D.4.6 Coastal Erosion

This section provides methods for Mapping Partners to define the shape and location of eroded beach profiles, upon which the 1% flood conditions (waves and water levels) will act and from which flood hazard zones and Base Flood Elevations (BFEs) will be mapped.

D.4.6.1 Overview

Erosion processes and consequences of erosion can either be “episodic” or “chronic.” These two descriptors assign a very important temporal component to erosion processes and their results. *Episodic erosion* is the shore and backshore adjustment that results from short duration, high intensity meteorologic and oceanic storm events. This type of event response results in shore adjustment and occurs during a single storm or during a series of closely spaced storm events within a storm season. Shore and backshore profile changes during intense storms and hurricanes can result in dramatic beach and dune erosion, retreat, breaching, or removal of backshore dunes; cause retreat and collapse of bluff and cliff formations; and culminate in greater landward encroachment of waves and flooding from the ocean. *Chronic erosion* is associated with slow, long-term processes such as gradual shoreline adjustment associated with: (1) sea level rise, (2) land subsidence, (3) changes in sediment supply due to watershed modifications or dam building, and (4) decadal adjustments in rainfall, runoff, and wave climate associated with global warming.

Current Federal Emergency Management Agency (FEMA) regulations are limited to risks and losses occurring as the direct result of a storm event. The National Flood Insurance Program (NFIP) does not address long-term gradual chronic erosion but focuses on flood-related erosion, episodic erosion, due to storm events[1]. FEMA does not currently map long-term erosion hazard areas as some local or state agencies do. FEMA Flood Insurance Rate Maps (FIRMs) do not inform property owners of erosion risks. FIRMs only indicate risks from flooding hazards in the form of BFEs and flood hazard zones. Therefore, flood assessment guidelines in this section only include methods for estimating eroded shore and backshore profiles during single large storm events, so runup and overtopping computations can be made to determine flood risks associated with those events. Section D.4.9 discusses how results from event-based erosion assessments are to be used by Mapping Partners to determine flood risks and delineate hazard zones.

D.4.6.2 Pacific Coast Characteristics Related to Storm-induced Erosion

Pacific storms track from the Pacific Ocean toward the coasts of California, Oregon, and Washington. Unlike hurricanes that occur along the Atlantic and Gulf coasts, Pacific Coast storms are frontal storms. These storms have smaller peak force wind speeds and surges than hurricanes, but have much longer durations (often on the order of several days). Intense Pacific storms are capable of generating 40- to 60-foot waves, and Pacific storms often “line up” in a series of back-to-back events that track thousands of miles across the Pacific Ocean to attack the West Coast of the United States for weeks with elevated tides and high surf. A series of storms

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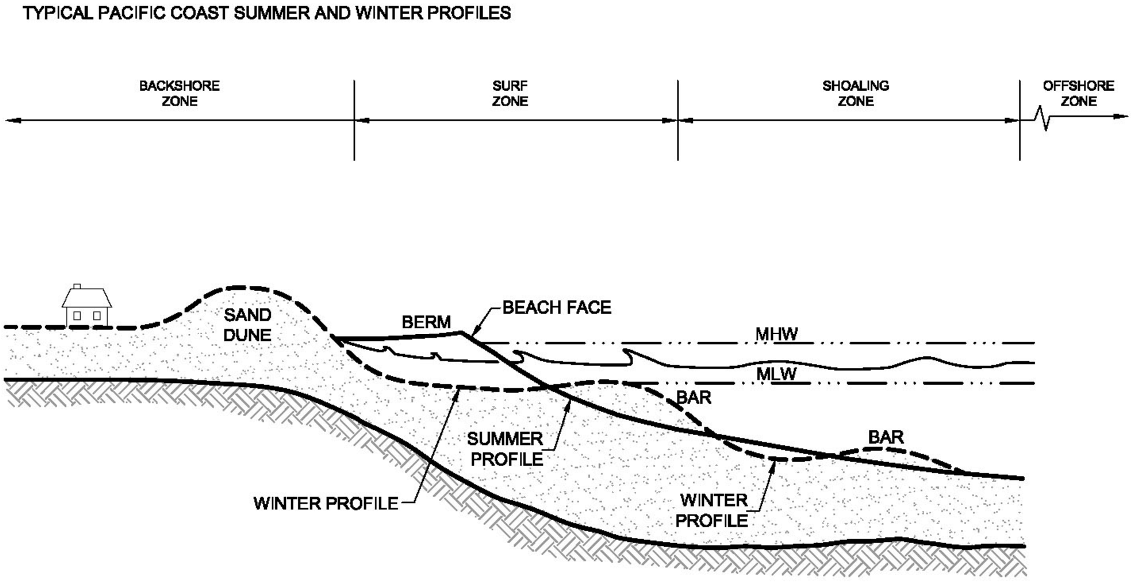
[1] Discussions of long-term erosion and the potential consequences of chronic erosion are found in materials listed in the reference section of this document and in many of the support documents referenced herein.

with only short periods of time between their peaks are capable of causing significant beach profile recession. One, two, or more storms may occur in a winter season before a severe storm event occurs. The periodic occurrence of El Niño oceanic conditions significantly amplifies the effects of Pacific storms with increased sea level and wave heights. This change in oceanic temperature, weather, and wave climate during El Niño periods is unique to the Pacific and usually represents meteorological and oceanic conditions when wind, waves, total water levels, and coastal erosion are the greatest.

Pacific Coast beaches undergo typical seasonal changes in profile and location from summer to winter conditions. During winter months, increased total water levels along with high-energy, steep waves tend to move sand offshore, adjusting the beach profile and its cross shore location. By the end of the summer or early fall after months of calm seas, the beach has recovered and the berms and back beach dunes may be well developed again. Figure D.4.6-1 provides a sketch of generalized seasonal profile changes that occur on sand beaches of the Pacific Coast.



Note: Location and width vary as wave conditions change

Figure D.4.6-1. Typical Pacific Coast Summer and Winter Beach Profiles (after Bascom, 1964)

D.4.6.3 Background and Definitions

By their nature, coastlines are extremely complex and dynamic environments. The type and magnitude of coastal erosion are closely related to general coastal exposure and beach setting.

D.4.6.3.1 Coastal Exposure

Coastal exposure refers to: (1) whether the coastline and beach are situated on the open coast, e.g., exposed to the undiminished waves, water levels, tides, winds, and currents associated with the open coast, or (2) whether the coastline is located within a sheltered area that is fully or partially protected from the direct action of ocean waves, winds, tides, water levels, and currents.

The latter condition is referred to as a *sheltered water area.* Beach erosion processes resulting from changes in total water level and wave action are similar along the open coast and within sheltered water areas; however, the magnitude, rate, and ultimate beach response may be quite different for sheltered water areas due to dramatic differences in total water-level changes and wave energy during large storms. Sheltered water areas typically have reduced wave energy and smaller runup. Some sheltered water areas found in confined embayments or estuaries may, however, experience higher still water elevations resulting from the combined effects of astronomical tides and fresh water runoff from streams and rivers and modified tidal and surge conditions.

The primary differences in estimating coastal erosion for these two types of beach exposures relate to how waves and water levels are determined for the 1% response storm condition. Refer to Section D.4.2 for guidance on how the 1% annual chance storm is determined and to Sections D.4.4 and D.4.5 for guidance on how waves and water levels are estimated for these two coastal exposures.

D.4.6.3.2 Beach Setting

Beach setting refers to localized geomorphic characteristics of the shore and backshore zone related to site-specific geology, profile shape, material composition, and material erodibility; proximity to other dominant features such as coastal inlets, storm outfalls, streams, and creeks; harbors and coastal structures; littoral sediment supply; and pocket beaches; and seasonal changes in beach width due to changes in wave direction. Six common beach settings representative of those along the California, Oregon, and Washington coastlines are addressed in these guidelines:

1. Sandy beach backed by a low sand berm or high sand dune formation
2. Sandy beach backed by shore protection structures
3. Cobble, gravel, shingle, or mixed grain sized beach and berms
4. Erodible coastal bluffs
5. Non-erodible coastal bluffs or cliffs
6. Tidal flats and wetlands

Figures D.4.6-2 through D.4.6-7 provide sketches and define terms for these six common beach settings found along the Pacific Coast. Table D.4.6-1 describes these settings, and lists recommended methods and data necessary for estimating beach profiles for use during runup computations. For the most part, these six settings are found in both open coast and sheltered water areas. However, the magnitude and net effects of tides, waves, currents, and erosion often differ between open coasts and sheltered areas. Policy and criteria for evaluating the stability and performance of costal beach nourishment projects are not yet developed, and only basic guidance is provided in Section D.4.1, Pacific Coast Guidelines Overview.

Beach settings (1) and (2) are likely to be the most important coastal settings from a hazards mapping perspective. These two settings tend to experience the most erosion and flooding during large storm events. The following sections describe procedures for estimating storm-induced erosion for all six Pacific Coast beach settings listed in Table D.4.6-1. Two different

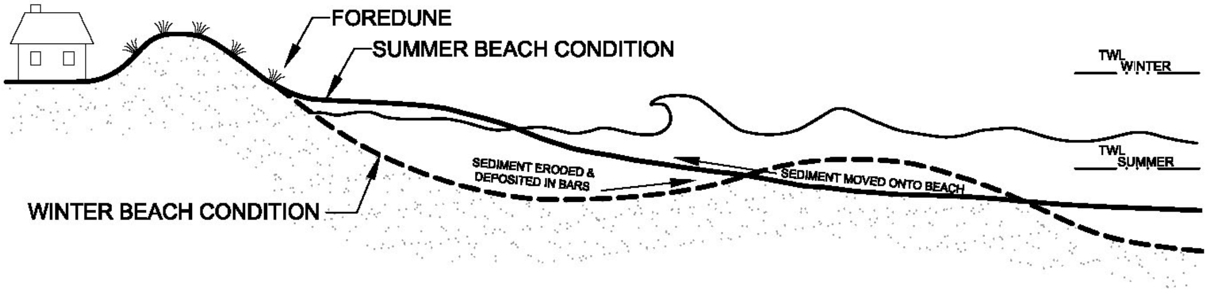


Figure D.4.6-2a. Sand Beach Backed by High Sand Dune (Beach Setting No. 1) (after Griggs, 1985)

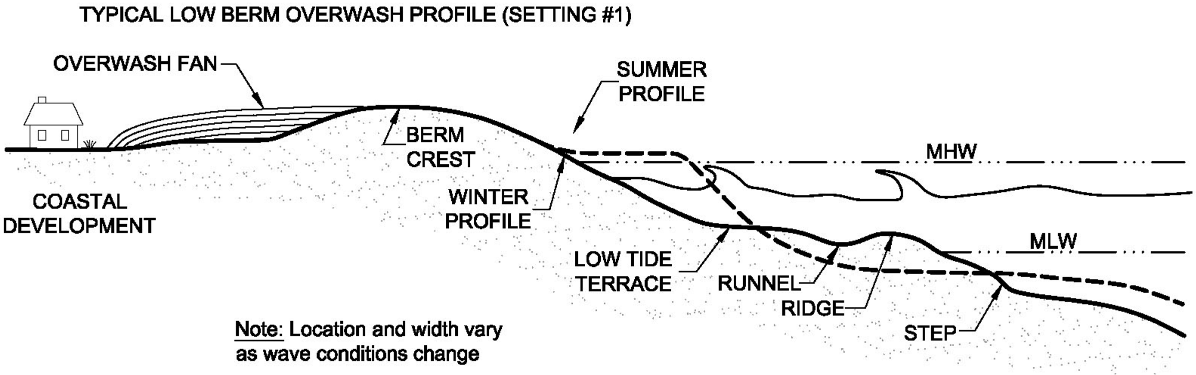


Figure D.4.6-2b. Sand Beach Backed by Low Sand Berm (Beach Setting No. 1) (after Bascom, 1964)

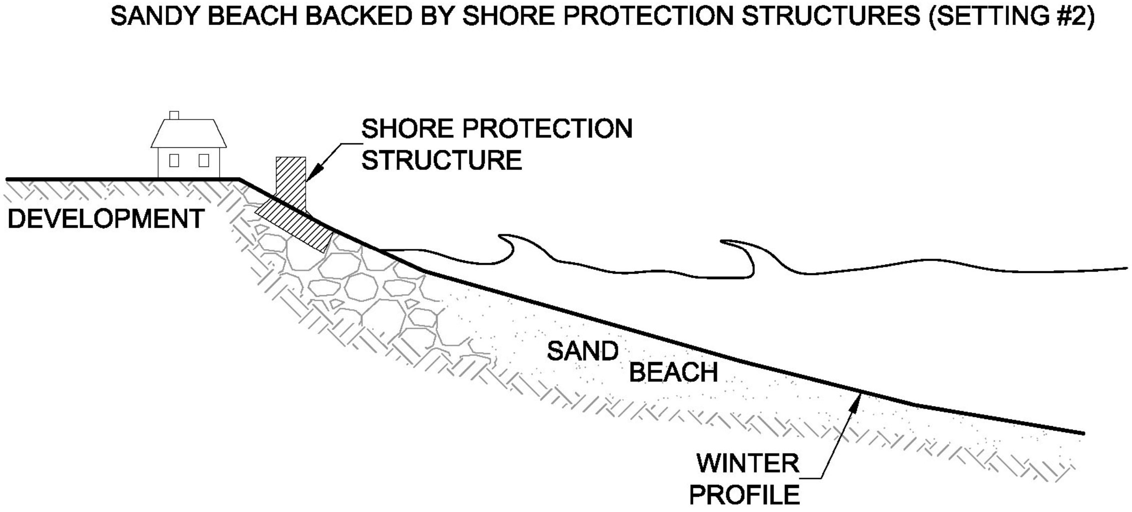


Figure D.4.6-3. Sand Beach Backed by Shore Protection Structures (Beach Setting No. 2)

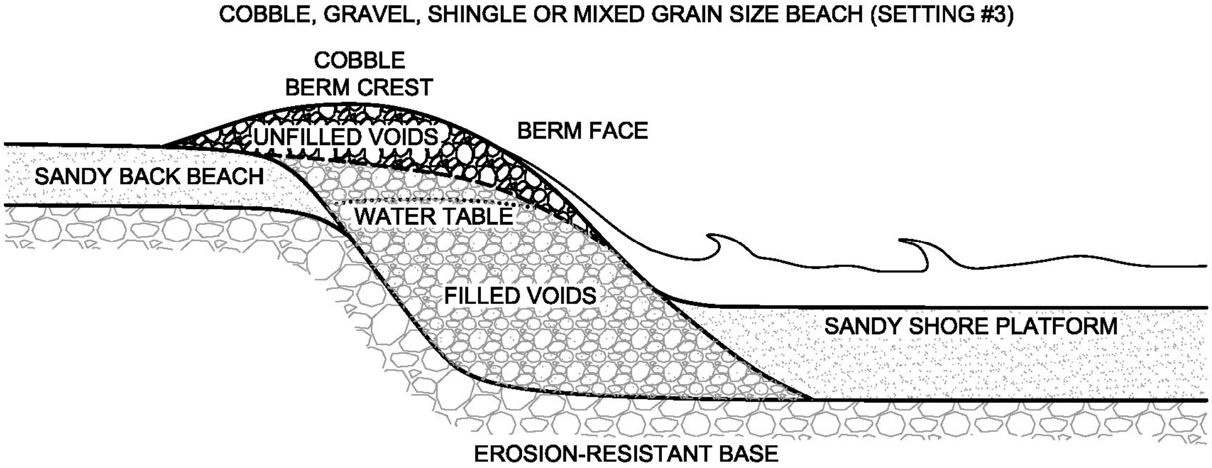


Figure D.4.6-4. Cobble, Gravel, Shingle, or Mixed Grain Sized Beach and Berms (Beach Setting No. 3)

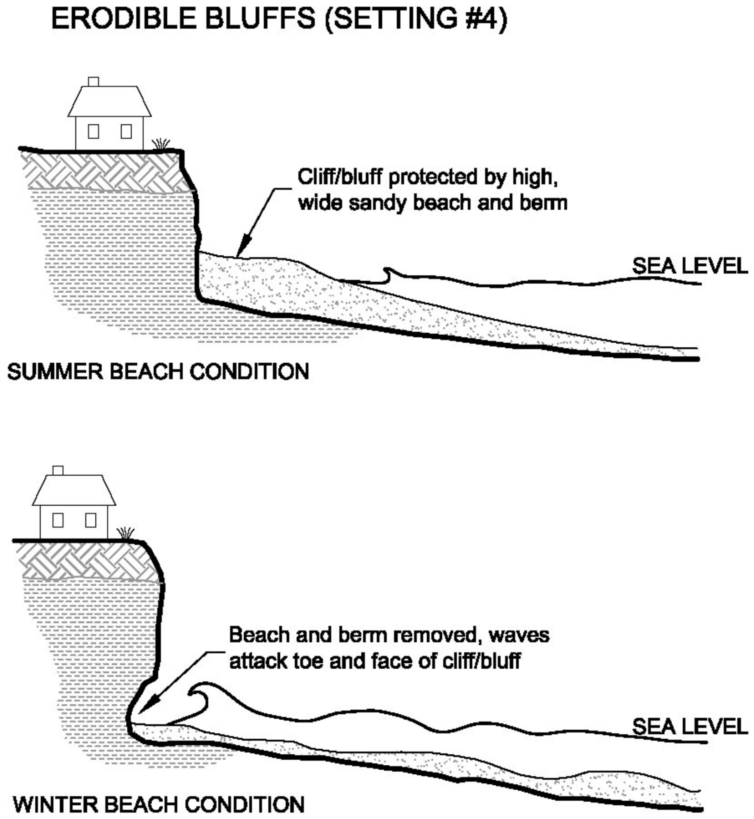


Figure D.4.6-5. Erodible Coastal Bluffs (Beach Setting No. 4) (after Griggs, 1985)

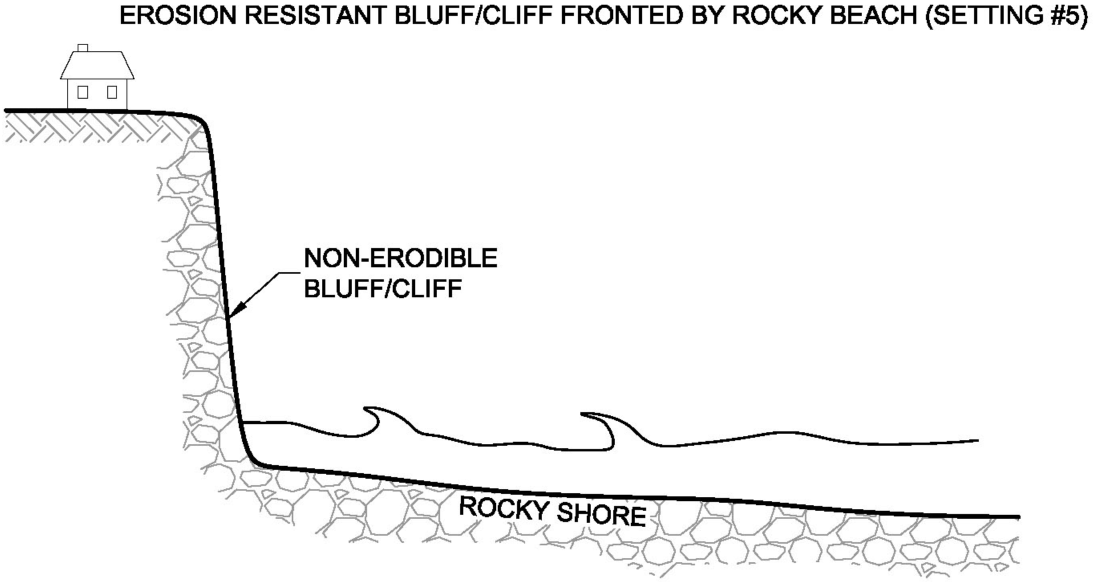


Figure D.4.6-6. Non-Erodible Coastal Bluffs and Cliffs (Beach Setting No. 5)

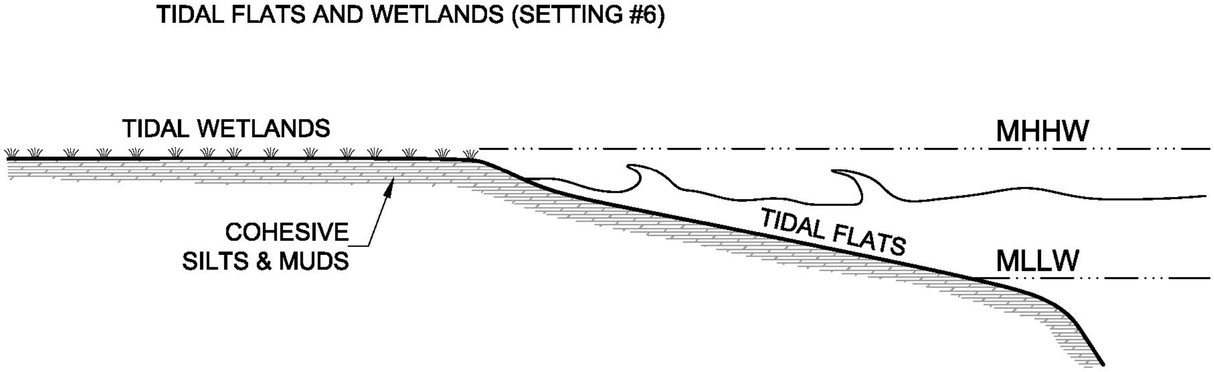


Figure D.4.6-7. Tidal Flats and Wetlands (Beach Setting No. 6)

Table D.4.6-1. Common Beach Settings Found Along the California, Oregon, and Washington Coastlines

Beach Setting	Reference to Sketch or Photo of Beach Setting	Materials	Recommended MLWP Methods	Recommended Eroded Profile Methods	Data Requirements
1. Sandy beach backed by low sand berm or high sand dune formation	Figures D.4.6-1, D.4.6-2a, D.4.6-2b D.4.6-8, D.4.6-9, D.4.6-10, D.4.6-11, D.4.6-12, D.4.6-13, D.4.6-14, D.4.6-15, D.4.6-16, D.4.6-17, D.4.6-18, D.4.6-19	Fine to coarse beach and dune sands	**See Subsection D.4.6.4** **1.** Begin with (surveyed) existing beach profiles. **2.** Develop MLWP and overlay on existing beach profile: **2.a.** *If have good post-large storm eroded beach profile data*: Use those data as initial winter beach profile, e.g., the MLWP. **2.b.** *If not:* Use MLWP methods listed in Subsections D.4.6.5 and D.4.6.5.2 if using MK&A geometric erosion model, or use methods listed in Subsections D.4.6.5 and D.4.6.5.5 if using the K&D geometric erosion model.	**See Subsection D.4.6.5** **1.** Begin with the MLWP. **2.** Select the MK&A or K&D method for computing beach erosion/recession that occurs to the MLWP during the 1% storm. **3.** Apply the (a) MK&A model (Subsection D.4.6.5) primarily for open coast OR and WA beaches backed by high dunes, and (b) the K&D model (Subsection D.4.6.5) for CA Open Coasts or Sheltered Waters.	- Local wave and water-level information - Local geology and beach and dune material characteristics - Historical beach profile data. - Recent data for project study area - LIDAR or surveyed profile data
2. Sandy beach backed by shore protection structures	Figures D.4.6-3, D.4.6-20, D.4.6-21	-Fine to coarse beach sands -Need characteristics of other fill or revetment materials	**See Subsections D.4.6.4 and D.4.6.6** 1. Estimate beach slope *m* from beach profile measurements immediately following winter storms, or 2. Estimate *m* from median grain size and beach exposure relationships (see Fig. D.4.6-9).	**See Subsections D.4.6.6 and D.4.7** 1. Use post large-storm beach profile data. 2. Compute local scour depths at toe in front of structures, (see CEM). 3. Determine whether structure fails or is overtopped (D.4.7). 4. Adjust profile from step 1 to account for effects computed in steps 2 and 3.	- Local wave and water-level information - Local geology and beach and dune material characteristics - Historical beach profile data - Recent data for project study area - LIDAR or surveyed profile data - Characteristics and dimensions of foundations and structures

Table D.4.6-1. Common Beach Settings Found Along the California, Oregon, and Washington Coastlines (cont.)

Beach Setting	Reference to Sketch or Photo of Beach Setting	Materials	Recommended MLWP Methods	Recommended Eroded Profile Methods	Data Requirements
3. Cobble, gravel, shingle or mixed grain size beach and berms	Figures D.4.6-4, D.4.6-22, D.4.6-23, D.4.6-24, D.4.6-25, D.4.6-26	Medium gravel to large cobble and small boulders	**See Subsection D.4.6.7** Assume cobble beach and berm profile is stable; however, fronting beach sands may erode during winter storms (see Figs. D.4.6-15 and 16) Therefore, assume MLWP is same as eroded winter storm profile.	**See Subsection D.4.6.7** Determine eroded winter storm profile from measured historical beach profiles, supplemented by probing or trenching to cobble bottom	-Local wave and water-level information -Local geology and beach and cobble berm material characteristics -Historical beach profile data -Recent data for project study area - LIDAR or surveyed profile data
4. Erodible coastal bluff fronted by narrow sandy beach	Figures D.4.6-5, D.4.6-27, D.4.6-28, D.4.6-29, D.4.6-30, D.4.6-31	*Bluff materials:* Loosely cemented sands and gravels *Beach materials:* Fine to coarse sands, some small gravels, cobbles	**See Subsection D.4.6.8** -Develop MLWP from measured historical beach profiles following large storm events; seek historical profiles during El Niño years if possible. -Supplement profile data with probing or trenching to confirm seasonal depth of scour. - If available, use historic eroded winter profile measured right after large storm.	**See Subsection D.4.6.8** -Develop eroded beach profile from measured historical beach profiles following large storm events during El Niño years if possible. -Supplement profile data with probing or trenching to confirm seasonal depth of scour. -If bluff is erodible, apply Noble Engineers Bluff Erosion Method for bluffs (USACE, 2003) using estimate beach slope and elevations from eroded beach profile, above.	-Local wave and water-level information -Beach and bluff material characteristics and erodibility information -Perform field inspections and sampling to determine geotechnical bluff erosion parameters -Historical beach profile and bluff retreat data -Recent data for project study area
5. Non-erodible coastal bluffs or cliffs (Note: This setting is often fronted by a rocky beach or rock platform capped with a thin layer of sand)	Figures D.4.6-6, D.4.6-32, D.4.6-33	*Bluff materials:* Erosion-resistant rock or cemented sands and gravels *Beach materials:* Thin layer of fine to coarse sands with some small gravels, over rocky bottom or rock platform	**See Subsection D.4.6.9** Assume the winter beach profile is stable and is estimated from measured historical beach profiles, supplemented by probing to rocky bottom	**See Subsection D.4.6.9** -Verify that bluff or cliff setting is non-erodible. -Determine winter beach profile from measured profile information and probing in March-April.	-Local wave and water-level information -Geologic information for study area -Historical beach, bluff and cliff profile data -Recent data for project study area

Table D.4.6-1. Common Beach Settings Found Along the California, Oregon, and Washington Coastlines (cont.)

Beach Setting	Reference to Sketch or Photo of Beach Setting	Materials	Recommended MLWP Methods	Recommended Eroded Profile Methods	Data Requirements
6. Tidal flats and wetlands	Figures D.4.6-7, D.4.6-34, D.4.6-35	*Tidal Flats:* Cohesive sediment and organic materials; cohesive clays and silts; *Wetlands:* cohesive clays, silts and organic materials often capped with marsh vegetation	**See Subsection D.4.6.10** -Assume tidal flats and wetland profiles are stable during single storm events. -Examine historical site information to determine whether profiles are stable, receding or accreting. -Determine winter profiles from LIDAR and/or other measured historical profiles.	**See Subsection D.4.6.10** Tidal flats and wetland surfaces typically do not erode during storm events; check local history of site; use LIDAR surveys or measured profiles to develop final winter profiles.	-Local wave and water-level information -Sediment & geologic information for study area -Historical profile data -Recent data for project study area -RU, OT and wave propagation computations will require estimates of vegetation density and roughness

methods are proposed for Beach Setting No. 1, depending on whether the backshore is a berm or dune and if there is overtopping during the 1% storm event.

D.4.6.3.3 Data Sources

Estimation of coastal erosion during storm events typically requires the following types of site-specific beach information and data:

1. Summaries and photos of historical coastal erosion
2. Aerial photos of study area
3. Local geology and shore and backshore material characteristics
4. Previous Flood Insurance Study (FIS) mapping and reporting
5. Historic and recent beach survey data: Light Detection and Ranging (LIDAR) topography and profile data

The following list provides references and websites where pertinent data may be obtained for use in event-based erosion analyses:

- Allan, J. C. and P. D. Komar. August 2004. Morphologies of Beaches and Dunes on the Oregon Coast, with Tests of the Geometric Dune-Erosion Model. Technical Memo. August 2004, 43 pp.

- Barton, C. C. 2004. U.S. National Coastal Assessment, USGS, Geologic Division, St. Petersburg, FL, website: <http://coastal.er.usgs.gov/national_assessment/>.

- Beach Morphology Monitoring Program Beach Profiles, 2004: <http//wwwecy.wa.gov/programs/sea/swces/research/change/monitoring/beach_profiles.htm>.

- California Coastal Zone Conservation Commission. 1975. *California Coastal Plan.* Prepared by the California Coastal Zone Conservation Commission, State of California, San Francisco, CA. 443 pp.

- Carr, E. E. 2002. Database of Federal Inlets and Entrances. U.S. Army Corps of Engineers, Coastal Inlets Research Program. <http://cirp.wes.army.mil/cirp/inletsdb/inletsdbinfo.html>. June 19.

- Coastal Natural Hazards Policy Working Group. 1994. *Improving Natural Hazards Management on the Oregon Coast*, Oregon Sea Grant, Oregon State University, Publication No. ORESU-T-94-002, 128 pp.

- Department of Navigation and Oceanic Development. 1977. *Assessment and Atlas of Shoreline Erosion Along the* California *Coast*, State of California Resources Agency, Department of Navigation and Ocean Development, Sacramento, CA, 305 pp.

- Elliott, D. L., C. G. Holladay, W. R. Barchet, H. P. Foote, and W. F. Sandusky. 1986. Wind Energy Resource Atlas of the United States, DOE/CH 10093-4, DE86004442. Prepared by Pacific Northwest Laboratory, Richland, WA. Prepared for the U.S. Department of Energy, Assistant Secretary, Conservation and Renewable Energy, Office of Solar Electric Technologies, Wind/Ocean Technologies Division. Published by the Solar Technical Information Program, Solar Energy Research Institute [now the National Renewable Energy Laboratory], Golden, CO. October. <http://rredc.nrel.gov/wind/pubs/atlas/atlas_index.html>.

- Flick, R. E. (ed.). 1994. *Shoreline Erosion Assessment and Atlas of the San Diego Region*, *Volume II*. California Department of Boating and Waterways, Sacramento, CA.

- Gerstel, W. J., M. J. Brunengo, W. S. Lingley, Jr., R. L. Logan, H. Shipman, and T. L. Walsh. 1997. Puget Sound Bluffs: The Where, Why, and When of Landslides Following the Holiday 1996/97 Storms. Washington Geology, vol. 25, no. 1. March. <http://www.dnr.wa.gov/geology/pugetls.htm>.

- Good, J. W. (ed.). 1992. *Coastal Natural Hazards, Science, Engineering and Public Policy*. Oregon Sea Grant, Oregon State University, Publication No. ORESU-B-92-001, 162 pages.

- Gornitz, V., Beaty, T., and R. Daniels. 1997. A Coastal Hazards Data Base for the U.S. West Coast. ORNL/CDIAC-81, NDP-043C, Oak Ridge National Laboratory, Oak Ridge, Tennessee. <http://cdiac.ornl.gov/epubs/ndp/ndp043c/43c.htm>.

- Komar, P.D. 1997. *The Pacific Northwest Coast: Living with the Shores of Oregon and Washington*. Duke University Press.

- Nichols, M. D., 2003. *Draft Review of California Coastal Erosion Planning and Response: A Strategy for Action.* California Resources Agency, Ocean Resources Management Program, Sacramento, CA.

- NOAA. 2000a. Tidal Datums and Their Applications. NOAA Special Publication NOS CO-OPS 1, Silver Spring, MD. June. <http://www.co-ops.nos.noaa.gov/publications/tidal_datums_and_their_applications.pdf>.

- NOAA. 2000b. Nautical Chart Symbols, Abbreviations and Terms, Chart No. 1, Eleventh Edition. Lighthouse Press, Annapolis, MD. 99 pp. NOAA Nautical Chart Users Manual. <http://chartmaker.ncd.noaa.gov/staff/ncum/ncum.htm>.

- NOAA. 2003. Computational Techniques for Tidal Datums Handbook, NOAA Special Publication NOS CO-OPS 2, Silver Spring, MD. September. <http://www.co-ops.nos.noaa.gov/publications/Computational_Techniques_for_Tidal_Datums_handbook.pdf>.

- Peterson, C. D, M. E. Darienzo, D. Hamilton, D. J. Pettit, R. K. Yeager, P. L. Jackson, C. L. Rosenfeld, and T. A. Terich. 1994. *Cascadia Beach-Shoreline Database, Pacific Northwest Region, USA*. State of Oregon, Department of Geology and Mineral Industries, Open File Report 0-94-2, Portland, OR.

- Southwest Washington Coastal Erosion Study, 1996: <http://www.ecy.wa.gov/programs/sea/swces/overview.htm>.

- U.S. Army Corps of Engineers (USACE-LAD). 2003. *Encinitas and Solana Beach Shoreline Feasibility Study,* San *Diego County, California - Coastal Engineering Appendix Without Project Conditions*, Los Angeles District Corps of Engineers. August 2003.

- ———. 1998. *Coastal Erosion Along the U.S. West Coast During the 1997-98 El Nino: Expectations and Observations*. USGS, Center of Coastal Geology. <http://coastal.er.usgs.gov/lidar/AGU_fall98/>.

- Important Links to Other Information Sites Regarding California Coastal Zone Management Topics: <http://www.coastal.ca.gov/web/sites.html>.

- <http://coastal.er.usgs.gov/lidar/AGU_fall98/>: Coastal Erosion (NOAA).

- <http://geodesy.noaa.gov/RSD/coastal/cscap.shtml>: Remote Sensing (NOAA).

- <http://gis.ca.gov/catalog/BrowseRecord.epl?id=1468>: Assessment and Atlas of Shoreline Erosion along the California Coast (Calif. Dept. of Boating & Waterways).

- <http://gis.sfsu.edu/data.htm>: Listing of GIS Data Bases for Various Types of Data.

- <http://www.californiacoastline.org/>: California Coastal Records Project-Aerial Photographic Survey of the California Coastline.

- <http://www.csc.noaa.gov/shoreline/>: Shoreline Data (NOAA).

- <http://www.csc.noaa.gov/crs/tcm/missions.html>: Topographic Data (NOAA).

D.4.6.4 Estimating Eroded Beach Profiles

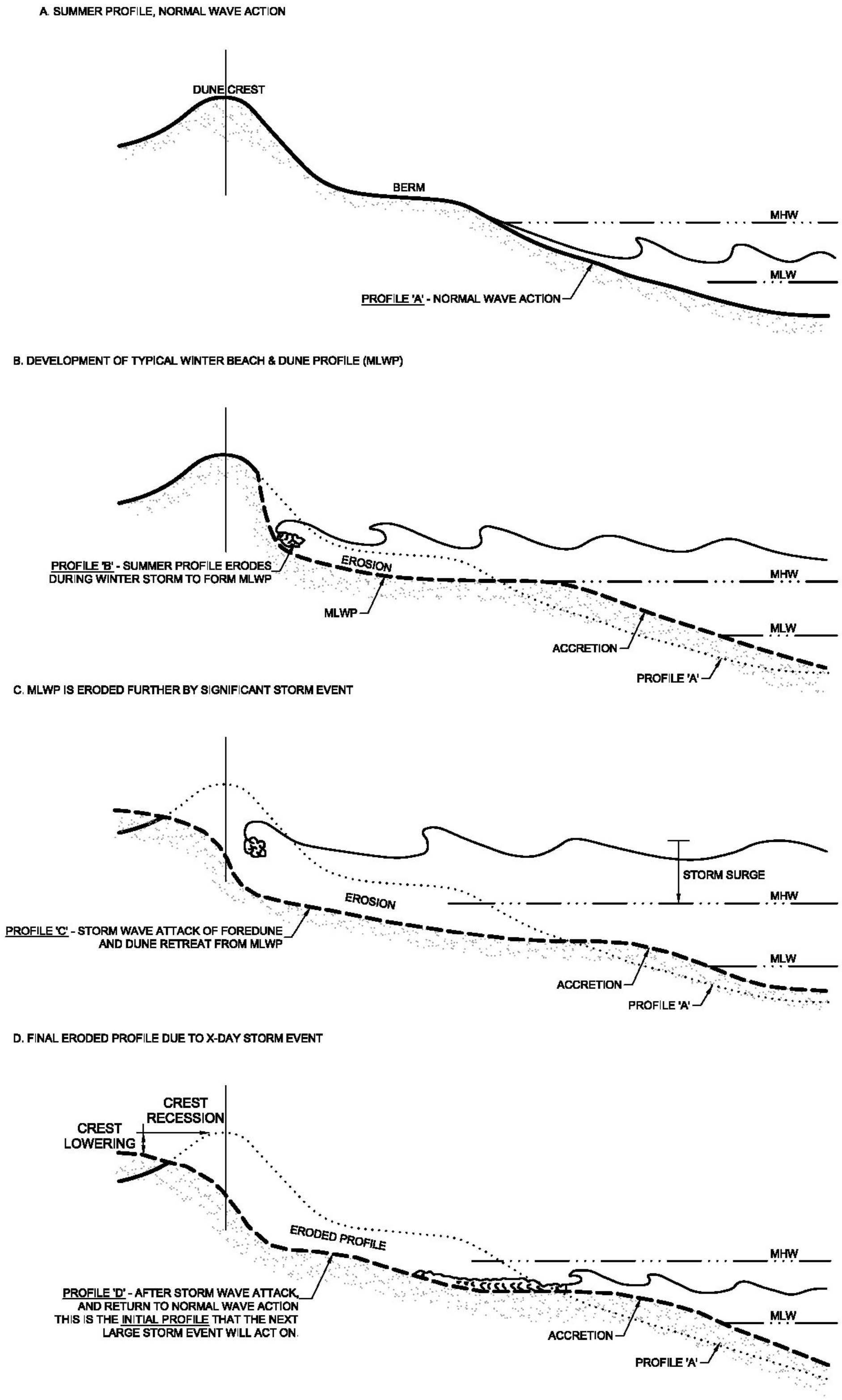
D.4.6.4.1 The Concept of the Most Likely Winter Profile

To estimate beach erosion and profile changes for a specific coastal setting that occurs during a particular winter storm event, it is important to first estimate the initial beach profile conditions that exist just before the occurrence of the storm (see Figure D.4.6-8). This initial beach profile represents the likely winter profile conditions for a particular coastal setting, defined as the *Most Likely Winter Profile* (MLWP). These initial conditions must be estimated before determining beach profile changes for a particular storm event. Once determined by the Mapping Partner, the MLWP is then modified according to the amount of erosion that occurs during a specified storm event as a result of increased water levels and wave action. Figure D.4.6-9 provides a generalized definition sketch of the MLWP for a typical sand beach backed by high sand dunes.

D.4.6.4.2 General Approach for Estimating Eroded Beach Profiles from Single Storms

The first step is to locate the site on a large-scale map. Next, determine the coastal exposure, open coast, or sheltered water area. Next, obtain and review mapping and published information regarding the site and its geologic, morphologic, seasonal water levels and wave climate, coastal processes, and erosional characteristics (e.g., refer to Subsection D.4.6.3.3 for references to sources for these types of information). Next, review historic summer and winter beach profile data if available, then determine the type of coastal setting(s) and the seasonal erosion characteristics that best represent the study area. Select from the six common beach settings applicable to coastlines of California, Oregon, and Washington that are described in Subsection D.4.6.3 and listed in Table D.4.6-1. Several different setting types may exist within the same study area depending on the aerial size and complexity of the study area. Therefore, a large project area with more than one type of beach setting, a variety of coastal exposures, and spatially varying material composition may require different data and the application of different procedures to estimate the MLWP or eroded profile for each representative setting. Mapping Partners should always establish subreaches within the larger study area that typify representative shore and backshore conditions within a particular subreach. If a series of cross-shore profiles is used to represent the shore and backshore for the study area, profiles must be carefully located to best capture the morphologic and potential erosional, runup, and overtopping aspects of each subreach.

After the study area is divided into representative subreaches, Mapping Partners must estimate the initial pre-storm event beach profile (MLWP) for each cross-shore profile in the subreaches. Methods for establishing the MLWP for each of the six primary settings defined above are presented in Subsections D.4.6.5 through D.4.6.10. Once determined by the Mapping Partner, the MLWP is then modified according to the amount of erosion that may occur for a particular setting and profile location during a specified storm event. Beach Setting No. 1 will always



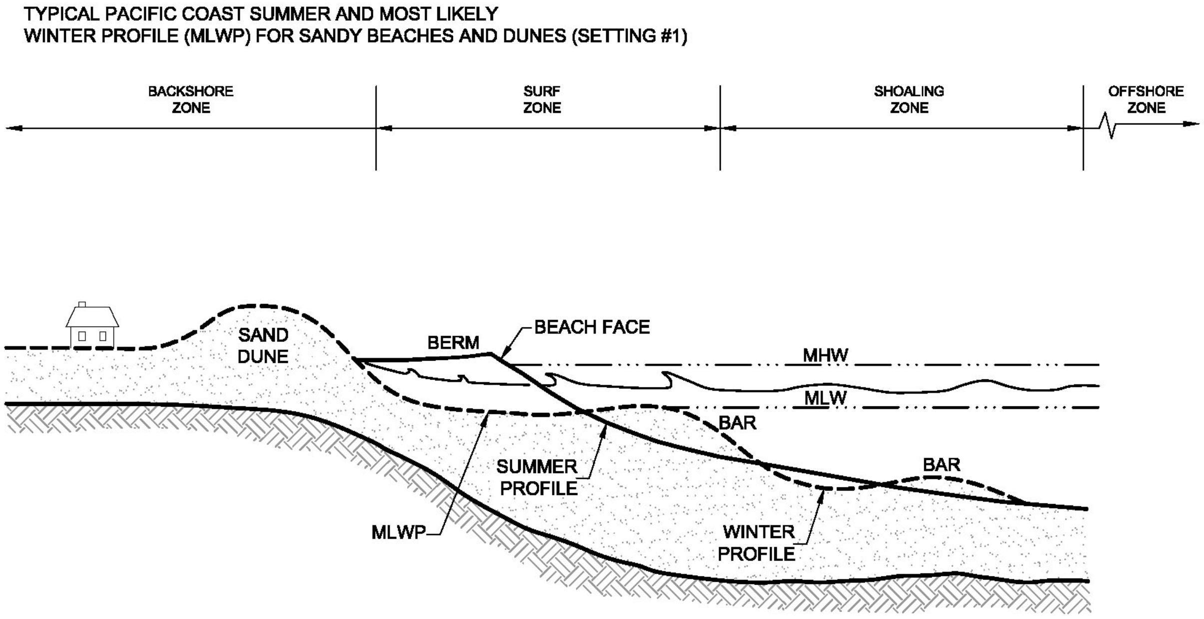
A. SUMMER PROFILE, NORMAL WAVE ACTION

B. DEVELOPMENT OF TYPICAL WINTER BEACH & DUNE PROFILE (MLWP)

C. MLWP IS ERODED FURTHER BY SIGNIFICANT STORM EVENT

D. FINAL ERODED PROFILE DUE TO X-DAY STORM EVENT

Figure D.4.6-8. Evolution of the Initial Beach Profile Before Occurrence of Large Storm Event (after SPM, 1984)



Note: Location and width vary as wave conditions change

Figure D.4.6-9. Definition Sketch of MLWP for Sand Beach Backed by Sand Dunes (Beach Setting No. 1) (after Bascom, 1964)

require development of the MLWP, followed by computation of the amount of additional profile adjustment (erosion) that may occur to the MLWP during any specified storm event. Depending on beach material properties and width of the beach, Beach Setting No. 2 may require a similar two-step process to determine the eroded beach profile in front of shore protection structures. Beach Setting Nos. 3 and 4 should be checked for erosion potential, but they are less likely to experience significant erosion beyond what one would estimate as the MLWP for those settings. Beach Setting Nos. 5 and 6 are typically stable and erosion-resistant, so once the Mapping Partner establishes the winter profiles, analyses of further erosion is not required. The amount of erosion and profile adjustment that occurs for Beach Setting Nos. 1 and 2 depends on the magnitude and duration of the event and is related to the total water level and wave characteristics. Methods and procedures for estimating beach profile changes for each of the six primary settings are presented next.

D.4.6.5 Estimating Profile Changes for Sand Beaches Backed by Low Sand Berms or High Dunes (Beach Setting No. 1)

The main erosion-related factors affecting beach profiles during storms are: (1) antecedent conditions of the beach and back beach (profiles and beach-dune juncture elevation) before the occurrence of the specified storm event (this issue of initial beach conditions is addressed by the MLWP); (2) forcing processes that include the duration and time histories of the wave characteristics, water levels, and runup; and (3) response elements that include the beach setting and the dune/bluff characteristics, including material erodibility. Mapping Partners need methods that account for the general effects of these processes for estimating the change in profile that the beach and back beach dunes will experience during the event in order to compute runup and overtopping and set BFEs, and establish depth and velocity hazard zones.

For Beach Setting No.1, a sandy beach backed by a low sand berm provides some buffer against storm wave attack. These beaches typically exhibit a very significant change in beach profile due to seasonal changes. The range of the seasonal change in berm width can vary from 50 to 250 feet as an extreme. Figures D.4.6-10 and D.4.6-11 show broad sandy beaches backed by low sand berms. Figure D.4.6-2b provides a sketch of a typical beach profile for broad sandy beaches backed by low sand berms (Beach Setting No. 1).

Figure D.4.6-10. Sandy Beach Backed by Low Berm, Newport Beach, CA (Source: Noble Consultants, Inc.)

Figure D.4.6-11. Sandy Beach Backed by Low Berm, Huntington Beach, CA (Source: Noble Consultants, Inc.)

Several event-based erosion assessment models are available, including simplified geometric models, simple process-based numerical simulation models, and more complex process-based simulation models. At the present time, process-based models have not been refined or calibrated for general application to Pacific Coast conditions. Therefore, use of process-based models is not recommended unless Mapping Partners have site-specific model calibration and validation data. Otherwise, Mapping Partners shall use the simplified geometric models discussed below.

The long-standing 540 ft^3/ft criterion previously adopted by FEMA for estimating Atlantic and Gulf coast dune erosion should not be used on the Pacific Coast. The Technical Working Group (2004) determined that general application of the 540 criterion is not applicable for the Pacific Coast and found that there are simple geometric models that are more reliable and applicable for assessing dune and berm erosion on the Pacific Coast. Two geometric models are recommended: the K&D model developed by Kriebel and Dean (1993) and the MK&A model that was developed by Komar et al. (2002) and further modified by McDougal and MacArthur (2004). The MK&A model was developed and tested for the Oregon and Washington coast, so it is most applicable to Type 1 beach settings found in Oregon and Washington. The K&D model is more generalized and has been regularly applied to Type 1 beach settings in California, with successful test applications in Oregon and Washington.

D.4.6.5.1 General K&D and MK&A Model Characteristics and Applicability

Regardless of the simplicity of these geometric models, both the K&D and the MK&A models produce reasonable estimations of sand beach and dune recession during single storm events. Both models were tested using measured beach profile and wave data in southern California and in Oregon. Model results agreed well with observed conditions. However, the determination of reliable input parameters is crucial to the accuracy of model results.

The erosion potential in the MK&A model is determined entirely by the change in the total water level and the beach slope, and is very sensitive to the slope. For the K&D model, the wave setup, event duration, D_{50} of the beach material, and profile characteristics (beach face slope and surf zone profile) determine the maximum beach erosion potential. The K&D model considers the conservation of sand volume between the erosion from the upper portion of the beach and its deposition offshore. For both models, the storm duration directly affects the maximum beach erosion and must be determined carefully.

The K&D model (Kriebel and Dean, 1993) was developed for four different beach profiles: (1) a square berm, (2) a sloping backshore, (3) a sand beach backed by high dunes (15 to 50 feet high), and (4) a sand beach backed by a low berm with a wide backshore. Therefore, the K&D model is applicable to a wider variety of beach conditions and settings. For the purposes of these guidelines, we only consider one of the typical equilibrium beach conditions (Beach Setting No. 1) available with the K&D model.

Southern California has many broad sand beaches backed by relatively low sand berms and broad back beach terraces. Beaches backed by high sand dunes are more common in northern California, Oregon, and Washington. The crest elevations of the low sand berms generally range between +5 to +15 feet high. If wave runup is included in the total water level, as is done in the MK&A model, the water level can easily exceed the low berm crest during moderate to large storms. The MK&A geometric model was developed primarily for applications along the Oregon and Washington coasts and is most appropriate for application to high dunes that are unlikely to be overtopped during a storm event. The K&D model is recommended for either case, where low berms can be easily overtopped during the storm event, or for high dunes that are unlikely to be overtopped. Figure D.4.6-12 shows a typical section of open Oregon coastline fronted by a long broad sand beach backed by high dunes where the MK&A model was successfully applied. All model results should be checked against observed post-storm data for reasonableness.

Figure D.4.6-12. Photograph of Netarts Bay, Oregon
(Photo Provided by Jonathan Allan)

D.4.6.5.2 MK&A and Its Application to Beach Setting No. 1

A geometric model for foredune erosion has been employed by Komar et al., (2002) on the Oregon and Washington coast to establish coastal setback distances for sandy beaches backed by dunes. This model was modified by McDougal and MacArthur (2004) to provide estimates of beach profile recession due to large storm events. The model is based on the underlying assumptions of an MLWP and the characteristic shape of shoreline recession that will result during a large wave and water-level event. The shoreline recession profile is characterized by the beach face slope, m, the beach-dune juncture elevation, E_j, and cross-shore location of the beach-dune juncture, y_j. These are shown in Figure D.4.6-13A. The juncture elevation is taken to occur at the maximum extent of the total runup plus the measured tide. The measured tide includes all processes that influence the water surface elevation such as surge and El Niño. The total runup is defined to include static and dynamic wave setup. The sum of the total runup plus the tide (including surge and El Niño) is referred to as the total water level (TWL). The sum of the astronomical tide, El Niño, and surge is the still water level (SWL) and is typically obtained from measurements. The setup and runup are calculated using methods described in Section D.4.5.

D.4.6.5.2.1 MK&A Methods for Estimating the MLWP

The first step for determining eroded beach profiles is to estimate the MLWP for each cross-shore profile. When using the MK&A method, the upper profile is specified by the beach face slope in the swash zone, *m* and the beach-dune juncture elevation and cross-shore location, $E_{j\ MLWP}$ and $y_{j\ MLWP}$ as shown in Figure D.4.6-13A. Because both the elevation and location of the juncture may be associated with different magnitudes of TWL events, the notation $()_{MLWP}$ is used to denote the MLWP case. The juncture elevation in the MK&A model is taken to occur at the maximum extent of the still water plus the total runup. The measured tide includes all processes that influence the water surface elevation such as the astronomical tide, surge, and El Niño. The runup is defined to include wave setup. The beach face slope is determined in the swash zone at high water levels. For the MLWP, *m* and $E_{j\ MLWP}$ are determined from beach profile measurements following a significant storm or at the end of the winter season, or they may be determined from typical winter wave and water-level conditions (as explained below).

The MLWP should be determined from profile data immediately following a significant storm or series of winter storms. The greater the time between the end of the storm conditions and the measurement of the profile, the less reliable the estimates of the MLWP. During this time, aeolian transport, sloughing of the dune face scarp, and re-construction of the upper profile all tend to mask the MLWP beach face (swash zone) slope and in particular, the beach-dune juncture. As these processes proceed, the elevation of the beach-dune juncture actually increases. Profiles taken during the summer and fall should not be used. Profiles measured later in the winter season are preferred as they should represent the maximum beach response due to the seasonal cycle.

D.4.6.5.2.2 Estimating $E_{j\ MLWP}$ and *m* from Profile Data

Komar and Allan (2004) suggest that $E_{j\ MLWP}$ can be determined from LIDAR data and field verification. Unfortunately, this requires data collected immediately following significant storm events in order to capture the most likely eroded profile before other processes occur that may mask $E_{j\ MLWP}$ or adjust its location. This procedure is also best supported by detailed site inspections immediately following storm events in order to survey and photo document beach profile conditions. McDougal and MacArthur (2004) discuss sensitivities and difficulties estimating the MLWP based solely on survey data.

D.4.6.5.2.3 Estimating *m* from Median Diameter of Beach Sands

Bascom (1964), Wiegel (1964), and others have shown that there are strong correlations between the beach face slope and the median diameter of the beach sands as shown in Figure D.4.6-14. These types of relationships can be used to estimate the beach face slope. The user must select the curve that best matches the coastal exposure, beach material characteristics, and settings represented by the curves prepared by the original authors. Open coasts along Oregon and Washington experience beach slopes approximately two times as steep as one would estimate using Wiegel's regional relationship as shown in Figure D.4.6-14, or approximately 1:25-30 (v:h). Therefore, Mapping Partners shall check estimated slope values from Figure D.4.6-14 with observed data. It is recommend that regional relationships similar to these be developed and tested for the different coastal exposures and settings found in California, Oregon, and Washington for estimating winter beach face slope.

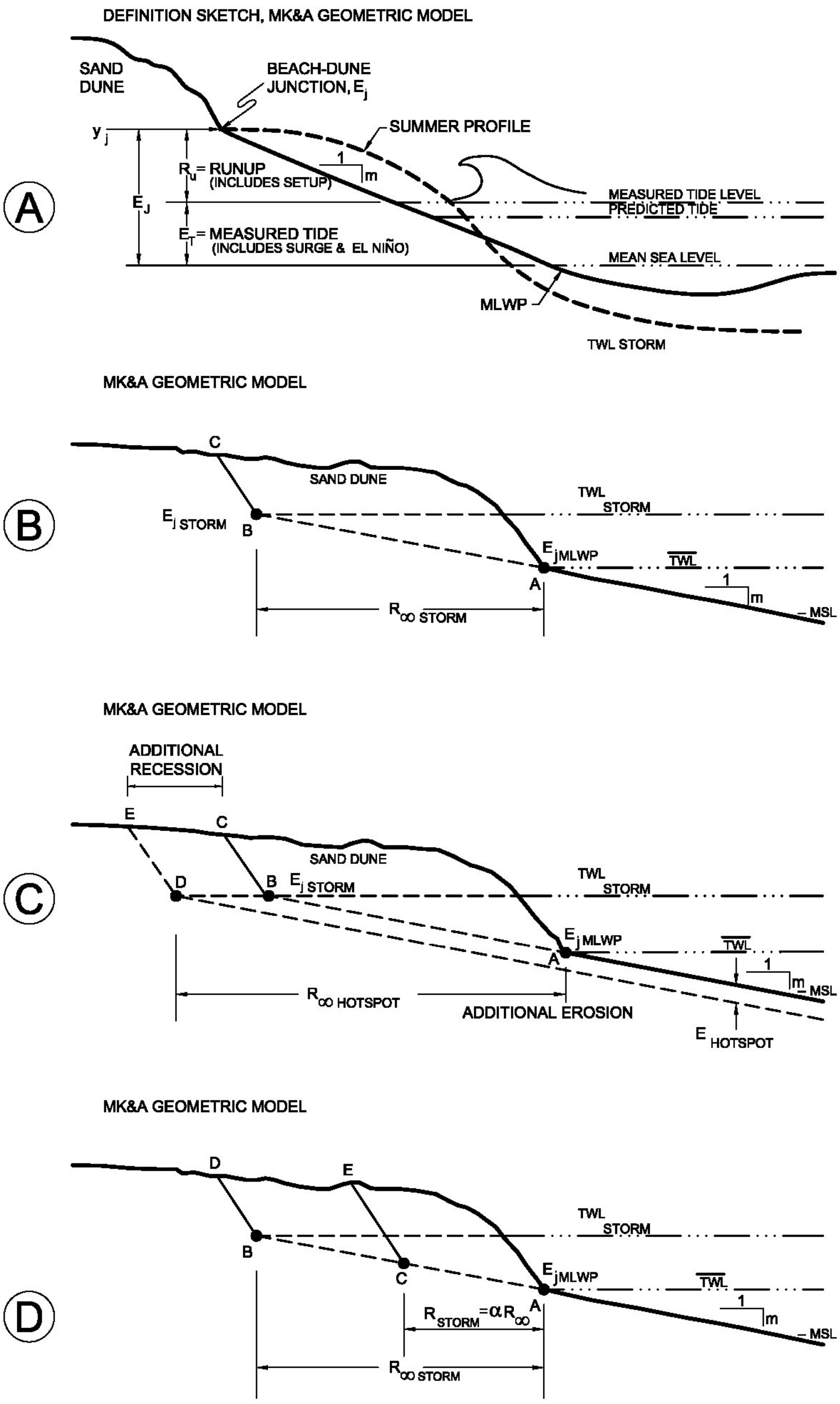


Figure D.4.6-13. Definition Sketches for Terms and Dimensions Required by the Modified Komar & Allan Geometric Model (after Komar et al., 2002, and McDougal and MacArthur, 2004)

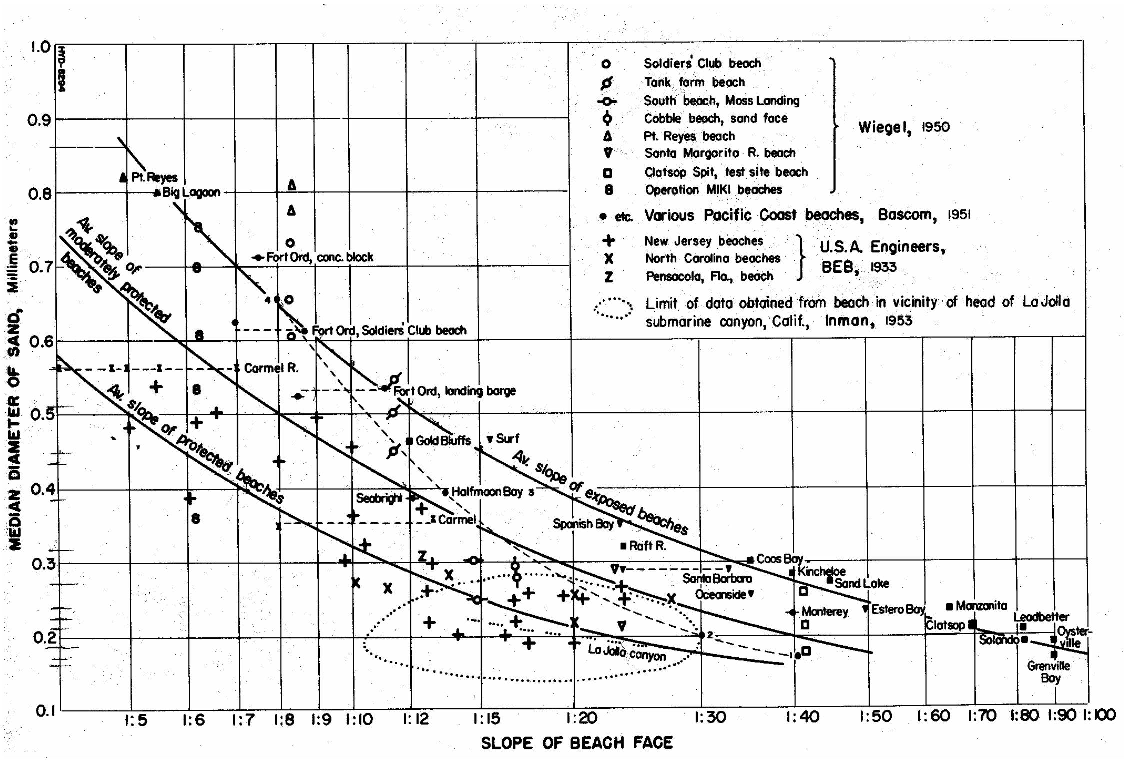


Figure D.4.6-14. Relationships Between Beach Slope and Median Diameter of Beach Sands (from Wiegel, 1964)

D.4.6.5.2.4 $E_{j\ MLWP}$ from Wave and Water Levels

Given the difficulty in identifying a single value to select for $E_{j\ MLWP}$ based on beach profile data alone, it may be possible to supplement the estimate with information about the waves and water levels that are typically responsible for producing the dune-beach juncture elevation, E_j . The juncture elevation can be estimated for the typical winter wave conditions as:

$$E_j = (R + E_T)_{winter\ storm\ average} \qquad \text{(D.4.6-1)}$$

where the runup includes the setup and the tide includes surge and El Niño (see Figure D.4.6-13A). In Equation D.4.6-1, E_j represents the average of the sum of R and E_T from 10 to 20 largest storms per year, averaged over the storm duration for the entire wave data record.

The following subsection provides detailed procedures for estimating beach profile changes for sandy beaches backed by berms and sand dunes (Beach Setting No. 1, Table 4.6-1) using the MK&A model.

D.4.6.5.2.5 MK&A Model for Estimating Beach Profile Changes

The key assumption in the MK&A model is that when a large storm event occurs, the upper beach face slope remains constant but the beach-dune juncture adjusts in response to the higher level of waves and tides. This is shown in Figure D.4.6-13B. A typical winter pre-storm (MLWP) condition is shown as the solid line. This is taken as the initial condition (the MLWP) to establish m and E_{jMLWP}. If a storm event elevates the TWL, then the shoreline erodes and retreats. The beach-dune juncture location associated with this retreat (point B in Figure D.4.6-13B) is estimated as the projection along the beach face slope onshore to the elevation of the storm's TWL. Above this elevation, the sand is assumed to remain at the angle of repose (approximately 30^o) up to the surface elevation of the dune. The recession in the MK&A model due to $E_{j\ \mathrm{Storm}}$ is calculated as the recession in excess of the MLWP. The maximum potential recession is given by:

$$R_{\infty Storm} = \frac{E_{jStorm} - E_{jMLWP}}{m} \tag{D.4.6-2}$$

where E_{jStorm} and E_{jMLWP} correspond to Equation D.4.6-1 beach-dune juncture elevations evaluated at the storm conditions and for the MLWP. The MK&A method gives the maximum potential equilibrium cross-shore change in shoreline position landward from the MLWP resulting from a storm event. However, the actual amount of beach erosion and dune recession depends on wave conditions, TWL, and storm duration. Therefore, the amount of beach erosion and dune recession for a particular storm event is less than the maximum potential cross-shore change represented by $R_{\infty Storm}$ by a factor referred to as the storm duration recession reduction factor, α, as discussed in Subsection D.4.6.5.3. Figure D.4.6-13D shows a sketch of this where the profile ACBD represents the maximum potential equilibrium cross-shore change in shoreline position, $R_{\infty\, Storm}$ and ACE is the actual eroded profile for the storm related to its duration. This is discussed further in Subsection D.4.6.5.3.

The cross-shore location of the juncture point, y_j is the initial location for the MLWP and may change with time (Figure D.4.6-13A). This can be in response to chronic erosion, sea-level changes, or other long-term effects. It may be necessary to adjust y_j for the MLWP if the time between the MLWP determination and the analysis of the recession is significant or if chronic shoreline position changes are significant.

If a beach consists of a thin layer of sand capping a wave-cut terrace or other erosion-resistant materials, then the MLWP occurs at the location and profile of the erosion-resistant layer.

Figure D.4.6-13C shows a second beach-dune juncture at point D. This additional recession is associated with other processes such as chronic erosion or local hot spots. Hot spots may develop when the profile is located in a rip current embayment or in the lee of a littoral barrier. Following Komar et al. (2002), where an adjustment was allowed for hot spots, the recession may be written as:

$$R_{\infty HotSpot} = \frac{E_{jStorm} - E_{jMLWP} + E_{HotSpot}}{m} \tag{D.4.6-3}$$

where $E_{HotSpot}$ is the localized lowering of the profile due to shoreline recession during a significant storm event due to local hot spots. Effects of site-specific hot spots and the amount of local beach lowering at that location is estimated from seasonal monitoring data from past large storm events.

D.4.6.5.2.6 Dune Overtopping with the MK&A Model

If $E_{j\ Storm}$ exceeds the dune crest elevation, then the dune will be overtopped. This occurs independently of the storm duration or profile recession. The overtopping volumes may be estimated using the excess runup, which is the height that the predicated runup exceeds the dune elevation. If $E_{j\ Storm}$ is less than the dune crest elevation, the dune crest may still be removed as shown by profile ACD in Figure D.4.6-15.

Note that the MK&A method is best applied to sand beaches with high dunes where overtopping is not expected to occur. The K&D method (discussed in Subsection D.4.6.5.5) will accommodate some overtopping, and therefore is more suitable for sand beaches with dunes and lower berms. However, neither model addresses the changes in the berm nor dune shape when overtopping occurs. Breaching typically results in a significant lowering of the dune profile and development of an overwash fan. The present methodologies do not provide a direct mechanism to address this breaching process. When overtopping occurs, the dune profile is adjusted by extending the MLWP slope *m* to the backside of the dune. Figure D.4.6-15B shows this scenario as profile ACE continuing seaward from the heel of the dune. Relationships like those shown in Figure D.4.6-14 by Wiegel (1964) can be used to estimate the ultimate beach face slope following significant dune breaching. If this approach is used, Mapping Partners should check the reliability of their results with observed information and data.

The following subsection describes how the effects of storm duration and seasonal responses are considered by the two recommended geometric models (MK&A and K&D).

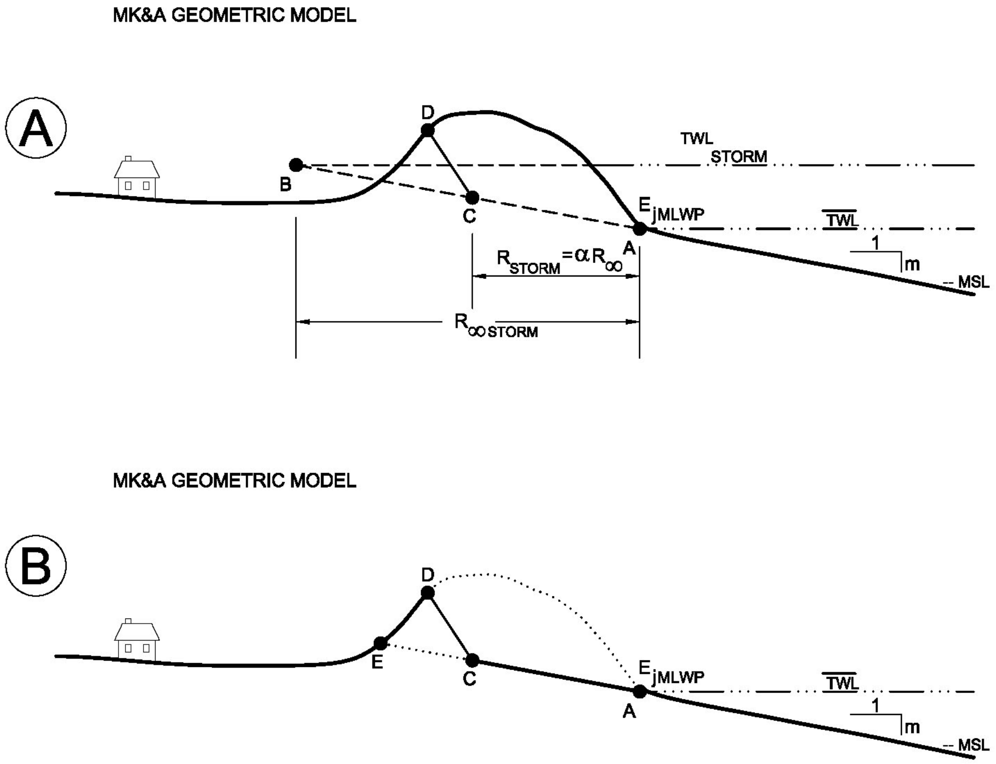


Figure D.4.6-15. Schematics of Dune Overtopping with the MK&A Model

D.4.6.5.3 Time Dependency of Profile Response (Within the MK&A and K&D Models)

The geometric models (MK&A and K&D) provide an estimate of the maximum potential cross-shore displacement of the profile. The wave and water levels must persist long enough to achieve this maximum. This is often not the case because a single storm event may have a shorter duration than is required to achieve the maximum potential cross-shore recession. Kriebel and Dean (1993) proposed a method to include the duration effects of a storm with respect to the response time scale of a beach profile.

The time scale for the beach profile was estimated from numerical model results to be:

$$T_s = C_1 \frac{H_b^{3/2}}{g^{1/2} A^3} \left(1 + \frac{h_b}{B} + \frac{m W_b}{h_b} \right)^{-1} \qquad \text{(D.4.6-4)}$$

in which T_s is the time scale, C_1 is an empirical constant (=320), H_b is the breaker height, h_b is the breaker depth, g is the acceleration due to gravity, B is the berm elevation, m is the beach face slope, W_b is the surf zone width, and A is the beach profile parameter that defines an equilibrium profile according to Equation D.4.6-5.

$$h = A\, y^{2/3} \qquad \text{(D.4.6-5)}$$

The beach profile parameter, A, depends primarily upon sediment grain size, D_{50}. Table D.4.6-2 summarizes A over a range of sediment sizes. The values in Table D.4.6-2 are well approximated by the equations:

$$A = \begin{cases} 0.0655\ln(D_{50}) + 0.208 & (\mathrm{m}^{1/3}) \\ 0.09973\ln(D_{50}) + 0.309 & (\mathrm{ft}^{1/3}) \end{cases} \qquad \text{(D.4.6-6)}$$

in which D_{50} is the sand diameter in mm and A is in $\mathrm{m}^{1/3}$ or $\mathrm{ft}^{1/3}$. Table D.4.6-3 gives estimates of the time scale for several representative conditions. It is seen that typical times are on the order of 10 to 100 hours. As the surf zone width increases, the response time also increases. Properties that increase the surf zone width include larger wave height, smaller sand size, and a milder slope. The response time also increases as the berm height increases. The longer profile response time associated with larger wave heights has the interesting result that the largest wave height may not yield the largest recession because it takes longer for the larger waves to achieve the maximum potential recession. Consider the first two waves in Table D.4.6-3, which only differ in wave height and the associated breaker depths. Assuming the period in both cases is 13 s and the storm duration is 24 hours and employing methods discussed below, the 10-foot wave height has a recession of 70 feet and the 20-foot wave has a recession of 55 feet.

Table D.4.6-2. Equilibrium Beach Profile Coefficients (Dean and Dalrymple, 2002)

D_{50} (mm)	A ($m^{1/3}$)	A ($ft^{1/3}$)
0.1	0.063	0.0936
0.2	0.100	0.1486
0.3	0.125	0.1857
0.4	0.145	0.2155
0.5	0.161	0.2392
0.6	0.173	0.2571
0.7	0.185	0.2749
0.8	0.194	0.2883
0.9	0.202	0.2987
1.0	0.210	0.3120

Table D.4.6-3. Estimates of the Beach Profile Time Response

H_b (ft)	h_b (ft)	D_{50} (mm)	A ($ft^{1/3}$)	m	B (ft)	W_b (ft)	T_s (hrs)
10	13	0.2	0.1486	0.05	10	801	28
20	25	0.2	0.1486	0.05	10	2267	53
30	38	0.2	0.1486	0.05	10	4164	77
20	25	0.2	0.1486	0.05	1	2267	14
20	25	0.2	0.1486	0.05	10	2267	53
20	25	0.2	0.1486	0.05	20	2267	64
20	25	0.2	0.1486	0.01	10	2267	96
20	25	0.2	0.1486	0.02	10	2267	80
20	25	0.2	0.1486	0.10	10	2267	34
20	25	0.1	0.0936	0.05	10	4533	138
20	25	0.2	0.1486	0.05	10	2267	53
20	25	0.5	0.2392	0.05	10	1110	18

The beach profile response is determined by a convolution integral. It is assumed that the time dependency of the storm hydrograph may be approximated as:

$$f(t) = \sin^2\left(\pi \frac{t}{T_D}\right) \quad \text{for } 0 < t < T_D \qquad \text{(D.4.6-7)}$$

where t is time from the start of the storm and T_D is the storm duration. The convolution integral is:

$$R(t)=\frac{R_\infty}{T_S}\int_0^t f(\tau)e^{-(t-\tau)/T_S}\,d\tau \qquad \text{(D.4.6-8)}$$

which integrates to:

$$\frac{R(t)}{R_\infty}=\frac{1}{2}\left\{1-\frac{\beta^2}{1+\beta^2}\exp\left(-t/T_S\right)-\frac{1}{1+\beta^2}\left[\cos\left(2\pi t/T_D\right)+\beta\sin\left(2\pi t/T_D\right)\right]\right\} \qquad \text{(D.4.6-9)}$$

where $\beta = 2\pi T_S / T_D$ and R_∞ is the maximum potential recession that would occur if the storm duration was infinite as yielded by Equations D.4.6-2 and D.4.6-3 (Figure D.4.6-13D) for the MK&A method. If the storm duration is long with respect to the profile time scale, then a significant portion of the maximum potential shoreline response will occur. As the ratio of T_S / T_D decreases, less of the maximum shoreline change will be realized. The time of the maximum recession is determined by setting the derivative of Equation D.4.6-9 equal to zero and solving for the time. This yields:

$$\exp\left(-\frac{t_m}{T_D}\right)=\cos\left(\frac{2\pi t_m}{T_S}\right)-\frac{T_D}{2\pi T_S}\sin\left(\frac{2\pi t_m}{T_S}\right) \qquad \text{(D.4.6-10)}$$

in which t_m is the time that the maximum occurs with respect to the start of the storm. Unfortunately, this is a transcendental equation and must be solved by approximation or numerical methods. The maximum recession that occurs as the result of a single storm or duration limited response is:

$$\alpha=\frac{R_m}{R_\infty}=\frac{1}{2}\left[1-\cos\left(2\pi\frac{t_m}{T_D}\right)\right] \qquad \text{(D.4.6-11)}$$

where α is the storm duration recession reduction factor, R_m is the maximum recession that occurs for the given storm duration that occurs at time t_m. Figure D.4.6-16 gives the solution to Equation D.4.6-11 in graphical form. Therefore, duration limited recession is:

$$R_m = \alpha R_\infty \qquad \text{(D.4.6-12)}$$

Multiple Storm Responses

The maximum recession observed on the Pacific Coast often results from the occurrence of several storms in succession. Unless there is site-specific information or guidance for using multiple storms, it is recommended that a single storm analysis be used. If multiple storms are to be considered, then the cumulative recession may be estimated by summing the contribution of each storm to the recession beyond the previous profile. McDougal and MacArthur (2004b) discuss methods for conducting cumulative recession analyses in their report entitled *EBE MLWP Discussion.* Before initiating a seasonal response investigation, Mapping Partners should check with the FEMA study representative to confirm that this level of analysis is necessary and that there are sufficient historical data to confirm the results.

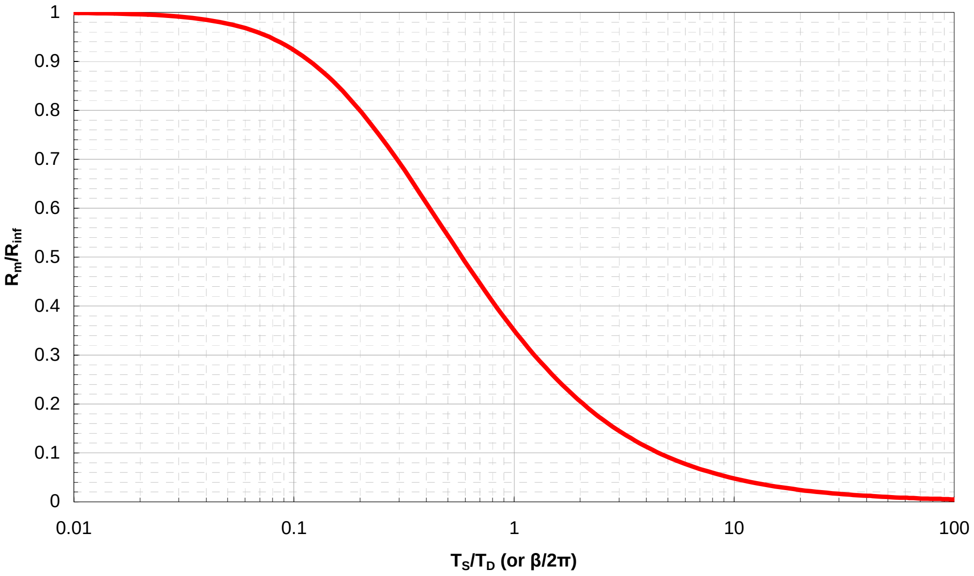


Figure D.4.6-16. Storm Duration Recession Reduction Factor

D.4.6.5.4 Summary of the MK&A Geometric Modeling Approach for Sand Beaches Backed by Sand Berms and Dunes (Beach Setting No. 1)

Mapping Partners evaluating sand beaches backed by sand berms and dunes (Beach Setting No. 1) using the MK&A model approach shall complete the following steps to estimate the beach erosion and recession associated with storm events. Figure D.4.6-17 shows the sequence of key activities and computational considerations required to determine storm-induced beach profile changes for Beach Setting No. 1.

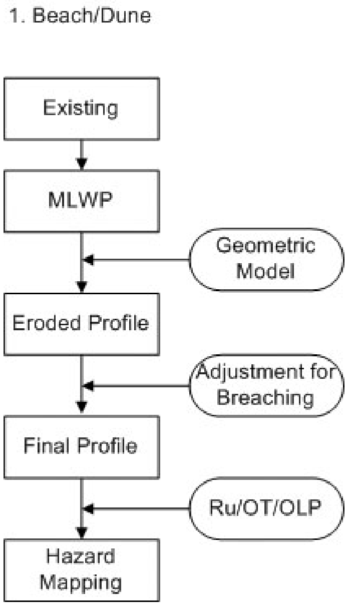


Figure D.4.6-17. Key Activities to Determine Beach Profile Changes for Beach Setting No. 1

Develop Data:

1. Obtain wave and water-level data necessary to define the waves and water levels for the 10-20 largest storms each year.

2. Determine existing shoreline location and conditions.

3. Define reaches alongshore in which wave, beach, and backshore conditions are nearly uniform. Data and calculations must be conducted for at least each subreach.

4. Obtain beach profile data required to establish the MLWP or the annual winter wave and water-level conditions to develop an MLWP for each subreach.

5. Determine median sand diameter, D_{50}, on the beach face for each subreach.

6. Obtain historical beach profile data required to estimate the magnitude of local hot spot erosion and site-specific beach lowering with each subreach being evaluated within the study area.

7. Seek historical data for use in validating results from the application of the simple geometric models.

Determine MLWP:

1. Estimate beach slope m from measured post-storm winter profile data as discussed in Subsection D.4.6.5.2 or use a relationship such as Wiegel's (1964) (Figure D.4.6-14) to relate median beach sand diameter to beach slope, m.

2. Estimate $E_{j\ MLWP}$ based on measured winter profile data following the occurrence of large storms or make estimates using winter wave and water-level conditions as outlined in Subsection D.4.6.5.2.

3. Estimate the cross-shore location for the MLWP, y_j, related to existing beach profile conditions.

Determine Beach Recession for Each Storm Event:

1. Determine static setup and/or TWL as required for the geometric recession model to calculate the potential recession for the storm, $R_{\infty storm}$.

2. Determine storm duration recession reduction factor for the storm, α (Figure D.4.6-16).

3. Determine duration limited recession for storm, R_{storm}, and if the berm/dune is breached, modify beach and berm/dune profile to account for breaching or local hot spot erosion if necessary according to Subsection D.4.6.5.3.

4. If runup is different on the modified profile, re-compute runup.

5. If runup results in overtopping, then compute overtopping. Save the maximim overtopping value. Also compute the overtopping volume as V = integral $Q\ dt$ over duration of storm.

6. For each year, save conditions corresponding to the largest annual TWL storm event: TWL, Q, V, α, H, T, D, γ, R_{storm} , etc.

Use Measured Profiles to Validate Results:

Mapping Partners shall always locate the best and most reliable measured data for their project site. They should also use measured beach profile data wherever possible: (1) to aid in estimating the MLWP, and (2) to determine, calibrate, and validate the eroded beach profile for a specified storm event. The eroded beach profile estimated for a particular storm event is the profile required for computing runup and overtopping associated for that event.

Determine the 1% Storm Event:

Mapping Partners shall follow procedures outlined in Section D.4.2 for determining the 1% percent storm conditions for use in determining flood hazards.

D.4.6.5.5 K&D Geometric Modeling Approach for Sand Beaches Backed by Sand Berms and Dunes (Beach Setting No. 1)

Kriebel and Dean developed an analytical solution to approximate the temporal beach-profile response to a single storm (Kriebel and Dean, 1993). The maximum potential recession of a sand beach profile, R_∞, was established based on the equilibrium principle proposed by Bruun (1962) for erosion due to long-term, sea-level rise. Kriebel and Dean assumed an equilibrium beach profile with respect to the prevailing water level and wave climate. Typically, the prevailing water level is referred to the mean sea level (MSL). The eroded profile is then shifted upwards by an elevation equal to the water-level rise caused by storm surge and wave setup, and landward by an amount of beach recession potential (R_∞) until a volume balance is achieved between sand eroded from the upper portion of the beach and sand deposited offshore. Based on this conservation of sand volume, the maximum erosion potential (R_∞) can be defined as a function of the water-level rise (S) during a storm, breaking wave depth (h_b), surf zone width (W_b), berm or dune height (B or D), and the slope (m) of the upper foreshore beach face. Along the Pacific Coast, the water-level rise during a storm event is mostly influence by wave setup, as the storm-induced surge tends to have a minor effect.

Kriebel and Dean presented analytical solutions to estimate the maximum erosion potential R_∞ for four different beach settings. The solution for one of the four settings that is typically observed on the Pacific Coast, as shown in Figures D.4.6-18 and D.4.6-19, is presented as follows:

- Maximum erosion potential for a beach backed by a low sand berm:

$$R_\infty = \frac{S\left(W_b - h_b / m\right)}{B + h_b - S/2} \qquad \text{(D.4.6-13)}$$

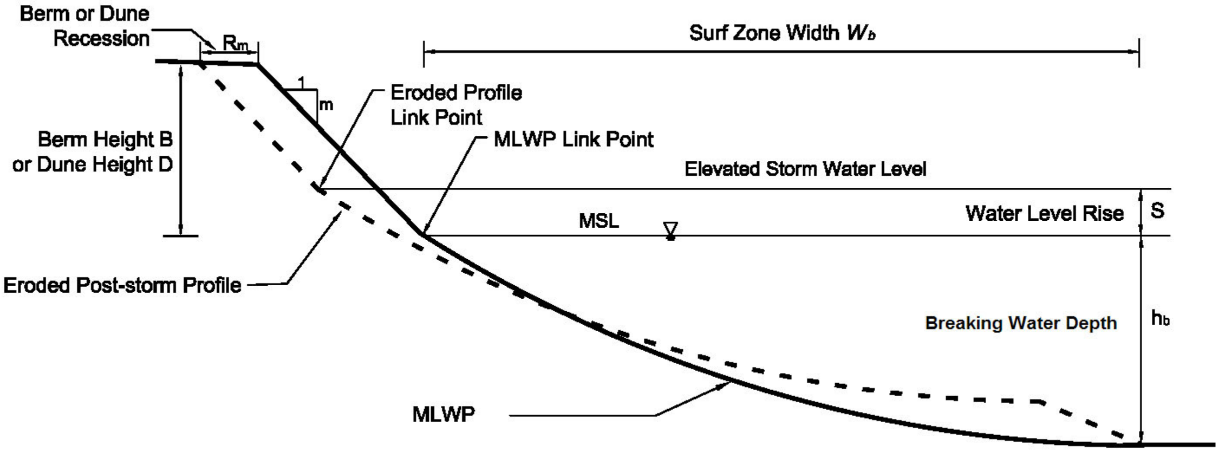


Figure D.4.6-18. Definition Sketch for K&D Geometric Model

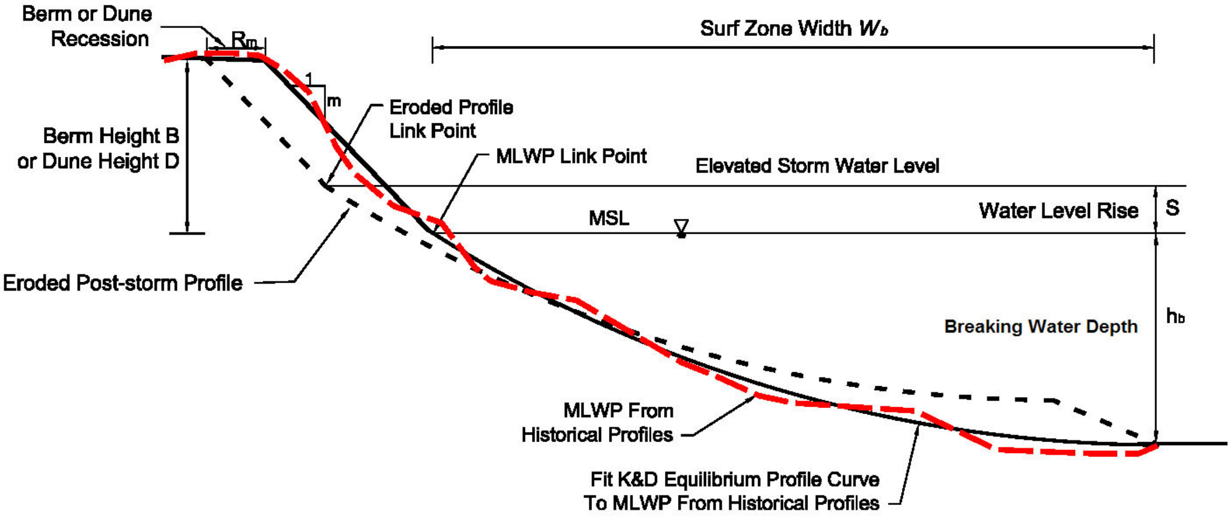


Figure D.4.6-19. Sketch for K&D Geometric Model for Case Where Historical Beach Profile Data Are Available to Prepare the MLWP

- Maximum erosion potential for a beach backed by a high sand dune:

$$R_\infty = \frac{S(W_b - h_b / m)}{D + h_b - S/2} \tag{D.4.6-14}$$

where S is the water-level rise representing the sum of the peak storm surge (wind effects and barometric pressure effects) and the wave setup, h_b is the breaking water depth, W_b is the surf zone width, m is the slope of the foreshore fronting face, and B and D are the berm and dune heights above the prevailing water level, respectively. Equations D.4.6-13 and D.4.6-14 estimate the maximum recession potential, assuming that the storm event lasts indefinitely. The actual storm-induced recession (R_m), which depends strongly on the duration of each storm event, must be multiplied by a storm duration recession reduction factor, α, as stated in Subsection D.4.6.5.3. For backshore profiles that are not well approximated by the analytical solutions given in Kriebel and Dean (1993), a conservation of sand volume equation (i.e., a simple balance of cuts and fills) may be solved numerically. Further discussion of this computational procedure is provided in the following guidelines.

Because the elevated storm water level is based on the magnitude of wave setup and storm surge only to a small extent on the Pacific Coast, it is likely that the storm water level is below the berm or dune height. In the event that the elevated storm water level is higher than the crest of the berm or dune, the K&D model may no longer be applied and the profile must be adjusted for overtopping. When the K&D model is applied to estimate the storm-induced erosion, various model input parameters are required. The calculation of storm-induced erosion, using the K&D convolution method, is delineated as follows:

Acquire Wave and Water-level Data:

1. Obtain hindcasted wave data (e.g., Global Reanalysis of Ocean Waves [GROW] data) and measured historical water levels necessary to define the oceanographic conditions including waves and water levels for 10-20 largest storm events for every hindcasted year.

2. Acquire historical beach profiles to establish the MLWP (i.e., pre-storm beach profile conditions).

3. Seek historical pre- and post-storm profiles to validate the application of the simple K&D geometric models.

Determine MLWP for K&D Method:

First, determine existing shoreline location and conditions. Then, establish representative reaches within the shoreline area being analyzed that are similar in coastal morphology (average offshore/nearshore bathymetry, wave exposure, onshore beach slope, beach materials, etc.). This may consist of only one typical reach or several different typical reaches for the shoreline area being analyzed. Following are procedures for establishing the MLWP for a sandy beach backed by either a low sand berm or a high sand dune for application with the K&D geometric model.

1. **Procedure for a Study Site Without Previously Surveyed Historical Profiles**

    a. Determine existing shoreline location and conditions.

    b. Always use measured historical post-storm winter beach profile data when available to establish the MLWP. However, if there are no historical post-storm winter beach profile data, conduct a basic wading survey from the crest of the berm or dune to the approximate mean low low water (MLLW) line (see National Oceanic and Atmospheric Administration [NOAA] tidal datum) following a series of winter storms in March or April to prepare a surveyed beach profile from the berm crest to approximately MLLW.

    c. Collect sediment samples, preferably in late March or early April to determine the median sand diameter (D_{50}) for use in Equations D.4.6-5 and D.4.6-6.

    d. Determine the MSL from NOAA's tidal datum, and identify the MSL location across the beach profile. This location divides the beach profile into an upper foreshore berm/dune section and the surf zone section.

    e. Plot the measured upper foreshore profile section above the MSL line based on the basic wading survey, site photographs, and available historical information (see Figure D.4.6-18).

    f. Determine the berm or dune height (B or D) above the MSL line and foreshore slope (m) from the estimated upper foreshore section (see Figure D.4.6-18).

    g. Approximate the surf zone section of the MLWP from Kriebel and Dean's equilibrium beach profile, based on the measured D_{50} and the application of Table D.4.6-2 and Eqs. D.4.6-5 and D.4.6-6.

    h. Assemble the entire MLWP based on the surveyed upper foreshore and surf zone sections linked at the MSL, as illustrated in Figure D.4.6-18.

    i. Document data sources, assumptions, and conversions.

2. **Procedure for a Study Site With Previously Surveyed Historical Profiles:**

    a. Determine existing shoreline location and conditions.

    b. Select a representative surveyed winter profile (see Figure D.4.6-19) from historical post-storm beach profile data, which was surveyed during the end of the winter season (March-April) and represents the typical winter beach profile conditions.

    c. Determine the MSL from NOAA's tidal datum, and identify the MSL location across the beach profile. This location divides the beach profile into an upper foreshore berm/dune section and the surf zone section.

d. Determine the berm or dune height (B or D) above the MSL line and compute the foreshore slope (m) through linear curve fitting to the upper foreshore section.

e. Determine the surf zone section of the MLWP by curve-fitting Kriebel and Dean's equilibrium profile from Eqs. D.4.6-5 and D.4.6-6 to the surf zone section of the surveyed beach profile below the MSL line (see Figure D.4.6-19).

f. Assemble the entire MLWP based on the approximated upper foreshore and surf zone sections linked at the MSL, as illustrated in Figure D.4.6-19.

g. After the MLWP is defined, determine the K&D model input parameters including the berm or dune height (B or D) and the foreshore slope (m) (see Figures D.4.6-18 and D.4.6-19).

Quantify Peak Storm Conditions of a Selected Storm Event:

The peak storm conditions for a selected storm event shall be used to determine the storm surge including the wave setup, wave breaking, and storm duration. Storm surge resulting from the fluctuations in the wind speed and atmospheric pressure is usually small in the Pacific Coast, and thus the wave setup is the primary parameter to determine the water-level rise. The increase in water level induced by El Niño events should also be included, if applicable (see Section D.4.4, Waves and Water Levels). The peak storm conditions include wave height, period, and incoming direction at the peak of the storm, as well as the storm duration that is characterized in Section D.4.4. These wave conditions are used to determine the wave setup (S), water depth of breaking wave (h_b), and the surf zone width (W_b) needed by the K&D geometric model. The MSL water depth can be used as a representative water depth to calculate wave transformation. The procedures are listed as follows:

1. Determine the breaking water depth (h_b) and the surf zone width (W_b), based on the MLWP and the selected wave event.

2. Estimate the wave setup using the formula presented in Subsection D.4.5.1.

3. Based on the procedures described in Section D.4.4, calculate the storm surge induced by wind effects and barometric pressure effects, if applicable.

4. Estimate the increase in water level induced by the El Niño Southern Oscillation (ENSO) events in accordance with the procedures stated in Section D.4.4, if applicable.

5. Determine the total increase in water level (S) induced by the storm (see Figures D.4.6-18 and D.4.6-19).

Calculate Storm-induced Beach Erosion:

1. Calculate the maximum beach erosion potential R_∞ using Equation D.4.6-13, if the subject beach is backed by sand berms with height B.

2. Calculate the maximum beach erosion potential R_∞ using Equation D.4.6-14, if the subject beach is backed by sand dunes with height D.

3. Calculate the time scale (T_S) from Equation D.4.6-4.

4. Determine the storm duration (T_D) from Subsection D.4.4.1, and compute the storm duration recession reduction factor, α, from Figure D.4.6-16 for the given value of T_D/T_S.

5. Multiply the maximum recession potential (R_∞) by the storm duration recession reduction factor to estimate the storm-induced beach erosion and recession distance (R_m).

Prepare Eroded Post-Storm Beach Profile:

1. Set back the upper foreshore profile above the elevated storm wave level (see Figures D.4.6-18 and D.4.6-19) landward by the calculated berm or dune recession distance R_m with the same fronting-face slope (m).

2. Place the new link point between the upper foreshore section and the surf zone section at the elevated storm water level (see Figures D.4.6-18 and D.4.6-19).

3. Shift the surf zone section of the MLWP below the MSL landwards and upwards to the link point (see dashed curve below the MSL line in Figures D.4.6-18 and D.4.6-19).

4. The adjusted profile from Steps 1 to 3 produces the “eroded storm profile” for a specified location and beach profile. Mapping Partners shall perform these steps for all beach profiles needed to describe the spatial adjustments to the beach and dune system being evaluated.

5. Document results and assumptions.

D.4.6.5.6 Potential Future Use of Process-based Models

Process-based models are typically more complex and have greater data input requirements than simplified geometric models, but are formulated to include the effects of more of the physical processes affecting beach erosion and coastal sediment transport. While conserving sand volumes, as done by the K&D geometric model, process-based models also compute the cross-shore transport of beach sand induced by nearshore storm waves, and determine the change in beach profile based on material grain size, wave energy, and the variation in sand transport rate. Two simple process-based models, SBEACH (Larson and Kraus, 1989, 1998; Larson et al., 1990) and EBEACH (Kriebel, 1984a, 1984b; Kriebel and Dean, 1985), have been widely used in the eastern United States to calculate storm-induced beach erosion. Other, more complex process-based models, such as the COSMOS model (Southgate and Nairn, 1993) developed in England, have also been used to calculate storm-induced beach erosion. More complex models can be data-intensive, time-consuming, and costly to use. However, for certain settings, application of simple or complex process-based models presents a significant opportunity to improve how beach profile changes are depicted over simplified geometric-based models.

Both SBEACH and EBEACH have been calibrated to the large-scale laboratory wave-tank experiments and field data on the Atlantic and Gulf coasts. They have been applied to numerous field case studies on the Atlantic and Gulf coasts, and to a lesser degree in the Great Lakes, environments that more closely fit the conditions for which they were developed and calibrated. However, several less-successful experiences using SBEACH, EBEACH, and COSMOS have occurred on the coasts of California (Noble Consultants, 1994) and Oregon (Komar et al., 1999; Komar, 2004). Documentation of these attempted applications indicates that these process-based models may underpredict the erosion during storms on the Pacific Coast, where the beach morphology and storm characteristics differ from the beach settings that were used in developing these models.

In August 2004, the U.S. Army Corps of Engineers (USACE) officially recognized the limitation of SBEACH to predict erosion on Pacific Coast beaches and funded a research program to explore the causes of the model’s underprediction of erosion on the Pacific Coast so as to improve its applicability for the Pacific Coast region. The Coastal and Hydraulics Laboratory (CHL) is currently modifying the SBEACH model, so it can be applied to the specific site characteristics and wave climate of the Pacific Coast region. Noble Consultants has provided the identical database to CHL for the four southern California shoreline locations that were used for field verification of the K&D (Kriebel and Dean, 1993) and MK&A (McDougal and MacArthur, 2004) simplified geometric models discussed above.

Eventually, simple and complex process-based models will become more reliable and will ultimately provide additional means for estimating event-based erosion along the Pacific Coast. However, further reformulation and validation are required before they can be used in FEMA coastal flood hazard assessments. At this time, without accurate calibration to local conditions, process-based models are not recommended for general use.

D.4.6.6 Estimating Profile Changes for Sandy Beaches Backed by Protective Structures (Beach Setting No. 2)

Figure D.4.6-20 shows a photograph of a typical sand beach backed by coastal development and protective structures in Southern California. This setting is often subject to dramatic beach erosion and profile adjustment during single events. Figure D.4.6-3 shows a typical beach profile for this setting, while Figure D.4.6-21 shows the sequence of key activities and computational considerations required to determine storm-induced beach profile changes for Beach Setting No. 2.

The Mapping Partner shall perform the following steps to develop the MLWP for this type of setting:

1. Review the references listed in the support documents and literature on assessing performance and erosion at coastal structures; review Section D.4.7.

2. Determine existing shoreline location and condition of structures.

3. Examine photos and historical pre- and post-storm event LIDAR and beach profile data for the study area and develop a MLWP for the beach by examining the envelope of seasonal post-storm event beach profile data.

Figure D.4.6-20. Sand Beach Backed by Shore Protection Structures, Crystal Cove, California (Source: Noble Consultants)

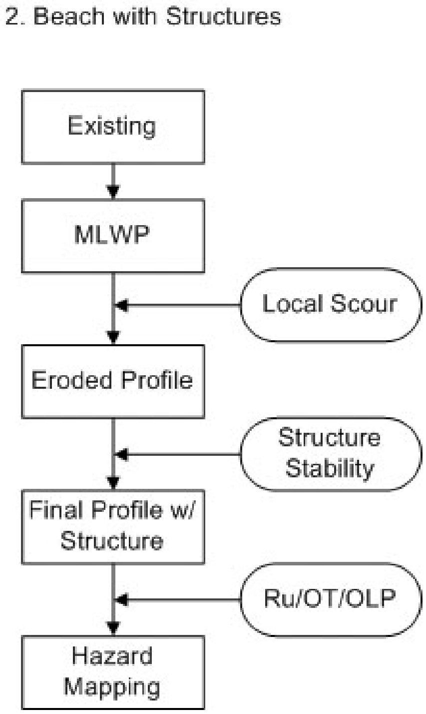


Figure D.4.6-21. Key Activities to Determine Beach Profile Changes for Beach Setting No. 2

4. The toe of a structure often becomes buried beneath sand deposits during calm sea conditions. Try to determine whether the MLWP profile is formed by the structure at its toe by probing through the sand along the toe of the structure to measure the depth of sand at the toe. Inspection trenches can also be dug and *profiled* by an experienced

coastal geologist (here *profiling* means identifying and mapping the vertical location and thickness of distinct sediment lenses along the cut face of an inspection trench). Results from this activity should provide information on the historical depth of scour that has occurred in front of the structure.

5. If a relatively broad sandy beach is located in front of the coastal structure, the MLWP for the sand beach portion must be estimated from historical winter beach profile data, supplemented with probing or inspection trench data down to an elevation of approximately MLLW.
6. Survey the elevation of the top of structures and back-beach profile. Depending on available data, some types of LIDAR data may be suitable for this purpose.
7. Next, splice the structural profile, average winter sand beach profile, and back beach profiles together to create a continuous beach profile that represents the complete MLWP for the beach, structure profile, and back beach areas.
8. Next, determine if the MLWP can experience additional erosion during a selected storm event.
9. If further erosion is possible during a large storm, determine likely depth of local scour in front of structures and compare to the scour depths determined from probing or trenching and smooth MLWP to reflect this local change; refer to Section D.4.7 and to the CEM (USACE, 2003).
10. Use this continuous beach profile for subsequent runup computations.
11. Determine whether the structures are overtopped, damaged, or removed during the storm event being evaluated according to methods prescribed in Section D.4.7.
12. Try to validate assumptions and results using observed data from previous large storm events.
13. Document assumptions, data that were used, and results.

D.4.6.7 Estimating Profile Changes for Gravel and Cobble Beaches (Beach Setting No. 3)

Explicit procedures for determining beach and back beach profile changes on gravel and cobble beaches are not as well developed or documented as for sand beaches. Figures D.4.6-22 and D.4.6-23 show typical Pacific Coast cobble berm-backed beaches. Figure D.4.6-4 provides a sketch of a typical cobble beach profile (Beach Setting No. 3) and shows the different material layering and composition present for these settings. Cobble beaches and berms are often quite stable features as indicated by the measured cross-beach profiles shown in Figures D.4.6-24 and D.4.6-25. The Mapping Partner shall assume that the cobble beach and cobble berms are stable features during storms and act like natural shoreline protection features, but that the toe and apron become partially covered with sands during summer months and mild winter seasons.

Figure D.4.6-22. Sand Beach Backed by Cobble Berm and Bluffs, South Carlsbad, California (Photo by Noble Consultants)

Figure D.4.6-23. Sand Beach Backed by Cobble and Shingle Berm and Sandy Terrace, Batiquitos Lagoon, California (Photo by Noble Consultants)

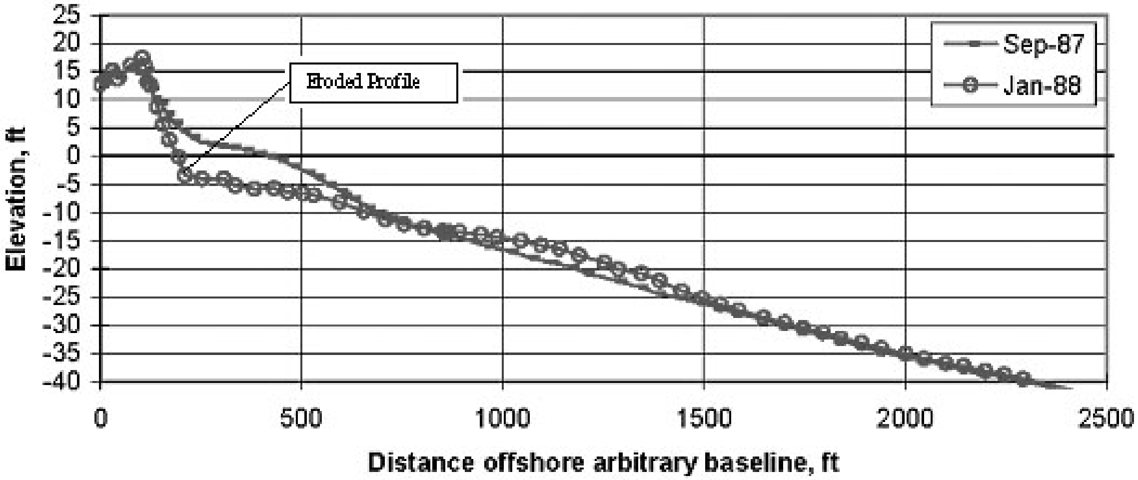


Figure D.4.6-24. Measured Beach Profile Change Due to January 1988 Storm, Batiquitos Lagoon, California

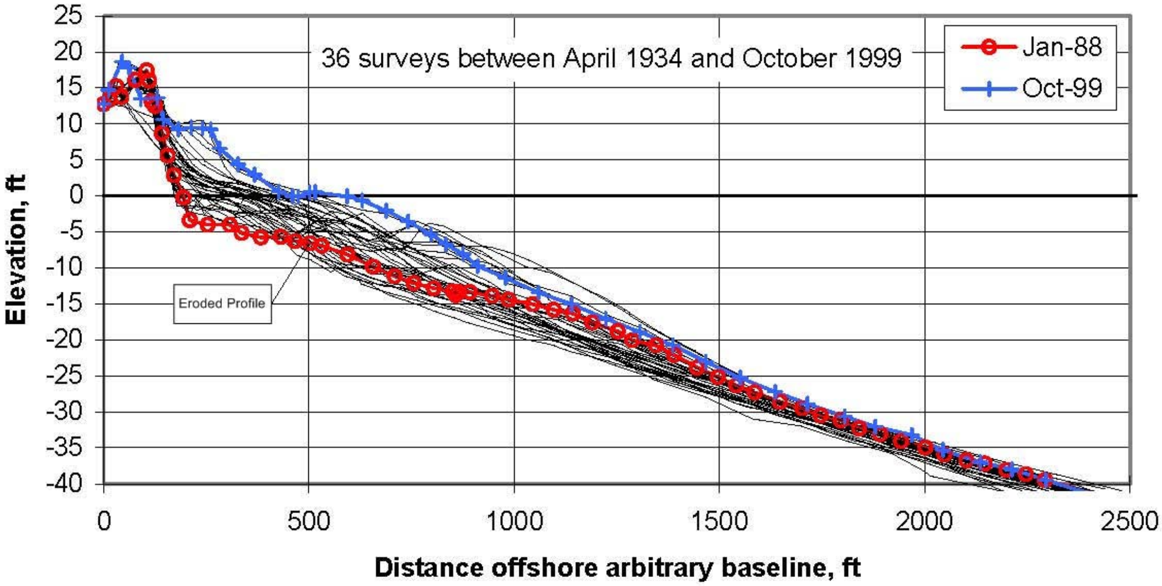


Figure D.4.6-25. Measured Beach Profile Change Before and After January 1988 Storm, Batiquitos Lagoon, California

Perform local probing and inspection trenching from the berm face out onto the beach to validate this assumption and to determine the typical eroded winter profile. If it is determined from other measured data from past storm events that the eroded winter profile underestimates the amount of cobble beach retreat during large storm events, then use the observed data for the eroded beach profile for runup and overtopping. Otherwise, use the eroded winter profile for subsequent runup and overtopping computations.

Figure D.4.6-26 shows the sequence of key activities and computational considerations required to determine storm-induced beach profile changes for Beach Setting No. 3.

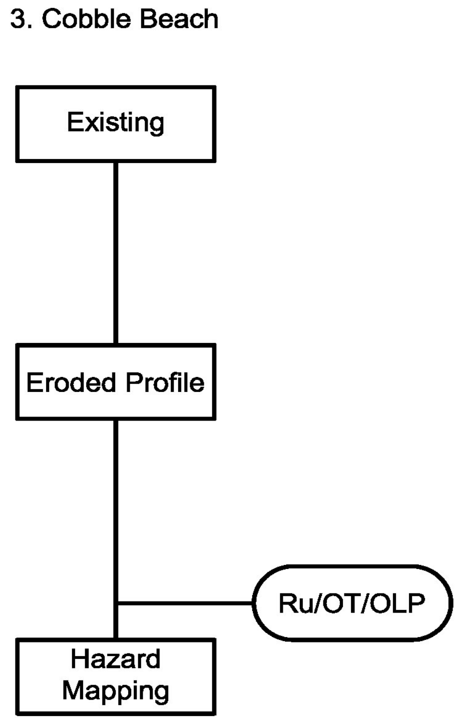


Figure D.4.6-26. Key Activities to Determine Beach Profile Changes for Beach Setting No. 3

Mapping Partners shall use the following procedure to establish the typical eroded winter profile for Beach Setting No. 3, Cobble, gravel or shingle beaches and berms:

1. Review the references listed in the support documents and literature on the design of and construction of dynamic revetments and cobble berms.

2. Examine photos and historical pre- and post-storm event LIDAR and beach profile data for the study area and develop a typical winter profile from observed data (refer to Figure D.4.6-25 for an example of historical profiles).

3. Verify this profile by probing or trenching through the sand along the toe of a cobble berm to measure the profile of the cobble berm left by the previous period of high wave conditions. (See Figures D.4.6-4 and D.4.6-25 that show how the toe of a cobble berm often becomes buried beneath sand deposits during calm sea conditions.) The eroded profile (circles) was surveyed only a few days following a major storm event in January 1988.

4. If a relatively broad sandy beach is located in front of the cobble berm, determine whether there is a history of significant erosion of the sand beach portion and include that information in the beach profile data.

5. Survey the top of berm and back-beach profile.

6. Splice the cobble berm profile, winter sand beach profile, and top-of-berm and back beach profiles together to create a continuous beach profile that represents the complete profile for the beach, cobble berm, and back beach areas.

7. Use this eroded beach profile for subsequent runup computations during the selected storm event, unless other information indicates the profile may need further adjustment during large storm events.

8. Check results and try to validate them with observed information.

9. Document assumptions and results.

D.4.6.8 Estimating Profiles for Beaches Backed by Erodible Bluffs or Cliffs (Beach Setting No. 4)

Significant portions of the California coast have narrow to nonexistent beaches backed by high, steep, erodible coastal bluffs and cliffs, as shown in Figures D.4.6-27, D.4.6-28, and D.4.6-29 and illustrated in Figure D.4.6-5. The evolution of this bluff-type shoreline is significantly different from that of the sandy beaches backed by either dunes or low-lying berms. A thin sand lens often overlays a rocky beach or bedrock platform fronting the bluff. These thin deposits of sand are removed each winter storm season. If storm water levels reach sufficient elevations to intersect the toe of the bluffs, storm waves can directly impinge upon the bluff face causing bluff toe erosion. If enough material is eroded from the toe during a storm, the upper portion of the bluff can fail, resulting in bluff retreat (Figures D.4.6-28 and D.4.6-29). This type of bluff failure and retreat is common along the Pacific Coast, and is particularly important in the highly developed coastal communities of central and southern California. It should be noted that significant bluff failure may not occur during all storm events. However, if the bluff materials are erodible, toe erosion and bluff failure is possible during single storm events. The rate and extent of bluff erosion and failure depends on the site-specific bluff profile conditions at the time of the event (toe elevation and setback distance from the surf zone) and on the erodibility of the bluff materials. In some locations, it may take several storms to cause sufficient toe erosion to lead to bluff failure, or only one significant event with sufficient TWL, duration, and wave orientation to result in significant storm erosion.

Previous estimates for coastal bluff retreat have typically resorted to temporally averaged rates over a long period. Though the average annual rate of coastal cliff erosion is a reasonable indicator of the gradual retreat of the bluff top, it does not adequately predict the episodic nature of bluff failure that can result in 3 to 50 feet of retreat during a single storm event. The average annual retreat rate provides a misleading indication of the hazards of coastal bluff or cliff erosion because the occurrence of storms of sufficient magnitude and duration to cause significant buff retreat are episodic. At some locations, coastal bluffs have fairly low elevations and may be overtopped by large wave events. Therefore, assessment of coastal flood and erosion hazards in coastal settings (Beach Setting No. 4) with erodible bluffs requires special methods and data.

Figure D.4.6-27. Wave Cut Coastal Bluff, Encinitas, California (Source: USACE, Los Angeles District)

Figure D.4.6-28. Bluff Failure and Retreat During 1998 El Niño Storms, Pacifica, California (Photo by Kevin Coulton)

Figure D.4.6-29. Bluff Failure and Retreat, Encinitas, California (Photo by Noble Consultants, Inc.)

During the reconnaissance phase of a coastal flood assessment, Mapping Partners shall determine whether the study area includes erodible coastal bluffs and cliffs (Beach Setting No. 4) and whether the bluff elevations are low enough for overtopping.

D.4.6.8.1 General Approach for Beach Setting No. 4

Figure D.4.6-30 shows the sequence of key activities and computational considerations required to determine storm-induced beach profile changes for Beach Setting No. 4.

Determine the coastal setting and history of episodic and chronic bluff erosion for the study area; then:

1. Obtain reliable beach and bluff profile data (surveyed cross-shore profiles or LIDAR) for existing conditions. Try to obtain these data near the end of the winter season in March or April.

2. Determine whether bluff erosion and failure monitoring data are available for the study area. Obtain and examine that information to determine the magnitude of episodic toe erosion and bluff retreat.

3. Estimate top-of-bluff elevations and compare to potential significant storm TWL and whether the bluff is subject to overtopping or frequent wave attach or toe erosion.

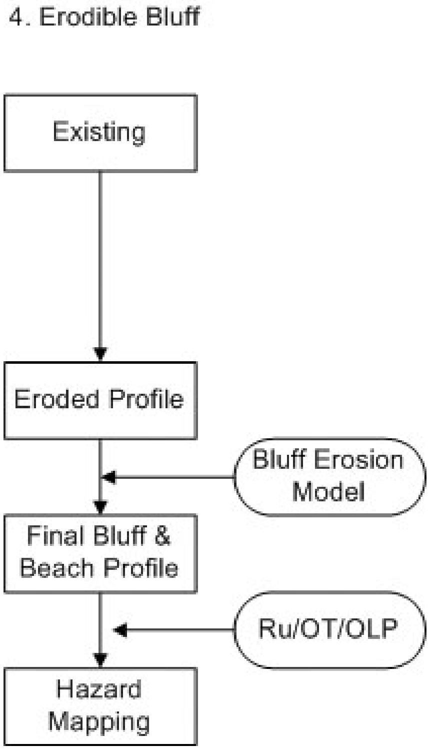


Figure D.4.6-30. Key Activities to Determine Beach Profile Changes for Beach Setting No. 4

4. Perform a site inspection to confirm general historical information related to episodic erosion or overtopping hazards associated with the site. Determine relative erodibility of the bluff materials using standard geologic/geotechnical field procedures (Sunamura 1983; USACE-LAD, 2003; and Williams et al., 2004).

5. If potential damage to structures or public safety are determined not to be significant, the Mapping Partner shall document those results and whether further analyses are recommended.

6. If further analysis of bluff erosion or overtopping is not recommended, or the site is determined to be non-eroding, assume the bluff or cliff is classified as Beach Setting No. 5 (and document why) and that the bluff or cliff is non-eroding during large events. Then apply methods listed in Subsection D.4.6.9 for analyses of non-erodible bluffs.

7. Perform all further runup and overtopping analyses on the surveyed existing winter conditions beach and bluff profiles for the site.

8. Document results, and summarize the data, methods used, and assumptions associated with the analyses.

If it is determined that the study site experiences significant erosion and retreat during large storm events, then the Mapping Partner shall document those findings and discuss with the

FEMA study representative whether there are sufficient data, time, and budget to perform a more detailed bluff erosion analysis. Depending on the site-specific characteristics of the setting and bluff materials, a detailed bluff erosion analysis is likely to require detailed geologic sampling, bluff erosion monitoring data, and bluff erosion simulation analyses. Data requirements and procedures for conducting detailed bluff erosion analyses are presented in the next subsection.

D.4.6.8.2 Detailed Bluff Erosion Analyses

As part of the effort for the USACE feasibility study along the Encinitas/Solana Beach shoreline, Noble Consultants, Inc., developed a statistical modeling procedure to characterize the bluff failure induced by storm wave attacks (USACE-LAD, 2003). The approach and statistical model have been certified by the USACE, Coastal Engineering Research Center as the preferred method to statistically quantify the random bluff failure for shoreline studies that include a bluff failure component. Information on this approach is available from USACE Los Angeles District and has been published in the *Journal of the American Shore & Beach Preservation Association* (Williams, Lu, and Qin, 2004).

Given wave and TWL characteristics and the erodibility of buff materials, the statistical bluff failure model estimates bluff toe erosion induced by impinging waves and predicts random episodic bluff failures for varying storm conditions. A semi-empirical formulation developed by Sunamura (1982, 1983) is used to quantify the short-term bluff toe erosion rate as a function of the intensity of impinging waves and the site-specific erosion resistance of bluff materials:

$$X = \sum_{i=j}^{N} X_i = \sum_{i=j}^{N} k\left(C + \ln \frac{\rho g H_i}{S_c} \right) \Delta t_i \qquad \text{(D.4.6-15)}$$

where X is the accumulated bluff toe erosion depth from N waves acting on the bluff toe, X_i is the individual erosion by the i-th wave with height of H_i and duration of Δt_i, S_c is the compressive strength of the bluff material, ρ is the density of water, g is the gravitational acceleration, C is a non-dimensional constant, k is a constant with dimensions of length over time [L/T], and subscript j is the group number of the critical wave height H_j to initiate the toe erosion, which is given by $H_j = S_c e^{-c} / \rho g$.

This procedure requires regional and site-specific data. A statistical Monte Carlo simulation approach is used to characterize the correlation between bluff toe erosion and bluff failure for temporally varying wave conditions. If the cumulative depth of the bluff toe notch induced by storm waves exceeds a locally determined threshold value for triggering a bluff failure, the individual upper bluff retreat is determined by a randomly selected retreat value from an historic database for the site. The threshold value is empirically determined from historical bluff failure events. It may vary from one coastal bluff region to another. In the Encinitas/Solana Beach region, the threshold value of the cumulative toe erosion at which a bluff failure is likely to occur is approximately 8 feet.

The methodology may be applied in any situation where undermining of the bluff toe triggers upper bluff block failure; however, substantial field data are required to determine several of the required parameters and for proper calibration of the bluff failure model. Therefore, if the

Mapping Partner determines that a detailed bluff erosion study is necessary, he/she must provide the following field data, at a minimum:

1. The type of rock formation and/or bluff soil materials from which stability and the erosion-resistant force of the bluff material can be quantified.
2. Field measurements of bluff toe erosion in response to cumulative wave energy associated with past storm events for determining and calibrating empirical coefficients required by the Sunamura formula used by the model.
3. Historical data of upper bluff failures, indicating approximate horizontal length and transverse width of bluff top land loss during past storm events for formulating the probability distribution of the severity of bluff failure.

Two sets of field data are required to establish and calibrate the wave-induced toe erosion and to establish the statistical representation of bluff failure events. To calibrate the toe erosion produced by the statistical model, the depth of the toe erosion shall be measured before and after significant storm events and correlated to the cumulative wave energy during those events at the bluff toe. At least two full years of data are required to capture seasonal variability of toe erosion, and up to five years of data may be needed to calibrate the correlation between the impinging waves and the resultant toe erosion. Longer monitoring periods are desirable and will include more storm events and more cumulative wave energy statistics, and thus result in higher accuracy in model calibration.

To assemble the representative statistics of random occurrences, adequate observations of upper bluff failures are required. At least two to five years of monitoring data are required to provide a reasonable representation of the size distribution of the failures. The larger the database, the less uncertainty there is in the predicting toe failure. There are no known analytical methods for forecasting bluff toe erosion and failure; therefore, a statistical approach is the only means of forecasting bluff failure and retreat due to the random temporal wave action during large storms. To capture any seasonal variability, at least 5 years of data are required, and to ensure a statistically valid database, up to 10 years of data may be needed if failures are uncommon. This is likely to limit the applicability of this approach for traditional FEMA coastal flood studies, unless these data are readily available at the beginning of the project. If it is determined that data are available and that the application of the statistical bluff failure model is necessary, use the following procedures:

Characterize Fronting Beach Conditions

The Mapping Partner shall perform Steps 1 through 6 under general approach, above. Assess whether the potential damage to the bluff-top developments resulting from bluff failure is highly probable. If a subject bluff is fronted by either a sand berm or dune with a sufficient width to separate the bluff from direct wave impingement during the winter months, the storm-induced erosion to the berm and dune, as stated in Subsection D.4.6.4, should be applied. If the protective sand berm or dune is removed during the winter months, use this eroded condition as the winter beach profile and apply the bluff failure model for that beach condition. If eroded winter profile data are not available, then the profile should be developed by probing down to erosion-resistant materials along beach transects to establish the bedrock profile. A typical eroded winter profile should be developed from surveyed and probing data of the underlying bedrock layer for each typical reach of shoreline area being analyzed. A sketch of a typical erodible bluff fronted by a rock platform capped with a thin sand layer is shown in Figure D.4.6-31. If the fronting beach is a broad sandy beach with berms or dunes, apply beach erosion methods prescribed in Subsection D.4.6.5.

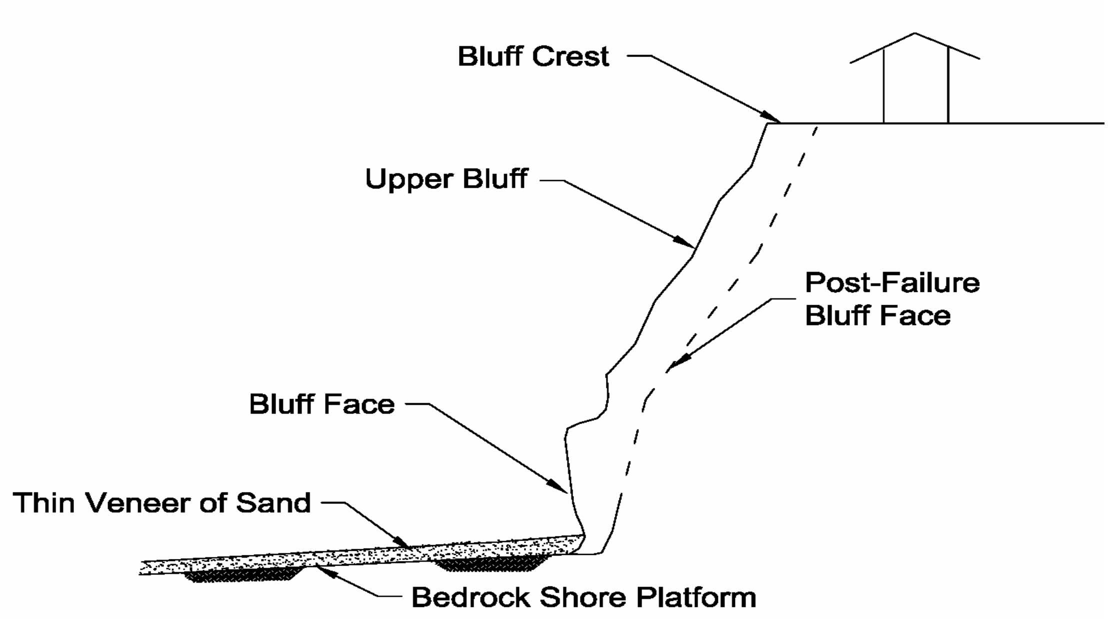


Figure D.4.6-31. Typical Erodible Bluff Profile Fronted by Narrow Sand-capped Beach

Apply Bluff Failure Model

Following are procedures for applying the statistical bluff failure model:

1. Collect field data for each setting and subreach along the study area.
    a. Measure bluff toe erosion during at least two separate periods.
    b. Conduct field probing to determine the bedrock layer across the beach area.
    c. Determine the elevation of the bluff toe and bedrock layer intercept and cross-shore slope.
2. Assemble historical bluff failure events.
    a. Determine bluff failure characteristics in terms of the length along the bluff crest-line and the transverse recession dimensions.
    b. Formulate probability distribution of the magnitude of various bluff failure events.
    c. Determine the threshold value of toe notch depth when the upper bluff failure occurs (see USACE, 2003; Williams et al., 2004).

3. Calibrate Sunamura’s empirical equation.
    a. Determine the wave histogram including storm events within the two separate historical wave and erosion periods.
    b. Estimate the temporal histogram of wave heights at the bluff base for each of the selected periods with synchronized tide levels.
    c. Determine the bluff resistance force for the type of bluff material at the site.
    d. Calibrate Sunamura’s empirical equation (i.e., Equation D.4.6-15) from the cumulative toe erosion measured in these two separate periods and quantify the total impinging wave energy during each period from hindcast data.
4. Calibrate bluff retreat model by simulating past bluff failure events.
    a. Assemble historical wave characteristics at the bluff base and synchronize with measured tide levels.
    b. Determine the probability distribution of wave characteristics at the bluff base.
    c. Apply the Monte Carlo sampling technique to randomly select the histogram of wave characteristics at the bluff base.
    d. Estimate the cumulative notch depth at the bluff toe using the calibrated toe erosion equation (Equation D.4.6-15).
    e. Apply the same Monte Carlo sampling technique to randomly select a bluff failure event if the accumulative notch depth is deeper than the prescribed threshold value deduced from Step 2. Assemble historical bluff failure events.
    f. Perform multiple simulations for a required long-term duration (e.g., 10 years) until a statistical representation regarding the occurrence of bluff failure is achieved.
    g. Derive the statistical mean and other pertinent properties, such as the exceeding probability of a cumulative bluff retreat distance at the end the modeled duration.
    h. Compare results with observed data from the site and adjust coefficients as necessary.
5. Apply calibrated model for 1% annual storm event.
    a. Determine winter profiles for fronting beach conditions and elevation of bluff-beach intercept.
    b. Apply calibrated model for entire 1% annual storm.
    c. Determine amount of toe erosion and bluff crest line recession for the 1% storm.

   d. Use this adjusted profile for all further runup and overtopping analyses associated with the 1% annual storm.

6. Document results, data, and assumptions.

D.4.6.9 Estimating Beach Profiles for Beaches Backed by Erosion-Resistant Bluffs or Cliffs (Beach Setting No. 5)

Erosion-resistant bluffs and cliffs are often fronted by rock terraces, rocky beaches, or narrow rock platforms capped with thin layers of sand or gravel. Once the thin sand cap is eroded from the rocky beach, this beach setting is stable; see Figure D.4.6-6 and Figure D.4.6-32. Therefore, Mapping Partners shall assume the sand cap is removed from the beach profile before a significant storm event and use the adjusted rocky beach profile along with measured profiles for the non-erodible bluffs or cliffs for all subsequent runup and overtopping computations. Document assumptions, methods, data resources, and results. Figure D.4.6-33 shows the sequence of key activities and computational considerations required to determine storm-induced beach profile changes for Beach Setting No. 5.

D.4.6.10 Profiles in Tidal Flats and Wetlands (Beach Setting No. 6)

Tidal flats and wetlands are low-gradient coastal features, usually found in sheltered water areas and comprised of fine cohesive silts and clays; see Figures D.4.6-7 and D.4.6-34. Figure D.4.6-35 shows the sequence of key activities and computational considerations required to determine storm-induced beach profile changes for Beach Setting No. 6.

Figure D.4.6-32. Photo of Erosion-resistant Cliff

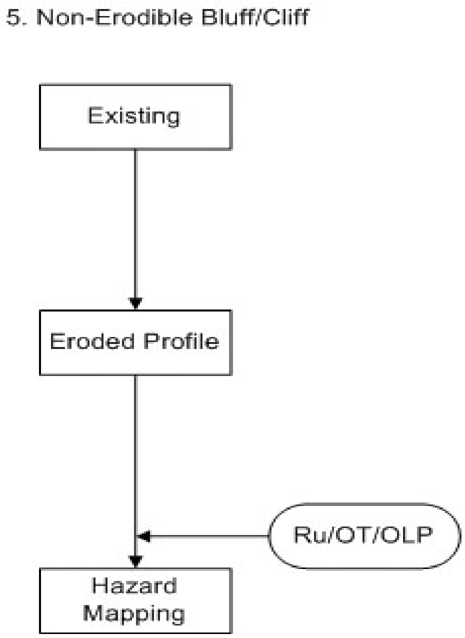


Figure D.4.6-33. Key Activities to Determine Beach Profile Changes for Beach Setting No. 5

Sedimentation processes in this beach setting are typically depositional. Over time, these coastal landforms may become capped with wetland vegetation and detrital deposits and debris from overland wave propagation during storm events. Therefore, Mapping Partners may assume that tidal mudflats and wetland profiles do not erode over the time-scale of single storm event. Mapping Partners should compare existing tidal flat and wetland profiles with recent post-storm profiles to verify this assumption. If it is determined that no measurable erosion occurs during single storm events, then the Mapping Partner shall use the existing profile information to determine runup, overtopping, and overland propagation. However, if it is found that measurable changes can occur during a single storm, the Mapping Partner should document the observed changes experienced at the site and propose to the FEMA study representative a procedure for using that information to adjust the existing profiles before determining runup, overtopping, and overland propagation. The Mapping Partner shall document assumptions, data used, and methods implemented to prepare the final profiles, and summarize the results.

Figure D.4.6-34. Photograph of Tidal Flats and Wetlands Complex (Photo by Northwest Hydraulic Consultants, Inc.)

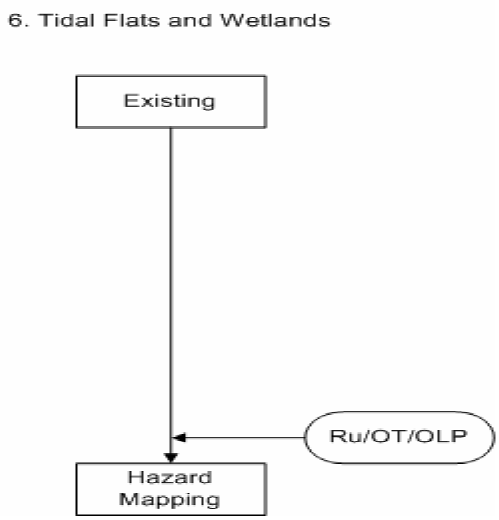


Figure D.4.6-35. Key Activities to Determine Beach Profile Changes for Beach Setting No. 6