Prediction of Damage to Shorelines and Coastal Structures

by

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FORWARD

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PREDICTION OF DAMAGE TO SHORELINES AND COASTAL STRUCTURES

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Keywords: Sea Level Rise, Storm Surge, Waves, Beach Erosion, Beach Nourishment, Tidal Inlet, Sand Bypassing, Seawalls, Breakwaters, Jetties

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Glossary of Terms, Abbreviations, and Symbols

Relative mean sea level: Average sea surface elevation relative to local land elevation.
Storm surge: Water level rise due to wind stress and atmospheric pressure reduction.
Wind waves: Waves generated by wind.
Beach erosion: Removal of beach materials by waves, currents and wind.
Tidal inlet: A short, narrow waterway maintained by tidal flow.
Seawall: A structure separating land and water areas to prevent erosion and flooding.
Breakwater: A structure protecting a shore area, harbor or anchorage from waves.
Jetty: A structure built at the mouth of a river or tidal inlet to help deepen and stabilize a waterway for navigation.

Summary

Tropical and extratropical storms can cause severe damage to shorelines and coastal structures due to extremely high wind, storm surge, waves and currents. To predict the damage caused by a storm, it is necessary to predict the water level, waves and currents during the storm. The water level determines the area inundated during the storm. Waves and currents cause sediment transport and shoreline changes. Waves and currents may also damage coastal structures such as seawalls, breakwaters and jetties. On the other hand, the gradual rise of mean sea level relative to local land elevation results in the retreat of shoreline which may be backed up by a dune, cliff or wetland. The shoreline retreat will become more serious if the mean sea-level rise accelerates due to the greenhouse effect.

First, the state of the art for the prediction of the water level, waves and currents is reviewed concisely. Second, available methods are summarized for the prediction of beach and dune erosion, cliff retreat, shoreline changes at a tidal inlet, and wetland loss. These prediction methods are extended to eroding beaches nourished through placement of sand and sand bypassing at a tidal inlet to restore natural longshore sand transport. Third, existing methods are reviewed for the design of seawalls, revetments, dikes, breakwaters and jetties against storm surge and waves.

1. Introduction

A significant and growing portion of the world's population lives near the sea as development and recreational activities increase in coastal zones. The coastal population growth results in the increase of damage caused by a storm with high wind that generates storm surge and large waves. Moreover, the mean sea level relative to local land elevation is rising gradually along many shorelines. Consequently, coastal communities are becoming more vulnerable to coastal hazards such as flooding and beach erosion. This article reviews methods available to predict storm damage to natural and developed shorelines.

2. Water Level and Wave Predictions

The surface of the sea varies with time due to tides and has been measured using tide gauges. The periodic rising and falling of the tidal water level due to gravitational attraction of the moon and sun can be predicted using tidal gauge records. The mean sea level at a specific location is the average sea surface elevation for all tidal stages. Storm surge is a rise above normal tidal water level due to wind stress acting on the water surface and atmospheric pressure reduction. Wind also generates waves on the sea surface whose elevation is determined by tides and storm surge.

2.1 Relative Sea Level Rise

The peak of the last ice age occurred approximately 15,000 years ago with the sea level 100-150 m below the present level. As the earth warmed, the glaciers retreated and the sea level rose. The present-day rate of eustatic (global) sea level rise is estimated at approximately 17 cm per 100 years. The rate of eustatic sea level rise may increase in the future due to the greenhouse effect and resulting increase in the earth's temperature.

Relative mean sea level rise at a particular location results from the combined changes in water and land levels. Lowering in the land level appears as a sea level rise in the tide gauge record. Relative sea level rise is already significant at locations of extreme land subsidence.

Long-term tide gauge records are used to estimate the past rate of relative sea level rise at a particular location. The future rate will be larger than the past rate if the eustatic sea level rise accelerates due to the greenhouse effect. The future rate of relative sea level rise may not be predicted accurately but the risk of the increased rise rate is sufficiently established to warrant consideration in the planning of coastal facilities.

2.2 Storm Surge

Storm surge is a long wave motion in relatively shallow coastal water forced by extremely high wind stress and reduced atmospheric pressure associated with an extratropical or tropical storm. Tropical storms are also called cyclones, hurricanes or typhoons. Storm surge can increase water levels several meters above normal astronomical tides. The combined storm surge and tides can also produce strong currents. Since storm surge and tides interact nonlinearly, it is now standard to include tidal calculations in storm surge prediction models.

Storm surge models generally consist of the continuity equation for mass conservation and the momentum equations for long waves under the usual hydrostatic pressure approximation. These governing equations are solved routinely using numerical methods with appropriate initial and boundary conditions. The computation domain is typically bounded by the edge of the continental shelf, somewhat arbitrary cross-shelf boundaries, and the coastline which is treated as a vertical wall or a moving boundary with flooding of coastal lowlands. The artificial boundaries open to the surrounding ocean water are necessary to limit the size of the computation domain. Any waves generated in the computation domain must be allowed to propagate outward without any reflection from these open boundaries but available open boundary algorithms are only approximate.

The input to the storm surge models includes the spatial and temporal variations of the wind and atmospheric pressure fields of a storm, the bathymetry and bottom roughness of the continental shelf, and the geometry of the coastline including bays, headlands, deltas, inlets and barrier islands. Storm surge at a particular shoreline location is sensitive to the detailed characteristics of the storm and topography. Since wind data on the continental shelf is very limited even if available, an accurate wind field model is required to predict storm surge accurately. Operational weather prediction models are available to predict the wind field of extratropical storms but no reliable model exists to predict the path and intensity of tropical cyclones well before the landfall.

Consequently, it may be possible to hindcast storm surge due to past cyclones with the know path and intensity but it is beyond our present capabilities to accurately forecast storm surge more than one day before the landfall of an approaching cyclone.

Storm surge models require the quadratic bottom friction coefficient to express the bottom shear stress in terms of the near-bottom water velocity as well as the quadratic drag coefficient to express the wind shear stress in terms of the wind velocity near the water surface. Empirical formulas for these coefficients are widely used but these formulas neglect the effects of wind waves which enhance the bottom and wind shear stresses. Furthermore, breaking waves on beaches cause wave setup (the landward increase of the mean water level) and longshore current along the shoreline due to the cross-shore and alongshore radiation stresses (the momentum fluxes associated with breaking waves). Coupled surge-wave models will need to be developed to account for the surge and wave interactions.

2.3 Wind Waves

Water waves observed in the ocean include various waves of different time and length scales. Gravity waves with periods on the order of 10 s are important in predicting coastal damages. Gravity waves are generated by wind. Wind-generated waves are separated into seas (waves caused by wind at the place and time of observation) and swell (waves that have propagated out of their generating area). Wind waves tend to become more regular and have longer periods as they propagate far from their generating area. Wind wave models predict waves generated by wind in the computation domain. If waves arrive from outside the computation domain, the incoming waves need to be specified at the boundaries of the computation domain.

Wind waves during an interval of constant wave conditions (typically a few hours) consist of waves with different heights and periods propagating in different directions. Statistical and spectral methods are used to describe irregular random waves in concise manners. The simplest method is to approximate wind waves by regular waves with one representative height and its associated period which are propagating in the single principal direction because various wave theories are developed for regular waves. The representative height may be the maximum height for the design of coastal and ocean structures that can be damaged by one large wave. The significant wave height defined as the average height of the one-third highest waves is widely used because this height crudely corresponds to the height observed visually. Alternatively, wind wave are assumed to be the sum of sinusoidal waves where the energy per unit surface area of a sinusoidal wave is proportional to the square of its height. The frequency spectrum shows the distribution of wave energy as a function of wave frequency (inverse of period). The directional spectrum gives the wave energy distribution as a function of wave frequency and direction.

Simple methods are available to predict the parameterized frequency spectrum or the significant wave height and period for an idealized wind with constant direction and speed in deep water where waves are not affected by the sea bottom. Waves grow due to energy input from wind but steep waves loose energy due to white capping (wave breaking in deep water). The wave height and period increase with the increase of the wind speed and duration and the horizontal distance (fetch) over which the wind generates seas. Seas can be fetch-limited if the wind duration is sufficiently long or duration-limited if the fetch is sufficiently large. The wave height and period for given wind speed become the maximum for the fully developed wave conditions when the energy input from wind is balanced by the energy dissipation due to white capping. On the other hand, advanced wave models based on the energy balance equation for the deep ocean predicts the spatial and temporal variations of the directional spectrum for predicted wind fields. These models include the quadruplet wave-wave interactions which transfer wave energy from the spectral peak to lower and higher frequencies.

In shallow water, waves are affected by the sea bottom. As waves travel to shallower depth (wave shoaling), the wavelength and speed decrease. The propagation direction of waves shoaling at an angle to the bottom contours becomes more perpendicular to the contours. This wave angle change is called wave refraction. Wave energy is also dissipated gradually due to bottom friction and percolation. If wave energy varies significantly in the direction normal to wave propagation, wave energy can be transmitted laterally in addition to the direction of wave propagation. This lateral wave energy transmission is called wave diffraction. Wave diffraction occurs in the sheltered region behind a barrier such as a breakwater. In very shallow water, triad wave-wave interactions become important for the energy transfer from the spectral peak to higher and lower frequencies. Shoaling waves eventually break on beaches and inclined coastal structures. In the surf zone where waves are breaking or broken, wave heights are on the order of local water depth and limited by water depth. Wave reflection from coastal structures and steep beaches causes the seaward propagation of the reflected part of incident wave energy.

Advanced wave models such as the Wave Model (WAM) include the finite-depth effects of shoaling, refraction and bottom friction in addition to wind generation, white capping, and quadruplet wave-wave interactions to predict directional random waves on continental shelves driven by local winds and boundary conditions. These large-scale models are not applicable to small-scale, shallow-water coastal regions in water depth less than about 20 m with geomorphological features such as tidal inlets and barrier islands. The SWAN (simulating waves nearshore) model includes triad wave-wave interactions, ambient currents and depth-induced wave breaking to predict the fairly rapid variations of directional random waves in shallow-water regions whose horizontal lengths are less than about 20 km.

Wave models based on the wave energy balance equation predict the wave energy or height as a function of frequency and direction. These models do not yield phase relations of sinusoidal wave components and cannot predict wave diffraction. Phase-resolving models based on mass and momentum conservation equations are required to predict the wave-induced water surface and velocities as a function of time and space. Various models including those based on Hamiltonian equations, mild-slope equations, Boussinesq equations, and nonlinear shallow-water equations are developed on the basis of different approximations for different applications. To predict the free surface variations over one wave period and wavelength, these models solve the governing equations using finite difference grids with small time steps (less than one second) and small grid spacings (less than 10 m) for computation domains with horizontal lengths of about 1 km. As a result, these models neglect wave generation by wind in relatively small computation domains.

For an actual engineering project, it is essential to collect wave data at the project site and assess the accuracy of the wave prediction which depends not only on the model accuracy but also on the accuracy of the model input such as the wind field and bathymetry. If long-term wave data are available seaward of the project side, the wave conditions at the project side can be predicted using an appropriate wave propagation model with the available wave data as its seaward boundary condition.

3. Shoreline Erosion Prediction

The still water level including tides and storm surge determines the still water shoreline in the absence of waves. The mean water level in the surf zone is higher than the still water level due to wave setup caused by the onshore radiation stress of breaking waves. Wave setup increases landward and becomes the maximum at the shoreline. The maximum wave setup is on the order of 20 percent of the incident significant wave height. In addition, wave uprush and downrush on the foreshore slope of a beach causes the shoreline oscillations. Wave runup is defined as the maximum elevation reached by the uprushing water above the still water level. Wave runup determines the landward limit of wave action. Irregular shoreline oscillations on gently sloping beaches tend to be dominated by slow oscillations whose periods are in the range of about 20 to 200 s. These low frequency oscillations can be caused by edge waves, which are long waves trapped in the nearshore by reflection and refraction, and leaky (untrapped) long waves, which are standing in the cross-shore direction (sum of incident and reflected waves). These infragravity waves with periods on the order of 100 s can be generated in the nearshore but can also be radiated from deep water. Existing wind wave models do not account for the infragravity waves radiating from deep water.

3.1 Beach and Dune Erosion

Most beaches are currently suffering from erosion due to various reasons such as relative sea level rise, interruption of longshore sand transport, and reduction of sand supply from upland due to damming a river. Long-term beach erosion or accretion at a particular location is estimated through an analysis of field data. At present, no model can predict long-term shoreline changes resulting from erosion during storms and recovery between storms.

Practical and empirical models are available for predicting beach and dune erosion caused by cross-shore sand transport during a storm. These models are based on the concept of equilibrium beach profiles (observed representative beach profiles), an empirical closure depth of the profile change (seaward limit of accurate bathymetry measurements), and an empirical criterion for beach erosion or accretion (offshore or onshore sand transport). The empirical models based on the adjustment of a beach profile toward an equilibrium profile in the presence of large storm surge can predict dune erosion reasonably well (within a factor of about 2) if empirical parameters are calibrated using site-specific field data.

Cross-shore beach profile models based on physical processes are also developed without relying on equilibrium profiles. These models consist of the same structure of modules for hydrodynamics, sediment transport and beach profile evolution but employ different degrees of empiricism. The hydrodynamic modules are mostly based on the horizontally one-dimensional, time-averaged equations for wave energy and momentum for predicting the wave height and setup as well as the vertically one-dimensional, time-averaged momentum equation for predicting the undertow (cross-shore mean velocity below wave trough level) flowing seaward to compensate the mass of water carried shoreward by breaking waves in the surf zone. For the sediment transport modules, use is made of the vertical diffusion equation of suspended sediment by breaking waves combined with formulas for bed load (sediment particles that respond to the instantaneous bed shear stress and the local bed slope without any time and spatial lag). Use is also made of the energetics formula in which the sediment transport rate is expressed in terms of the near-bottom horizontal fluid velocity and sediment characteristics without any time lag between the fluid velocity and sediment transport rate. These sediment transport models assume that the local sediment transport rate is determined only by the local forcing and sediment characteristics without regard to cross-shore sediment advection. The beach profile change is computed using the continuity equation for the sediment that is solved using different numerical methods and smoothing procedures. These models cannot predict accreted beach profiles with sediment deposited above the still water shoreline.

In summary, none of the existing models can explain the physical processes for the post-storm recovery of eroded beaches during which sand grains are transported onshore in spite of fairly strong undertow (offshore) currents in surf zones. Consequently, it is not possible to predict the long-term cycle of beach erosion and recovery caused by sequences of storms. Sand transport by wind may be important for the recovery of eroded dunes but has not been accounted for in existing models.

3.2 Cliff Retreat

Cliffs comprised of unconsolidated sediments can be eroded as fast as sandy beaches if such cliffs are exposed to storm surge and wave action. Cliffs also retreat gradually due to rainfall and groundwater seepage and episodically due to slope instability. The coarse sediments such as sand and gravel supplied by retreating cliffs are deposited on beaches but the fine sediments such as silt and clay are easily transported by waves and currents. Wide and high beaches protect cliffs against storm surge and wave action.

Empirical models for cliff retreat attempt to correlate cliff retreat with measurable parameters such as storm surge, wave runup, wave energy, cliff height, sediment composition and rainfall. To predict cliff retreat in more physical manners, use can be made of the continuity equation for the coarse sediments supplied by the retreating cliff and transported by waves and currents on the fronting beach. However, no formula is available to predict the rate of cliff retreat for given water level and wave action. At present, long-term cliff retreat at a particular location can be estimated only through an analysis of field data.

3.3 Tidal Inlets

Longshore current driven by the alongshore radiation stress of obliquely-incident breaking waves is generally dominant in the surf zone on beaches. Tidal and wind-induced currents become important outside the surf zone. Density-induced currents may also become important at the mouth of a river. Sediment particles entrained by breaking waves are transported by longshore current in the downwave direction along the shoreline. The longshore sediment transport does not cause beach erosion if it does not vary alongshore. The longshore current and sediment transport can be predicted more reliably than the cross-shore current and sediment transport because the longshore motions of water and sediment are much more uni-directional and crudely similar to those in rivers. However, the cross-shore and vertical distributions of the longshore current and sediment flux are not well established. For practical applications, the longshore sediment transport rate over the entire surf zone is predicted empirically as a function of the wave energy flux and incident wave angle at the breaker line.

Longshore sediment transport is interrupted naturally at a tidal inlet, river mouth and headland. The construction of coastal structures for shoreline protection and navigation may result in the interruption of longshore sediment transport which reduces downdrift sediment supply and causes shoreline erosion downdrift of the barrier. Jetties are built at tidal inlets and river mouths to maintain deep and narrow waterways for navigation. Shore-perpendicular groins are built to reduce the local longshore sediment transport rate and foster sand accumulation along the shoreline segment of economic importance. Shore-parallel offshore breakwaters, whose crests can be above or below the mean sea level, act like groins but also reduce wave heights landward of the breakwaters. Shore protection measures are shifting from coastal structures to beach restoration and nourishment through placement of sand at locations where sand sources are available nearby. Nevertheless, jetties are necessary to maintain tidal inlets for navigation.

The long-term shoreline retreat or advance caused by the alongshore interruption or variation of longshore sediment transport is normally predicted using a one-line numerical model where one line corresponds to the shoreline. The one-line model assumes that the shoreline evolves on a long-term average without changing the cross-shore beach profile between the berm and closure depth. The shoreline is divided into a large number of segments. Each segment represents a horizontal area surrounded by the berm, closure depth and two cross-shore lines. The longshore sediment transport volume over a specified time interval at each cross-shore line is estimated empirically for the predicted wave energy flux and incident wave angle at the breaker point of the cross-shore line. The difference of the estimated longshore sediment volumes transported at the two adjacent cross-shore lines is the same as the sediment volume change over the specified time interval for this shoreline segment because of the conservation equation of sediment volume based on longshore sediment transport only. The sediment volume change is then converted to the retreat or advance of the shoreline segment over the time interval. The new shoreline configuration is obtained by connecting the new positions of all the segments. This computation procedure is repeated for a large number of time intervals to predict the shoreline evolution in time. The one-line model based on the highly simplified littoral processes is useful in predicting the long-term shoreline evolution caused by jetties, breakwaters and beach nourishment for the estimated long-term statistics of breaking wave characteristics. The future shoreline evolution can be predicted only probabilistically because the future wave conditions are uncertain.

3.4 Wetlands

Marshes, swamps and mangrove forests occur along the shorelines of lagoons, bays and estuaries in areas sheltered from the direct attack of ocean waves. These coastal wetlands generally consist of low-relief topography and are influenced by tide ranges and storm surge. The plant species in tidal wetlands are sensitively adjusted to local tidal elevations and water-quality conditions such as salinity. These wetlands are important for coastal ecology, water quality and recreation.

Shorelines protected with vegetation are fairly resistant to the action of relatively small waves in sheltered areas. No quantitative model is presently available to predict the erosion of such shorelines. These shorelines will become very vulnerable if they are exposed to ocean waves due to the disappearance or migration of protective barriers such as sand bars and islands. The long-term damage to coastal wetlands depends on relative sea level rise. Wetlands with large sediment inputs and biogenic production have kept pace with historic sea level rise. Wetlands with small sediment inputs and large local sea level rise have been naturally translated landward but will be drowned in place if the translation is prevented by the construction of bulkheads. For example, the relative sea level rise in parts of the Mississippi delta plain is approximately 1 cm per year predominantly due to land subsidence and elimination of sediment supply by levee construction. This rise has resulted in the wetland loss of 100 km^2 per year in Louisiana.

3.5 Beach Nourishment

Beach nourishment is widely adopted to restore eroding recreational beaches and protect the upland area of social importance. The design of beach nourishment involves the determination of the quantity, quality and configuration of the sediment to be placed along a specific shore in view of site conditions, erosion rates, wave climate, available sand, costs, finances, and environmental impacts. Beach nourishment does not eliminate the cause of beach erosion. The nourished beach is expected to erode as fast as the prenourished beach even if the borrow sand is the same as the native sand.

No comprehensive model is presently available to predict the detailed performance of nourished beaches because of the complexities of nearshore processes. The cross-shore profile of nourished beaches is normally assumed to become equilibrium quickly and erode at a rate estimated from observed long-term shoreline positions. The differences of borrow and native sands are accounted for empirically in estimating the equilibrium profile and erosion rate. One-line numerical models are generally applied to predict the alongshore and long-term variations of the shoreline of the nourished beach. The numerical models can include the effects of coastal structures constructed to retain the placed sand and increase the longevity of beach nourishment projects.

3.6 Sand Bypassing

Tidal inlets and harbor entrances generally interrupt the natural drift of sediment along the shoreline. The interrupted sediment tends to accumulate and form shoals on the seaward and landward sides of such a shoreline opening where tidal currents are normally strong in the opening. Some of the interrupted sediment may eventually be transported to the downdrift side of the opening. Jetties and breakwaters built to maintain deep channels for navigation may block the longshore sediment drift completely and cause the shoreline erosion downdrift of these structures.

To restore the natural sediment drift along the shoreline, it is recommended now to place the sediment dredged for the maintenance of the shoreline opening to the downdrift side of the opening. Artificial sand bypassing is performed at some tidal inlets with jetties. The sand accreted on the updrift side is transported hydraulically or mechanically to the downdrift side. The design of sand bypassing includes the estimation of longshore sediment transport rates using field data and empirical formulas.

4. Design of Coastal Structures

Coastal structures constructed for the protection of shores and harbors are traditionally designed to withstand design storm surge and waves that occur infrequently, for example, statistically once in 100 years. Since an actual structure experiences a range of storms, a probabilistic approach is being adopted to predict the reliability or the risk of failure of the structure during its service life. Furthermore, a life-cycle cost analysis is being introduced to minimize the total cost of the structure which may need to be repaired or rehabilitated during its life. Both traditional and new approaches require the prediction of damage to the structure under the specified storm surge and wave conditions.

4.1 Seawalls and Revetments

A seawall separating land and water areas protects the land area from wave attack. A revetment is a facing of stone or concrete built to protect an embankment or dike against erosion by wave action or currents. The seaward slope of the seawall is typically vertical or very steep, whereas the revetment is generally inclined to allow the stable placement of stone or concrete units. Incident waves are almost completely reflected from vertical walls but may break on inclined slopes.

A seawall or revetment built along an eroding shoreline eliminates or reduces sediment supply from the protected upland and may increase the erosion of beaches in the vicinity of the structure. The sediment budget in the area affected by the structure needs to be examined using field data to assess the impact of the structure on the surrounding beaches. In addition, protection measures against local toe scour undermining the structure are generally necessary, although the geometry of a scour hole cannot be predicted accurately at present.

The crest elevation of the structure protecting the land immediately behind it must be higher than the combined water level of storm surge and tides to prevent the overflow of water in the absence of waves. Wave overtopping of the structure occurs when wave runup defined as the upper limit of wave uprush exceeds the crest elevation. Since incident irregular waves consist of individual waves with different heights and periods, individual wave runup heights are analyzed probabilistically. The height exceeded by a small number such as 2 percent of individual runup heights is conventionally regarded as the structure crest height of little wave overtopping. To assess the impact of wave overtopping, use is normally made of the average overtopping rate defined as the volume of overtopped water per unit crest width divided by the duration of water collection.

The prediction of wave runup and overtopping for a specific project is based on laboratory model tests. Empirical formulas based on such tests are available but limited to the specific test conditions because wave runup and overtopping depend on a large number of parameters required to describe the incident wave, bottom and structure characteristics. Numerical models based on mass and momentum conservation equations are being developed to predict wave runup and overtopping for the incident wave, bottom and structure characteristics specified as input to the models. These models can predict the quantities that are difficult to measure in laboratory experiments. However, the accurate numerical prediction of irregular breaking waves on coastal structures is still a major challenge for researchers.

Damage to a vertical wall structure includes the overturning and sliding of the structure, and the failure and settlement of the foundation. The forces acting on the structure are the structure weight, the earth forces from the surrounding soil, the hydrostatic pressure forces from the surrounding water, and the wave forces on the seaward side and possibly bottom of the structure. Ponding of undrained water behind the structure increases the hydrostatic pressure force directed seaward. If incident waves do not break in front of the structure, the wave pressure and resulting force can be predicted using nonlinear wave theory for standing waves. However, wind waves are irregular and it is hard to judge which waves may be breaking or nonbreaking. Consequently, the wave force is estimated using the empirical formula which is applicable to both breaking and nonbreaking waves. The individual wave with the maximum wave height in the incident wave train is generally used to estimate the maximum wave force and moment because a single large wave may cause the sliding or overturning of the vertical wall structure. A wave breaking directly on the vertical wall may cause an additional impact force lasting for a very short duration. This impact force may be important for the design of the wall thickness but its duration may be too short to cause the significant movement of the structure. Since the wave impact force and its consequences cannot be predicted definitely, it is safer to minimize its occurrence by modifying wave breaking patterns in front of the structure.

Damage to an inclined revetment of stone or concrete armor units include the dislodgement and breakage of individual armor units by wave action, the sliding of the entire armor layer, the migration of subsoil particles through the filter and armor layers, and the geotechnical slip of the slope. If stone of sufficient weight and quality is available locally, it is the most economical to use such stone for the armor layer. If such stone is not available nearby, use is made of concrete armor units or blocks. Slender concrete armor units shaped to increase interlocking are more stable against wave action than stone of the same weight but more susceptible to breakage. If waves are not very large, use is made of flat concrete blocks placed orderly on the slope. It is easier to walk on placed blocks but wave runup is higher on the smooth surface of placed blocks than on the rough surface of stone or concrete armor units. Furthermore, the water pressure under the relatively impermeable blocks may build up and uplift blocks.

For revetments with adequate filter layers on the slope which is not too steep, the most important design problem is generally the dislodgement of individual armor units. The wave uprush and downrush on the revetment exerts the wave forces on individual units which are normally separated into the drag, lift and inertia forces. The stability of each unit against sliding, uplifting and rolling can be predicted using the force and moment balance equations. When the unit becomes unstable, the equation of motion can be solved numerically to predict the trajectory of each moving unit. However, the accurate prediction of the flow field and resulting forces among a large number of interacting armor units is not possible at present. For engineering applications, it is necessary to conduct laboratory model tests and evaluate the performance of specific revetments. Empirical formulas based on extensive laboratory tests are available for a preliminary design to estimate the required weight of individual armor units for the estimated significant wave height and period during the peak of a design storm. The temporal progression and spatial variability of damage are being investigated experimentally to quantify the damage processes in more realistic manners.

4.2 Breakwaters and Jetties

Breakwaters, which are connected to or detached from the shore, are constructed to reduce wave action behind breakwaters for the protection of harbors and shorelines. Jetties connected to the shore are built at the mouth of a river or tidal inlet to stabilize a navigation channel. Breakwaters and jetties are often rubble mounds of dumped small stones covered with layers of large stones or concrete armor units. Concrete caissons placed on rubble mound foundations are also common at places where large stones of sufficient strength are not available. The wave propagation models discussed above in relation to wind waves are used to predict the diffracted waves behind these structures. Partial wave reflection and wave transmission over and through the porous structures are taken into account empirically in the wave propagation models. On the other hand, local wave models are also available to predict the detailed wave fields on and inside the porous structures.

Damage to breakwaters and jetties is similar to damage to the inclined and vertical structures discussed above in relation to seawalls and revetments except that breakwaters and jetties are practically surrounded by water. Some large breakwaters are also located in relatively deep water. Since no land exists immediately behind these structures, some wave overtopping is often allowed to reduce the structure crest elevation and cost. Limited laboratory data are available to estimate damage to the crest and rear side of low-crested structures due to overtopping waves. Damage to large breakwaters in relatively deep water can be sensitive to the accuracy of predicted wind waves, whereas design waves for structures located in shallow water are generally depth-limited breaking waves and more sensitive to the accuracy of predicted storm surge.

5. Conclusion

Numerical models for predicting tides, storm surge and wind waves have improved significantly over the past 30 years. Relative sea level rise may increase due to the greenhouse effect but cannot be predicted accurately at present. The quantitative understanding of the various components involved in cross-shore and alongshore sediment transport has also improved but it is still not possible to predict the long-term cycle of beach erosion and recovery caused by sequences of storms. The capabilities for predicting damage to coastal structures have improved considerably for the last 20 years owing to the improved laboratory experimental capabilities followed by the development of advanced numerical models. To further advance our capabilities for predicting damage to shorelines and coastal structures, hybrid approaches based on numerical models coupled with field and laboratory experiments will be the most promising and practical.

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