated in a tank 36.6 m long, 0.9 m wide, and 1.2 m deep, for which both 0.09- and 0.18-mm sand was used in separate tests. An "anticipated sea state typical of a 100-year storm" at Highland Beach, in Palm Beach County, Florida, facing to the Atlantic Ocean, was modeled. Scaling criteria are discussed and applied, which encompass the sea wall at Highland Beach, as well as the model scale and (random) wave conditions. A maximum deep-water wave height of 16 cm in the model represented a 4-m high wave in the field, and a model wave period of 1.65 sec replicated an 8.25-sec wave in the field. The tests, conducted with and without a vertical plywood seawall, were comprehensive and included examination of overtopping water volume, toe protection, and seawall failure. Here we focus on the beach–seawall interaction. Measured scour depth was found to agree well with predictions from an empirical equation of FOWLER (1992) (*cf.*, Part II). The maximum scour depth always occurred during the peak storm-surge level (reason not given by MISELIS, but this result can be understood by noting that greater water depth would allow higher waves to attack the wall (*cf.*, KRAUS 1988), and regular waves produced greater scour than random waves). The scour hole tended to fill in during the storm but after the peak surge. Wave reflection coefficients reached 25 to 30%, and reflection bars were observed in the model that have not been seen in the field (KRAUS 1987b, 1988, Part II). MISELIS concludes that a "seawall's presence had little effect on the beach evolutionary process except for the immediate area around the seawall."

MOODY (1996) conducted tests of the seawall and beach interaction under normally incident random waves. The experimental section, part of a larger basin, was 10.7 m long and 4 m wide. A divider wall split the upper 4.9 m of beach into two 2-m sections to investigate "how the two beaches reacted differently when separated by a dividing wall and subjected to equivalent wave conditions and then how the beaches interact when the dividing wall was removed." The seawall was a sloping 1H:5V plywood sheet upon which two layers of 2- to 5-cm diameter gravel was affixed. The sediment was 0.2-mm sand. Before a test, the initial beach profile was formed by running random accretionary waves of height 5 cm and period of 2.08 sec. The wave conditions in the experiment were typically of this small scale, giving a concern (by the present authors) about the results. Nevertheless, findings in the tests seem reasonable and systematic, and are presented here as stimulation for future work. An interesting result pertains to the generation of apparent universal accretionary equilibrium profile (for the experiment conditions) for beaches with and without seawalls: "These two experiments show that the beaches have an equilibrium profile that is reached when subjected to accretionary waves, even after a case of extensive erosion. After extensive erosion, there may be a permanent beach change, but this change is evident for both the dune and the sea wall beaches. This shows the lack of a demonstrable sea wall effect." Concerning scour, for this sloping wall no significant scour occurred, even if the wall was fully in the surf zone. In comparing beach profile change of the walled beach and a beach with a dune, for the same erosional storm waves, Moody found "The (beach) region in front of the dune recovered better than in front of the sea wall because of the sediment supplied by the dune. The sea wall side did not have this large supply of sediment, hence it appeared not to have recovered as well. In reality, the protected beach fared remarkably well. The beach in front of the sea wall was not permanently lost, compared to a large permanent dune erosion of the unprotected beach." Concerning DEAN'S (1986) approximate principle, Moody concluded: "Based on the Dean's principle, we were expecting the beach in front of the sea wall to be significantly eroded with the eroded volume the same order of magnitude as the volume eroded from the dune, but this was not the case. The two beaches were nearly identical seaward of the sea wall; there was no additional or excess erosion in the sea wall profile to match the erosion from the dune." Also, it is interesting to note that the erosion rates for the two (walled and unwalled) beaches were almost identical. For smaller (storm) events, both beaches recovered nearly completely to their original profiles. Finally, Moody summarizes his results to state that for the sloping seawall tested "This small-scale laboratory investigation showed that beaches protected with sea walls behave as unprotected beaches under the limiting conditions of normally incident spectral waves." This conclusion is in accord with results of previous (KRAUS 1987b, 1988) and the present literature reviews of laboratory and field observations.

Longshore Transport

KAMPHUIS *et al.* found that the longshore sand transport rate decreased in front of the seawall as the foreshore eroded, ". . .because energy dissipation resulting from breaking waves decreased towards the end of the test." They also state "As depths increased, more wave reflection and less breaking occurred," and "The longshore sediment transport rates tended toward equilibrium values." The location of the "breaker peaks" in the longshore bed load and suspended load distributions moved slightly offshore as the beach eroded, and the peak in the swash zone disappeared as the foreshore eroded. RAKHA and KAMPHUIS (1996a), using the same and similar laboratory data, conclude that "Both the numerical model and the physical model results showed that the reflection coefficient had a small effect on the longshore current and wave setup." In developing and testing a 3D morphology change model RAKHA and KAMPUIS (1996b) found "For the cases studied, the reflected wave was found to have a small effect on beach profile development." (see also MCDOUGAL *et al.* 1994, Part II).

Cross-Shore Transport

KAMPHUIS, RACHET, and JUI (1992) found that sand taken from the beach in front of the wall moved offshore and formed a relatively flat plateau that extended to the breaking zone. A scour trough was found near the wall for all tests, but the average local scour depth could not be related to the deep-water incident wave height. KAMPHUIS *et al.* conducted an equilibrium profile shape analysis and stated that the thickness of the expected deposition layer offshore due to a storm is less at a wall because of the absence of sand that would otherwise be available for removal from the beach by the storm waves. The present authors suggest that the lack of dependence of scour depth on wave height as observed in the field and some other laboratory tests (KRAUS 1987, 1988) may be due to the combination of the small scale of the tests and the apparent dependence of scour depth on initial beach profile shape. Scour depth is discussed below.

FOWLER (1992) describes midscale laboratory tests of beach profile change at a vertical wall (cf. HUGHES and FOWLER 1990). The tests were conducted under a scaling law that preserved similitude of the dimensionless fall speed number N between model and field. Eighteen random-wave tests and four monochromatic-wave tests were conducted, with offshore wave heights in the range of about 20 to 30 cm. A fine-grained sand (0.13 mm, with fall speed of 1.9 cm/sec) was used, which improves the scaling. The initial beach profile was a 1V:15H slope in all tests. Despite the relatively mild initial slope, the present authors believe the planar initial slope, which is not an equilibrium form under surf zone waves, may have exaggerated the scour produced. Results from the tests were compared with those from several previous laboratory studies conducted by other researchers. An empirical equation for scour depth was developed in which the ratio of the depth of water at the wall to the deep-water wavelength was identified as an important parameter. This equation is examined in PART II. The study supported the rule of thumb that the limiting scour depth is approximately equal to the deep-water wave height (cf. KRAUS 1988).

FOWLER (1993) reviews the literature on the data base and calculation procedures for predicting scour at rubble-mound structures, piles and vertical supports, and vertical seawalls. No new results concerning seawalls beyond those in FOWLER (1992) are given.

The large-scale SUPERTANK Laboratory Data Collection Project (KRAUS, SMITH, and SOLLITT 1992; KRAUS and SMITH 1994; SMITH and KRAUS 1995) included three seawall tests. Heights of the random significant waves ranged between 0.4 and 1.0 m, and periods between 3 and 8 sec. Wave heights and periods were selected to correspond to destructive and constructive wave conditions. The profile showed a rather small response, even to very steep waves. The profile typically had a local variation near the wall, but the majority of the profile remained similar to an unwalled profile. The limited scour found suggests that the scour trench sometimes observed in the field after storms may be a result of longshore transport or combined cross-shore and longshore transport occurring at the time of the storm. The SUPERTANK results are discussed in detail in PART II.

As an alternative to physical modeling for understanding and predicting the beach and wall interaction, numerical modeling has also been employed. In principle, mathematical or numerical models do not suffer from the potential ambiguity of scale effects inherent in physical models. However, mathematical modeling requires that the main governing physical processes and interactions be well represented, and these are not well known. The following section reviews present knowledge on numerical modeling of the beach and wall interaction.

NUMERICAL MODELING STUDIES

DEAN and YOO (1994) investigated analytically, numerically, and in the laboratory the longshore movement of a discrete quantity or slug of beach nourishment sand placed in front of a seawall at which no exposed native beach or other source of transportable sediments exist. Two pairs of laboratory tests were conducted for nourishment either in the presence of a wall without an exposed beach or on a sandy beach (grain size of 0.2 mm) without a wall for normal wave incidence and incident at 30°. The offshore wave height was 2.2 cm, which makes it a test at very small scale, implying to the present authors that the results should be considered qualitative and not quantitative. DEAN and YOO show that the centroid of an isolated slug of sand at a seawall moves much differently than a slug placed on a sand beach. Instead of simply diffusing, even under obliquely incident waves, the isolated slug at a seawall moved rapidly downdrift as a coherent body. The results of DEAN and YOO are consistent with the aforementioned field observations of JOHNSON (1992).

HANSON and KRAUS (1985, 1986) had previously developed a similar but more general method of calculating shoreline change at a seawall based on observations of shoreline change in the vicinity of a seawall in the field. This calculation procedure is implemented in the shoreline change model GENESIS (HANSON and KRAUS 1989) and produces numerical results similar to those found by DEAN and YOO (KRAUS and HANSON 1995).

Several numerical models have been developed to simulate beach profile changes for beaches backed by berms, dunes, and a vertical wall (STIVE and BATTJES 1984; KRIEBEL and DEAN 1985; LARSON and KRAUS 1989; STEETZEL 1987, 1991). These models do not include reflected waves that are produced if water reaches the seawall. Recently, MCDOUGAL, KRAUS and AJIWIBOWO (1994) developed a model which includes the reflected wave. This model is discussed in detail in PART II. A result, that is in agreement with observations, is that the reflected wave has little influence on the overall profile response.

CONCLUSIONS AND RECOMMENDATIONS

Review of the literature shows that considerable attention has been turned to the seawall and beach interaction over the past six years. Field monitoring became more active, and several innovative laboratory experiments were performed at small-, mid-, and large scale. Alongshore movement of sand at walls has been observed in the laboratory and in the field, although with somewhat conflicting results. The concept of using sloping seawalls to reduce wave reflection and scour, accepted by KRAUS (1988) in a critical review of the literature, is now in doubt. Also, much uncertainty remains in understanding of a central engineering quantity—scour at a wall. The following is a synthesis of conclusions and recommendations based on a critical review of the literature and the authors' experience in large-scale physical modeling of the beach and seawall interaction at SUPERTANK.

Conclusions and Discussion

As our understanding of beach and seawall interactions increases, it is clear that much of the controversy regarding the effectiveness and impacts of seawalls can be eliminated by applying two sets of basic terminology. The first is the recognition that seawalls are shore-protection structures and not beach-protection structures. The second is to separate the passive erosion which would occur in the absence of the seawall and the active erosion which is directly attributed to the seawall (PILKEY and WRIGHT 1988). The following are major conclusions of this literature review.

1. Reflection is probably not a significant contributor to beach profile change or to scour in front of seawalls, at least for the duration of a storm (BARNETT and WANG 1988; GRIGGS *et al.* 1991; McDOUGAL, KRAUS, and AJIWIBOWO 1994; SUPERTANK results in PART II; MOODY 1996). This conclusion is contrary to that given by KRAUS (1988) based on review of previous studies. As concluded by KRAUS (1988), experiments still need to be performed to achieve unambiguous resolution of this question. For example, it could be argued that the return of runup on a sloping wall would cause scour as described by NISHIMURA *et al.* (1978) for the return flow from tsunami overtopping. Data at sites where there is persistent reflection off a wall are not yet available. Also, increase in sediment suspension alone does not cause profile change; a gradient in sediment *flux* must exist, and limited evidence suggests this gradient may more typically be alongshore than across shore.
2. If the beach profile is close to its equilibrium shape, then the arrival of a storm may not change the profile greatly (or cause erosion). Profile change would be expected to occur in proportion to the difference from the equilibrium condition caused by the storm, as from an increase in water level. DEAN's (1986) approximate principle states that the scour volume in front of a wall by cross-shore transport is only equals the amount denied by the wall; however, if the profile is in near equilibrium, significant scour is not expected because no demand is made for sand to move out on the profile. Erosion of a foredune should be independent of profile shape offshore, and hence erosion of the dune can occur independent of the "approximate principle" (MOODY 1996). However, if turbulence and suspended sediment increase in front of a wall (due to wave reflection), then even though there is no net movement across shore, the suspended sand could be moved alongshore and out of the walled area, thus increasing local scour. Scour observed at seawalls in the field may be more a result of a gradient of longshore transport or a product of combined longshore and cross-shore transport processes (UDA 1989; SUPERTANK results in PART II).
3. Scour does not necessarily occur at seawalls (GRIGGS *et al.* 1991, GRIGGS *et al.* 1994) or may be difficult to predict as not being related to incident wave height (KAMPHUIS *et al.* 1992). However, the tests of KAMPHUIS *et al.* are suspect due to the small scale and to the complexity of the initial bottom condition. The maximum scour is expected to occur when the water level is highest (peak surge), because the higher water level can support larger waves (MISELIS 1994).
4. During storms, the beach profile in front of a wall retains about the same amount of sand (has about the same general shape) as a beach without a wall (HUGHES and FOWLER 1990), because wave reflection does not appear to greatly influence overall profile shape (MOODY 1996). The main difference is general downward displacement of the slope near the wall (DEAN 1986, BARNETT and WANG 1988, SUPERTANK and numerical modeling results described in PART II). Post-storm field observations by FITZGERALD *et al.* (1994) showed that the huge Halloween storm of 1991 had depleted the subaerial beaches in front of seawalls more than adjacent beaches without seawalls. Pre-storm beach conditions were not well known, however; consequently, it is difficult to make firm conclusions.
5. Sediment can move alongshore past a seawall (HANSON and KRAUS 1985, 1986; UDA 1989; JOHNSON 1992; KAMPHUIS *et al.* 1992; DEAN and YOO 1994; KRAUS and HANSON 1995), and a slug of sediment in front of a wall can maintain its form. However, it has not been observed in the field whether the longshore sediment transport rate will match the potential (HANSON and KRAUS 1985, 1986; DEAN and YOO 1994) or decrease (KAMPHUIS *et al.* 1992). Additional field observations and laboratory experiments on the longshore movement of sand and gravel past a wall are needed.
6. Small-scale physical model results are likely to be misleading and should be considered as yielding qualitative information at best and completely erroneous information at worst. The authors recommend that future laboratory experiments be done with justification of the scale used and with awareness of the ambiguities that have arisen in previous experiments done at small scale.

Recommendations

Several new issues have been raised on the seawall and beach interaction based on the cumulative work performed since 1988. We summarize these issues by recommending the following actions:

1. Continue long-term profile surveying at seawalls concurrent with measurement of incident waves and detailed observations of the processes that comprise the seawall and beach interaction.
2. Conduct physical-model experiments on scour with realistic initial profile shapes, such as equilibrium profiles or wave-conditioned profiles.
3. Cease conducting physical model tests at small scale, unless a competent scaling law is applied. As a rule-of-thumb guidance, for tests performed with fine or very fine sand, the wave height should exceed about 15 cm. Also, wave-conditioned or similar realistic initial beach profiles should be used.
4. Conduct physical model experiments under combined longshore and cross-shore transport (three-dimensional experiments), and compare the hydrodynamic and sediment transport processes with field observations.
5. Investigate the influence of the water table on foreshore and swash zone sediment transport (PLANT 1990, PLANT and GRIGGS 1994).
6. Pursue numerical modeling of beach profile change because of the flexibility of this tech nology to represent arbitrary initial profile shape, wave conditions, and sediment size. The numerical modeling must be ground-truthed with focussed physical model tests done at mid- to full-scale, supplemented by field data.

ACKNOWLEDGMENTS

The authors appreciate helpful discussions with Mr. Yoshiaki Kuriyama, Port and Harbour Research Institute, Japan, and Mr. Ryuichiro Nishi, Department of Ocean Civil Engineering, Kagoshima University, Japan, who were guest researchers at the Conrad Blucher Institute during preparation of this paper. Drs. David Basco, Per Bruun, Gary Griggs, and Greg Stone each made several helpful suggestions in review of the manuscript. This project is a continuation of work conducted by the authors as part of the SUPERTANK Laboratory Data Collection Project sponsored by the Coastal Research Engineering Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

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