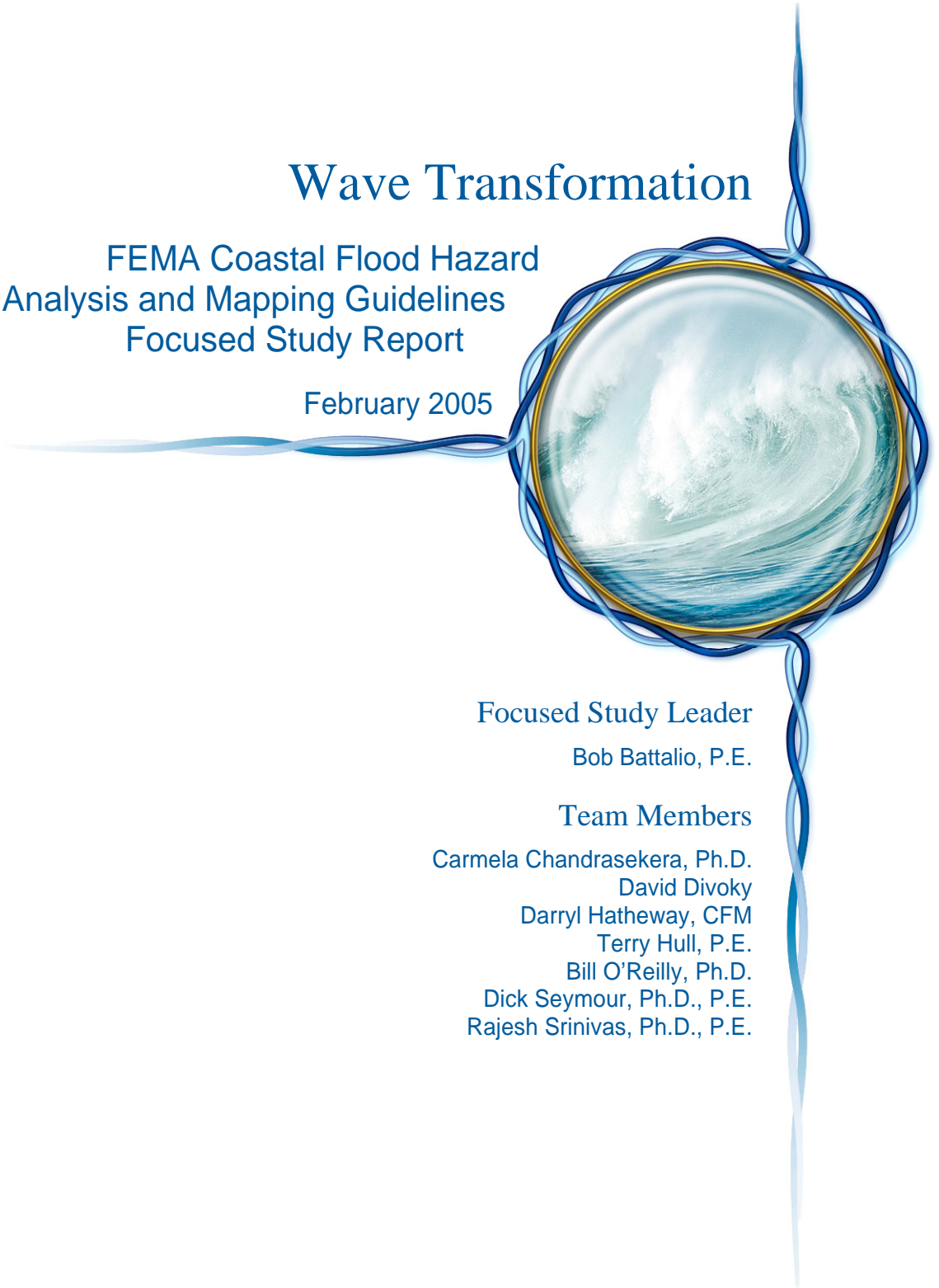


# Wave Transformation

FEMA Coastal Flood Hazard  
Analysis and Mapping Guidelines  
Focused Study Report

February 2005



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## 1 Wave Transformations Discussion

**Acronyms**

ACES	Automated Coastal Engineering System
CDIP	Coastal Wave Data Information
CEM	Coastal Engineering Manual
FHF	Flood Hazard Factor
GROW	Global Re-analysis of Ocean Waves
NGCD	National Geological Data Center
USACE	U.S. Army Corps of Engineers
WES	Waterways Experiment Station
WIS	Wave Information System

# 1 INTRODUCTION

This document describes an approach to develop guidelines for addressing Wave Transformation, as part of new Guidelines and Specifications (*G&S*). Four study topics are addressed as listed below.

## 1.1 CATEGORY AND TOPICS

This paper addresses Wave Transformations, which is a focus study area comprising four Study Topics:

Wave Transformation Topics and Priorities					
Topic Number	Topic	Topic Description	Priority		
			Atlantic / Gulf Coast	Pacific Coast	Non-Open Coast
7	CDIP California	California Regional Wave Transformation Models	--	C	--
8	Overall Wave Transformation	Wave Transformations With and Without Regional Models	H	C	C
9	Dissipation	Wave Energy Dissipation over Shallow, Flat Bottoms	C	H (C)	C
10	WHAFIS	Overland Wave Propagation; Candidate Improvements to WHAFIS	I (C)	I (C)	H

Key: C = critical; A = available; I = important; H = helpful  
(Recommend priority italicized if focused study recommended a change in priority class)

Study Topic 8 also encompasses Topics 7, 9, and 10. Therefore, topic 8 is discussed before topic 7 in this report. Revisions were made based on information exchanged in Workshop 2, held in Sacramento, February 23-26, 2004. Version 2.0 was provided before the workshop. This is Version 5.0.

## 1.2 WAVE TRANSFORMATION FOCUSED STUDY GROUP

The Wave Transformation Focused Study group members are Bob Battalio, the leader of the study group, Carmela Chandrasekera, Richard Seymour, Bill O'Reilly, Darryl Hatheway, Terry Hull, Rajesh Srinivas, and David Divoky.

## 1.3 GENERAL DESCRIPTION OF WAVE TRANSFORMATION PROCESSES AND PERTINENCE TO COASTAL FLOOD STUDIES

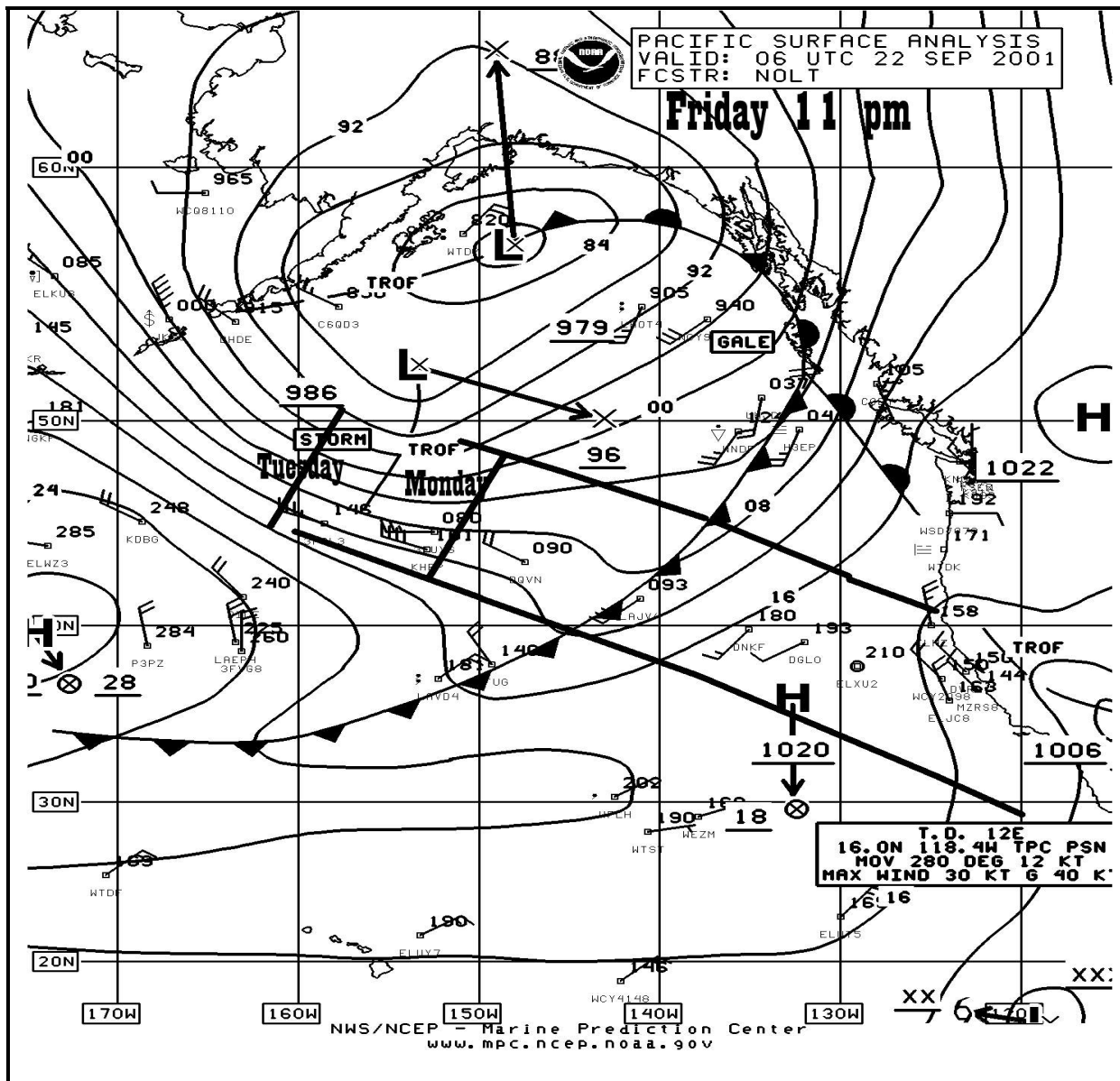
Wave Transformation refers to changes in wave characteristics during propagation, generally propagating from deep through shallow water. The primary processes affecting wave

transformations are refraction, diffraction, shoaling, dissipation, and nonlinear effects. Wave refraction is a key process affecting the distribution of wave energy and power, and hence the potential for coastal flooding along a shoreline. Wave refraction results from a change in local wave propagation speed due primarily to local depth changes. Wave refraction can result in convergence or divergence of the wave energy producing changes in wave height as well as wave direction in the nearshore. Diffraction of water waves is a phenomenon in which energy is transferred laterally along the wave crest. As waves slow down in shallow water, wave-length reduces and wave height increases. The increase in wave height is referred to as wave shoaling. As waves move into shoaling water they eventually become unstable and break. Wave breaking is the prominent method of wave energy dissipation. Waves also lose energy due to bottom friction and viscous damping when they propagate over shallow and intermediate waters, and through inundated marshes.

Wave transformations are important processes to consider in coastal flood studies, especially where long period swell is prevalent, and where coastal morphology focuses wave action. Wave transformations are addressed as an intermediate step between forcing processes (wave generation) and response processes (wave runup and overtopping). An example of forcing processes is provided in Figure 1, which shows the surface atmospheric pressure and wind fields estimated for a north Pacific storm. The heavy black lines and text identify the zone expected to generate swell incident to the California shore approximately 3 days later. Figure 2 characterizes swell exposure for the central California Coast from close range and distant storms, in terms of swell travel path and time. The West Coast of the United States is exposed to large swell from distant storms, resulting in very long wave lengths that are especially sensitive to wave transformation processes such as depth-induced refraction. An example of response processes is provided in Figure 3, which shows coastal flooding in Pacifica, California, caused by wave runup and overtopping.

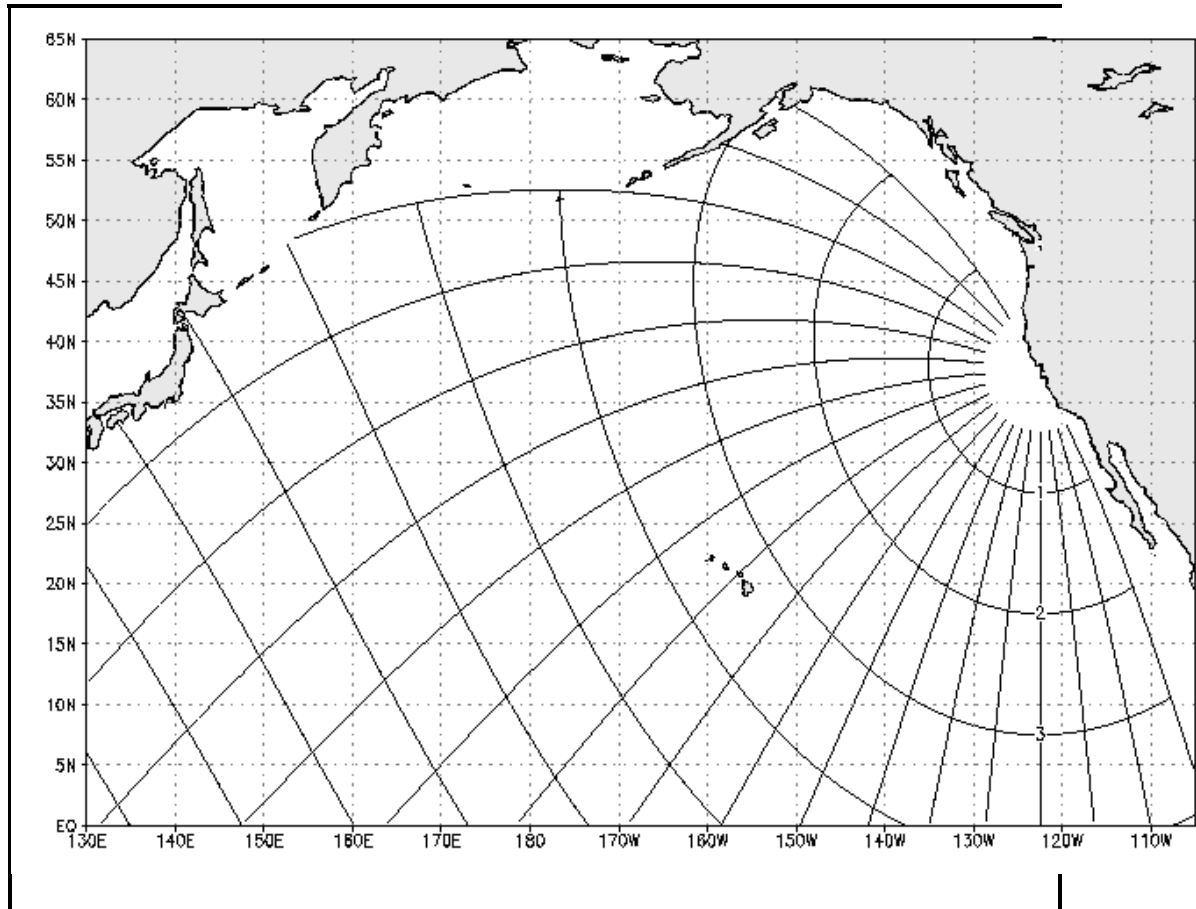
Regional wave transformation modeling is ongoing in California, most notably via the Coastal Wave Data Information Program (CDIP). Figure 4 shows a public-domain output of wave refraction modeling by CDIP for the San Francisco, California area. The graphic shows that wave transformations can greatly increase swell exposure for some areas and decrease it in others. This point will be amplified by looking at swell observations for three locations identified in Figure 4:

1. Ocean Beach, San Francisco;
2. Bolinas Bay and Lagoon Inlet, Marin County;
3. Crissy Field Shore and Lagoon Inlet, San Francisco (inside San Francisco Bay).



Map source, NOAA internet site: Forecasting Marks, Approximate Analysis by Bob Battalio.

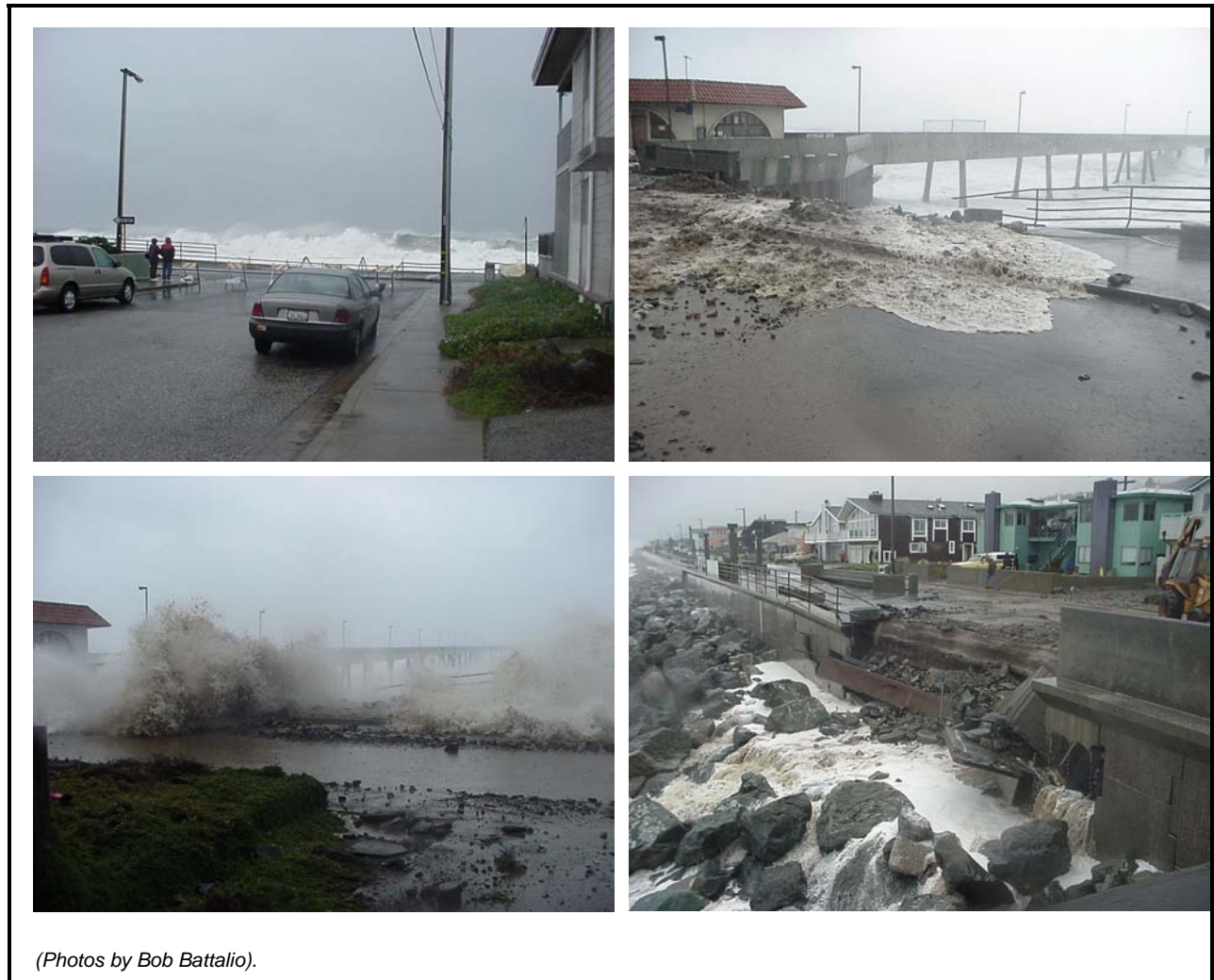
**Figure 1. Offshore wave generation by a North Pacific Storm, with Forecast Swell arrival on the West Coast of the U.S. about three days later.**



Source: Public Internet Site.

**Figure 2. North Pacific swell paths incident to central California. Rings are one-day travel distances for moderate period swell, and radial lines are swell travel paths.**

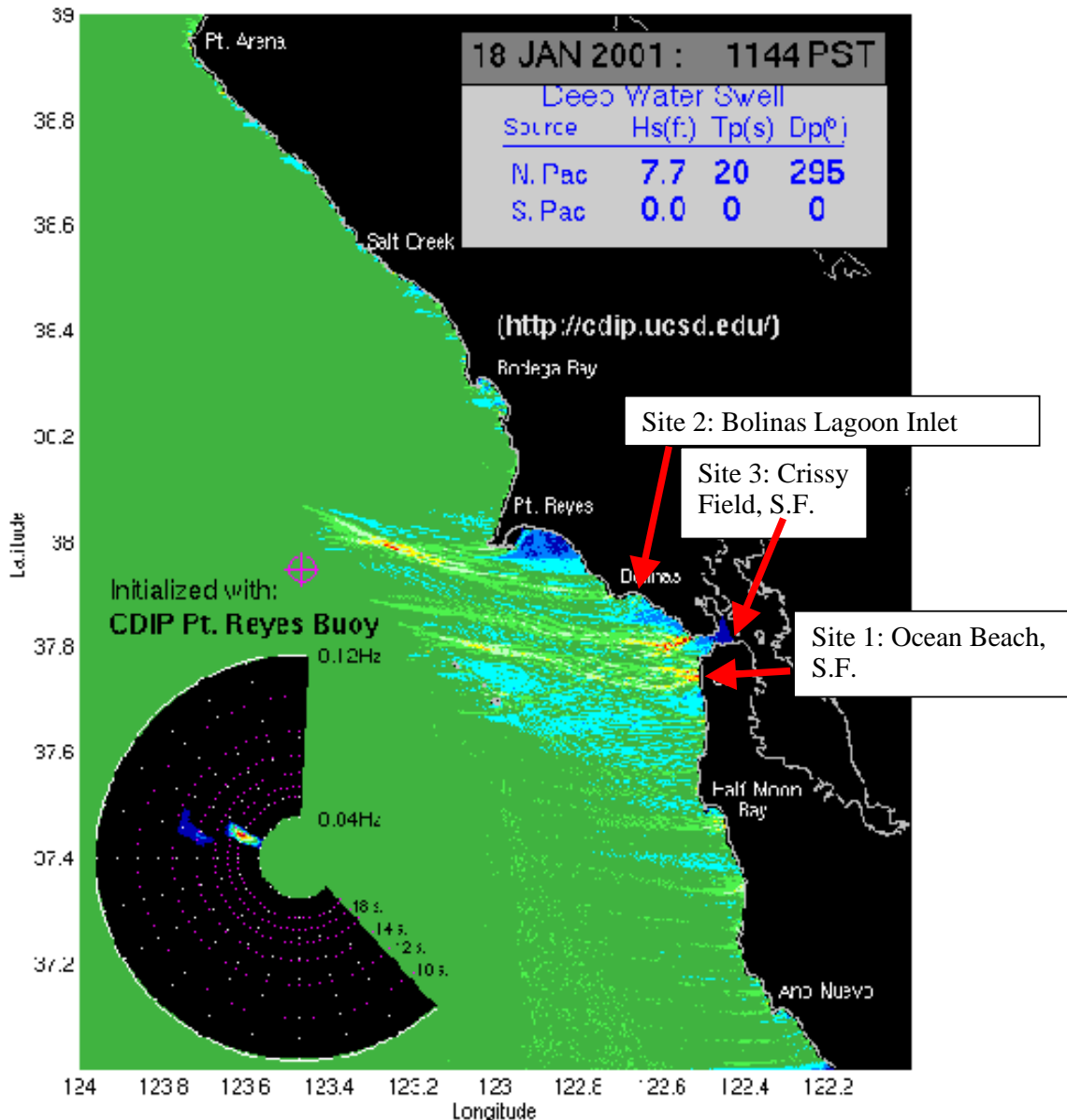




(Photos by Bob Battalio).

Source: CDIP Internet Site

**Figure 3. Wave setup, runup, overtopping and coastal structure damage, Pacifica, CA.**



**Figure 4. Wave transformation modeling by the Coastal Data Information Program at Scripps Institution of Oceanography.**

The CDIP regional wave modeling predicts large waves at Site 1, smaller waves at Site 2 and much smaller waves at Site 3.

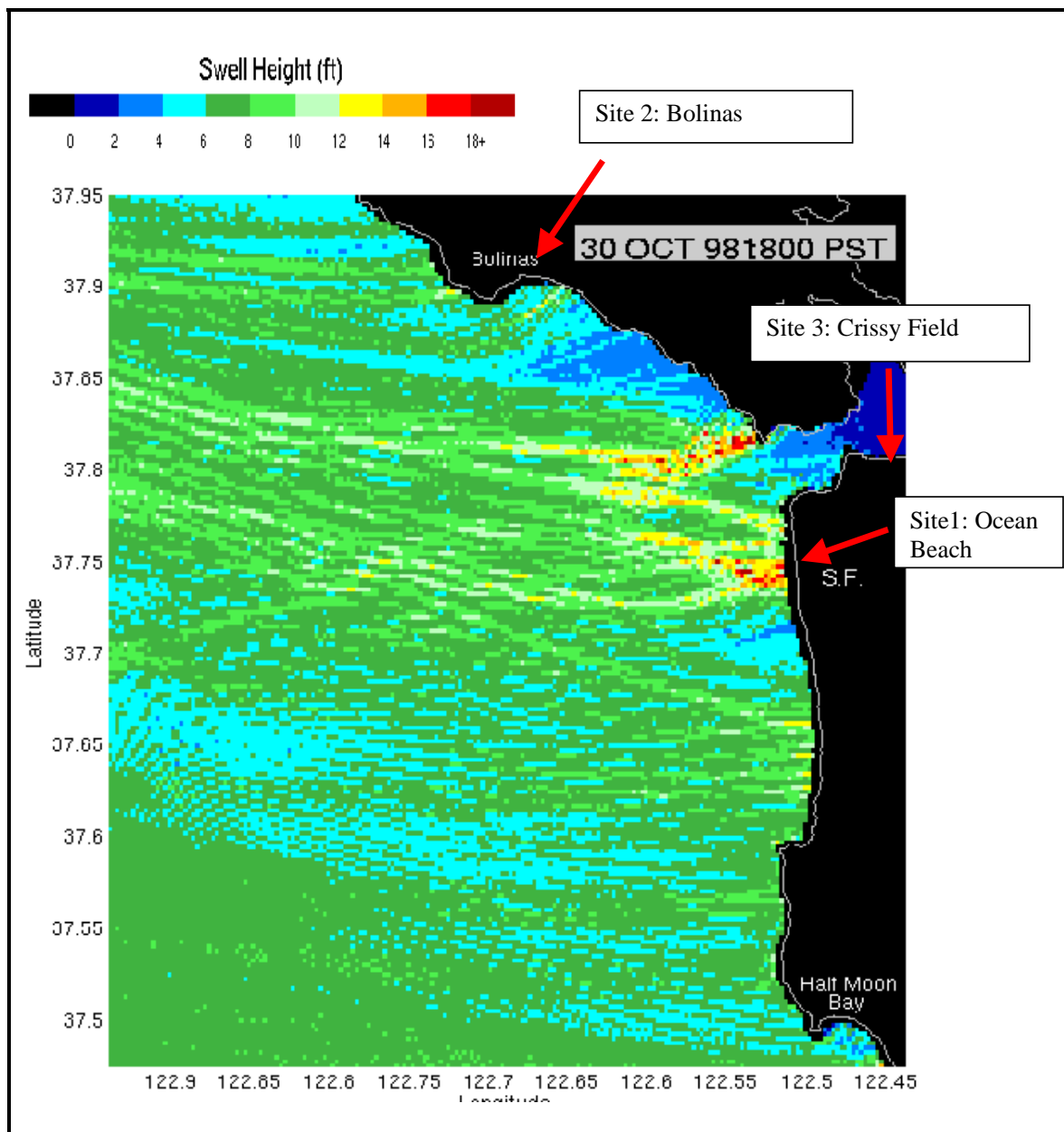
Figure 5 is another CDIP product showing a close-up view of wave refraction effects around the San Francisco Golden Gate area. An aerial photograph of Site 1 (Ocean Beach) shows wave crossing patterns consistent with the CDIP modeling (Figure 6). Figures 7 and 8 are photographs of breaking waves at Site 1 with heights on the order of 20 to 40 feet. Note that these waves are long-period swell with little relation to local weather.

Wave exposure at Site 2, Bolinas Bay, is characterized in Figure 9. This figure shows wave heights measured offshore and used as input to CDIP refraction modeling, wave heights measured nearshore, and wave height output from the CDIP modeling for the nearshore location. A comparison between the modeled and measured wave heights shows good agreement and confirms that wave transformations greatly reduce incident wave heights for this section of the coast.

Wave exposure at Site 3, Crissy Field, is characterized in Figures 10 and 11. Crissy Field is located in the San Francisco Bay, and swell has propagated through the Golden Gate. Figure 10 shows a time series of wave heights and periods measured offshore in the Pacific Ocean and near the Crissy Field shore. While the wave heights are much lower at Site 3 than in the open ocean, maximum heights from swell can approach the height of other locally generated wind waves potentially governing coastal flooding potential. Figure 11 is a photograph of a swell breaking at Crissy Field.

Wave transformations can also be important in sheltered water areas such as Puget Sound, as determined in a recent flood study at Sandy Point, Whatcom County (Figure 12). Sandy Point is exposed to wind waves generated within the greater Puget Sound, with particular exposure to a long open fetch in the Strait of Georgia (Figures 13 and 14). 100-year wind wave heights over 16 feet were calculated, with peak periods up to 11 seconds (Figure 15). The bathymetry offshore of Sandy Point includes a shallow area called Alden Bank (Figure 16), which was found to focus wave energy at Sandy Point (Figure 17). The wave focusing results in increased flood potential for a part of the Sandy Point community, as verified by observations during a moderate flooding event (Figure 18).

Wave Transformations discussed in this report include all changes to wave conditions during propagation from offshore waters to nearshore waters pertinent to coastal flood studies. Wave Transformation analyses are typically applied after offshore wave conditions are defined, with results used as input for nearshore runup analysis or overland wave propagation, both used for flood risk mapping.



Source: CDIP Internet Site.

**Figure 5. Wave transformation close-up at (1) San Francisco, (2) Bollinas and (3) Half Moon Bay, CA.**



Source: U.S. Army Corps of Engineers, South Pacifica Division.

**Figure 6. Wave Refraction Resulting in Large Breaking Waves at Ocean Beach, CA (Site 1 in Figures 4 and 5).**



Photograph: Tim Britton

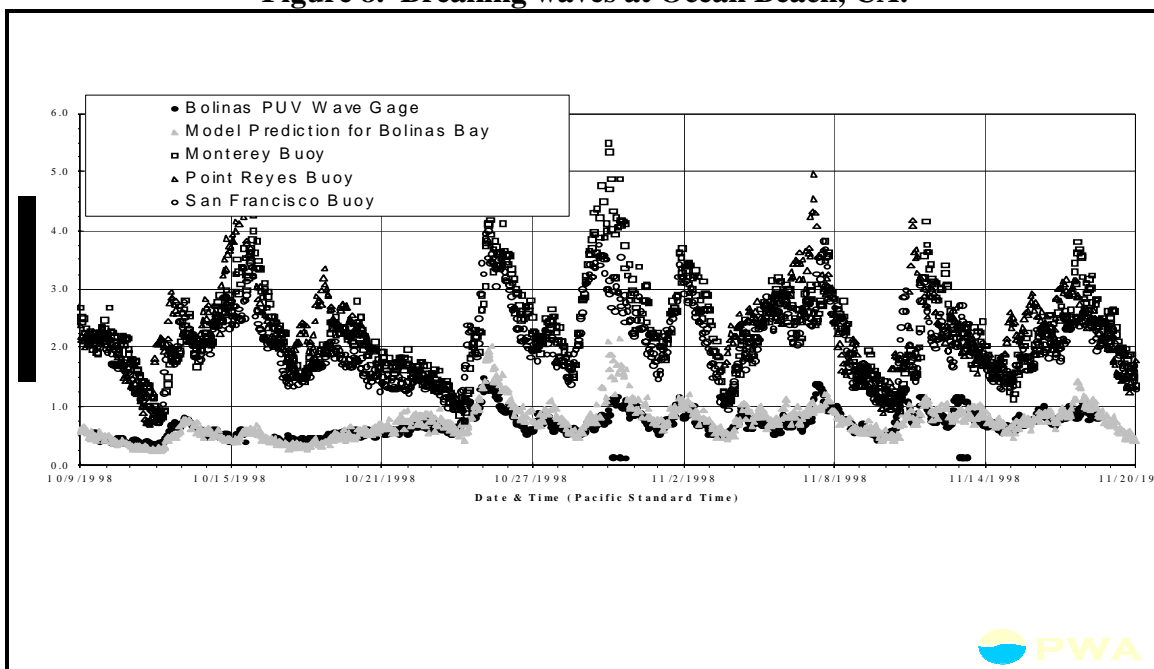
**Figure 7. Breaking waves at Ocean Beach, CA.**



Photograph: Tim Britton.

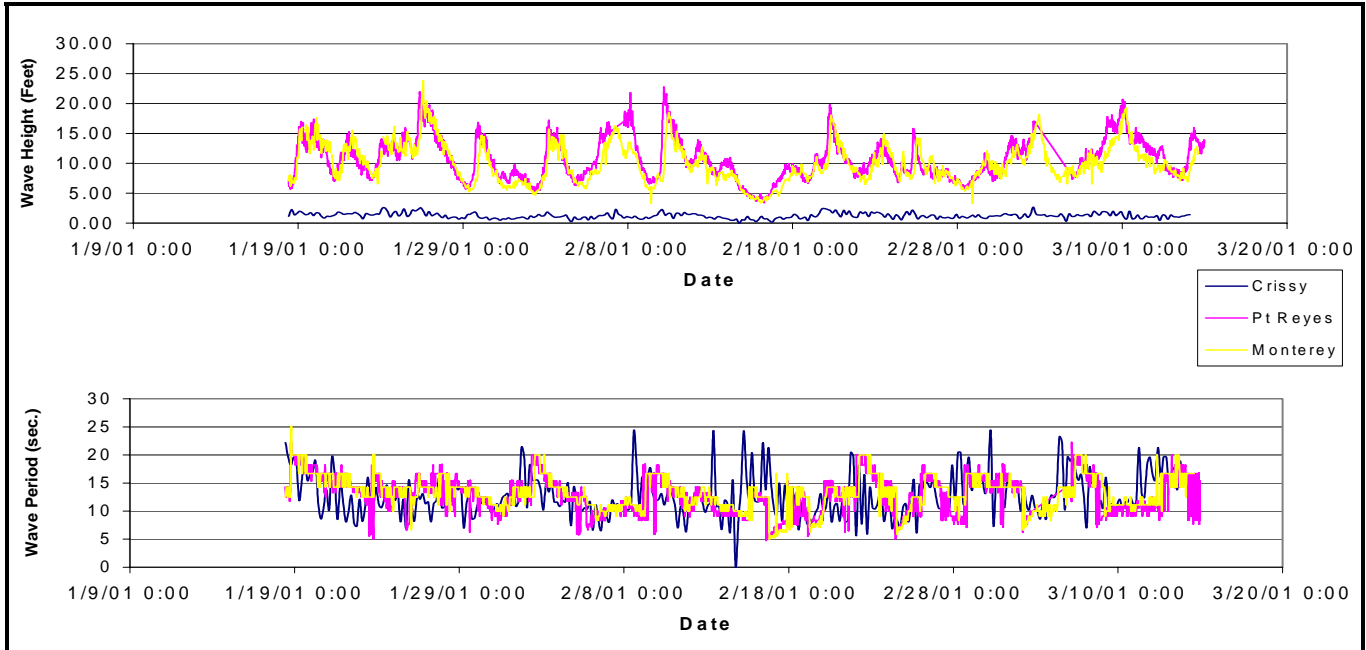
Note surfer paddling up wave, for scale.

**Figure 8. Breaking waves at Ocean Beach, CA.**



Offshore Data from CDIP (Point Reyes Buoy) and NABCO (Monterey Bay Buoy). Nearshore (Bolinas PUV Wave Gauge) Wave Data from PWA. Model Predictions from CDIP Refraction Analysis. Bolinas Bay is Site 2 in Figures 4 and 5 (PWA, 1999).

**Figure 9. Wave height comparison at Bolinas, California vs. offshore and nearshore wave measurements.**



Offshore wave data from CDIP (Point Reyes Buoy) and NDBC (Monterey Bay Buoy). Crissy Field data from PWA. Crissy Filed is Site 3 in Figures 4 and 5.

**Figure 10. Wave height and period comparison at Crissy Field vs. offshore buoy measurements.**



Photograph by Bob Battalio.

**Figure 11. Reduced swell wave heights at Crissy Field, east of Golden Gate Bridge, San Francisco, CA (Site 3).**



**Figure 12. Example in sheltered waters, Sandy Point, Whatcom County, WA.**



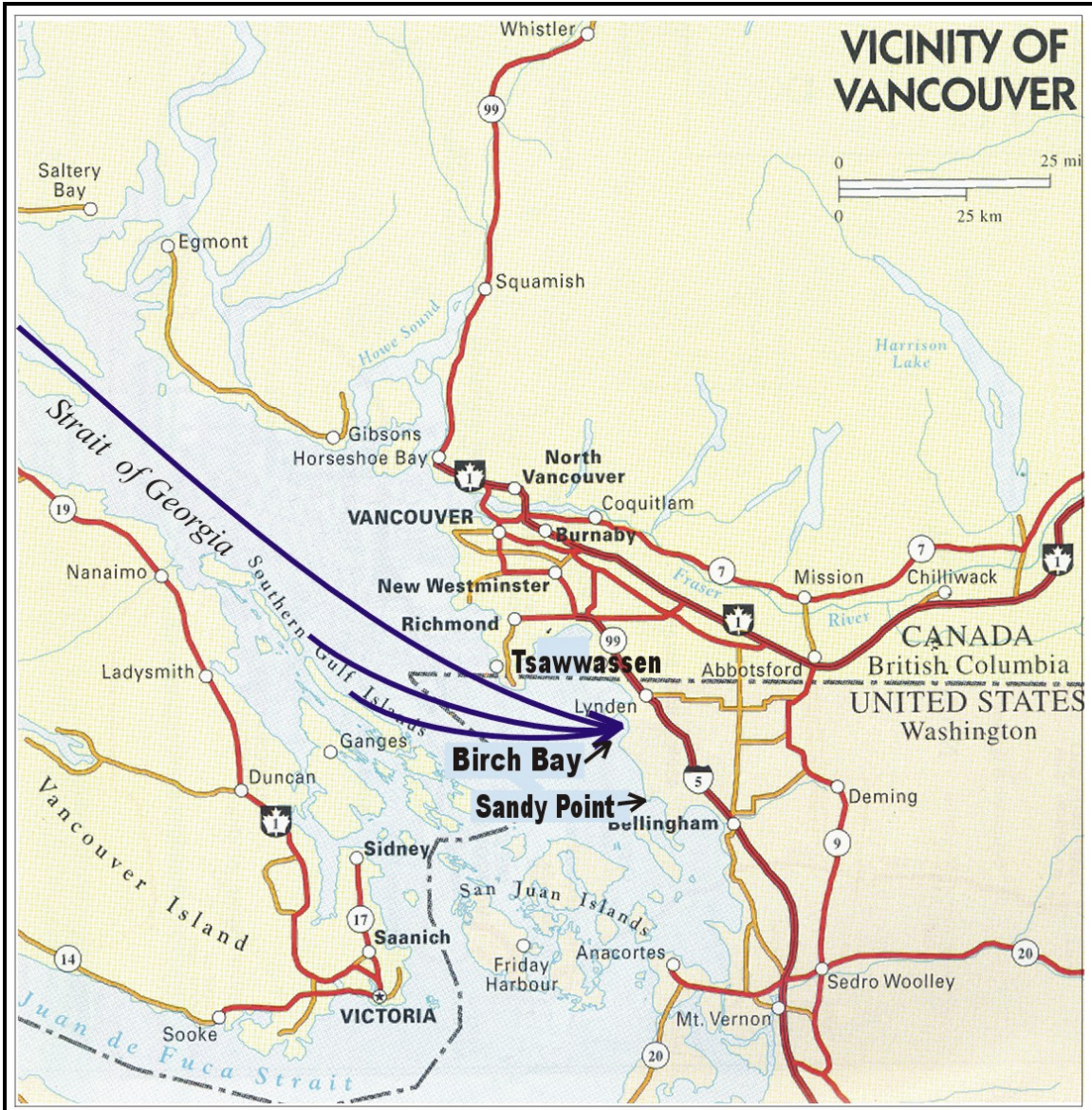
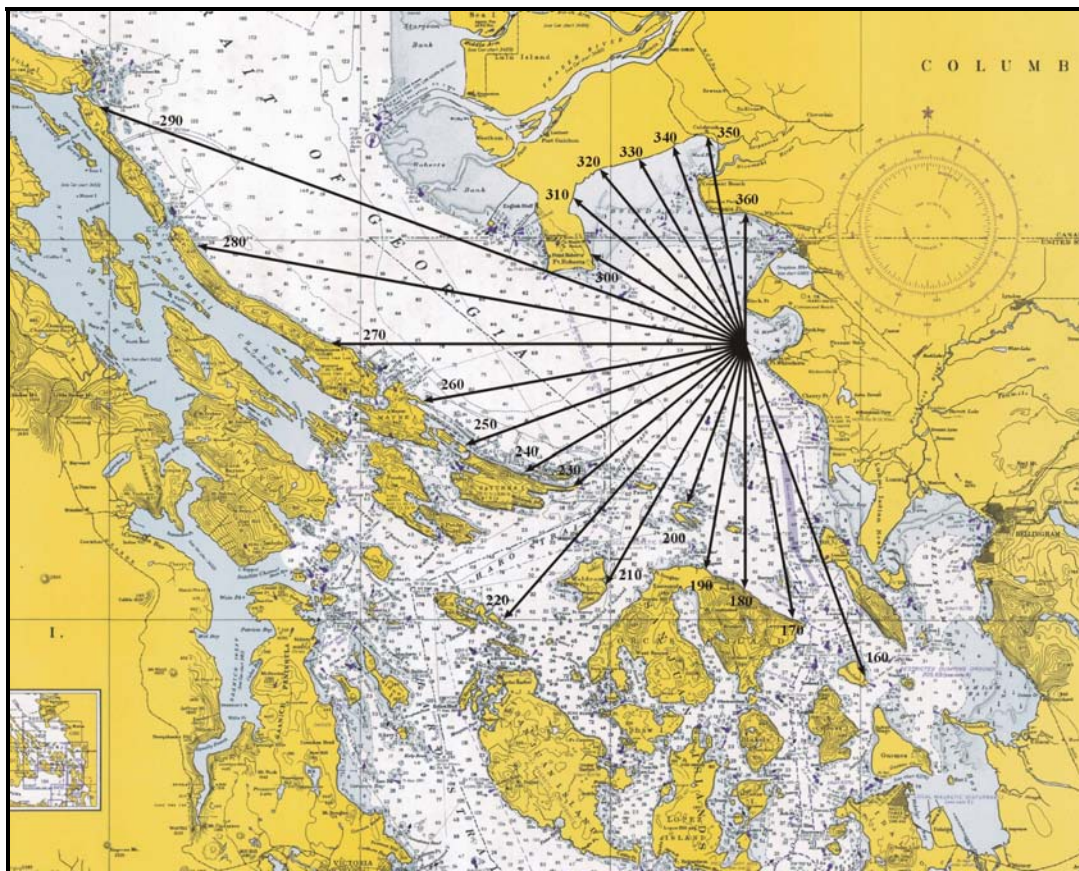
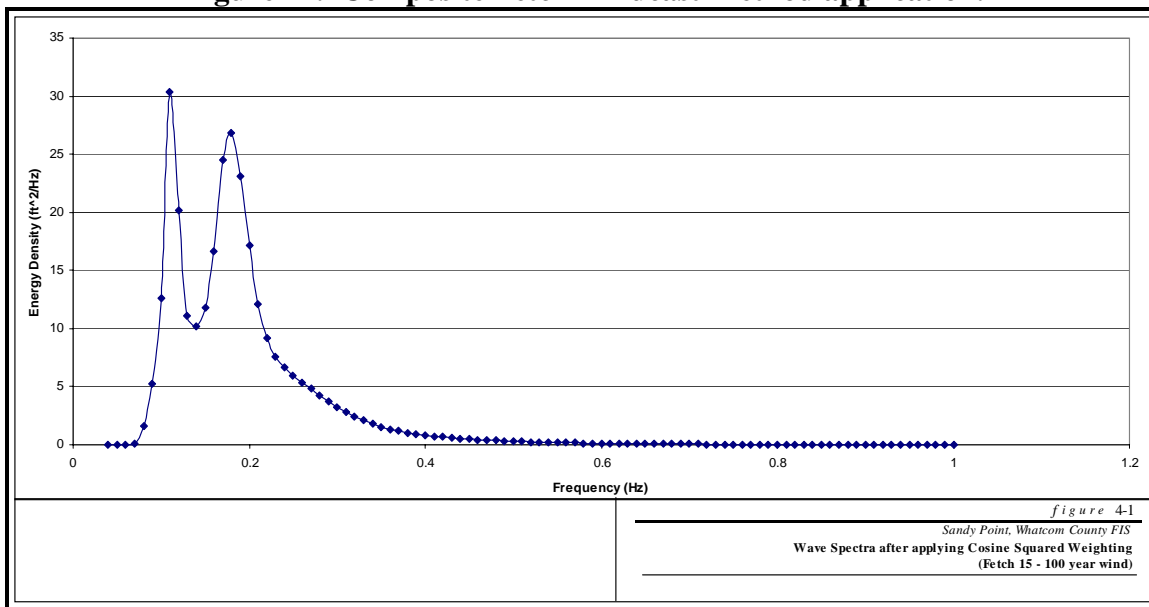


Figure 13. Local wind sea forcing in Strait of Georgia, WA.

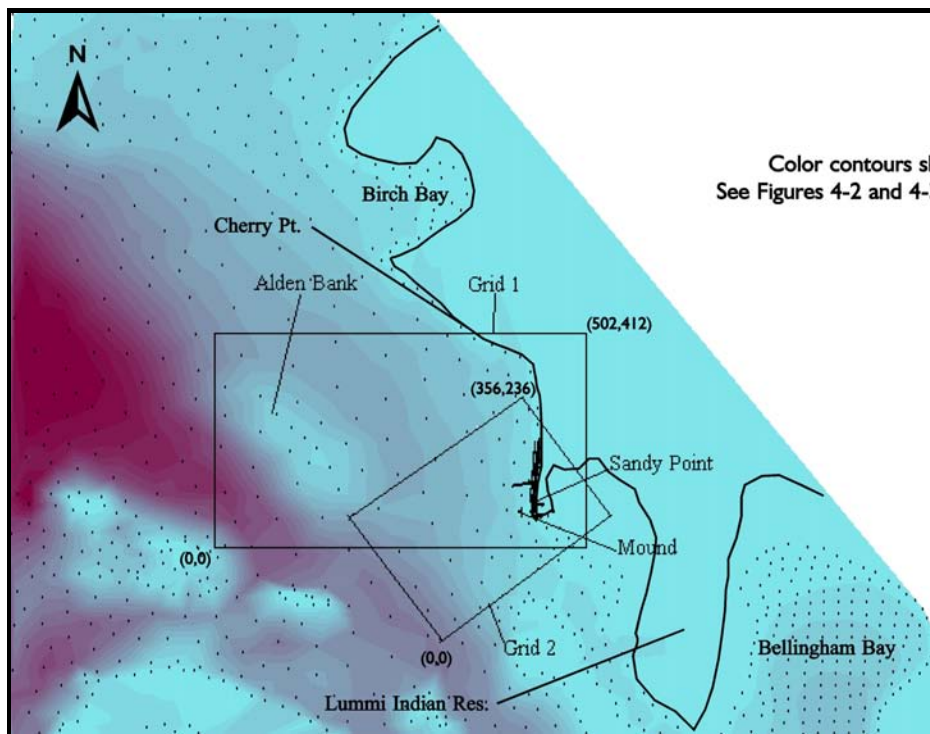


Example Shown for Birch Bay is Similar to Fetches for Sandy Point, Whatcom County, Washington.

**Figure 14. Composite Fetch Hindcast Method application.**

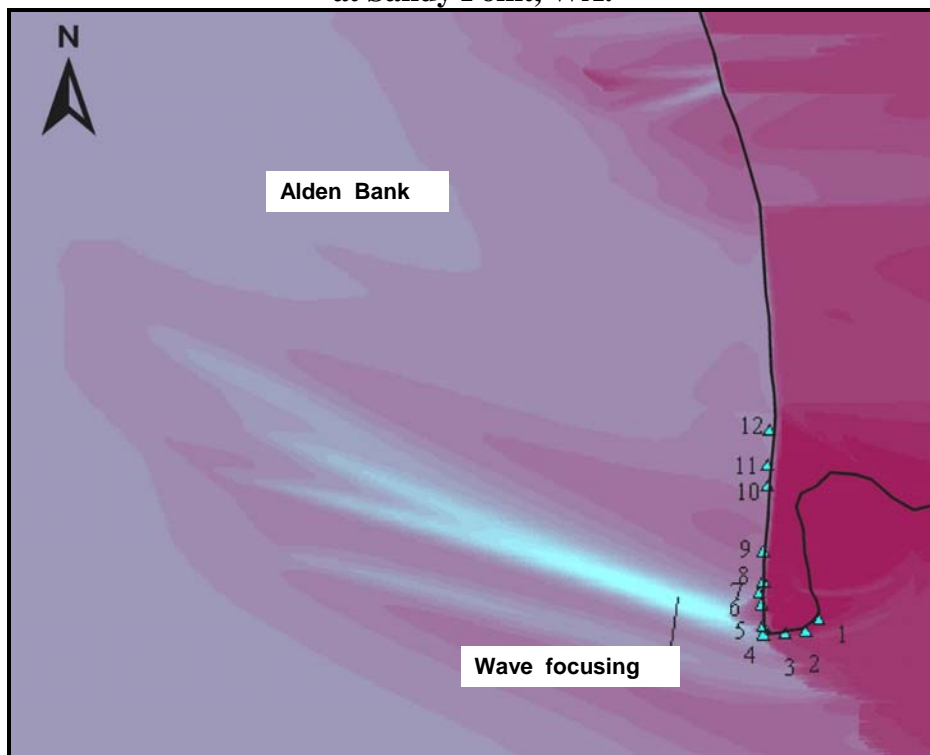


**Figure 15. Calculated wind wave energy spectrum for 1% event.**



Note Shallow Reef 'Alden Bank'.

**Figure 16. Bathymetry grids for wave transformation modeling at Sandy Point, WA.**



Focusing Caused by Shallow Area (See Figure 16, Alden bank).

**Figure 17. Wave focusing due to wave transformation affects flood risk.**



Flood Risk Shown to be Affected by Wave Refraction.

**Figure 18. Coastal flooding event 12/15/2000 at Sandy Point, WA.**

## **2 CRITICAL TOPICS**

### **2.1 TOPIC 8: WAVE TRANSFORMATIONS WITH AND WITHOUT REGIONAL MODELS**

#### **2.1.1 Description of the Topic and Suggested Improvement**

Wave Transformations refer to changes in wave characteristics during propagation. The primary processes are refraction, diffraction, shoaling, dissipation, and nonlinear effects. For practical reasons, Wave Transformations are often considered in the regime bracketed by wave generation (typically in “deep water”) and depth-induced breaking (typically “near shore”). See the Storm Wave Characteristics Focused Study for guidance on developing offshore wave conditions for input to wave transformations. See the following topics for guidance on related nearshore processes that use the output from Wave Transformation: Wave Setup; Wave Runup and Overtopping, and Overland Propagation. FEMA G&S address coastal flooding by wave action via wave runup (RUNUP 2.0 software) and or overland propagation (WHAFIS software), both of which require wave conditions at the beginning of the surf zone. However, wave transformations through the surf zone are important to wave setup and wave dissipation

processes and hence shallow water wave breaking processes are included in Wave Transformations and in Wave Setup. Wave reflection and current-induced refraction are typically ignored, and guidance can be found elsewhere (USACE SPM, 1984; USACE CEM, 2003).

Refraction, diffraction, shoaling, and dissipation are strongly dependent on the wave length, with longer waves (higher wave periods) being affected the most (wave height is important, and dissipation due to propagation through vegetation can be greater for shorter, steeper waves). Irregular and steep bathymetry also increase wave transformations. Wave transformations are important for Pacific Coast flood studies owing to the longer waves, and generally steeper and less regular bathymetry. Wave transformations on the Pacific Coast are graphically depicted by near-real-time wave models applied under CDIP see for example [http://cdip.ucsd.edu/models/socal\\_now.shtml](http://cdip.ucsd.edu/models/socal_now.shtml). In Southern California, near shore wave heights can vary by a factor of 5 over a few miles of shoreline. Wave energy can be significantly dissipated (wave heights attenuated) during propagation over extensive shallow areas and intertidal marsh due to friction effects, viscous damping, and flow obstruction. These processes are particularly important in the Gulf Coast where sand and mud flats and marsh may extend for miles. Similar conditions can be found in some estuaries (Sheltered Waters) such as San Francisco Bay (West Coast) and Chesapeake Bay (East Coast).

Presently, the *G&S* do not include a description of wave transformations, and no *G&S* are written for the Pacific Coast (FEMA, 2003). Yet, prior Pacific Coast studies have addressed wave transformations in some detail (Tetra Tech, 1982; PWA, 2002a, b). Hence it is recommended that the Pacific Coast *G&S* be written to include Wave Transformations. Other regions could use the information in the Pacific Coast *G&S* as appropriate.

### **2.1.2 Description of Procedures in the Existing Guidelines**

There are no *G&S* procedures for the Pacific Coast. In this case, guidance can be derived from the *G&S* for other geographical areas. Wave Transformations are addressed in Appendix D of the FEMA *G&S* in terms of overland travel (Sections D.2.6 - 2.6.4) and application of the WHAFIS model. This treatment is one-dimensional (defined by a profile), and limited to shallow water breaking and dissipation processes. Dissipation due to propagation over shallow areas and marsh plants is included. However, wave refraction, diffraction and shoaling are not addressed, except in passing references such as on page D-70: “Where land shelter or wave refraction may result in reduced incident waves, it is appropriate to specify an initial significant wave height for the transect.” The emphasis of the *G&S* on depth-limited, shallow water propagation and dissipation is logical given the bias toward the Atlantic and Gulf Coasts.

### 2.1.3 Application of Existing Guidelines to Topic–History and/or Implications for NFIP

The existing *G&S* are not adequate for Pacific Coast Flood Insurance Studies, and depending on site characteristics, are often not adequate for other regions, including sheltered waters. However, some wave transformation methods have been used in the following case studies.

#### ***Case Studies on the West Coast***

Following are selected flood insurance studies on the Pacific Coast that address wave transformation at different levels of complexity.

##### **Sandy Point, Whatcom County, Washington (PWA, 2002a)**

Sandy Point is located close to the southern end of the Strait of Georgia, in the Pacific Northwest (Figure 12). The morphology consists of a 2-mile-long southward prograded sand and gravel spit. Swell wave existence at Sandy Point was ruled out because of its sheltered location. Governing wave conditions are locally generated seas and the highest waves are caused by winds blowing along the Strait of Georgia (Figures 13 and 14). The longest fetch to the northwest dominates the deepwater wave characteristics, and effects of varying fetch lengths in different directions were visible in wave spectra (Figure 15).

Deepwater waves were transformed to near breaking waves using RCPWAVE, a two-dimensional numerical model for wave refraction, diffraction, and shoaling. The main bathymetric features include a large offshore shoal, the Alden Bank (Figures 16 and 19). The grids generated for wave transformation are shown in Figure 16. The wave transformation results revealed wave energy focusing by the shoal, which accounted for the extreme flood hazards close to the tip of Sandy Point (Figure 17). Although wave focusing is real, the degree of variation of wave heights from focusing to de-focusing areas was overestimated. This is attributed to the monochromatic (non-spectral, single period) calculation method used by RCPWAVE and extreme refraction. Therefore, a parameterized directional spectrum weighting function (Goda, 1985) was used to average the distribution of wave energy in shallow water, for waves of all applicable directions. The highest averaged breaking wave heights were selected for wave runup calculations. Wave setup due to the highest average breaking wave was calculated. The stillwater level (SWL) was increased appropriately inside the surf zone when calculating smaller waves breaking close to the shore. Simplified methods from the SPM (1984) were used for wave breaking and setup calculations. The results were quantitatively verified by comparison with flood limits resulting from a large event that occurred during the study period.

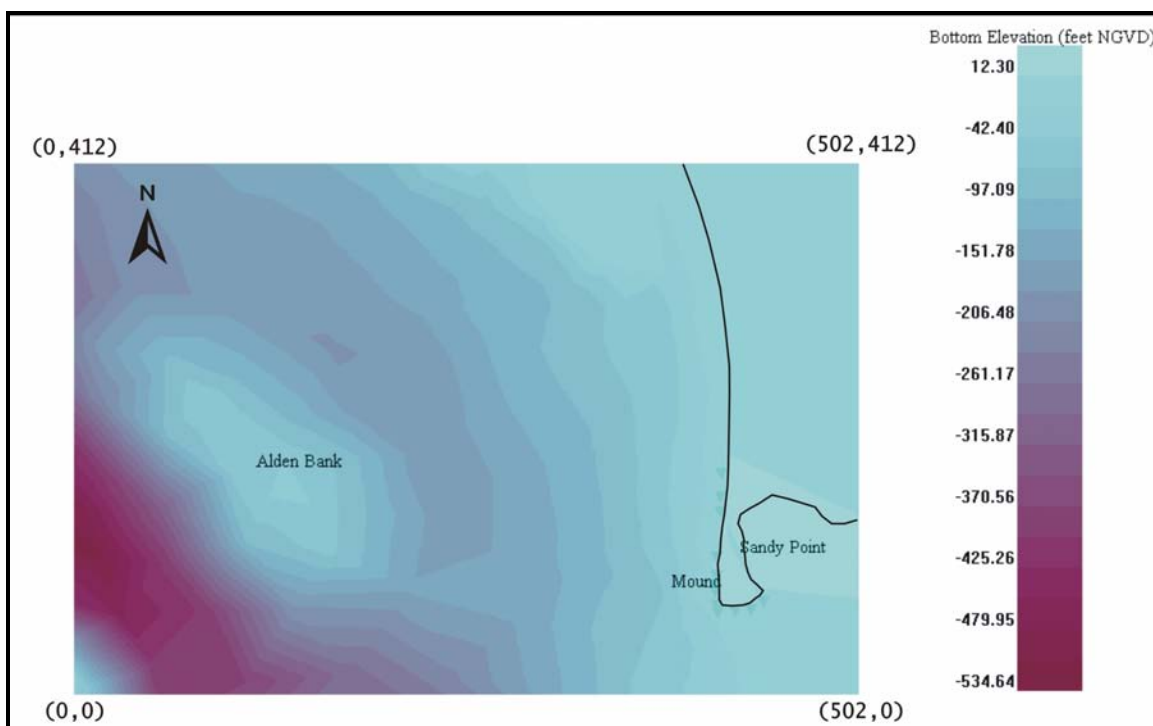
##### **Birch Bay, Whatcom County, Washington (PWA, 2002b, ongoing)**

Birch Bay is located within the unincorporated limits of Whatcom County, Washington. Principal coastal flood problems occur at Birch Bay when strong northwest or southwest winds occur during periods of low barometric pressure, resulting in high storm surge conditions. The morphology at Birch Bay is different than Sandy Point because of the bay bathymetry and the extended mudflats.

The wave analysis for Birch Bay consisted of three steps:

- ① a windwave-hindcast for three large wind and water level cases,
- ② transformation of the deepwater waves to breaking, and,
- ③ selection of wave conditions to be used for each shoreline reach.

The focus of the wave analysis was to select an appropriate range of wave conditions for each section of shore as input to the runup and overtopping analyses, including the effect of wave setup by the largest waves. The important wave characteristics were the wave periods (spectral average and range) and the wave heights, (the largest average breaking waves). The RCPWAVE computer program was used to transform deepwater waves to shallow water, and directional smoothing procedures of Goda (1985) were applied to the near breaking wave heights. The selected highest average waves for each reach was used for wave setup calculations and for wave runup and overtopping calculations. Wave dissipation over the shallow mud and sand flats was ignored. The approach used for wave transformations was similar to those used for Sandy Point.



**Figure 19. Bathymetry - Sandy Point, WA.**

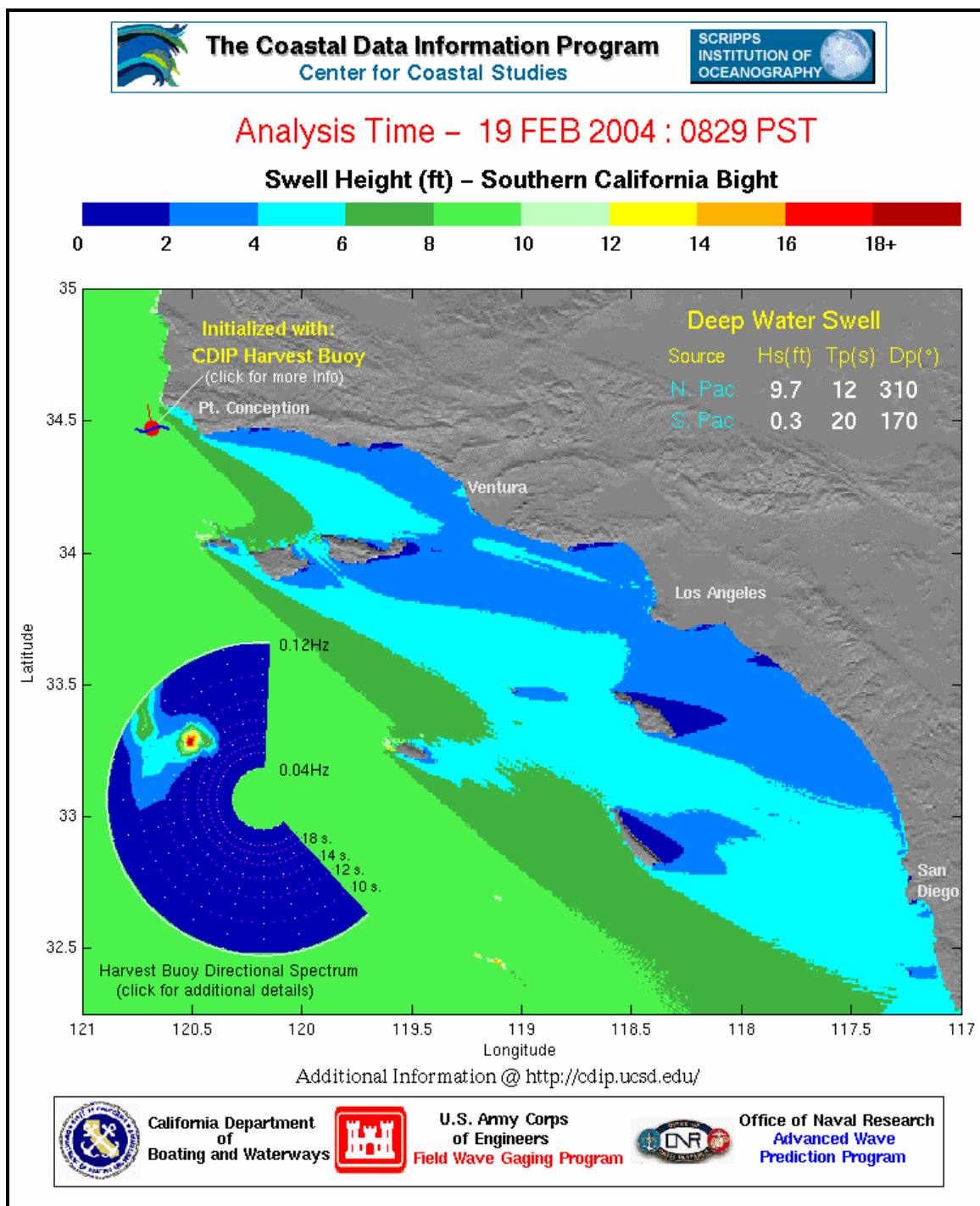


Figure 20. Example of CDIP wave predictions for Southern California.



**Bandon, Oregon (CH2M Hill, 1995)**

The City of Bandon is located at the mouth of Coquille River in the southwestern Oregon, in Coos County on the Pacific Ocean. The Flood Study was performed based on corrections to SWLs at a long-term tide station and return period wave runups based on the U.S. Army Corps of Engineers (USACE) Phase III Wave Information Studied (WIS).

Phase III WIS data (at 33 ft depth) were used in the wave analysis work. CH2M Hill compared the WIS monthly mean wave heights to the waves recorded by a Corps pressure gauge and found that WIS waves were slightly higher than the gauge records. The report mentions that wave refraction and shoaling were investigated to the extent necessary to verify that results from simplified methods were reasonable. Namely, to confirm that the selected large high waves could approach the study site, and confirm the limiting assumptions used in WIS data to transform Phase II waves (deepwater) to Phase III waves (at 33 ft depth), of uniform bottom slope and parallel, straight depth contours. Applicability of WIS Phase III results were verified by calculating nearshore wave heights using SPM (1984), Plate C-6 and ACES software. Plate C-6 shows change in wave direction and height due to refraction on slopes with straight, parallel depth contours including wave shoaling. This is an example of the simplified method usage for wave transformation.

**Northern California Coastal Flood Studies (Ott Water Engineers, 1984)**

Several sites along the northern California Coastline were included in the study. Offshore wave data were obtained from the U.S. Navy Weather Prediction Model. Storm waves (local) were calculated from the Sverdrup, Munk, and Bretschneider (SMB) method and tsunami levels were obtained from the U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi. The Wave Track model was used to obtain nearshore wave conditions due to shoaling and refraction. This model outputs wave height at breaking, and direction in the shallow water.

**San Francisco Bay and Puget Sound (Baker, 1989)**

Baker (1989) proposed an effective-fetch method for wave analysis and the SPM (1984) methods for wave refraction, shoaling and determining breaking wave locations. The breaking wave heights are input into the WHAFIS program to determine changing wave heights, as the waves progress further landward along representative shore profiles.

**Puget Sound (Coulton, 1988)**

A finite difference program called WAVES2 was used to compute refraction and shoaling of incoming deepwater, fetch limited waves as they approach the study sites. Input data include nearshore bathymetry, deepwater wave height and period, and the direction and starting location of the wave train. Wave ray location and directions are established on a two-dimensional depth grid and the output includes, refraction and shoaling coefficients, shallow water wave height and length, and the water depth to wave height ratio. Graphical output enables the refinement of the starting location of the wave rays enabling intercept of the study site transects.

**Pacific Northwest (Dorratoague, et al.1977)**

Deepwater wave conditions at the continental shelf were obtained by the SMB method, using deepwater wave charts, with wind speed, fetch, and duration as input. These waves were tracked to the shore using a wave shoaling and refraction computer program that was not specified.

**Southern California Coastal Flood Studies (Tetra Tech, 1982)**

Tetra Tech completed coastal flood studies for southern California in the 1980s. Their approach to wave transformations was documented in a report titled *Methodology for Computing Coastal Flood Statistics in Southern California*. A linear wave refraction routine was applied to transform waves from deep to shallow water for winter swell and hurricane wave sources. Approximately 183 model runs were required. Wave setup was calculated using the change in wave radiation stress using a spectral wave model. The spectral wave model uses simplified assumptions, such as linear super-position of spectral components (with consideration of maximum high-frequency energy), parameterized directional spectral shapes and wave breaking. However, the results indicate benefits relative to non-spectral approaches. Wave runup was calculated using a similar approach, with Hunt's method (similar to RUNUP 2.0) as the runup calculator. The methodology employed in this study is the most detailed and robust for open Pacific Coast conditions.

**2.1.4 Alternatives for Improvement*****Introduction***

Guidelines and Specifications for Wave Transformations need to be written, as part of the *G&S* for the Pacific Coast. *G&S* for other regions could be left as is, with the presumption that guidance on wave transformations could be derived for the *G&S* for the Pacific Coast.

Key areas that need to be included and expanded in the *G&S* are identified below in "Guidelines for Wave Transformation."

***Guidelines for Wave Transformation***

There are many methods that can be employed to successfully simulate nearshore wave characteristics in an FIS. The Study Contractor faces the important task of selecting the appropriate methods for the study. The *G&S* need to address the selection of methods based on the physical parameters that are encountered in the wave transformation process. Guidance can be provided based on the following criteria:

- ④ *Region and Site Geomorphology:* A starting point is to select methods based on the site conditions at the regional level (e.g., exposure, island sheltering, etc.) and at the site level (mild sandy slopes, or steep cobbles, etc.) ;
- ④ *Contour regularity / irregularity:* The irregularity of farshore and nearshore bathymetry has a major affect on the degree of wave refraction and diffraction that will occur, and hence the level of analysis necessary to achieve reasonable accuracy;

- ④ *Seabed steepness*: Bottom slope affects shoaling rates, refraction and diffraction, and dissipation;
- ④ *Wave parameters*: Wave period (length), steepness, height and possibly spectral shape affect wave transformations;
- ④ Information needed for subsequent analyses, such as setup and runup, may affect the methods used.
- ④ Evaluation of analysis results: Identify results that would indicate a more detailed methodology is appropriate, such as wave ray crossings. Identify methods for validating the results from model applications.

### **Description of Wave Transformations**

The *G&S* will include a description of wave transformations and pertinent factors as background for subsequent analysis. Appendix 1, Section A-1.1 provides a “feel” for the content and level of detail proposed

### **Relationship with Other Analyses Steps**

In a flood study, the final task is to determine the flood elevations and landward extent by evaluating storm surge elevations, wave runup, and overtopping during a 100-year return-period flood event. Wave transformation accounts for the changes in wave characteristics between offshore and nearshore. The nearshore waves are important as input into the runup and overtopping calculations and also to estimate the increase in stillwater elevation due to wave setup. *G&S* need to be written to identify methods that will provide adequate information for subsequent analyses. The text in Appendix 1, Section A-1.1.1, is an example of the proposed coverage and content.

The following topics would be addressed in the *G&S* to identify linkages. Cross references would be provided.

- ④ Storm Wave Characteristics
- ④ Wave Setup
- ④ Wave Runup and Overtopping
- ④ Overland Propagation (WHAFIS)
- ④ Tsunami

### **Processes**

The *G&S* should provide a description of the following processes addressed within Wave Transformations. The section A-1.1.2 in Appendix 1 provides an example of what may be written, with additional polishing, graphics, and references.

- ④ Wave Refraction and Diffraction

- ④ Wave Shoaling and Breaking
- ④ Wave Energy Dissipation, Non-Breaking
- ④ Wave Propagation Over Inundated Land Areas
- ④ Wave Generation
- ④ Wave Reflection
- ④ Nonlinear Effects

### **Regional and Geomorphic Considerations**

The *G&S* should include information to help determine the type and level of analyses to use. The *G&S* should categorize the coastal areas in terms of regional and local site conditions, and link these characterizations to appropriate methods.

### **Regional Models**

Regional wave transformation models have been developed for most of California under the CDIP, jointly funded by USACE and the State of California Department of Boating and Waterways. These models address wave refraction using a spectral back-refraction model and have been calibrated and verified using wave data collected with directional wave gauges. The models and the resulting data represent a significant potential resource for future coastal flood insurance studies. For a given site, wave height transformation coefficients can be used to transfer selected deepwater wave conditions to the nearshore. Alternatively, where available, nearshore hind cast time series can be analyzed directly. Also, where available, radiation stresses can be obtained for wave setup calculations.

As discussed in Section 2.2, regional wave modeling using the CDIP approach is recommended for the California Coast, including the proposed development of a nearshore wave climate based on transformed wave hindcast data (see also the Storm Wave Characteristics Focus Study). While expansion of the CDIP is recommended to satisfy FEMA's needs for coastal flood studies in California, interim procedures are needed both for use of CDIP data and other regional models that may become available, to address site-specific wave transformation studies, and for other locations.

Wave transformation coefficients have been developed by the CDIP for much of the California Coast. The data are generally more developed for Southern California and progressively less developed for Central and Northern California and other West Coast regions. In Southern California, very detailed and well-verified data exist. Guidance is required for the use of these data, including how to address wave growth due to winds within the domain of wave transformation modeling. For Central and Northern California, substantial data are also available but have not been verified to the same extent and require additional guidance for use.

For the Pacific Northwest (Oregon and Washington), some data are available now and more may be developed as part of the CDIP over time, and hence appropriate guidance will be needed. In

these areas, the 40-year commercially available GROW data set could serve as the deep water input and simplified wave transformation models may be appropriate.

The G&S will probably recommend the use of regional modeling where appropriate and use of output from regional modeling where available. It is recommended that the CDIP regional modeling products be used for California, to the extent appropriate, with a reference to a “user manual” or other document by FEMA and or CDIP. It is important to note that regional modeling is not an absolute need. That is, a coastal flood study could include wave transformation analyses only as required for a given community. This may be the case along a sparsely populated coast where only limited detailed coverage is needed in the foreseeable future, or where results are needed before regional modeling can be accomplished.

### ***Input and Output Parameters***

The G&S should provide details on required input and possible output for different analysis methods. The text given in Appendix 1, section A-1.2 would be augmented as the other portions of the Pacific G&S are developed. References and graphics would be added to clarify concepts. Input and output parameters appropriate for a given coastal flood study can be selected by considering the following topics.

#### **Geographic / Geomorphic**

Input data requirements should be identified along with guidance on spatial domain and boundaries, based on regional and geomorphic characteristics. Graphics and quantified criteria will be developed based on available guidance. The text given under section A-1.2.2 in Appendix A is the beginning.

#### **Wave Characteristics**

Descriptions of wave characterization appropriate for the different types and levels of wave transformation analyses will be provided in the Wave Transformations G&S to be written. The text provided in Appendix 1, section A-1.2.3, outlines the range of characterizations to be described. Text will be augmented based on available literature with references and graphics. As described in the Storm Wave Characteristics Focused Study report, a deepwater wave climate should be available for input to the wave transformations. The objective is to allow a nearshore shallow water wave climate to be developed, including directional spectra. Common representations of waves and concerns are:

- ④ Mono chromatic - basic characteristics such as significant height, peak period, and central direction.
- ④ Frequency Spectra – wave height is a function of wave frequency. Guidance on shallow water spectra is needed.
- ④ Directional Spectra – both wave height and direction are a function of wave frequency. Guidance on deepwater and especially shallow water spectra is needed.

- ④ Groups and Infra-gravity Waves – this subject requires further research.
- ④ Breaker Parameters – guidance other than a constant breaker height to breaker depth ratio of 0.78 is necessary. Adequate information exists in the literature to write this guidance, and should be used to develop recommended methods.

### **Radiation Stress**

The *G&S* will build upon published methods for regular and irregular wave setup calculation. One methodology that could be employed is described in Tetra Tech (1982). Coordination is required with Wave Setup Focused Study.

### ***Wave Refraction and Diffraction Methods***

#### **Method Selection**

A range of techniques is available for transformation of waves from deep to shallow water. The type of bathymetry is a key parameter in selecting the appropriate method. Simple techniques can be applied in the case of simple bathymetry (straight and parallel bottom contours) to account for wave shoaling and refraction. For random, directional waves it is necessary to transform all component waves in the spectrum and use superposition to obtain wave conditions in finite water depths. Model selection is subject to the key parameters of input/output terms, bathymetric features, and wave characteristics. Guidance on methods selection will be provided in the *G&S*.

#### **Simplified Methods**

The simple techniques can be applied in the case of simple bathymetry (straight and parallel bottom contours).

#### **Refraction by Snell's Law**

The path traced by the wave orthogonal as a wave crest propagates onshore is called a wave ray. Simple wave propagation problems can readily be visualized by construction of wave rays manually or by graphical techniques. In the case of straight and parallel contours, and for monochromatic waves the Snell's law ( $\sin \theta/C = \text{constant}$ ) can be applied to draw the path of the wave ray.

In addition, the wave height variation can be estimated by considering two closely spaced wave rays. Assuming no transfer of energy takes place across the wave ray boundary, wave height at any location along the wave ray is given in terms of the offshore wave height, shoaling, and refraction coefficients. These coefficients can be calculated in terms of the water depth and the orthogonal distance between wave rays at the interested location. The CEM provides solution nomograms (Figure II-3-6) which are also automated in the ACES program.

#### **Linear Refraction**

If the bathymetry has variations along the shore, then the simple Snell's law approach cannot be used, rather a 2-D approach must be used. One common method is wave ray tracing. The ray approach for wave refraction has had problems caused by wave ray crossing, at which point wave height becomes infinite. These problems are caused by the fact that each ray is traced independently of the other rays and there is no refraction or breaking. Some numerical methods overcome this problem by artificial smoothing techniques. Results need to be checked for signs of wave ray crossings (caustics) and in that event a simple refraction-diffraction model is more appropriate.

### **Graphical Diffraction**

Graphical Diffraction methods are available in SPM (1984); Goda (1985); and CEM (2003). Methods include monochromatic and simplified spectral approaches. These methods can be applied relatively easily and are reliable for most cases. A description of application of Goda's methods using the  $s$  factor (directional spread) will be included.

### **Refraction / Diffraction Models**

The following text provides a summary of contemporary wave refraction / diffraction analysis methods. Some are approved for use by FEMA and some are not. As part of the *G&S*, it is recommended that those not approved be applied to a test case to identify the differences in results, and that further literature review be accomplished to gauge the accuracy of the models. Based on the results, recommendations for approval and guidance on application will be developed and included in the *G&S*.

When waves propagate into water depth that is less than about one-half of the wave length, the direction of wave propagation gradually changes. These changes can cause energy concentrations or spreading depending on the bathymetry. Sometimes when diffraction is not considered in the wave transformation method, wave heights can increase to unrealistic elevations. In reality, wave heights are limited by breaking either because of depth or steepness constraints. Diffraction effects (the spread of energy along the wave crest) can also, reduce locally high wave heights and reduce the tendency for local wave breaking. For more complex bathymetry with shoals, islands or other major geological features, both refraction and diffraction need to be modeled.

A series of programs are available that deal with diffraction, in addition to modeling wave refraction and shoaling. A brief discussion of these models is available in CEM, 2003. The CEM lists the computer programs RCPWAVE (Ebersole, 1985; Ebersole, Cialone, and Prater, 1986), REFDIF1 (Kirby and Dalrymple, 1991) for monochromatic wave refraction, as available and in use by USACE but cautions the users to apply these models within the limits of their use.

FEMA pre-approved RCPWAVE is a steady-state linear wave model based on the mild-slope equation and includes wave breaking. The program is limited to open coast areas without structures or islands etc. A comparison of wave refraction and diffraction models was performed by Maa et al., (2000). Wave transformations were estimated across the elliptic shoal and

compared with experiments carried out by Berkhoff et al., (1982).RCPWAVE performed poorly in simulating the wave height distribution and wave direction. Therefore this model may be inadequate in modeling areas with sand shoals and other complex bathymetry.

The CDIP has applied a linear, spectral back-refraction model along the California Coast. Detailed application of this model has included verification using directional wave data collected at deep and shallow water wave gauges. Very good results have been obtained.

REFDIF1 is a steady-state model based on the parabolic approximation solution to the mild-slope equation. Although this model is not pre-approved by FEMA, it is known to provide more accurate wave heights than from the RCPWAVE model in certain bathymetric situations (Maa et al., 2000). However, if the study domain has complicated geography and/or bathymetry, or if there is a strong wave diffraction and /or reflection, elliptic mild slope models are appropriate.

MIKE 21 EMS is based on the numerical solution of the Elliptic Mild-Slope equation formulated by Berkhoff (1972) and is capable of reproducing the combined effects of shoaling, refraction, diffraction, and back-scattering. Energy dissipation from wave breaking and bed friction, is included along with partial reflection and transmission through pier structures and breakwaters. MIKE 21 EMS can be used to study wave dynamics in smaller coastal areas and in harbors. The Module is particularly useful for the detection of harbor resonance and seiching due to, for instance, long-period swell.

The extended mild-slope models may be more appropriate for steep and rapidly varying bathymetry. These models are computationally expensive and therefore only applicable to smaller areas.

### **Spectral Refraction Models**

#### **STWAVE**

Developed by the USACE Waterways Experiment Station (WES), STWAVE is a steady state, spectral wave transformation model, based on the wave action balance equation. A wave action approach can handle a current correctly, where as an energy spectrum approach cannot. STWAVE is able to simulate wave refraction and shoaling induced by changes in bathymetry and by wave interactions with currents. The model includes wave breaking based on water depth and wave steepness. Other features of STWAVE include wind induced wave growth, and influences of wave white capping on the distribution and dissipation of energy in the wave spectrum.

STWAVE is most applicable to wave transformation problems where the following assumptions can be made:

- ④ Mild bottom slope and negligible wave reflection.



- ④ Spatially homogeneous offshore wave conditions with steady state wave, current, and wind conditions.
- ④ Linear wave refraction and shoaling with negligible effects from bottom friction

Wave energy dissipation due to bottom friction and viscous damping effects may occur as waves propagate over shallow areas. Dissipation is not included in the standard version of STWAVE. However, a version that addresses dissipation is being used by the USACE (personal communication, Resio, at Workshop 2) and other versions have been developed and used by others with good results.

### SWAN

The numerical wave transformation model SWAN was developed at the Delft University of Technology, Delft, Netherlands. SWAN and STWAVE have many similarities. Like STWAVE, the formulation of SWAN is based on the spectral wave action balance equation. This model currently has many well-developed features, which provide the user with many execution options. These features range from purely convenient options that allow several different formats for input and output data, to options that allow control of fundamental physical processes in the model, for example wave generation, dissipation, and interaction. Linear wave refraction and shoaling are included in the model. Some differences from STWAVE are:

- ④ Input wave conditions can be varied spatially along open boundary, and wind, water level elevation, and current inputs can be varied spatially over the entire computational domain.
- ④ Simulations may be steady state or dynamic. SWAN has the ability to compute a time varying solution, rather than just a series of steady state solutions.
- ④ Users of SWAN must consider the following model assumptions in a specific application:
- ④ SWAN does not model wave diffraction or reflection, and therefore is most useful in applications where accuracy of the computed wave field is not required in the immediate vicinity of obstacles.
- ④ Mild bottom slope with negligible wave reflection

### REF/DIF S

REF/DIF S was developed at the Center for Applied Coastal Research, at the University of Delaware. This spectral wave transformation model is a further development of the REF/DIF 1 model, which solves for monochromatic waves only. REF/DIF uses the parabolic form of the mild-slope equation, and the complex amplitude of each separate wave component. Because the mild-slope form of the governing equation is used, the model includes the effects of wave diffraction, unlike STWAVE and SWAN.

### **Alternatives to Spectral Models**

If the wave-wave interactions can be ignored, a simplified method of “energy transfer functions” can be used to construct the nearshore wave energy spectrum at a specified location for any given off-shore spectrum. The procedure involves calculating the response matrix using a linear refraction-diffraction model with a unit incident wave height (or amplitude) for the range of wave frequencies and directions. The transfer functions need to be calculated only once since the refraction-diffraction model is linear. The response to any desired incident directional spectrum is then constructed by appropriately weighting each discrete component. This method has been used by O’Reilly and Guza (1991, 1993) for wave predictions in an analytical circular shoal configuration and at Southern California locations. They used the spectral refraction model of LeMehaute and Wang, (1982) and a spectral refraction-diffraction model (linear version of the higher order PEM derived by Kirby 1986a, Kirby 1986b, and Kirby and Dalrymple, 1986). The CDIP has applied a linear, spectral back-refraction model along the California Coast. Detailed application of this model has included verification using directional wave data collected at deep and shallow water wave gauges. Very good results have been obtained. See the write-up for Topic 7: California Regional Wave Transformation Models for a more complete description.

### **Use of Directional Spreading Functions**

Wave directional spectra are not available as output from many of the above discussed models. In such a situation, if wave directional spectra are required as input to another model or for smoothing out the artificial wave energy focusing effects, an approximate method would be to use directional spreading functions. This is a semi-parametric approach for generating directional wave spectra. Goda (1985) discusses a couple of functions including the Mitsuyasu type (Mitsuyasu et al., 1975).

### **Wave Shoaling and Breaking**

#### **Method Selection**

Adequate information exists in the literature to complete the following *G&S* for Wave Shoaling and Breaking. Method selection is primarily based on wave characteristics and morphology.

#### **Linear Shoaling**

Waves slow down upon entering shoaling water and consequently wave height increases and sometimes decreases depending on group/phase velocity relations. The change in wave height due only to the change in wave group velocity is referred to as shoaling. Linear shoaling assumes the waves are of small amplitude and therefore the linear wave theory can be used to derive the shoaling coefficient ( $K_s = H/H_o$ ) by equating the offshore wave power to the wave power at any nearshore location (before breaking). When other processes such as wave refraction, diffraction, and dissipation are involved in the transformation process, equivalent deepwater wave height is used instead of the deepwater wave height in the shoaling equation ( $K_s = H/H_o'$ )

#### **Non-Linear Shoaling**

As waves approach very shallow water, several wave lengths seaward of breaking, shoaling becomes highly non-linear and the linear shoaling coefficient may significantly under predict the

wave height, especially for long waves in shallow water. Non-linear shoaling coefficients are available in several publications, which relate shoaling coefficients to parameters of wave steepness, relative depth and beach slopes (Goda, 1985, SPM and others).

### **Breaking Indices**

In shallow water, breaking is limited by water depth and the point of breaking is influenced by wave steepness and beach slope. Simple wave breaking indices for regular and irregular waves are discussed in the CEM (2003), Part II-4.

A breaking wave model (series of equations) that operates on a site-specific nearshore profile (one-dimensional) is needed to calculate wave setup, as described in the Focused Study report for Setup (see in particular Topics 44 through 48, Wave Setup). The breaking wave model should be adequate to calculate wave radiation stress through the surf zone for irregular wave conditions. The wave radiation stress is used to calculate wave setup. Guidance is also needed for the dynamic component of wave setup, using available information. The breaking wave model shall be applicable for the Gulf, Atlantic and Pacific Coasts, including sheltered waters, but is critical for the Pacific Coast.

### **Spectral Transformations**

Vincent and Briggs (1989) showed by their lab experiments that wave transformation over a shoal is sensitive to the shape of the incident wave directional spectrum and differ significantly from a single unidirectional wave. Therefore, the approach of defining a single wave height to represent the offshore spectrum and using this wave height in the unidirectional wave transformation models does not prove to be satisfactory when shoals and complex bathymetries exist.

Transformation of incident wave frequency-directional spectra can be achieved by combining multiple model runs, each for a single frequency and direction (Izumiya and Horikawa, 1987; Panchang et al., 1990). These spectral models do not explicitly predict the directional spectrum, but have been used to estimate the directionally integrated energy to determine the wave height.

### ***Wave Energy Dissipation, Non-Breaking***

#### **Method Selection**

Method selection will be based on bed and wave conditions and or region and other site conditions. To the extent practicable, coefficients will be provided for the described methods based on published data. Where data are not adequate to calculate wave dissipation, calibration will be recommended.

#### **Friction**

Friction related energy dissipation occurs mainly in shallow water (Tubman and Suhayda, 1976). The friction effect varies with the type of bottom material and also as a function of wave parameters, relative depth, propagation distance etc. Guidelines for selection of criteria are in Section 2.3

### **Viscous Bottom**

Unlike friction related dissipation, which usually occurs in shallow water, soft (flexible) bottom dissipation can also cause significant wave attenuation in intermediate water depths.

Suhayda (1984) documents the use of a numerical model to develop wave crest elevation attenuation coefficients by simulating the effects of wave generation by wind, shoaling, and dissipation due to breaking, bottom friction, and soft muds during extreme hurricanes. The author models wave height/energy to change exponentially with distance along the wave travel direction. To compute its effects on wave dissipation, he models the soft muddy bottom as a visco-elastic medium, in accordance with the MacPherson (1980) model. The results summarize wave height to water depth ratios in the range of 0.42 to 0.78 for the 21 transects, that he used in this study. Guidelines for selection of criteria are addressed in Section 2.3.

### **Marsh Vegetation**

G&S Appendix D (2002) considers marsh vegetation (pg. D-72 to D-80) under description of the WHAFIS 3.0 model. Eight parameters are used to describe the dissipation properties. This procedure was specifically developed for the Gulf and Atlantic Coasts. Applicability of these guidelines for the Pacific Coast wetland areas need to be explored. Also see the section “Method for Wave Attenuation in Pacific Marsh Conditions” under Topic 9.

### ***Wave Propagation over Inundated Land Areas***

This condition is commonly observed in the Atlantic and Gulf Coasts, and WHAFIS 3.0 approved by FEMA is applied in the present FIS. Although not common, overland wave propagation can be significant in marshes surrounding bays (e.g., San Francisco Bay). The changes to wind characterization may be necessary to use the WHAFIS model for the Pacific conditions.

Continuation of the two-dimensional wave transformation models into the inundated regions may be the next step of improvement. However, application of two-dimensional models may be constrained by data availability. The G&S will address use of WHAFIS for Pacific Coast FIS. Extensive G&S exist for application of WHAFIS to the Gulf and Atlantic Coast FIS, with additional guidance in Section 4.1.

### **2.1.5 Recommendations**

Recommended improvements are:

1. Write G&S for Wave Transformations as a section within the G&S for the Pacific Coast;
2. Include several focused studies to demonstrate the Wave Transformations G&S;
3. Use available publications to identify a range of methods from simplified to more detailed so that study managers and contractors have a range of “tools” to select from, to provide defensible and cost beneficial studies;

4. Develop criteria for level of analysis required based on region, site geomorphology, wave characteristics, available input data and regional models, and required output data. These criteria will guide the procedures used for refraction, diffraction, shoaling, and dissipation. Include development of guidelines for spatial coverage and wave parameters, and address use of regional models such as CDIP;
5. Research available literature to adequately define wave groups, infragravity waves, shallow water spectra, and radiation stress formulations for input into wave setup and runup calculations;
6. Evaluate adequacy of linear wave transformation models and needs to supplement these models. Place emphasis on representation of infragravity waves;
7. Evaluate wave transformation models using available case studies or a selected data set, in order to compare results. Review available literature and guidance on the range of applicability of contemporary computer models. Recommend models for inclusion on the FEMA pre-approved coastal model list, and provide guidance on their application to the FEMA FIS.
8. Incorporate applicable sections of existing *G&S* for other geographical areas that cover the overland propagation and wave energy dissipation topics.

### **2.1.6 Preliminary Time Estimates for Preliminary Guideline Preparation**

Table 2 summarizes the preliminary estimates of time required for Critical Topic 8. These time estimates do not include responding to comments and suggestions associated with the review of the Guideline improvements.

### **2.1.7 Related Available and Important Topics**

Wave Characteristics Focus Study Topic 4: Swell and seas originating in the open ocean can penetrate coastal inlets, and may control coastal flood risk near the mouths of sheltered waters.

Wave Transformations Focus Study Topic 9: Bottom friction factor used for very shallow waters may affect wind wave generation.

Wave Transformations Focus Study Topic 10: WHAFIS is included in Wave Transformations.

Storm Surge and wind setup may affect depths to the extent that wind wave generation is affected.

## **2.2 TOPIC 7: CALIFORNIA REGIONAL TRANSFORMATION MODELS**

CDIP regional modeling can now provide transformation coefficients for most locations in the Southern California bight and some locations in Central California.

### 2.2.1 Description of the Topic and Suggested Improvement

The CDIP at Scripps Institution of Oceanography maintains a database of linear, spectral refraction-diffraction transformation coefficients for shallow coastal areas from the U.S.-Mexico border to Point Arena north of San Francisco (O'Reilly and Guza, 1991). The database nominally extends into depths as shallow as 10m with alongshore spacing of approximately 200m. The wave model coefficients are for waves with periods longer than 8 seconds (frequencies less than or equal to 0.12 Hz) and are primarily used to produce the swell wave height maps on the CDIP website. Figure 20 is an example of the CDIP product for the southern California Coast.

The spectral refraction-diffraction model uses a parabolic approximation to the mild slope equation and is computationally well suited for making wave predictions across large regions like the Southern California Bight. However, waves refracting around islands and over submarine canyons can propagate at high angles to the x-axis of the model bathymetry grid. This violates the small angle approximation in the underlying parabolic equations, resulting in numerical noise that makes it difficult to extract directional wave information from the model output. In addition, anomalously large transformation coefficients can occur near extreme bathymetry owing to the high wave angle propagation errors. Because of the model limitations, only nearshore frequency spectra between 0.04–0.12Hz (no direction information) can be estimated from input deep water frequency-directional spectrum, and care must be taken to ensure that numerical errors have not corrupted any of the coefficients if they are going to be used for FEMA Coastal FIS. As a result, CDIP does not widely distribute specific data from this transformation coefficient database without careful QC by the CDIP staff.

Because of the numerical limitations of the spectral refraction-diffraction model for nearshore coastal engineering and scientific studies, CDIP is now implementing a simpler spectral refraction modeling method to derive regional, alongcoast wave predictions just seaward of the surfzone. This technique has recently been applied to the Los Angeles County coastline, as part of the region's USACE Storm and Tidal Waves Study, with good results. See also the discussion in the Introduction to this report and Figure 9 for an application in northern California at Bolinas Bay (PWA, 1999).

### 2.2.2 Description of Procedures in the Existing Guidelines

There are no *G&S* procedures for the Pacific Coast and regional model use is not covered in FEMA existing *G&S*.

### 2.2.3 Application of Existing Guidelines to Topic—History and/or Implications for NFIP

There are no *G&S* procedures for the Pacific Coast and regional model use is not covered in FEMA existing *G&S*.

## 2.2.4 Alternatives for Improvement

### ***Basic Methodology***

A linear, spectral refraction model will be used to transform deep water hindcasts of extreme storm wave spectra to nearshore wave spectra at locations just outside the surf zone along the entire U.S. West Coast. The resulting nearshore database will be validated against wave measurements on a regional basis, and made available to FEMA contractors as an approved source of incident wave information for coastal hazard modeling and mapping.

### ***The Spectral Refraction Model***

The transformation of deep ocean directional wave spectra to the nearshore will be performed using a spectral wave refraction model (Longuet-Higgins, 1957; LeMehaute and Wang, 1982; O'Reilly and Guza, 1991). The model accounts for island blocking, wave refraction, and wave shoaling. Spectral refraction back-refracts wave rays from the site of interest to unsheltered deep water over the entire range of possible wave frequencies and wave directions. The retained starting and ending ray angles are then used to map a deep water directional spectrum to a sheltered or shallow water spectrum at the back-refraction site. The resulting solutions are more realistic than those obtained using an assumption of unidirectional, monochromatic deep ocean waves.

The spectral model is linear; therefore the model calculation needs to only be performed once for a particular location and sea level elevation to obtain linear transformation coefficients between the offshore and nearshore wave spectra. As a result, the creation of a nearshore wave spectra database for the entire U.S. is feasible, and future improvements to all or parts of the database should be straightforward. The spectral refraction model has undergone extensive validation in Southern California (O'Reilly and Guza, 1993a, O'Reilly et al., 1993b) and is well suited for the U.S. West Coast, where the continental shelf is relatively steep and narrow and bottom dissipation effects are small. Recent field validation of the spectral refraction model in the vicinity of a submarine canyon (Ray, 2003) demonstrated that diffraction effects are small over even extreme natural bathymetries, and spectral refraction is an adequate methodology in these situations.

### ***Model Application and Validation on the U.S. West Coast***

From a wave modeling perspective, the U.S. West Coast can be divided into two distinct regions:

1. Southern California, from the U.S.-Mexico border to Point Conception.
2. The open coast from Point Conception north to the U.S.-Canada border.

The Southern California region is partially sheltered from deep ocean waves by islands, resulting in a local wind generated sea wave climate that must be considered separately from incident swell waves in some areas. In addition, the coastal wave climate at the east end of the Santa

Barbara Channel, approximately between the cities of Ventura and Santa Barbara, is significantly affected by the reflection of northwest swell off the coastal cliffs on the north side of Santa Cruz Island (O'Reilly et al., 1999). The spectral refraction model has been tested extensively in Southern California and a large database of wave measurements exist to assist in the development and validation of a FEMA extreme wave database for this region.

North of Point Conception, owing to a lack of islands, the transformation of deep water waves to the coast is more straightforward. However, far fewer directional wave measurements have been made outside Southern California, particularly north of San Francisco, so the model has undergone little validation along most of the U.S. West Coast. Based on CDIP's experience with the model in Southern California, and an application of the model to a site at the entrance of Bolinas Lagoon near San Francisco by Philip Williams and Associates, it is anticipated that the spectral refraction model will perform well north of Point Conception. Nevertheless, new directional wave measurements specifically for model validation in Oregon and Washington are needed.

### ***Wave Model Information Needs***

The primary boundary condition information needed to develop the nearshore wave model database is bathymetry and hindcasts of extreme deep water wave spectra.

#### **Bathymetry**

Adequate bathymetric data is believed to exist for the West Coast. CDIP currently maintains a bathymetric wave model grid for the California Coast. In addition, the National Geological Data Center (NGDC) has recently released high resolution bathymetric grids for the West Coast, and maintains a database of digital bathymetric survey data for this region.

Combining the various data sets into an optimal wave model bathymetry grid for Oregon and Washington will be required, but is not foreseen as a significant hurdle in the development of the nearshore wave database.

#### **Deep Water Spectra**

Several deep water hindcast databases currently exist or are being developed in the public and private sector. The USACE has been revising its Wave Information Study (WIS) database for the Pacific Coast, and several private companies (e.g., Oceanweather) have developed similar databases. FEMA will need to acquire an extreme deep water spectra database, nominally with 1 to 2 degree latitude spacing up the West Coast, for use as an offshore boundary for the wave model. Extreme event hindcasts, and resulting nearshore model predictions for approximately 1980 to the present, will be validated against deep water wave data collected by CDIP and NOAA where possible. As mentioned previously, significantly more wave data are available in California (and Southern California in particular) for this purpose.



### **Nearshore Database Limitations**

Linear spectral refraction modeling of wave spectra makes several important assumptions and has known limitations.

- ④ The model is a “propagation only” model, and assumes that additional wind input to the spectrum is small from the deep water boundary to the nearshore site. In Southern California, this means incident swell from the open Pacific and seas generated within the islands by local winds must be treated separately. North of Pt. Conception, this assumption needs further validation, particularly in Oregon and Washington where the continental shelf is widest and additional wind input to the spectrum across the shelf may be large enough to measure.
- ④ The model assumes currents are weak and bottom dissipation effects are small. Validation of the model in Southern California has confirmed that these assumptions are reasonable. However, the model may not be appropriate for a nearshore site directly seaward of an inlet where tidal currents are strong.
- ④ The model assumes wave diffraction effects are weak. This assumption has also been confirmed through inter-model comparisons in Southern California. An exception would be very close (1 wavelength) to a coastal structure like a jetty or groin. However, it is anticipated that the nearshore model prediction sites will be seaward of any coastal structures in order to remain outside the surf zone when modeling large wave events.
- ④ The model assumes the bathymetry seaward of the nearshore model sites does not change. CDIP’s experience in Southern California, comparing old bathymetric surveys to recent ones, suggests this is a reasonable assumption. In addition, spectral wave model results are generally not sensitive to small changes in the model bathymetry, or tidal elevation, in water depths greater than 10m. Nevertheless, the nearshore database may require periodic updating in some coastal areas if local knowledge suggests that significant bathymetric changes occur seaward of the nearshore model site (e.g., near river mouths or large inlets). An example of this would be the San Francisco Bar, which has not been surveyed since the 1950s (Battalio and Trivedi, 1996).
- ④ Nonlinear effects are not included. Specifically, the effects that generate infragravity (IG) waves as a result of the interaction of two linear spectral components are not taken into consideration seaward of the inshore location of the wave transformation. Although this interaction is known to be strongest in shallower water, it is also known to be strong on the Pacific Coast and there may be substantial contributions to the growth of the IG portion of the spectrum seaward of the landward point of linear wave transformation.

### **Required Tasks for Wave Database Development and Validation (Long-term)**

- ④ Task 1: Literature and Data Search.

- ✦ Gather all the literature (reviewed and gray) on the application of the spectral refraction model on the West Coast.
  - ✦ Locate all the sources of digital bathymetric data for the West Coast.
  - ✦ Locate all potential sources of deep water wave hindcast spectra for the West Coast.
- 📍 Task 2: Model and Field Measurement Validation Planning (Based on what we learn from Task 1).
- ✦ Decide on one or more hindcast data sets to acquire/use.
  - ✦ Decide on what bathymetric data sets to use to make the official FEMA West Coast bathymetric grid.
  - ✦ Decide where to make additional wave measurements. The goal is for FEMA to have a comprehensive set of studies/references to support the use of the final database.
- 📍 Task 3: Model Development and Field Measurements.
- ✦ Deploy additional wave buoys to begin acquiring optimal validation data.
  - ✦ Assemble U.S. West Coast wave model bathymetry grid.
  - ✦ Make initial model runs at various locations on the West Coast with simulated high energy wave spectra. Use these to decide how to select locations of nearshore sites (water depths, and alongshore spacing) and where to apply special regional modeling needs (local seas inside islands, island wave reflection).
- 📍 Task 4: Field Validation of Deep Water Hindcasts and Nearshore Predictions.
- ✦ Use all the existing data, both historical and newly acquired, to validate the deep water hindcast and nearshore model accuracy during large wave events. Modify modeling methodology in some areas if necessary. Document findings with appropriate reports and/or peer reviewed papers.
- 📍 Task 5: Evaluate need to include nonlinear effects in some manner.
- 📍 Task 6: Create FEMA Nearshore Wave Spectra Database.
- ✦ Generate the database using field validated hindcast data and wave transformation code.
  - ✦ Prepare a simple instruction manual on the use of the database.

- ✦ Install the data and the manual on a secure Internet site.

### **Required Tasks for Interim and Short Term**

See Short-Term (Phase 2) Recommendations, in the following section.

## **2.2.5 Recommendations**

### **Long-Term Recommendations**

1. A substantial amount of nearshore data exists to validate the magnitude of changes to the high frequency part of the spectrum during extreme events. A study of these data should be undertaken and the errors evaluated to determine if they are significant. This may require a subregional approach (i.e., wind effects in the Santa Barbara Channel may differ significantly from those off San Diego County.) If the potential error is small, then Approach (a) should be used in establishing the standard database of nearshore waves in Southern California. Approach (a) is to assume no wind-induced change in the spectrum. Note that this would result in a uniform approach being taken for the entire West Coast wave database because the broad shelf problem does not exist elsewhere on this coast. If the error is too large to be ignored, then a separate database of measured variations in the wind wave spectra should be undertaken. This will allow for the correction to be treated as an independent variable additive to the modeled nearshore spectrum.
2. Adopt regional wave modeling for the Southern California Coast.
3. Expand CDIP for the California Coast of the US:
  - a. Use regional models to develop near shore directional spectral wave climate,
  - b. Acquire and process bathymetry,
  - c. Acquire hindcast offshore wave database,
  - d. Verify hindcast by comparison with recent (after 1980 buoy deployment) buoy data, and
  - e. Verify nearshore wave spectra with wave measurements.
4. Evaluate any limitations due to the linearity of the transformation models.
5. Consider expanding regional wave modeling for Washington and Oregon Coasts using CDIP or other programs (e.g., WIS) at the appropriate time and depending on the need, recognizing that regional wave models are more logical in densely populated areas. Individual studies may be performed in sparsely located communities (see Topic 8).

**Short-Term (Phase 2) Recommendations**

1. Develop Interim Guidance for: (This work is proposed as critical for the Study Topic 8 Wave Transformations, but is included here for completeness.)
  - a. Southern California: Develop *G&S* for use of CDIP information for this region where the CDIP program is the most mature and wind wave growth may be important within the modeling domain.
  - b. Central California: Develop *G&S* for use of CDIP data for this region where the CDIP program is less mature;
  - c. Northern California: Develop *G&S* for use of CDIP data for this region where the CDIP program is the least mature.
2. Use existing CDIP bathymetry grids for the California Coast.
3. Use an alongshore spacing of 400m on the 20m depth contour for the entire coastline.
4. Create 2 sets of transformation coefficients in Southern California. One set for swell (waves modeled from outside the islands to the 20m contour) and a second set for seas (waves modeled from the mainland shelf break, inside the islands, to the 20m contour).
5. In each of 3 regions (Southern California, Central California, Northern California) demonstrate the models capability for predicting nearshore wave conditions during large winter storms using existing buoy data (very limited data available for Northern California).
6. Create a database on the CDIP server that is accessible to FEMA contractors. Provide a user's manual, and simple Fortran and MATLAB code, to assist contractors in using the model coefficients with their hindcast wave spectra.

**Limitations of the short-term plan:**

- ④ The short-term modeling effort will not address known underprediction of wave heights between Santa Barbara and Ventura owing to reflection of NW swells from Santa Cruz Island.
- ④ Recent bathymetric survey data for some areas of California will not be included in the fast-track product.
- ④ The 400m spacing of alongshore points may be somewhat coarse in areas with extreme nearshore bathymetry (e.g., around submarine canyon heads).
- ④ It is assumed that FEMA will provide CDIP with at least minimal funding to maintain the database after the 6-month contract period.

## 2.2.6 Preliminary Time Estimates for Preliminary Guideline Preparation

Table 2 summarizes the preliminary estimates of time required for Critical Topic 8. These time estimates do not include responding to comments and suggestions associated with the review of the Guideline improvements.

## 2.2.7 Related Available and Important Topics

Not Applicable.

## 2.3 TOPIC 9: PROPAGATION OVER DISSIPATIVE BOTTOMS

### 2.3.1 Description of the Topic and Suggested Improvement

The sea floor starts to influence the heights and directions of waves when they enter regions with water depths less than half a wavelength. Common mechanisms for such change include refraction, reflection, shoaling, breaking, diffraction, and bottom dissipation.

This section addresses the effects of bottom dissipation on wave transformation. The nature of the bottom (roughness, porosity, rigidity, etc.) and its interaction with surface waves causes wave damping and changes in wave kinematics. Appreciable wave height attenuation may occur if the wave propagation distance is long or if the bottom is not very rigid.

Ignoring bottom dissipation mechanisms can lead to overestimated nearshore wave heights, particularly when the transformation distances are great or when the bottom contains soft muds. In turn, the overestimated wave heights may lead to overestimates of flood hazard risk for shorefront development.

*G&S* needs to address this topic, because wave energy dissipation is a significant part of wave transformation in the Gulf of Mexico and for beaches with similar or other local geomorphologic conditions in the Atlantic and Pacific regions.

### 2.3.2 Description of Procedures in the Existing Guidelines

Presently there is little or no guidance on wave dissipation mechanisms for wave transformation analysis in FEMA guidelines. For overland wave propagation, WHAFIS model includes wave dissipation from marsh vegetation (*G&S*, Appendix D, 2002). However, wave dissipation from muddy bottoms has not been included in WHAFIS.

### 2.3.3 Application of Existing Guidelines to Topic–History and/or Implications for NFIP

Significant wave dissipation and damping can occur before waves travel overland during extreme wave events. The guidance in the current *G&S* are inadequate, given different site characteristics encountered in FIS.

### 2.3.4 Alternatives for Improvement

#### Overview

Typical wave propagation analysis involves transforming hindcast or buoy data in deep water to the nearshore through numerical models that simulate generation, shoaling, refraction, diffraction, and breaking; bottom dissipation effects are not routinely considered.

A literature review on the above topic demonstrates that bottom dissipation mechanisms can lead to significant wave height attenuation in the nearshore. Consideration of such dissipation mechanisms can help increase the accuracy of predicting nearshore wave heights. In the *G&S* development, guidance shall be provided for when and where dissipation can become significant to consider in FIS. The guidance can be based on bottom type, propagation distance, relative depth (depth/wave length or depth/wave height), wave steepness, wave height and length, and shall identify what methods to use for each bottom type.

#### Technical Background

##### Existing Procedures

Bottom dissipation mechanisms can be mathematically expressed as a negative forcing term in the conservation of wave energy equation as follows.

$$\frac{\partial E}{\partial t} + \nabla_h \cdot (E \overline{C_G}) = -\varepsilon \quad (1)$$

where  $E$  is the wave energy,  $C_G$  the wave group velocity,  $\varepsilon$  the energy dissipation rate per unit area, and  $t$  time.  $\nabla_h$  is the horizontal gradient operator. For steady state, longshore uniform conditions, Equation (1) reduces to

$$\frac{dEC_G}{dx} = -\varepsilon \quad (2)$$

where  $x$  is the direction of wave propagation. Dissipation can occur at the surface, at the bottom, and due to wave breaking. One may consider  $\varepsilon$  as the sum of energy dissipations due to wave breaking and bottom effects. Dissipation due to bottom effects dominates seaward of the break point; dissipation due to breaking dominates landward of the break point. The following sections describe commonly accepted relations for dissipation due to rough, porous, and mud bottoms and vegetated marshes.

#### Rough Bottom

Dean and Dalrymple (1991) express energy dissipation due to bottom friction as

$$\varepsilon_F = \frac{\rho f}{48\pi} \left( \frac{H\sigma}{\sinh kh} \right)^3 \quad (3)$$

where  $\rho$  is the density of water,  $f$  the friction factor,  $H$  the wave height,  $\sigma$  the angular wave frequency,  $k$  the wave number, and  $h$  the water depth. The friction factor is a function of the Reynolds number of the flow at the bottom and relative bed roughness (a ratio of the excursion of the water particles at the bottom to the bottom roughness). Typical friction factor values lie in the range  $10^{-3}$  to 100. An alternate form of Equation 3 used by some researchers defines a modified friction factor  $c_f$  equal to  $f/8$ .

### Porous Bottom

Dean and Dalrymple (1991) express energy dissipation due to bottom percolation as

$$\varepsilon_p = \frac{\rho g^2 H^2 K k}{8\nu \cosh^2 kh} \quad (4)$$

where  $g$  is the acceleration due to gravity,  $K$  is the permeability constant,  $\nu$  the kinematic viscosity of water. Typical values for  $K$  for sand are in the range of  $10^{-9}$  to  $10^{-12}$  m<sup>2</sup>.

### Viscous Bottom

Dean and Dalrymple (1991) express energy dissipation due to a viscous bottom as

$$\varepsilon_v = \frac{\rho_2 \sqrt{\sigma \nu_2} H^2}{16\sigma^2} e^{2kh} (\sigma^2 - gk)^2 \quad (5)$$

where  $\rho_2$  and  $\nu_2$  are the density and kinematic viscosity of the mud layer,  $H$  the wave height of the surface wave. The angular wave frequency is

$$\sigma^2 = \frac{gk(\frac{\rho_2}{\rho} - 1) \tanh kh}{\frac{\rho_2}{\rho} + \tanh kh} \quad \text{and} \quad \sigma^2 = gk \quad (6)$$

in which  $\rho$  is the density of the water.

### Other Formulations

Other formulations for non-rigid beds are also possible. Lee (1995) provides a general summary of dissipation described by different models for non-rigid beds, Lee (1995) also suggests a wave attenuation function of the form

$$H = H_0 e^{-k_i x} \quad (7)$$

to model the effects of soft mud on wave propagation in uniform water depth.  $H_0$  is the incident wave height and  $k_i$  is the wave attenuation coefficient for soft muds. Lee recommends the range  $10^{-4} \leq k_i \leq 0.05$ .

Substituting Equation 7 into Equation 2, assuming a horizontal bottom for a wave traveling a distance  $X$  from location 1 to location 2, yields

$$\varepsilon_v = C_G E_1 (1 - e^{-2k_i X}) / X \quad (8)$$

where  $\varepsilon$  is the energy dissipation experienced by the wave as it travels from location 1 to 2 and  $E_1$  is the wave energy at location 1. Note that Suhayda (1984) adopts a similar approach in his numerical model to simulate wave energy dissipation due to both soft muds and bottom dissipation—in fact, he uses the form of Equation 7 to model the effects of both bottom friction and soft muds on wave height evolution.

### Vegetated Marsh

WHAFIS simulates the effects of energy dissipation by flexible and rigid vegetation on wave height. When necessary, this WHAFIS methodology, developed for overland energy dissipation by marsh plants, can also be adopted for computing the effects of such vegetation seaward of the shoreline. In practice, this suggests that the WHAFIS computations should begin at the seaward edge of the marsh vegetation rather than at the generally-adopted mean sea level shoreline start point.

### Method for Wave Attenuation in Vegetated Marsh Conditions

Many investigators have suggested that vegetation damps wave energy. Knutson et al. (1982) performed a field experiment to quantify this phenomena in Smooth cordgrass (*Spartina alterniflora* also called Atlantic cordgrass) marshes. Dean (1978) suggests that marshes will affect waves in much the same manner as an array of vertical cylinders. Knutson et al. (1982) modified this equation to calculate wave damping by marsh plants and calibrated the coefficients for smooth cordgrass. The equation relates  $H_1$ , the incident wave height seaward of a stand of marsh grass to  $H_2$ , wave height landward of the stand of marsh grass as follows.

$$H_2 = \frac{H_1}{1 + AH_1 w} \quad (9)$$

where  $w$  = width of the stand of grass from seaward to landward through which waves propagate and

$$A = \frac{C_p C_d D}{3\pi S^2 d} \quad (10)$$

in which,  $C_p$  = plant drag coefficient,  $C_d$  = typical drag coefficient approximately 1.0,  $S$  = stem spacing, and  $d$  = water depth. This was derived for constant depths. For smooth cordgrass marshes, Knutson et. al found that  $C_p = 5$ .



It should be noted that marsh vegetation and morphology differ from region to region and with salinity levels. Pacific cordgrass (*Spartina Foliosa*) is less substantial than Atlantic cordgrass (Figure 21). Application of these equations can be considered for the Pacific Coast marshes with test cases to calibrate the coefficients. The above equations have been used to evaluate a minimum distance of vegetation required to damp wave energy in large and normal wind wave and tide conditions in the marshes in San Francisco Bay. The wave-damping model assumes that the transmitted waves actually encounter the vertical plants, therefore is less valid for larger water depths.

Hansen (2002) measured the effectiveness of tules (cat tails) in dissipating incoming boat wake energy in the Sacramento-San Joaquin Delta. Prior to commencing his research, a literature review was done and he found that studies on wave energy dissipation along the West Coast are sparse. Knutsen et al. (1981) conducted a study on erosion control by inter-tidal vegetation. His work included California marshes, but provided few results relevant to the present topic.

#### **Method for Wave Attenuation in Pacific Mudflats**

Waves are damped when traveling across mudflats, because of the sediment rich water column and movement of the bed, friction, and wave breaking. The attenuation of ferry wakes propagating over mudflats in San Francisco Bay has been analyzed by applying the Ippen-Keulegan (Ippen and Kulin, 1955; Keulegan, 1948) equations (PWA, 1995). The best-fit dynamic viscosity value was found using wave measurements. This reference can be used to provide guidance on wave dissipation over mudflats in San Francisco Bay. Figure 22 (PWA, 1995) shows the attenuation of wave heights with mudflat distance. Waves over mudflats have a wave height to depth ratio that is much lower than the standard depth limited breaking criteria; therefore, wave breaker location for soft mud beds can be different from that of a sandy bottom for the same gradients.

#### **Selected Literature Review and Recent Studies**

Recent wave measurements and modeling work by Surfbreak Engineering Sciences (unpublished work) suggests that bottom friction can be an important dissipation mechanism for waves traveling over both sandy bottoms and hard bottoms. In fact, wave dissipation because of bottom friction over a hard bottom may be an order of magnitude higher than that over a sandy bottom.

Previous work by Suhayda (1984), Forristal and Reece (1985), Sheremet and Stone (2003a, 2003b), and ongoing work by Taylor Engineering suggests that dissipation by soft muddy bottoms can cause substantial attenuation in the offshore delta regions of the Mississippi and Atchafalaya Rivers.

#### **Sheremet and Stone (2003a, 2003b)**

The authors present concurrent measurements of wave height, wave period, wind speed, and wind direction at two sites 100 km apart in the Gulf of Mexico offshore Louisiana. Bottom sediments at one site (CSI 3) are cohesive and at the other sandy (CSI 5); both sites are located in about 5 m water depths and exposed to similar atmospheric and fetch conditions.

The analyses show that wave heights at CSI 3 were strongly damped relative to those at CSI 5; the damping was especially high for larger wave heights. They also tracked the evolution of wave energy with the passage of a storm whose wind speeds monotonically increased to a maximum and then decreased rapidly. Swell energy increased monotonically to a maximum and then decreased monotonically at both stations; however, the energy level at CSI 3 was much lower than that at CSI 5. Sea energy increased non-uniformly to a maximum at both locations and then attenuated rapidly; though this phenomena seemed to appear at both stations, the attenuation rate was higher for CSI 3. Thus, at the muddy location, seas rapidly dissipated after the wind forcing ceased.



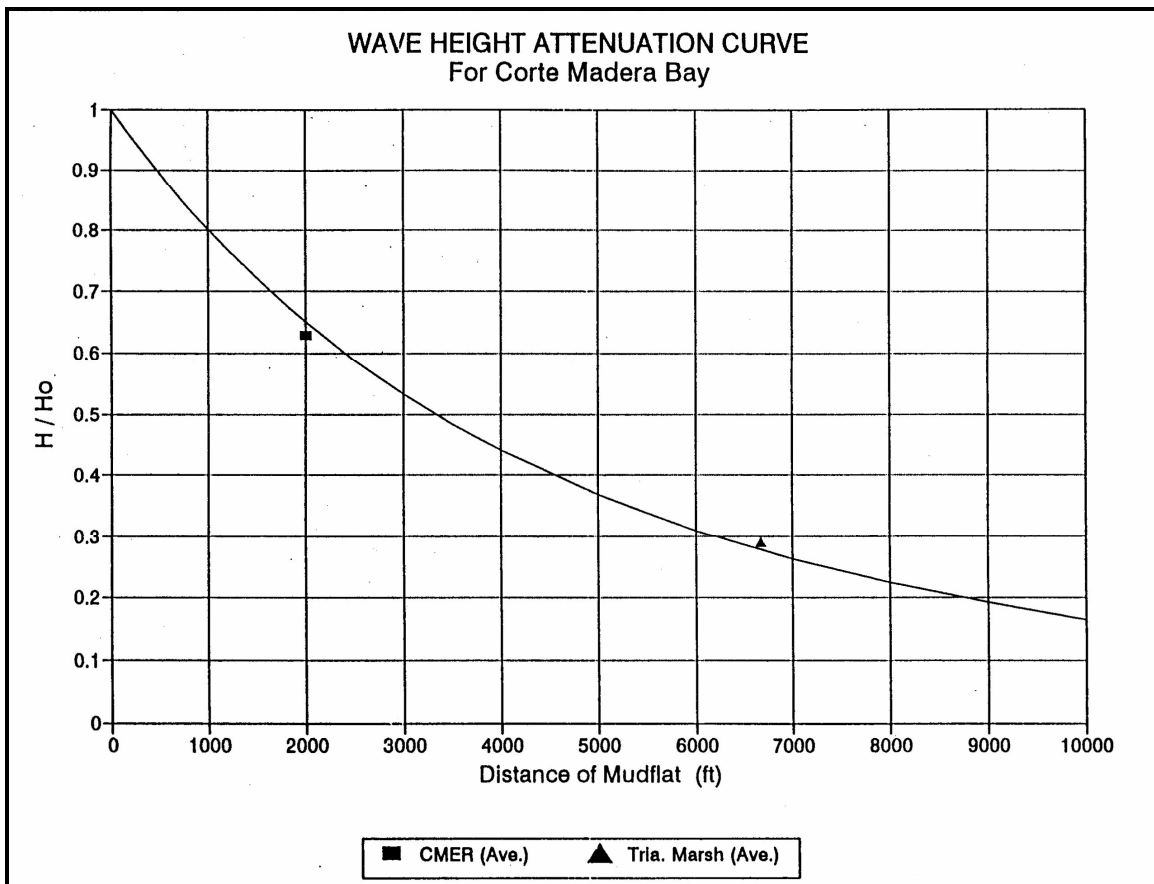
Native Pacific cordgrass meadow at Blackie's Pasture, Marin County.



A tall stand of Atlantic smooth cordgrass hybrids invading a native Pacific cordgrass meadow near Tiburon, Marin County.

Source: CSCC, 2003

**Figure 21. Cordgrass Species.**



Source: PWA (1995)

**Figure 22. Wave height attenuation curve for Corte Madera Bay, CA.**

Sheremet and Stone also applied the wave propagation model SWAN at the two measurement stations. SWAN does not model the effects of viscous bed dissipation. Predicted waves at CSI 5 were close to those measured; while the predicted wave heights at CSI 3 were too high compared to those measured. The authors hypothesize that the lack of an appropriate mud-related dissipation mechanism in SWAN was the cause of the inaccurate predictions.

A significant finding of their studies is that mud-induced wave dissipation extends across both low and high frequencies. They point out that bottom friction-type bottom dissipation mechanisms should only affect low frequency waves with little effect on high frequency waves. They suggest that short wave damping is related to cohesive sediment resuspension and fluid mud layer formation.

#### **Forristal and Reece (1985)**

The authors measured directional spectra of waves propagating in the Gulf of Mexico offshore Louisiana from deep (310 m) to relatively shallow (6 m) water depths. In particular, the authors report on measurements and analyses of data for seven storms, including Hurricane Frederic

(1979) and Hurricane Allen (1980) and five winter storms, between 1979 and 1981. Maximum deepwater significant wave heights ranged from 1.88 to 8.59 m.

The primary purpose of the field data collection was to measure the attenuation of waves, caused by energy dissipation due to a soft bottom (a result of deposits of the Mississippi River), as they propagated from the offshore to the shallow water station. The authors shoaled and refracted the waves and accounted for wave travel time to transfer the deepwater spectra to the shallow water location. They then compared the transformed and measured spectra at the shallow water location.

Spectral analysis for Hurricane Frederic showed strong attenuation of energy across frequencies less than 0.2 Hz. For low frequencies, wave attenuation increased with wave height and was almost independent of frequency. During a modest winter storm in December 1979, wave energy attenuation was apparent for frequencies less than the peak spectral frequency; minimal change was observed for frequencies greater than the peak. In contrast, during the strongest measured winter storm in November 1980, spectral energy between 0.07 and 0.20 Hz was strongly attenuated.

Data from three storms, Frederic, Allen, and Winter 1980, show that wave height attenuation was a strong function of the deepwater energy and a weak function of frequency for low frequencies.

Bottom motion data showed that the bottom was 180 degrees out of phase with the surface wave.

In summary, bottom dissipation did not appear to be important for small waves; such a mechanism became increasingly important for larger waves. The attenuation rate was a strong function of deepwater wave height and a weak function of wave frequency.

#### **Tubman and Suhayda (1976)**

The authors measured wave characteristics and bottom oscillations in East Bay offshore Louisiana, an area covered by muds. The actual work done on the mudline was found to correspond to the dissipation on the surface wave. The authors computed wave energy dissipation to be one order of magnitude larger than that computed by general expressions for energy dissipation by bottom friction or percolation. Unlike friction-related dissipation, which occurs mostly in shallow water, soft (flexible) bottom dissipation cause significant wave attenuation in intermediate water depths.

#### **Suhayda (1984)**

The report documents the use of a numerical model to develop wave crest elevation attenuation coefficients by simulating the effects of wave generation by wind; shoaling; and dissipation due to breaking, bottom friction, and soft muds during extreme hurricanes. The author models wave height/energy to change exponentially with distance along the wave travel direction. To compute its effects on wave dissipation, he models the soft muddy bottom as a visco-elastic medium, in accordance with the MacPherson (1980) model.

The results summarize representative wave height to water depth ratios for 21 transects spanning St. Bernard to Vermilion Parishes along the Louisiana Coast. The ratios range from a low of 0.42 at Plaquemines Parish to a high of 0.78 at Lafourche Parish. The report also presents nomographs, developed from the numerical model, to relate the wave height to water depth ratio to mud shear strength, bottom friction coefficient, fetch length, and wind speed.

#### **Surfbreak Engineering Sciences (SES) Unpublished, Ongoing Work**

In 2001, SES collected two months of wave data at a nearshore location in water depths of 10 m offshore Brevard County, Florida (Figure 23). This open water site has a large offshore fetch and sandy bottom. Using the wave propagation model STWAVE, an offshore wave hindcast in 80 m was transformed to the wave measurement site; model predictions were compared to measured data. To accurately simulate the measured time series, SES had to modify STWAVE to include dissipation due to friction caused by a sandy bottom. In 2002-2003, SES collected wave data off the seaward and landward edges of low relief hardbottom offshore Indian River County, Florida (Figure 24). Water depths at the measurement sites, spaced about 700 m apart, were 10 m and 4 m respectively. These open water sites have large offshore fetches. SES used STWAVE to transform the offshore wave data to the nearshore site. To accurately mimic the lower wave heights recorded landward of the hardbottom, SES had to include dissipation due to friction by a hardbottom in STWAVE. The appropriate friction factor for hardbottom was one order of magnitude larger than that for sand.

In summary, the standard STWAVE model tended to overpredict wave heights in the nearshore for beaches with both predominantly sandy and predominantly hard bottoms when bottom friction, was not included. By modifying STWAVE to include a dissipation mechanism related to bottom friction, SES was able to substantially improve the accuracy of the model predictions.

#### **Taylor Engineering Unpublished, Ongoing Work**

Taylor Engineering is applying the STWAVE wave propagation model for an ongoing project investigating the feasibility of restoring Acadiana Bays, located offshore southwestern Louisiana. Preliminary results suggest that the standard STWAVE model routinely overpredicts wave heights for modeled cases in both Terrebonne and Acadiana Bays. Modification of the STWAVE code to include bottom dissipation mechanisms, either due to friction or soft muds, increased the accuracy of the model predictions in 3.3 m water depth for storm waves which occurred in 1981 (Figure 25). Exclusion of bottom dissipation clearly overpredicts nearshore wave heights. Ongoing wave measurements will be compared to STWAVE predictions to further refine model dissipation parameters and investigate their dependence on common non-dimensional coastal parameters (e.g., wave steepness).

#### **Wave Dissipation Availability in Wave Transformational models**

REFDIF (Kirby and Dalrymple, 1994), a monochromatic wave propagation model, accounts for dissipation because of laminar surface and bottom boundary layers, turbulent bottom boundary layers, porous bottoms, and wave breaking. It does not simulate the effects of soft mud bottoms.

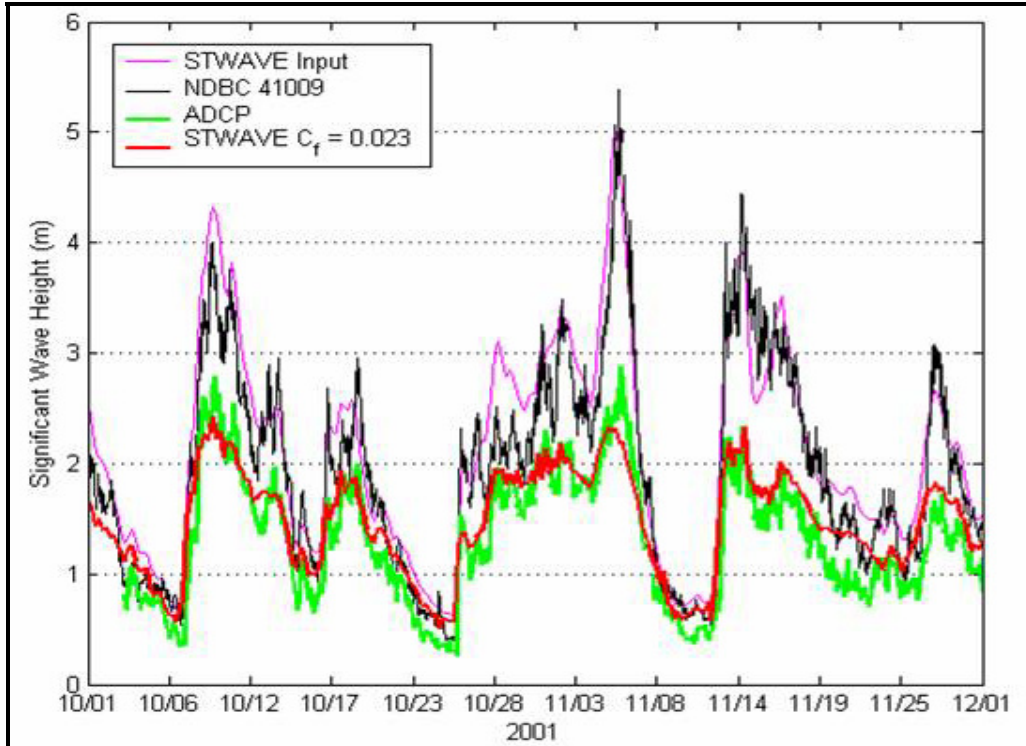
STWAVE (Smith et al., 2001), a spectral wave propagation model, accounts for dissipation due to energy transfer to high frequencies and white capping; but does not account for bottom dissipation mechanisms. Surfbreak Engineering Sciences and Taylor Engineering have recently modified STWAVE to include the effects of bottom friction and soft mud bottoms, respectively.

### 2.3.5 Recommendations

A Study Contractor may cautiously employ numerical wave transformation models to obtain nearshore storm wave heights. Blindfolded applications of bottom dissipation mechanisms in wave propagation models is inadvisable given the large ranges in the possible values of the attenuation coefficients. Consequently, a study contractor should calibrate the numerical models so that predictions accurately mimic measured wave data. The contractor should select the appropriate bottom dissipation mechanisms and calibrate the relevant dissipation coefficients for site-specific conditions.

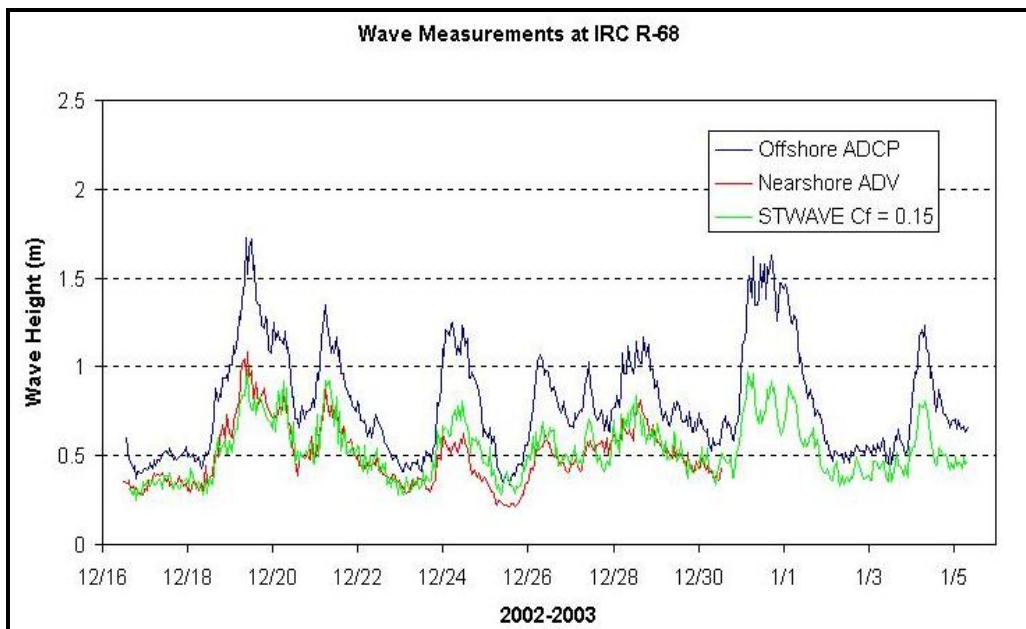
To provide guidance, typical ranges for dissipation coefficients corresponding to a variety of bottom conditions could be included in the Guidelines and Specifications. The data collected by Surfzone Engineering Sciences may help determine representative dissipation coefficients for sandy beaches and for beaches fronted by large expanses of hardbottom. Suhayda's (1984) work and ongoing work by Taylor Engineering may provide further information on wave dissipation by soft beds. The Guidelines and Specifications could also include regional-scale data about nearshore bottom conditions whether it is rough, soft, porous, or marshy between, say, the 100-foot contour and the shoreline. The Study Contractor can then include the appropriate bottom dissipation mechanism(s) in the wave propagation model when transforming offshore wave hindcast/buoy data to nearshore conditions.

Until verified guidance is available, the Study Contractor should locate reliable offshore and nearshore wave height data and calibrate a suitable wave transformation model. The contractor should also have knowledge of the bottom conditions throughout the study area. The calibrated model should only be applied to areas with bottom conditions similar to those characterizing the wave gauge area. The contractor should then employ the calibrated wave transformation model where appropriate to obtain the design wave heights (starting conditions for WHAFIS) required for flood insurance studies. Sensitivity studies are advisable to apprise the contractor of the effects of poorly known coefficients.



(courtesy of Surbreak Engineering Sciences, Inc.)

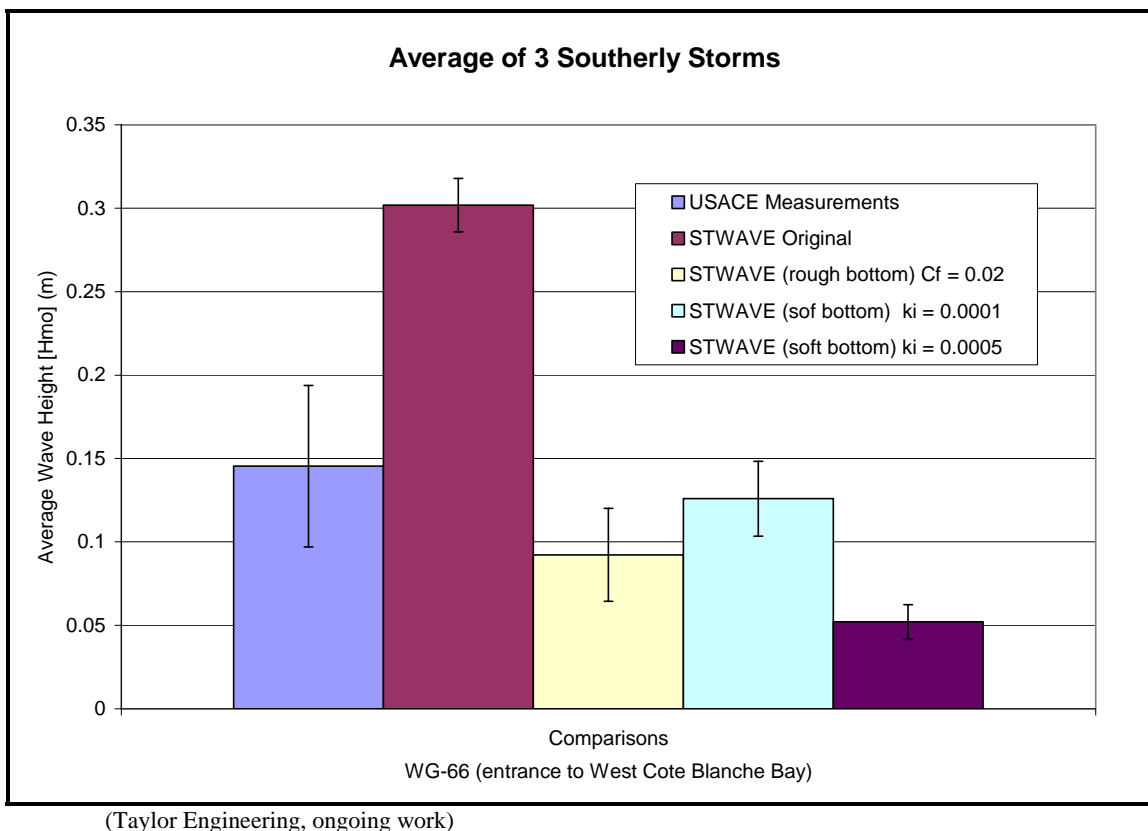
**Figure 23. Comparison of bottom friction-included STWAVE wave height predictions with measurements for sandy bottom.**



(courtesy of Surbreak Engineering Sciences, Inc.)

**Figure 24. Comparison of bottom friction-included STWAVE wave height predictions with measurements for hard bottom.**





**Figure 25. Average wave heights measurements, in 3.3 m water depth, for three storms compared to predictions with different formulations of STWAVE.**

If model calibration is not possible, the contractor should, with one exception, ignore bottom dissipation effects in wave transformation analyses. Suhayda's (1984) methods and results appear reasonable and may be used to develop nearshore waves in Louisiana. Improvement could be gained by updating his results.

Recommended improvements are:

1. Write *G&S* to include a section on wave energy dissipation over shallow and flat bottoms.
2. Develop typical ranges for dissipation coefficients for a variety of bed and wave conditions to include in the *G&S*
3. Categorize bed and wave conditions for the U.S. coastlines.
4. Revise *G&S* to adopt Suhayda (1984) method.
5. Develop better guidance for West Coast conditions, namely for shallow surge over mudflats and West Coast marsh vegetation.

### 2.3.6 Preliminary Time Estimates for Guideline Preparation

Table 2 summarizes the preliminary estimates of time required for Critical Topic 8. These time estimates do not include responding to comments and suggestions associated with the review of the Guideline improvements.

### 2.3.7 Description and Suggested Improvement

Issues related to the WHAFIS program were categorized as Important for the Atlantic and Gulf coasts and as Helpful for the Pacific Coast. However, in considering possible improvements to WHAFIS, several topics have been identified that could be considered Critical instead of Important or Helpful, since they could be accomplished within a 6-month period, and because they would be valuable for near-term use in studies and map revisions on both the Atlantic/Gulf and Pacific Coasts.

Of particular importance are changes to the program that would make it more suitable for Pacific Coast applications. These include:

- ④ The capability to specify wind speeds that would be more appropriate to the Pacific than those used by default for Atlantic/Gulf hurricanes
- ④ Addition of new Pacific Coast marsh grass types
- ④ Incorporation of dissipation over a muddy bottom

These and other Important/Helpful but potentially Critical topics are included in the WHAFIS discussion in Section 4.

## 3 AVAILABLE TOPICS

There are no available topics for Topic 10, Overland Wave Propagation; Candidate Improvements to WHAFIS.

## 4 IMPORTANT TOPICS

### 4.1 CONTINUATION OF TOPIC 10: WAVE PROPAGATION – WHAFIS IMPROVEMENTS

#### 4.1.1 Description of the Topic and Suggested Improvement

In the current coastal guidelines, FEMA's WHAFIS program is prescribed for modeling the overland propagation of waves. WHAFIS, now version 3, is an implementation and expansion of the wave propagation methods suggested by the NAS in *Methodology for Calculating Wave Action Effects Associated with Storm Surges* (1977).

WHAFIS is applied along *wave transects* which consist of one-dimensional descriptions of the terrain over reaches oriented approximately perpendicular to the shoreline. Each transect is divided into multiple segments defined by: station along the transect measured from the initial seaward point of the transect; ground elevation at each station; and nature of the segment just prior to each station.

Transect segments may be of several sorts, each either dissipative or regenerative for waves. The regenerative segments are identified as either *over water fetch* or *inland fetch*, where the two character identifiers are used to identify each line of data in an input file (in earlier parlance, they are *card types*). Over water fetch and inland fetch segments differ only in the wind speed which is used to compute the wave regeneration rate. The most important dissipative segments are regions of energy loss through *vegetation* and through rows of buildings. Areas in which the terrain rises above the local surge are identified with *above surge* stations, while natural and man-made narrow *dune*-like barriers are sometimes identified as DU stations.

Energy loss through vegetation is modeled as the loss through an equivalent stand of rigid vertical cylinders, defined by fixed values of diameter, height, average spacing, and drag coefficient throughout a segment. Energy propagation through rows of buildings is determined by the fractional open aperture between the buildings along a row, and the number of rows within the transect segment. The fraction of incident energy passing through a row is assumed to be equal to the average fractional open aperture between adjacent buildings; between rows, energy is assumed to be laterally redistributed before encountering the subsequent row. A rather detailed treatment of marsh grass was added to the initial WHAFIS implementation. It is denoted by the VH segment designation, and is the only segment type which considers the effects of both damping and regeneration.

Transects are spaced alongshore at intervals as necessary to reasonably represent the variation of conditions encountered by waves. The spacing may range from more than a mile on very uniform coasts, to on the order of a thousand feet in developed areas with rapid variation in landcover. A spacing of ½ mile is typical in many studies.

Conditions at the first transect point (usually at zero elevation on the beach) are defined by an *initial elevation* card which provides starting information such as the 100-year surge level (including setup), and the wave period and initial height. Alternatively, a fetch length can be specified, and the program will determine default values for height and period. A key assumption of the model is that wave heights are always limited to the breaking wave height (taken to be 78% of depth) at the local depth (surge elevation minus land elevation). This means, for example, that the wave height computed at the beach will generally be 78% of the surge height, irrespective of the starting wave height specified (neglecting wave setup).

The WHAFIS program follows the propagation of the wave along the transect, determining the variation of height and period. The surge elevation may be revised at any segment, in order to represent the surge variation over a barrier and across a protected bay. WHAFIS produces an

output table dividing the total transect into zones (VE and AE) and base flood elevations, according to FEMA's coastal mapping rules.

#### 4.1.2 Description of Potential Alternatives

A number of WHAFIS improvements have been identified for consideration. Although this topic is categorized as Important for the Atlantic/Gulf Coasts, and as Helpful for the Pacific and non-open waters, it may be that the WHAFIS program will continue to be used for some time, both in restudies and in coastal LOMRs, and that improvements categorized as Critical might be considered and completed within a relatively short time (less than 6-months). The following items have been identified, arranged in order of increasing level of effort.

##### ***Minor Effort (Could be re-categorized as Critical)***

- ④ Eliminate use of the 10-year stillwater elevation throughout WHAFIS. The 10-year level was needed in earlier mapping which included determination of the so-called Flood Hazard Factor (FHF). This is no longer necessary, and introduces confusion to the user.
- ④ Eliminate the FHF information from Part 7 of the WHAFIS output.
- ④ Revise WHAFIS to insert the run date and time into the output file, as an aid to documentation.
- ④ Revise the code to locate and delete scratch files left over from a prior failed run; WHAFIS fails again if, upon loading, it encounters prior scratch files.
- ④ Revise the code (eliminating SUBROUTINE READIN) so that the marsh grass data file is bound into the exe file. Even if WHAFIS is on the path, it does not look in its own directory for mg.dat, only in the current directory.
- ④ Revise the code to allow comment lines, CM cards, which would simply be ignored during execution. This would be helpful in making the input files self-documenting.
- ④ Revise the code to permit free-format input data files (as an option).
- ④ Although it purports to do so, WHAFIS does not always reinitialize the wave period properly if the water depth (and wave height) goes exactly to zero (but if the terrain rises epsilon above the surge, then the period is reset to zero for subsequent regeneration). The regeneration rate is strongly affected by the period, sometimes leading to large excursions of zone boundaries between two adjacent transects, one reset and one not reset.

##### ***Moderate Effort (Could be re-categorized as Critical)***

- ④ Presently, the computation of starting wave period, if not specified on the IE line, is based on shallow water wave growth resulting in wave periods of less than 7 seconds.

This should be modified to also allow computation of a reasonable default suitable for open coast conditions.

- ④ Restrict the use of Above Surge cards, making them unnecessary or seldom necessary. There may still be good reasons to use Above Surge cards in some cases (perhaps to help the interpretation of surge height changes), but the program should often be able to determine where the terrain rises above the surge, and where it falls back down.
- ④ Improve the so-called “interpolation” that WHAFIS does between surge changes (SUBROUTINE SCANE). This is closely tied to the AS issue, above.
- ④ Improve the default internal subdivision of long reaches, to better reflect the variation across the reach. If a reach, VE say, is very long, the ending wave height is OK, but the variation may not be well represented in mid-reach. Dividing the reach into two shorter reaches may be necessary – WHAFIS should take care of this better than it does.
- ④ Presently, the WHAFIS treatment of regeneration over over-water fetch and inland fetch reaches is governed by the assumption of fixed wind speeds of 80 and 60 mph, respectively, deemed appropriate for hurricane conditions on the Atlantic/Gulf Coasts. It is proposed that the program be revised to use different default values for the Pacific, and also to permit the user to specify arbitrary wind speeds.
- ④ Modify the program to include additional marsh grass varieties encountered on the Pacific Coast. This would actually be achieved through additions to the MG.DAT file which, as suggested above, should be bound into WHAFIS.
- ④ Modify the program to include a new dissipative category, MB say, representing wave damping over a muddy bottom. This feature should account not only for damping, but also for the continuing influence of wind of user specified speed (with an appropriate default). The procedures would most likely follow the suggestions of Topic 9 included in another section of this Focused Study report.
- ④ Modify the code to include output of the zone breaks and zone data in shapefile format, or in dbf format which can be imported by ArcView, for example, as a point theme.
- ④ Modify the code to include creation of an optional HP/GL output file of the terrain and wave crest profiles.

***Clarify Existing Guidelines and Incorporate New Guidance for the Items Above***

- ④ The input requirements for all data fields need to be clarified, including such factors as proper units.
- ④ Provide better guidance for the Dune card (DU).

- ④ Provide guidance for choosing between inland fetch and over water fetch cards.
- ④ Provide Pacific Coast guidance for optional windspeeds to be used with inland fetch and over water fetch cards (if implemented).
- ④ Provide guidance for representation of elevated structures. This could include, for example, simulation as vegetation (rigid cylinders) if dissipation is appropriate; as fetch, if the effects of wind should be dominant; or as buildings with open fraction of 1.0, representing a zone with neither damping nor growth.
- ④ Provide additional guidance regarding the selection of vegetation parameters, perhaps including photos showing various types of typical coastal vegetation along with recommended values of parameters. Include new guidance for Pacific Coast vegetation type, including Pacific marsh grasses (if implemented).
- ④ Provide new guidance for dissipation over muddy bottoms (if implemented).

### ***Significant Effort (categorized as Important)***

WHAFIS divides the transects into reaches that are either dissipative or regenerative, not both (except marsh grass). It is frequently problematic whether one should account for whatever dissipation might exist, or whether to account for wind effects. A typical example is a reach of scattered vegetation, perhaps overtopped by the surge. In some cases, such a reach could be subdivided into a succession of alternating fetches and VE regions, but this would be laborious and seldom desirable. Similarly, the first few rows of elevated structures may offer little wave resistance, while (near the coast) wind effects may still be large. In this case, the problem is not only how to account for the damping (by representing the structural supports by a VE card, for example), but also how to account for the wind (as could be done by using an OF or IF card instead). A significant improvement to the accuracy of wave estimates would be made if WHAFIS were revised to consider the combined effects of damping and wind action over each segment, accounting for vegetation height and for wind sheltering by non-submerged elements.

### **4.1.3 Recommendations**

Recommended improvements are:

- ④ Change code for more user-friendly program (Minor Effort)
- ④ Significant code changes for improvement in accuracy and graphics (Moderate Effort)
- ④ Clarify Existing Guidelines and Incorporate New Guidance for the Items Above
- ④ Improve WHAFIS to include combined effects of damping and wind action over each segment (Significant Effort)

- ④ Evaluate applicable 1-percent wind condition for each region (e.g., Pacific, Atlantic, Gulf of Mexico) and change WHAFIS to incorporate a series of wind conditions to choose from.
- ④ Revisions to WHAFIS should include associated revisions to the software CHAMP, which is a “shell” program used to operate WHAFIS in the Microsoft Windows environment.

#### 4.1.4 Preliminary Time Estimate for Guideline Preparation

Table 2 summarizes the preliminary estimates of time required for Critical Topic 8. These time estimates do not include responding to comments and suggestions associated with the review of the Guideline improvements.

## 5 ADDITIONAL OBSERVATIONS

None.

## 6 SUMMARY

The Wave Transformation Focused Study is comprised of four topics: Topic 7 (California Regional Wave transformation Models), Topic 8 (Wave Transformations with and without Regional Models), Topic 9 (Wave Energy Dissipation over shallow flat bottoms), and Topic 10 (Overland Wave Propagation; Candidate improvements to WHAFIS). The recommendations are shown in Table 1.

Wave Transformations will be a key component of the *G&S* for the Pacific Coast Region. These *G&S* will be of use to other regions as well, including sheltered waters, owing to the very limited treatment in the existing *G&S*. Wave Transformations are processes that are conceptually intermediate between the flood forcing functions (see Focused Study for Storm Wave Characteristics) and flood response functions (See Focused Studies for Wave Setup and Wave Runup and Overtopping). Wave transformations are generally crucial for Pacific Coast Flood Studies, as demonstrated by prior efforts in Region IX and X, because of different geographic and oceanographic conditions than found in the Gulf and Atlantic Coast Regions. For example, the Pacific Coast is exposed to very long wave length swell that “feels bottom” much farther offshore, resulting in varying nearshore conditions that can only be quantified via wave transformation analysis.

It is recommended that the *G&S* identify a range of tools that can be applied based primarily on consideration of the site characteristics. Other factors should be identified, such as whether regional analysis of wave transformations has already been accomplished. Recommended actions will clarify the use of regional model products, the U.S. Army Coastal Engineering Manuel

(CEM), and readily available, contemporary computer programs of wave transformation processes. Also recommended is improved guidance to determine when wave dissipation effects are important to coastal flood studies, and how these effects can be quantified. Finally, a range of improvements to WHAFIS software used to quantify overland wave propagation in flood studies is identified and prioritized for implementation.

**Table 1. Summary of Findings and Recommendations for Wave Transformation**

Topic Number	Topic	Coastal Area	Priority Class	Availability / Adequacy	Recommended Approach	Related Topics
7	CDIP California	AC	--	--	Use existing CDIP bathymetry grids for California Coast; Create 2 sets of transformation coefficients in Southern California; Demonstrate the model skill for predicting nearshore wave conditions during large winter storms using existing buoy data (for southern Central and northern California Coast); Create database, Provide user's manual, and Fortran and MATLAB codes to assist contractors in using the model coefficients.	8
		GC	--	--		
		PC	C	MAJ		
		SW	--	--		
8	Overall Wave Transformation	AC	H	MIN	Refer to PC G&S for potential use of regional models	6, 7, 9, 10, 11, 44, 45, 47, 48, 49, 54, 55
		GC	H	MIN		
		PC	C	MAJ	Write G&S for Wave Transformations. Tasks: 1. Conduct several focused studies to inform the Wave Transformations G&S. 2. Use available publications to identify a range of methods. 3. Develop criteria for level of analysis. 4. Include development of guidelines for spatial coverage and wave parameters, and include use of regional models such as CDIP. 5. Research available literature to adequately define wave groups, infragravity waves, shallow water spectra, etc. for input into wave setup and runup calculations. 6. Evaluate wave transformation models using a selected data set. 7. Review available literature and guidance on the range of applicability of contemporary computer models, recommend models for inclusion on the FEMA pre-approved coastal model list, and provide guidance on their application to FEMA FISs. 8. Incorporate applicable sections of existing G&S for other geographical areas that cover the overland propagation and wave energy dissipation topics. (Topics 9 &10)	
		SW	C	MIN	Include in PC G&S; reference for AC and GC	



**Table 1. Summary of Findings and Recommendations for Wave Transformation**

Topic Number	Topic	Coastal Area	Priority Class	Availability / Adequacy	Recommended Approach	Related Topics
9	Dissipation	AC	C	MAJ	Write <i>G&amp;S</i> to include a section on wave energy dissipation over shallow and flat bottoms based on available information. Develop typical ranges for dissipation coefficients for a variety of bed and wave conditions to include in the <i>G&amp;S</i> from available information. Revise <i>G&amp;S</i> to adopt Suhayda (1984) method. Provide guidance on calibration if available data not adequate to select coefficients. Conduct studies to develop typical ranges for dissipation coefficients for variety of bed and wave conditions to include in the <i>G&amp;S</i> . Categorize bed and wave conditions for U.S. coastlines. Revise <i>G&amp;S</i> to provide dissipation coefficients on a geographic basis to the extent appropriate	8,10
		GC	C	MAJ		
		PC	C	MAJ	Evaluate wave dissipation over marsh and mudflats in the Pacific using available information provide interim guidance for calculating wave dissipation. Conduct field data collection to characterize wave dissipation over marsh and mudflats in the Pacific; provide guidance for calculating wave dissipation.	
		SW	C	MIN	Include in PC <i>G&amp;S</i> ; reference for AC and GC	
10	WHAFIS propagation; evaluate new methods to better represent vegetation effects, treatment of elevated pile supported buildings	AC	I (C)	PRO	Clarify where WHAFIS, 1-D, and 2-D models are most appropriate Update WHAFIS and tie back to CHAMP. Minor Effort – code changes for more user friendly program. Moderate Effort – more intense code changes for improvement in accuracy and graphics, add wind direction. Update <i>G&amp;S</i> accordingly. Significant Effort – improve WHAFIS to include combined effects of damping and wind action over each segment. Include realistic wave breaking model for setup and other processes after developed.	8, 9
		GC	I (C)	PRO		
		PC	I (C)	PRODAT		
		SW	H	PRO		
<p><b>Key:</b>                      Coastal Area                      AC = Atlantic Coast; GC = Gulf Coast; PC = Pacific Coast; SW = Sheltered Waters                      Priority Class                      C = critical; A = available; I = important; H = helpful                      (Recommend priority italicized if focused study recommended a change in priority class)                      Availability/Adequacy                      “Critical” Items: MIN = needed revisions are relatively minor; MAJ = needed revisions are major                      “Available” Items: Y = availability confirmed; N = data or methods are not readily available                      “Important” Items: PRO = procedures or methods must be developed; DAT = new data are required;                      PRODAT = both new procedures and data are required</p>						

<b>Table 2. Time Estimates for Wave Transformation Topics</b>		
<b>Topic Number</b>	<b>Topic</b>	<b>Time (person months)</b>
7	<b>Evaluate regional models for California</b>	
	Task 1: Literature and Data Search	6
	Task 2: Model and Field Measurement Validation Planning	5
	Task 3: Model Development and Field Measurements (includes 4 buoys. Measurement time period includes 2 winters)	19
	Task 4: Field Validation of Deep Water Hindcasts and Nearshore Predictions. (Can Critical Topics include field measurements?)	13
	Task 5: Evaluate need to include nonlinear effects in some manner.	2
	Task 6: Create FEMA Nearshore Wave Spectra Database	7
	Note: Short-term recommendations can be achieved within 6-months, and will be tailored to available budgets to the extent practicable.	
	<b>TOTAL</b>	<b>52</b>
8	<b>Assess need for regional models</b>	
	Write <i>G&amp;S</i> for wave transformations as a section within the <i>G&amp;S</i> for the Pacific Coast	1.7
	Use available publications and thorough literature survey to identify range of methods to select from	0.5
	Develop general criteria for level of analysis required	0.6
	Research available literature to adequately define wave groups, infragravity waves, shallow water spectra, communicate with the other analysis groups which need output from the wave transformation study, and develop approaches for <i>G&amp;S</i>	1.2
	Evaluate adequacy of linear wave transformation models and needs to supplement these models. Place emphasis on representation of infragravity waves;	1.2
	Evaluate wave transformation and, review available literature and guidance of the range of applicability of contemporary computer models and recommend models for inclusion on the FEMA pre-approved coastal model list	3.5
	Incorporate applicable sections of existing <i>G&amp;S</i> for other geographical areas that cover overland propagation and wave energy dissipation topics	0.5
	<b>TOTAL</b>	<b>9.2</b>
9	<b>Wave Energy Dissipation over shallow, flat bottoms</b>	
	Develop typical ranges for dissipation coefficients corresponding to a variety of bed and wave conditions. Revise Guidelines to reflect recommended dissipation relationships and coefficients.	6
	Categorize bed and wave conditions for U.S. coastlines. Revised Guidelines to provide dissipation coefficients on a geographic basis.	6
	Revise Guidelines to adopt Suhayda's (1984) results for Louisiana. Provide guidance on use by study contractors.	0.3
	<b>TOTAL</b>	<b>12.3</b>
10	<b>Candidate Improvements to WHAFIS</b>	
	Perform Minor Effort tasks	1
	Perform Moderate Effort tasks	4
	Clarify guidelines and incorporate items above	3
	<b>TOTAL</b>	<b>8</b>

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## **APPENDIX 1**

# **WAVE TRANSFORMATIONS DISCUSSION**

WAVE TRANSFORMATION

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# APPENDIX 1

## WAVE TRANSFORMATIONS DISCUSSION

### A-1 INTRODUCTION

The following text provides additional, detailed discussion supporting Topic 8, Wave Transformations. The organization was selected to be consistent with anticipated future Guidelines and Specifications, for the Pacific Coast Region.

#### A-1.1 DESCRIPTION OF WAVE TRANSFORMATIONS

Wave Transformations refers to changes in wave characteristics during propagation. The primary processes are refraction, diffraction, shoaling and dissipation. Wave Transformations are considered in the regime bracketed by wave generation (typically in "deep water") and depth-induced breaking (typically "near shore").

Wave reflection and current-induced refraction are typically ignored. Refraction, diffraction, shoaling and dissipation are strongly dependent on the wavelength, with longer waves (higher wave periods) being affected the most (wave height is important, and dissipation due to propagation through vegetation can be greater for shorter, steeper waves). Irregular and steep bathymetry, also increase wave transformations.

Wave transformations are more likely to be important for West Coast flood studies owing to the longer waves, and generally steeper and less regular bathymetry. In southern California, nearshore wave heights can vary by a factor of 5 over a few miles of shoreline.

##### A-1.1.1 Relationship with Other Analyses Steps

###### A-1.1.1.1 Storm Wave Characteristics

Storm wave characteristics will be established, and used as input to wave transformations. Hence, *G&S* for Wave Transformations need to identify input requirements. Simple situations will allow the use of simple input, such as wave height and period. More complex situations may require directional spectra.

###### A-1.1.1.2 Wave Setup

Wave setup is the super-elevation of the mean water level caused by wave action (USACE CEM, 2003). As waves break, the still water level lowers at the breaking point and then increases between the break point and the shoreline. The simplified methods available for calculation of wave setup require the knowledge of the wave parameters at breaking (steepness) and other geometric parameters like the foreshore slope past breaking point. Output from wave

transformation models, serve as input into wave setup models. Some wave transformation models calculate the radiation-stress within the program, which is used in wave setup calculations.

#### ***A-1.1.1.3 Wave Runup and Overtopping***

Runup is the maximum elevation of wave uprush above still-water level (USACE CEM, 2003). The current *G&S* supports programs RUNUP 2.0 and ACES for runup calculations and ACES for overtopping calculations. The maximum breaker height, height to depth ratio, and equivalent deepwater heights are needed as input into these models. More accurate assessments of runup and overtopping may require additional information such as wave height distributions and wave group characteristics.

#### ***A-1.1.1.4 Overland Propagation (WHAFIS)***

WHAFIS currently uses the depth limited breaking wave height to provide the upper bound of the wave crest profile. Improved estimates of height to depth ratios may be useful.

#### ***A-1.1.1.5 Tsunami***

Tsunamis are extremely long waves generated by disturbances associated primarily with earthquakes occurring below or near the ocean floor. Underwater volcanic eruptions and landslides can also generate tsunamis. In the deep ocean, their length from wave crest to wave crest may be a hundred miles or more but with a wave height of only a few feet or less.

Tsunami Predictions for parts of the West Coast are available for FEMA FIS in a report prepared by the US Army Engineer Waterways Experiment Station (1975) and more recent studies. This document does not consider Tsunami propagation as part of the guidelines.

### **A-1.1.2 Processes**

#### ***A-1.1.2.1 Wave Refraction and Diffraction***

When parts of the wave are in different water depths, the part of the wave in shallow water moves slower than the rest of the wave in deeper water and causes the wave to bend, changing the spatial distribution of wave energy and height. This phenomenon is known as wave refraction.

Wave refraction can result in convergence or divergence of the wave energy, producing changes in wave height as well as wave direction in the nearshore. The output from refraction analysis provides input into wave runup and overtopping processes.

Wave diffraction is a process of wave propagation that can be important as refraction and shoaling (USACE CEM 2003). Diffraction of water waves is a phenomenon in which energy is transferred laterally along the wave crest (USACE SPM, 1984). Diffraction is mostly noticeable when waves encounter surface-piercing obstacles, such as a breakwater or an island. The waves

after passing the barrier, would penetrate into the geometric shadow zone turning toward the lee side of the barrier with reduced heights along the wave crests.

#### ***A-1.1.2.2 Wave Shoaling and Breaking***

The speeds at which waves travel depend on the water depth. In deep water, the wave propagation speed does not change. When the water depth reaches about one half of the wave length, the waves begin to slow down. As they slow, their lengths diminish and their heights increase due to a reduction in group velocity, increasing the wave steepness. The increase in wave height due to slowing down of the waves is referred to as wave shoaling.

In shallow water, wave crests become sharper and wave troughs flatter, approaching a Solitary wave form. As a solitary wave moves into shoaling water it eventually becomes unstable and breaks. A solitary wave breaks when the water particle velocity at the wave crest becomes equal to the wave speed. The ratio of breaking wave height to water depth is commonly used to define the breaking point, mathematically. Guidance is available in CEM(2003). Wave breaking is the prominent method of wave energy dissipation.

#### ***A-1.1.2.3 Wave Energy Dissipation, Non-Breaking***

Waves lose energy due to bottom friction and viscous damping when they propagate over shallow and intermediate waters, and through inundated marshes. While it is “conservative” to ignore wave energy dissipation, in some cases dissipation must be considered to achieve realistic results.

#### ***A-1.1.2.4 Wave Propagation Over Inundated Land Areas***

If the land areas are inundated due to storm surge, the non-broken waves or the regenerated waves will continue to propagate over these areas, with wave growth due to wind energy input and decay due to frictional effects. This condition is important in the US East Coast, and is modeled with FEMA’s WHAFIS 3.0 program.

#### ***A-1.1.2.5 Wave Generation***

While waves from distant storms are propagating from deep to shallow water, the local winds can impart energy and generate new waves which are called wind waves or local seas. These waves have shorter wave periods than the swells arriving from distant origin.

#### ***A-1.1.2.6 Wave Reflection***

Wave energy could reflect off steep shorelines and barriers causing changes in wave height and direction. In the case of a vertical, hard structure, the fraction of wave energy reflected can be very large. Wave reflections from the channel islands (Santa Cruz) have been observed in the measured data near Santa Barbara in southern California. The transformational model used did not account for swell wave reflection and therefore the wave heights were under predicted.

### **A-1.1.1.7 Nonlinear Effects**

As waves propagate, their nonlinear character results in interaction between the various spectral components. This nonlinear interaction is most significant in shallow water, for large wave heights and long periods and is evident along the Pacific Coast in terms of infragravity waves also called surf beat and harbor oscillations.

### **A-1.1.3 Regional and Geomorphic Considerations**

Different regions of the coast have different wave exposures and other characteristics that help frame the range of analysis methods typically appropriate. The major regions and their characteristics pertinent to wave transformations will be identified. A table would be developed to include a list of regions (Sheltered waters: San Diego Bay, San Francisco Bay, Puget Sound, etc.) and characterization of distinguishing coastal morphologies (offshore islands, canyons, wind sandy beaches, etc.).

The simplest geomorphic form consists of straight and parallel bottom contours leading to straight coastlines without offshore or nearshore features affecting the wave propagation. Although some coastlines can be simplified in the above category, most existing shorelines are far from the ideal straight and parallel contours. Curved coastlines carry their shape well into the deeper water contours.

Offshore shoals and reefs of different geometry and scale, and water depth at the shoal can affect the wave propagation. Wave energy focusing behind the shoal and defocusing in other areas is possible in the case of non-breaking waves, and the same shoal can be a source of wave dissipation for larger breaking waves.

Special cases include submarine canyons, river deltas, estuary ebb shoals and inlets, islands, submerged reefs and rock shelves, and distinct holes and channels.

## **A-1.2 INPUT AND OUTPUT PARAMETERS**

In wave transformation modeling, offshore wave parameters are needed as input to generate the nearshore wave parameters. Output from wave transformation models are necessary as input in to other models for evaluation of wave setup, runup and overtopping etc.

### **A-1.2.1 Input and Output Parameter Selection**

Input parameter selection is based on the requirements of the wave transformation technique that will be adopted subjected to constraints in availability of data (or type of data). In the least, wave transformation models require information on bathymetry, offshore wave height(s), period(s) and direction(s) or wave spectral information. Additionally, two-dimensional numerical models would need, lateral boundary conditions, wind, current or water level input and other coefficients for friction etc.

Output parameters are basically the wave parameters (wave height or breaking wave height, period, and direction in the nearshore or nearshore spectra and other available information such as radiation stress for calculation of wave setup). The input requirements of other wave runup and overtopping models control the output selection.

### **A-1.2.2 Geographic / Geomorphic**

Wave transformation processes are mostly dominated by the bathymetry in the intermediate and shallow water. Regularity or irregularity of bathymetry is a key factor determining the appropriate method of transformation.

Some experience or guidance is necessary for study contractors to select between different methods of wave transformation depending on the bathymetry of the area in consideration. Also, questions arise about the geographic limits and resolution of the bathymetric information necessary in setting up refraction-diffraction models. The former is governed by the wave period information, and the latter by the type of model used. In addition, geological and coastal bathymetric features can largely influence the wave transformation process.

### **A-1.2.3 Wave Characteristics**

Characteristics of waves can be defined in many different ways. Basically waves can be defined by a height, period and direction or in terms of energy distribution in each wave period and direction (a directional or two-dimensional spectrum).

#### **A-1.2.3.1 Simplified**

In the analysis of ocean waves, the irregular seas are represented by parameters of varying complexity. The simplest form of these is a sinusoidal wave defined by a wave height and a wave period. The complex irregular sea is random, and therefore can be considered as a superposition of waves of several wave heights and periods. However, a single wave height and period is sometimes selected to represent the random sea. The most commonly used simplified parameters are shown in Table D-2 (pg. D-25), Appendix D, *G&S* (2002).

#### **A-1.2.3.2 Frequency Spectra**

A more realistic approach of defining the random sea is the energy distribution at different frequencies (reciprocal of wave periods). A graph of wave energy vs. frequency is commonly known as a wave spectrum and usually has a single peak or multiple peaks of energy. Statistical methods are available to convert the energy spectrum to various wave height representations ( $H_{mo}$ ,  $H_{rms}$ ,  $H_s$  etc., *SPM* (1984)). Energy spectra without the wave direction information (directional distribution) are called frequency (or one dimensional) spectra  $S(f)$ .

Two parameters are commonly used to describe the spectra. These are spectral width  $\nu$  and spectral bandwidth  $\epsilon$  and are used to determine the narrowness of the spectra (*USACE CEM*, 2003). For a narrow-band spectrum, both of these parameters are close to zero. Since  $\epsilon$  tends to

amplify noise in the high frequencies of spectra, an alternative parameters called the spectral peakedness parameter  $Q_p$  was introduced by Goda (1974). The two parameters are not directly related, but in general, a small  $\varepsilon$  implies that  $Q_p$  is large. Approximate relations for most common wave parameters by statistical analysis are given in CEM, Part II, Chapter 1, pg 87.

Wave spectra are measured by buoys or by other wave gages. These are archived commonly as bulk parameters. In instances where wave spectra are needed as input for wave transformation modeling, these parameters need to be converted back to spectral form. For this purpose, theoretical wave spectra (parametric spectrum models) developed by validating with measured data may be used. Two commonly used parametric model spectra are the single parameter Pierson-Moskowitz, PM spectrum (Pierson and Moskowitz; 1964), and the five-parameter JONSWAP spectrum (Hasselmann et. al.; 1973, 1976). In the JONSWAP model, three of the parameters are usually held constant. Other parametric spectral models which are essentially derivatives of the above two spectra are given in CEM (2003).

Wave energy spectra change from deep to shallow water due to the effects of depth and the interaction between the spectral components. It can be a simple reduction of wave energy in each of the wave frequency bands without change in the spectral shape, or a different spectral shape due to energy being transferred to different frequencies. Typically, high frequency portions of the spectrum decrease more rapidly owing to limitation on wave steepness, and a depth-dependent maximum can be applied for frequencies above the peak frequency. Bouws et. al. (1984) proposed a variation to the JONSWAP energy spectrum called the TMA (Texel, Marsen, and Arsole) spectrum to represent the wave spectra in finite-depth water. Also, energy can move into the lower frequency bands in the surf zone, frequently called infra gravity waves and often associated with wave groups and wave crossings.

#### **A-1.2.3.3 Directional Spectra**

Directional (or two-dimensional) spectra  $S(f, \theta)$  show the distribution of wave energy as a function of frequency and direction. These are essential input for advanced wave propagation models, and are increasingly available through recent wave measurement programs or global scale model (WAM, WaveWatch III, etc.) outputs.

If wave directional spectra are not available but are required as input to another model or for smoothing out the artificial wave energy focusing effects, an approximate method can be applied using directional spreading functions. This is a semi-parametric approach for generating directional wave spectra. Goda (1985) discusses a couple of functions including the Mitsuyasu type (Mitsuyasu et al., 1975). Directional distributions typically become more focused with propagation into shallow water owing to refraction and wave / wave interactions.

#### **A-1.2.3.4 Groups and Infra-gravity Waves**

Long wave motions on the order of 30 sec to several minutes contain a considerable portion of the surf zone energy. These motions are termed infragravity waves (USACE CEM, 2003).



Bounded long waves are one type of infragravity waves related to wave groups. The mean water level is lowered at the higher waves of the group while it is raised at the lower waves of the group and that forms the oscillation of water level at group wave period. The oscillation is not free, but is bounded to the group and travels at the group speed (USACE CEM, 2003).

Although energy spectra at incident wave frequencies are usually saturated due to breaking, at infragravity frequencies, the energy density can increase linearly with increasing wave heights offshore. Therefore, infragravity energy becomes considerable part of energy during storm conditions.

#### **A-1.2.3.5 Breaker Parameters**

The ratio of breaking wave height ( $H_b$ ) to the equivalent deepwater wave height ( $H_o'$ ) is frequently called the breaker height index. Breaking wave height and the breaking depth ( $db$ ) are functions of the bottom slope and wave steepness (ratio of wave height to wave length). SPM (1984) provides curves to obtain breaker index given the wave steepness and beach slope. Goda (1985) provides guidance on calculating depth-dependant wave height distributions.

#### **A-1.2.4 Radiation Stress**

Radiation stresses arise because of the excess momentum flux due to the presence of waves. Radiation stresses can be used to calculate Wave Setup.

### **A-1.3 WAVE REFRACTION AND DIFFRACTION METHODS**

#### **A-1.3.1 Method Selection**

A range of techniques is available for transformation of waves from deep to shallow water. The type of bathymetry is a key parameter in selecting the appropriate method. The simple techniques can be applied in the case of simple bathymetry (straight and parallel) to account for wave shoaling and refraction (for offshore waves arriving at an angle to the shoreline). However, the randomness and directionality of waves may need to be addressed in complex sea states, using an offshore spectrum to transform all component waves in the spectrum and use superposition to obtain wave conditions in finite water depths, in order to model storms and extreme events. Model selection is subject to the key parameters of input/output, bathymetric features, and wave characteristics. Guidance on methods selection will be provided in the *G&S*.

#### **A-1.3.2 Simplified Methods**

The simple techniques can be applied in the case of simple bathymetry (of straight and parallel contours). These would be hand calculations or simple graphical methods.

### **A-1.3.2.1 Refraction by Snell's Law**

The path traced by the wave orthogonal as wave crest propagates onshore is called a wave ray. Simple wave propagation problems can readily be visualized by construction of wave rays manually or by graphical techniques. In the case of straight and parallel contours, and for monochromatic waves the Snell's law ( $\sin \theta / C = \text{constant}$ ) can be applied to draw the path of the wave ray.

In addition, the wave height variation can be estimated by considering two closely spaced wave rays. Assuming no transfer of energy takes place across the wave ray boundary, wave height at any location along the wave ray is given in terms of the offshore wave height, shoaling and refraction coefficients. These coefficients can be calculated in terms of the water depth and the orthogonal distance between wave rays at the location of interest. The Coastal Engineering Manual (USACE CEM, 2003) provides solution nomograms (Figure II-3-6) which are also automated in the Automated Coastal Engineering System (ACES) program.

### **1.3.2.2 Linear Refraction**

If the bathymetry has variations along the shore then the simple Snell's law approach cannot be made but a 2-D- wave ray approach has to be used. The ray approach for wave refraction has had problems caused by wave ray crossing, at which point wave height becomes infinite. These problems are caused by the fact that each ray is traced independently of the other rays. Some numerical methods overcome this problem by artificial smoothing techniques. Results need to be checked for signs of wave ray crossings (Caustics) and in that event a simple refraction-diffraction model is more appropriate.

### **A-1.3.2.3 Graphical Diffraction**

Graphical Diffraction methods are available in SPM (1984); Goda (1985); and CEM(2003). Methods include monochromatic and simplified spectral approaches. These methods can be applied relatively easily and are reliable for most cases. A description of application of Goda's methods using the  $s$  factor (directional spread) will be included.

### **A-1.3.3 Refraction / Diffraction Models**

The following text provides a summary of contemporary wave refraction / diffraction analysis methods. Some are approved for use by FEMA and some are not. As part of the *G&S*, it is recommended that those not approved be applied to a test case to identify the differences in results, and that further literature review be accomplished to gauge the accuracy of the models. Alternatively, existing literature describing case studies can be used as the sole basis of evaluation. Based on the results, recommendations for approval and guidance on application will be developed and included in the *G&S*.

When waves enter into a region of shallower water (water depth is less than about one-half of the wave length), the direction of wave propagation gradually changes. These changes can cause

energy concentrations or spreading depending on the bathymetry. Sometimes when diffraction is not considered in the wave transformation method, wave heights can increase to unrealistic elevations. In reality wave heights are limited by breaking either due to depth or steepness constraints. Diffraction effects (spread of energy along the wave crest) can however, reduce the wave heights and keep it below the breaking height. For more complex bathymetry with shoals, islands or other major geological features, both refraction and diffraction need to be calculated or modeled.

A series of programs are available that deal with diffraction, in addition to modeling wave refraction and shoaling. A brief discussion of these models is available in the CEM, 2003. The CEM lists the computer programs RCPWAVE (Ebersole, 1985; Ebersole, Cialone and Prater, 1986), REFDIF1 (Kirby and Dalrymple, 1991) for monochromatic wave refraction, as available and in use by the Corps of Engineers but cautions the users to apply these models within the limits of their use.

FEMA pre-approved RCPWAVE is a steady-state linear wave model based on the mild-slope equation and includes wave breaking. The program is limited to open coast areas without structures or islands etc. A comparison of wave refraction and diffraction models was performed by Maa et al., (2000) based on the performance of wave transformation across the elliptic shoal experiment carried out by Berkhoff et al (1982), and RCPWAVE performed poorly in simulating the wave height distribution and wave direction. Therefore this model may be inadequate in modeling areas with sand shoals and other complex bathymetry.

The California Data Information Program (CDIP) has applied a linear, spectral back-refraction model along the California Coast. Detailed application of this model has included verification using directional wave data collected at deep and shallow water wave gauges. Very good results have been obtained. See the write-up for Topic 7: California Regional Wave Transformation Models for a more complete description.

REFDIF1 is a steady-state model based on the parabolic approximation solution to the mild-slope equation. Although this model is not pre-approved by FEMA, it is known to provide more accurate wave heights than from the RCPWAVE model in certain bathymetric situations (Maa et. al. 2000). However, if the study domain has complicated geography and/or bathymetry, or if there is a strong wave diffraction and /or reflection, elliptic mild slope models are appropriate.

MIKE 21 EMS is based on the numerical solution of the Elliptic Mild-Slope equation formulated by Berkhoff (1972) and is capable of reproducing the combined effects of shoaling, refraction, diffraction and back-scattering. Energy dissipation, due to wave breaking and bed friction, is included as well as partial reflection and transmission through, for instance pier structures and breakwaters. MIKE 21 EMS can be used to study wave dynamics in smaller coastal areas and in harbors. The Module is particularly useful for the detection of harbor resonance and seiching due to, for instance, long-period swell.

The extended mild-slope models may be more appropriate for steep and rapidly varying bathymetry. These models are computationally expensive and therefore only applicable to smaller areas.

#### **A-1.3.4 Spectral Refraction Models**

##### **A-1.3.4.1 STWAVE**

Developed by the U.S. Army Corps of Engineers (USACE) Waterways Experiment Station (WES), STWAVE is a steady state, spectral wave transformation model, based on the wave action balance equation. A wave action approach can handle a current correctly where as an energy spectrum approach cannot. STWAVE is able to simulate wave refraction and shoaling induced by changes in bathymetry and by wave interactions with currents. The model includes wave breaking based on water depth and wave steepness. Other features of STWAVE include wind induced wave growth, and influences of wave white capping on the distribution and dissipation of energy in the wave spectrum.

STWAVE is most applicable to wave transformation problems where the following assumptions can be made:

- ④ Mild bottom slope and negligible wave reflection.
- ④ Spatially homogeneous offshore wave conditions with steady state wave, current, and wind conditions.
- ④ Linear wave refraction and shoaling with negligible effects from bottom friction

Wave energy dissipation due to propagation over shallow areas (bottom friction and viscous damping effects) are not included in the standard version of STWAVE; however, a version that addresses dissipation is being used by the Corps of Engineers (personal communication, Resio at Workshop 2) and other versions have been developed and used by others (see write-up for Topic 9: Wave Energy Dissipation over shallow, flat bottoms) with good results.

##### **A-1.3.4.2 SWAN**

The numerical wave transformation model SWAN was developed at Delft University of Technology, Delft, The Netherlands. SWAN and STWAVE have many similarities. Like STWAVE, the formulation of SWAN is based on the spectral wave action balance equation. This model currently has many well developed features, which give the user many options on how each model run is executed. These features range from purely convenient options that allow several different formats for input and output data, to options that allow control of fundamental physical processes in the model, like wave generation, dissipation, and interaction. Linear wave refraction and shoaling are included in the model. Some differences from STWAVE are:

- ④ Input wave conditions can be varied spatially along open boundary, and wind, water level elevation, and current inputs can be varied spatially over the entire computational domain.
- ④ Simulations may be steady state or dynamic. SWAN has the ability to compute a time varying solution, rather than just a series of steady state solutions.

Users of SWAN must consider the following model assumptions in a specific application:

- ④ SWAN does not model wave diffraction or reflection, and is therefore most useful in applications where accuracy of the computed wave field is not required in the immediate vicinity of obstacles.
- ④ Mild bottom slope with negligible wave reflection

#### **A-1.3.4.3 REF/DIF S**

REF/DIF S was developed at the Center for Applied Coastal Research, at the University of Delaware. This spectral wave transformation model is a further development of the REF/DIF 1 model, which solves for monochromatic waves only. REF/DIF uses the parabolic form of the mild-slope equation, and the complex amplitude of each separate wave component. Because the mild-slope form of the governing equation is used, the model includes the effects of wave diffraction, unlike STWAVE and SWAN.

#### **A-1.3.4.4 Alternatives to Spectral Models**

If the wave-wave interactions can be ignored, the simple method of “energy transfer functions” can be used to construct the nearshore wave energy spectrum at a specified location, for any given off-shore spectrum. The procedure involves calculating the response matrix using a linear refraction-diffraction model with a unit incident wave height (or amplitude) for the range of wave frequencies and directions. The transfer functions need to be calculated only once since the refraction-diffraction model is linear. The response to any desired incident directional spectrum is then constructed by appropriately weighting each discrete component. This method has been used by O’Reilly and Guza (1991, 1993) for wave predictions in an analytical circular shoal configuration and at Southern California locations. They use the spectral refraction model of LeMehaute and Wang, (1982) and a spectral refraction-diffraction model (linear version of the higher order PEM derived by Kirby 1986a, Kirby 1986c, and Kirby and Dalrymple, 1986 ). The California Data Information Program (CDIP) has applied a linear, spectral back-refraction model along the California Coast. Detailed application of this model has included verification using directional wave data collected at deep and shallow water wave gauges. Very good results have been obtained. See the write-up for Topic 7: California Regional Wave Transformation Models for a more complete description.

#### **A-1.3.4.5 Use of Directional Spreading Functions**

Wave directional spectra are not available as output from many of the above discussed models. In such a situation, if wave directional spectra are required as input to another model or for smoothing out the artificial wave energy focusing effects, an approximate method would be to use directional spreading functions. This is a semi-parametric approach for generating directional wave spectra. Goda (1985) discusses a couple of functions including the Mitsuyasu type (Mitsuyasu et al., 1975).

### **A-1.4 WAVE SHOALING AND BREAKING**

#### **A-1.4.1 Method Selection**

Adequate information exists in the literature to complete the following *G&S* for Wave Shoaling and Breaking. Method selection is mainly based on wave characteristics and morphology.

#### **A-1.4.2 Linear Shoaling**

Waves slow down in entering shoaling water and consequently wave height increases and sometimes decreases depending on group/phase velocity relations. The change in wave height due only to the change in wave group velocity is referred to as shoaling. Linear shoaling assumes the waves are of small amplitude and therefore the linear wave theory can be used to derive the shoaling coefficient ( $K_s = H/H_o$ ) by equating the offshore wave power to the wave power at any nearshore location (before breaking). When other processes such as wave refraction, diffraction, and dissipation are involved in the transformation process, equivalent deepwater wave height is used instead of the deepwater wave height, in the shoaling equation ( $K_s = H/H_o'$ )

#### **A-1.4.3 Non-Linear Shoaling**

As waves approach very shallow water, several wave lengths seaward of breaking, shoaling becomes highly non-linear and the linear shoaling coefficient may significantly under predict the wave height, especially for long waves in shallow water. Non-linear shoaling coefficients are available in several publications, which relate shoaling coefficients to parameters of wave steepness, relative depth and beach slopes (Goda, 1985, SPM and others).

#### **A-1.4.4 Breaking Indices**

In shallow water breaking is limited by water depth and the point of breaking is influenced by wave steepness and beach slope. Simple wave breaking indices for regular and irregular waves are discussed in the CEM(2003), Part II-4.

A breaking wave model (series of equations) that operates on a site-specific nearshore profile (one-dimensional) is needed to calculate wave setup, as described in the Focused Study report for Setup (see in particular Topic 51 Interim Approach, and also Topics 44 through 48). The breaking wave model should be adequate to calculate wave radiation stress through the surf zone

for irregular wave conditions. The wave radiation stress is used to calculate wave setup. Guidance is also needed for the dynamic component of wave setup, using available information. The breaking wave model shall be applicable for the Gulf, East and Pacific Coasts, including sheltered waters, but is critical for the Pacific Coast.

#### **A-1.4.5 Spectral Transformations**

Vincent and Briggs (1989) showed by their lab experiments that wave transformation over a shoal is sensitive to the shape of the incident wave directional spectrum and differ significantly from a single unidirectional wave. Therefore, the approach of defining a single wave height to represent the offshore spectrum and using this wave height in the unidirectional wave transformation models does not prove to be satisfactory when shoals and complex bathymetries exist.

Transformation of incident wave frequency-directional spectra can be achieved by combining multiple model runs, each for a single frequency and direction (Izumiya and Horikawa, 1997 and Panchang et. al., 1990). These spectral models do not explicitly predict the directional spectrum but have been used to estimate the directionally integrated energy to determine the wave height.

### **A-1.5 WAVE ENERGY DISSIPATION, NON-BREAKING**

#### **A-1.5.1 Method Selection**

Method selection will be based on bed and wave conditions and or region and other site conditions, as described in the write-up for Study Topic 9: Wave Dissipation over Shallow, Flat Bottoms. To the extent practicable, coefficients will be provided for the described methods based on published data. Where data are not adequate to calculate wave dissipation, calibration will be recommended.

#### **A-1.5.2 Friction**

Friction related energy dissipation occurs mainly in shallow water (Tubman and Suhayda, 1976). The friction effect varies with the type of bottom material and also as a function of wave parameters, relative depth, propagation distance etc. Guidelines for selection of criteria will be addressed under study topic 9.

#### **A-1.5.3 Viscous Bottom**

Unlike friction related dissipation, which occurs mostly in shallow water, soft (flexible) bottom dissipation cause significant wave attenuation in intermediate water depths.

Suhayda (1984), documents the use of a numerical model to develop wave crest elevation attenuation coefficients by simulating the effects of wave generation by wind; shoaling; and dissipation due to breaking, bottom friction, and soft muds during extreme hurricanes. The author models wave height/energy to change exponentially with distance along the wave travel

direction. To compute its effects on wave dissipation, he models the soft muddy bottom as a visco-elastic medium, in accordance with MacPherson's (1980) model. The results summarize wave height to water depth ratios in the range of 0.42 to 0.78 for the 21 transects, that he used in this study.

#### **A-1.5.4 Marsh Vegetation**

*G&S* Appendix D (2002) considers marsh vegetation (pg. D-72 to D-80) under description of the WHAFIS 3.0 model. Eight parameters are used to describe the dissipation properties. This procedure was specifically developed for the Gulf and Atlantic Coasts. Applicability of these guidelines for the Pacific Coast wetland areas, need to be explored. Also see the section "Method for wave attenuation in Pacific marsh conditions" under Topic 9.

#### **A-1.6 WAVE PROPAGATION OVER INUNDATED LAND AREAS**

This condition is commonly observed in the US East Coast, and WHAFIS 3.0 approved by FEMA is applied in the present FIS. Although not common, overland wave propagation can be significant in marshes surrounding bays ( e.g., San Francisco Bay). The changes to wind characterization may be necessary to use the WHAFIS model for the Pacific conditions.

Continuation of the two-dimensional wave transformation models into the inundated regions may be the next step of improvement. However, application of two-dimensional models may be constrained by data availability. The *G&S* will address use of WHAFIS for Pacific Coast FIS, based on the write-up for Study Topic 10: Overland Wave Propagation, Candidate Improvements to WHAFIS. Extensive *G&S* exist for application of WHAFIS to the Gulf and Atlantic Coast FIS, with additional guidance in the Topic 10 write-up.