

CHAPTER 89

GENERIC TREATMENT OF DUNE EROSION FOR 100-YEAR EVENT

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Abstract

Quantitative procedures provide the eroded dune geometries expected during an extreme storm on U.S. Atlantic and Gulf coasts. A criterion for either dune face retreat or dune removal is based on measured erosion cross sections in many cases where the pre-storm dune proved to be a durable barrier to wave effects. After that decision, the eroded profile is constructed using specified planar segments cut into or across the existing dune. This empirical treatment appears appropriately detailed for assessing hazards due to the 100-year event considered within the U.S. National Flood Insurance Program, and an example assessment is outlined. Additional discussion addresses other site-specific factors possibly affecting dune erosion, along with another potential application for this simplified methodology.

INTRODUCTION

The Federal Emergency Management Agency develops a Flood Insurance Study (FIS) for each community participating in the U.S. National Flood Insurance Program (NFIP). The focus of an FIS is expected effects in the flood having a one-percent chance of being equalled or exceeded in any year. This "base flood" is equivalent to the 100-year event for a given site, expected to recur once each 100 years on the average. Open-coast communities are subject to particularly extreme hazards due to storm surge and wave action from large water bodies. Coastal areas of special flood hazard in 100-year events are designated as V zones, having the potential for inundation by water flows with significant velocity. Within a V zone, floodwater depth is sufficient to permit a wave height of at least 3 feet (0.9 meters).

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Proper delineation of V zones requires quantitative determination of wave effects associated with the base flood, including coastal erosion.

Coastal sand dunes usually extend above local 100-year flood elevations, but such apparent barriers to flooding may not prove durable in view of the massive erosion associated with extreme storms. Several levels of dune effectiveness as a flooding barrier need to be distinguished, as outlined in a schematic manner by Figure 1. These four cases correspond to the eroded dune providing:

- a. a reliable barrier to flood effects from the sea;
- b. a nearly complete barrier, with some overtopping;
- c. a partial barrier, with some wave transmission; or
- d. an ineffective barrier, as relatively deep water and high waves reach past the initial dune site.

Sound analysis of potential flood hazards thus requires an objective estimate of dune geometry during the base flood.

Treatment of expected erosion must be consistent with other NFIP methodologies. First, it should be recognized that the base flood represents a statistical measure rather than the actual effects arising in some particular coastal storm. Second, erosion assessment must conform to the standard FIS transect viewpoint: representative shore-normal profiles are considered. Third, the 100-year still-water flood level (SWFL) has a known elevation on a given coastal transect, evaluated prior to treating additional wave effects expected to occur in the base flood. Fourth, eroded dune geometry must be determined by a uniform but perhaps highly simplified method, appropriately reflecting basic physical principles, as in FIS procedures for treating wave dimensions (National Academy of Sciences, 1977).

This paper outlines objective procedures specifying coastal dune erosion expected to accompany the base flood. These estimates of eroded dune geometry are meant for application at exposed U.S. sites along the Atlantic Ocean and Gulf of Mexico. The present erosion treatment has a broad empirical basis and appears appropriate in the context of other NFIP methodologies for wave effects in extreme events.

DUNEFACE RETREAT AND DUNE REMOVAL

The Federal Emergency Management Agency (1986) assessed usual procedures and developed several recommendations to correct weaknesses in FIS identification of coastal high-hazard areas, or V zones. Recognizing the transient and sensitive nature of coastal sand dunes, it was recommended that the entire primary frontal dune be designated a V zone. Since NFIP regulations prohibit alteration of sand dunes in V zones, this serves to protect natural dunes. Substantial construction standards and adequate insurance rates now automatically apply in this area exposed to high hazards, by means of an NFIP rule effective October 1, 1988 (Federal Emergency Management Agency, 1988).

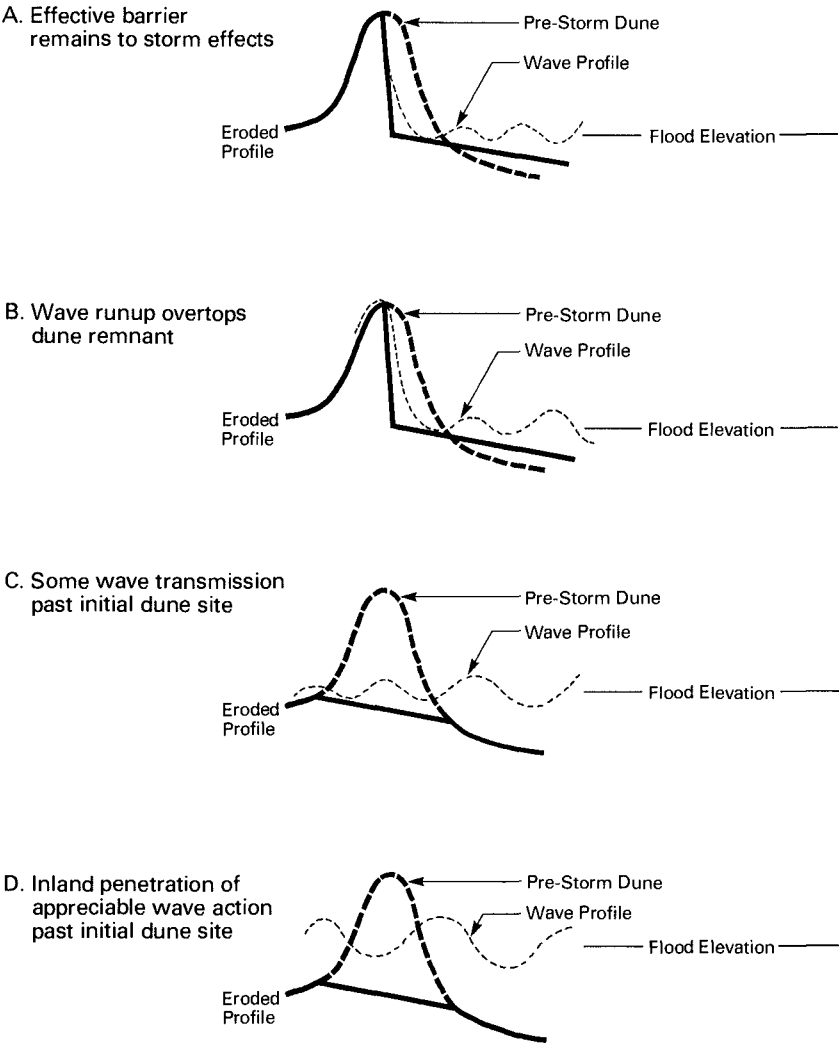


Figure 1. Schematic illustration of possible levels of flood protection provided by eroded frontal dunes

Another recommendation was for full consideration of storm-induced erosion in determining effects of the base flood. Coastal erosion can be crucial to the inland extent of V zones, but FIS treatments of erosion had been rather variable, with occasional underestimation of wave penetration associated with the base flood. The required erosion methodology would be capable of taking objective account of the range in expected effectiveness of existing dune barriers.

Figure 2 provides examples of sizable coastal erosion in the distinct categories of duneface retreat and dune removal. These instances relate to Gulf coast landfalls of Hurricane Eloise in 1975 and Hurricane Frederic in 1979, with profile changes documented by the Florida Department of Natural Resources (1987). In one case, the sizable dune remained intact as a barrier to coastal flooding, whereas the other dune was completely eradicated by storm-induced erosion. Methodology appropriate for NFIP application must provide the eroded profile geometry corresponding to each case.

Available computation models treating dune erosion were reviewed and found to have unproven capability for the entire range of effects possible in U.S. base floods. Two well documented but fundamentally different models, those by Kriebel and Dean (1985) and by Vellinga (1986), address only sand transport directed seaward, and thus can treat only cases of duneface retreat. Another important consideration is the marked variability of actual dune erosion in severe storms and the more sizable scatter to be expected in computed erosion amounts. For closely-spaced profiles along a coastal reach exposed to nearly constant storm forces, measured erosion cross section might have a median value of $2X$ and a range from X to $3X$, but computed erosion would likely vary from 0 to $4X$.

Simplified procedures specifying expected erosion geometry appear appropriate in view of the limited capabilities of available computation models and the NFIP need to treat an idealized 100-year event. Such procedures for immediate FIS application have been developed using documented erosion in extreme storms along the U.S. Atlantic and Gulf coasts. The first necessary element in this erosion treatment is a criterion to decide whether duneface retreat or dune removal would be associated with the 100-year event at a site.

EXPECTED DUNEFACE RETREAT IN 100-YEAR EVENT

The central analysis in this methodology development defined the sand reservoir above SWFL required for a dune to remain intact during specific storms. Published data were reviewed to accumulate 38 separate cases of duneface retreat, where pre- and post-storm profiles confirm that all eroded sand was transported seaward. In each case, the existing dune at a site provided a durable and effectively unlimited barrier during the particular storm. The data define a relationship between erosion cross sections and

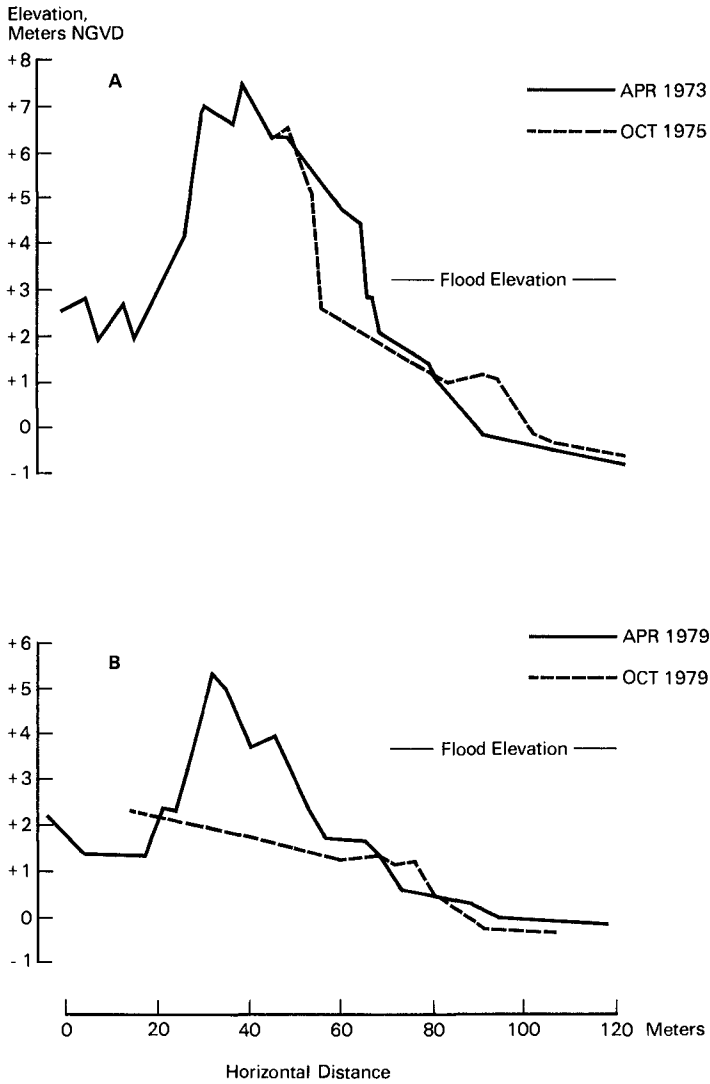


Figure 2. Examples of duneface retreat and dune removal, as documented by Florida Department of Natural Resources (1987). Effects are: A - September 1975 Hurricane Eloise, Profile R-15, Walton County, Florida; B -September 1979 Hurricane Frederic, Profile B-13, Baldwin County, Alabama.

storm intensities, as measured by recurrence interval for SWFL at specific sites, and thus indicate expected erosion in duneface retreat for the 100-year event (Hallermeier, Rhodes, and Buckley, 1988).

These 38 cases include hurricane and extratropical storm impacts in 11 states, with particularly good representation of sites in Florida, North Carolina, New Jersey, and New York. The data base was restricted to the U.S. Atlantic and Gulf coasts, to ensure that flooding is definitely related to storm effects (rather than tsunamis, for example). The exception to these geographical limits is inclusion of five events documented for the Dutch North Sea coast (Vellinga, 1986), to provide better coverage of duneface retreat in extreme extratropical storms, for which U.S. examples are scarce. In addition, to address effects relating to extreme storms rather than seasonal cycles, the data set was limited to events where SWFL has a recurrence interval of two years or longer. The exception (Birke-meier, 1979) is a December 1977 extratropical storm at sites where a more extreme event had occurred two months earlier, likely ensuring a generally meaningful response to the later storm.

About half these cases have changes recorded on multiple profiles, where median erosion is taken to summarize storm effects. Erosion is measured above the open-coast flood elevation, since such elevated change leads to failure of the initial dune barrier. The database includes median cross-sectional erosion from 5 to 105 m² for coastal floods with recurrence intervals of 1.25 to 300 years. Relatively common events have much better representation than truly extreme events, but data are rather uniformly distributed when considered using the logarithm of recurrence interval. The number of cases appears sufficient to be considered large for the purposes of statistical analysis.

Over the wide ranges represented, the trend in these field data is definite, yielding this relationship for median erosion in duneface retreat:

$$\text{Erosion [m}^2\text{]} = 8 (\text{Recurrence Interval [yr]})^{0.4} \quad (1)$$

Figure 3 presents residual differences between the measured erosion area and that given by the relationship in separate cases, along with an empirical error band for results. For the generic 100-year event, results indicate that expected duneface retreat will amount to $(50 \pm 15)\text{m}^2$ above local SWFL at U.S. Atlantic or Gulf sites. The uncertainty in this estimate refers to median erosion, not the actual erosion variability along the coast in a specific storm.

Figure 3 reveals little pattern among residual differences, showing this relationship has no distinct empirical defect. Relatively large underestimates of erosion appear somewhat more common than large overestimates, so that the expected duneface erosion has not been summarized as too extreme. However, few U.S. frontal dunes are massive enough to permit the indicated erosion for the 100-year event. This

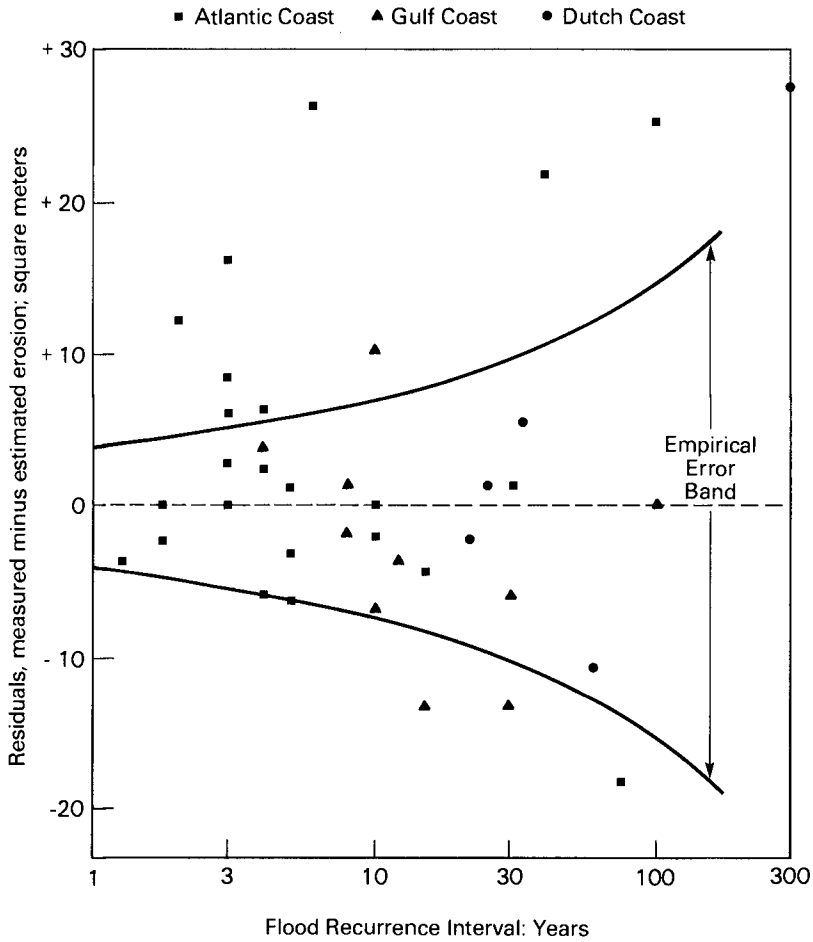


Figure 3. Residuals between measured erosion cross section and that from equation 1, for 38 cases of duneface retreat.

finding is certainly not surprising, since overwash is recognized to be a crucial process on barrier islands.

ERODED GEOMETRIES

The preceding results are expressed as a definite rule for FIS application in treating base flood effects (Federal Emergency Management Agency, 1988). For erosion to be limited to duneface retreat, an initial cross section of at least 50 m^2 is required above 100-year SWFL and seaward of the dune crest. With lesser cross sections, the existing dune will be considered to be completely eroded in analyzing effects of the base flood. An exception to this cross-sectional requirement may be granted at a specific site where authoritative historical documentation demonstrates that sand dunes have withstood storm surge and wave action approximating that expected for the base flood.

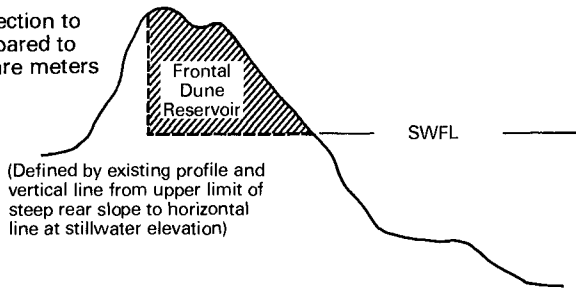
There is no intermediate erosion geometry between duneface retreat and dune removal. The basic reasoning is that when duneface retreat would proceed past the dune crest to the steep landward face, the dune remnant becomes susceptible to rapid and complete removal. This erosion treatment appears fundamentally consistent with the experienced field judgment expressed in original guidelines for identifying V zones (U.S. Army Engineer District, Galveston, 1975): "Unless historical data indicate that sand dunes in the area have repeatedly withstood wave attack during storms, they should not be considered as effective surge and wave barriers." New procedures permit definitive and objective analysis for the extent of sizable wave action in the base flood.

Figure 4 outlines the entire treatment of sand dune erosion appropriate in an FIS. Figure 4a indicates the Frontal Dune Reservoir examined in deciding between duneface retreat or dune removal for the base flood. Figure 4b demonstrates the geometric construction giving the retreated dune profile. Figure 4c shows the eroded profile appropriate in cases where the pre-storm dune is completely removed.

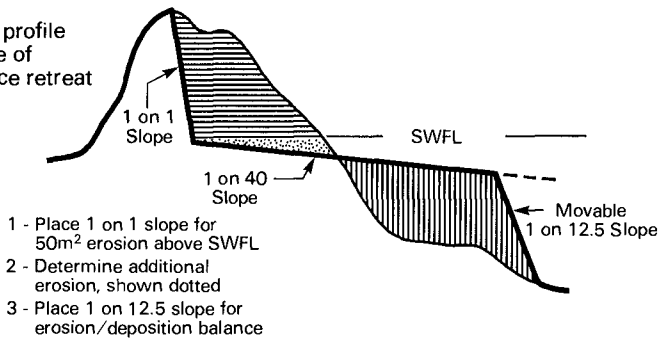
In regard to the Frontal Dune Reservoir of Figure 4a, consideration is restricted to sand located above 100-year SWFL and seaward of the steep rear slope. The vertical line as the landward boundary to the frontal dune reservoir seems a proper simplification, given that a steep escarpment occurs in duneface retreat and that sand in the rear dune wedge has some resistance to removal. The indicated reservoir is a straightforward measure for primary dunes with a prominent ridge or with a mound configuration but a marked rear slope. For some complicated dune profiles, judgment may be required to identify the dune segment expected to be fully effective in resisting removal.

The geometry for duneface retreat in Figure 4b represents a simplification of the erosion computation model developed by Delft Hydraulics Laboratory (Vellinga, 1986). Besides a

A - Cross section to be compared to 50 square meters



B - Eroded profile for case of duneface retreat



C - Eroded profile for case of dune removal

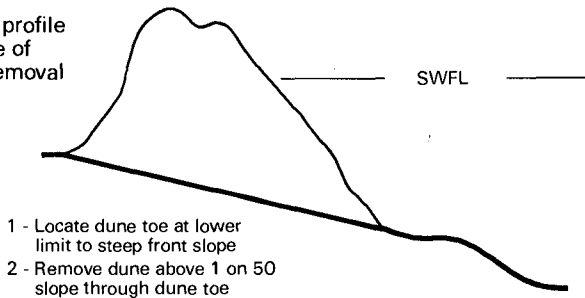


Figure 4. Treatment of sand dune erosion in 100-year event for a coastal Flood Insurance Study.

rectilinear rather than a curvilinear eroded profile, the present treatment specifies erosion above 100-year SWFL to be 50 m^2 , as expected in a generic 100-year event on the U.S. Atlantic or Gulf coasts. The constructed profile provides a balance between erosion and deposition, by adjustable seaward extent of the 1 on 40 slope segment between the 1 on 1 duneface escarpment and the 1 on 12.5 terminus to sand deposition. This eroded geometry is spliced onto unaffected landward and seaward segments of the existing profile, to give a complete transect suitable for assessing potential overwash of the dune remnant in the base flood.

Where the frontal dune reservoir is less than 50 m^2 , dune removal is effected as in Figure 4c. This procedure erases the major vertical projection of the primary frontal dune from a given transect, yielding a gentle seaward-dipping ramp for storm waves and flood waters. That ramp begins at the dune toe, defined as the seaward point on the steep duneface, with the 1 on 50 slope taken as an appropriate inclination in view of the extensive 1 on 40 slope occurring in duneface retreat with a steep landward barrier. This erosion treatment shows distinct agreement with post-storm profiles for Gulf coast cases of frontal dune removal in the 1957 Hurricane Audrey, 1965 Hurricane Betsy, 1979 Hurricane Frederic, and 1985 Hurricane Kate. There is no attempt to balance dune erosion by sand deposition elsewhere, since current knowledge of overwash processes is inadequate to address that redistribution (Birkemeier, et al., 1987).

There are major differences between eroded profiles in the two distinct categories. Duneface retreat occurs almost entirely above SWFL, but a cut at much lower elevation can take place during dune removal. For a sizable dune not meeting the stated cross-sectional criterion, erosion quantity might amount to three times that expected for duneface retreat in the 100-year event. However, potential alternatives in estimated erosion geometry for marginal dune cross sections may have diminished effects on FIS hazard assessment due to the rule that the primary frontal dune is entirely a V zone. Exceptions will occur where landward elevations in dune removal control V-zone extent.

Figure 4 procedures are intended for immediate FIS usage in treating the base flood at typical sandy sites on the U.S. Atlantic or Gulf coasts. This erosion methodology is efficient and objective, with a broad empirical basis in recorded storm effects on these coasts. Erosion estimates should be finalized with full consideration of documented historical storm effects at the particular study site.

EXAMPLE OF FIS APPLICATION

This example treats dune erosion expected to be associated with the 100-year event for a coastal site in Massachusetts. As shown in Figure 5, the shore topography is divided into two reaches, each represented by a typical

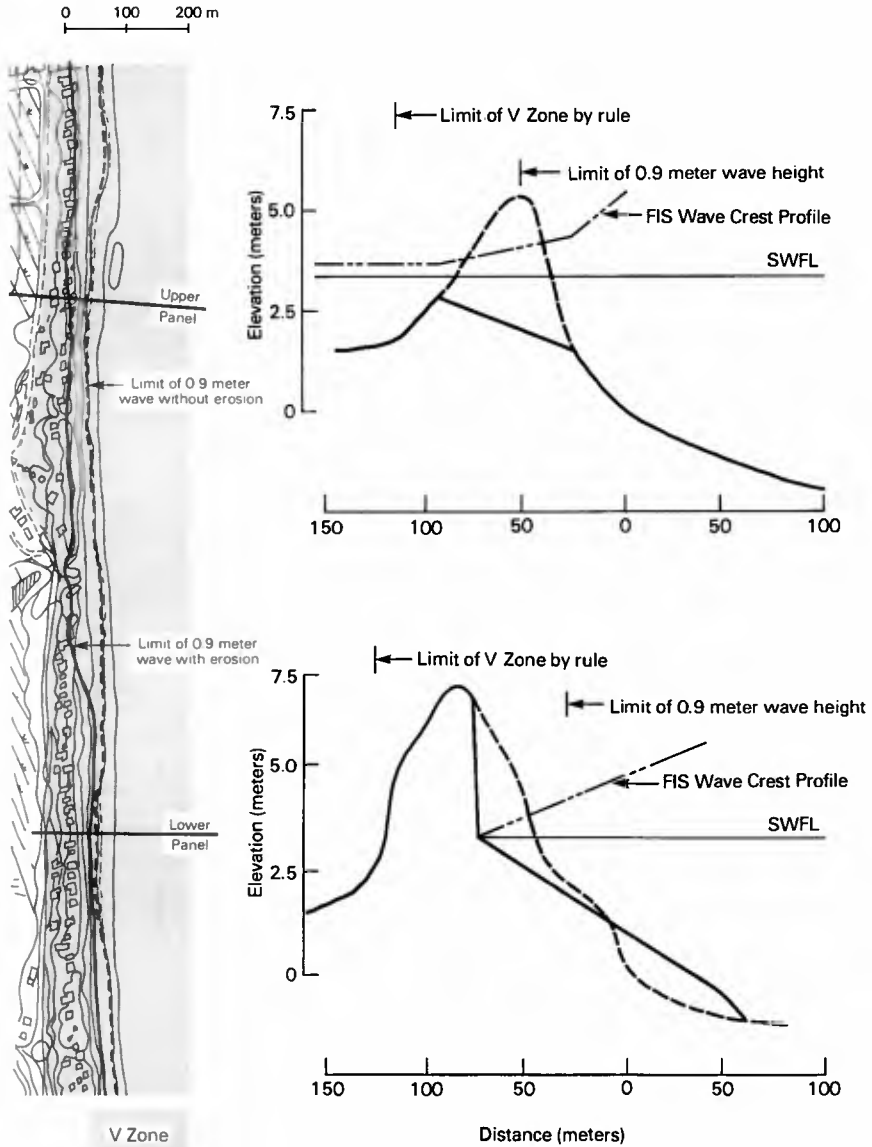


Figure 5 - Coastal topography (at left) and two representative transects in example of dune erosion treatments and FIS V Zone determination.

transect profile. On the upper transect, the Frontal Dune Reservoir is less than 50 m^2 so that the dune removal procedure is employed. The resultant profile is entirely submerged by the 100-year SWFL, permitting propagation of a 3-foot-high wave about to the initial dune crest. The inland limit to 3-foot wave height is generally dependent on the width of the dune, the location of the dune toe, and the SWFL.

The entire dune will be designated as V zone by NFIP rule, although the high-hazard zone according to wave height would not be so extensive in this example. For cases where the eroded profile allows the propagation of 3-foot-high waves past the pre-storm dune, the rule will have no effect since the V zone identified by wave height analysis will extend further inland. In either case of dune removal, expected erosion certainly can make the entire frontal dune an area of high hazard in the 100-year event, regardless of the wave height criterion.

The Frontal Dune Reservoir exceeds 50 m^2 for the other transect of Figure 5 and the duneface retreat procedure is applied. The resultant profile allows 3-foot-high waves to approximately the face of the pre-storm dune. This is slightly landward of the limit to 3-foot-high waves if no erosion is presumed. As with all cases of duneface retreat, the rule defining the primary frontal dune as V zone will fundamentally control the hazard zonation.

The V zone for FIS purposes is indicated on the topography shown in Figure 5. The limits of 3-foot wave heights with and without the erosion treatment are also delineated. This example demonstrates that dune erosion allows increased wave penetration, more so with dune removal than with duneface retreat. However, the main consequence of erosion treatment in an FIS will usually be in the determination of flood elevations including wave effects. The extent of the V zone is often controlled by the new NFIP rule, except for narrow dunes with low elevations landward.

FURTHER DISCUSSION

This erosion methodology offers maximum simplification along with the absolutely necessary distinctions for the intended application. Flood elevation and dune cross-sectional area are the predominant factors in the present schematization of expected erosion. Other site and storm characteristics are thought to affect dune erosion in a particular event, but the lack of definitive parametrizations for effects of ignored variables precludes quantitative considerations as a supplement to the present generic procedures.

One potentially important factor is the storm surge duration, since massive dune erosion must require appreciable time to occur. Also, storm intensity has been characterized by recurrence interval of local flood elevation, but erosion is actually caused by associated waves impacting

the dune. A fundamental obstruction to more detailed erosion treatment in the present application is that the base flood is simply a water elevation recurring at a definite frequency; this 100-year event cannot be specified as a certain storm surge and wave sequence. The present erosion methodology has a broad empirical basis, reflecting expected effects in various storms and thus approximating a generic event.

Another notable set of site-specific factors includes dune characteristics such as sand size, consolidation, and vegetation. Those variables must figure in dune resistance to erosion, but general quantitative guidance is not available. The present treatment is based on effects at a variety of sites, and can be expected to be usually applicable to sand dunes established by natural processes. Another presumption is that detailed dune geometry can be summarized by cross-sectional area; any independent effect of dune height can be considered in terms of wave runup and overtopping after erosion assessment is completed.

The Dutch computation model incorporates strong dependences of erosion cross section on both sand size and dune height (van de Graaff, 1986). Effects of those dependences can be compensatory only if higher dunes are naturally associated with coarser sands, which seems unlikely. Thus, the most significant factor ignored in the present treatment appears to be detailed dune characteristics, since storm intensity has been at least partially considered by means of the flood recurrence interval. Still, the relationship in Equation 1 accounts for a majority of the variance in the present data base, demonstrating the usefulness of a simplified erosion treatment. Considering the natural irregularity in erosion amounts, there appears to be little room for improvement by detailed consideration of causative and response variables.

The only site characteristics treated in the Figure 4 procedure are the 100-year SWFL and some aspects of existing shore profile. However, exceptionally wide sand beaches have been documented to limit the extent of dune erosion or wave damages during extreme storms, and such sheltering effects should be taken into account. For duneface retreat, a stable inner surf zone is provided by slope of 1 on 40, and comparable existing shore slope must limit dune erosion by effecting gradual dissipation of storm waves. That shore situation must complicate eroded profile construction with the specified duneface erosion and sand balance, but a simple and consistent adjustment of procedure might limit retreat to the point defined by 1 on 40 slope from usual sea level up to 100-year SWFL. Note that the existing profile considered should be that for the season when extreme storms are expected at the site.

The present erosion procedures are intended for sandy open-coast sites where the basic transect viewpoint is adequate. This excludes application in three-dimensional regions such

as an inlet vicinity, or near coastal structures influencing water level, waves and erosion. Even focusing on relatively ideal sites, it appears that only rather generalized erosion treatment might have a direct empirical basis since data are scarce. Present simplifications presume that erosion is mainly independent of site-specific details: existing conditions may reflect some long-term equilibrium, so that a generic response to the 100-year event can be anticipated.

OTHER APPLICATIONS

Without additional investigation, present results cannot be applied with confidence beyond the geographic limits of the data base. This guidance could be useful for quantitative erosion analyses where a simplified viewpoint suffices. Away from the 100-year recurrence interval addressed here, erosion geometries would require empirical modification: bed slopes steeper than 1 on 40 or 50 will be appropriate in dissipating smaller waves of more common storms. However, the erosion climatology of equation 1 has a broad basis and is conducive to other direct applications, for example, in designing artificial sand dunes as storm protection.

Considering a dune project with a 50-year design life, there is 50% risk of a 73-year event as the extreme, according to the binomial distribution usually employed (U.S. Interagency Advisory Committee on Water Data, 1982). That event entails erosion of a frontal dune reservoir of 44.5 m^2 according to equation 1. Likely storm events between dune maintenance operations determine the needed increase of the sand reservoir over that required to withstand the design storm. With a 10-year interval chosen between dune replenishments, notable expected storms (50% risk) have recurrence intervals of 14.9 and 6.1 years, presuming a berm provides protection against storms less severe than a 5-year event. Those two storms could yield additional upper-dune erosion totaling 40 m^2 , nearly doubling advisable cross section.

Natural recovery or dune growth by aeolian processes would lessen requirements for placed sand. However, computations refer to erosion expected with established dunes, and should be increased for a safe upper bound to effects with loose sand. It seems clear that such estimates could assist in optimization of interrelated design choices: berm and dune geometries; maintenance interval and project lifetime; etc.

CONCLUDING COMMENTS

Geometries provided for duneface retreat and dune removal are recommendations for appropriate erosion treatments rather than official FIS procedures. Present results are certainly liable to improvement based on advances in detailed erosion modeling and particularly in knowledge of

dune removal processes. Fundamental simplifications here currently seem necessary and appropriate in view of the marked variability of storm-induced erosion quantities, limitations apparent in published erosion treatments, and the basic idealization in FIS consideration of base flood effects along representative transects. Given present knowledge of dune erosion processes in extreme storms, only a simple treatment of coastal erosion can be expected to provide sufficiently generic estimates for a 100-year event.

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