PROPOSED OAHU TSUNAMI HAZARD ZONE
NATIONAL FLOOD INSURANCE PROGRAM

By
Doak C. Cox

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PROPOSED OAHU TSUNAMI HAZARD ZONE
NATIONAL FLOOD INSURANCE PROGRAM

By Doak C. Cox

Summary

In some aspects, the methodology used in establishing the proposed limit of the tsunami hazard zone for the national flood insurance program quite possibly represents significant improvements over the methodology used previously to establish potential tsunami inundation limits to guide evacuation on tsunami warning occasions. However, the historic runup data used in developing the criteria for establishing the newly proposed limits have been misidentified and misused in the criteria for hazard zone determination for flood insurance purposes. In general, correct usage would result in establishing limits further inland. Reconsiderations of the methodology, criteria, and proposed limits is recommended.

Introduction

Modifications of the zoning code and other regulations of the City and County of Honolulu (and presumably other counties as well) are under consideration to bring them into conformity with the requirements of the 1973 federal Flood Disaster Protection Act. The modifications will affect land-use and structural-design criteria in a proposed flood hazard district, whose boundaries are shown in maps now accessible for public review. From a report prepared for the federal Flood Insurance Administration (Towill Corp., 1976), it appears that the flood hazard district includes two zones supposedly subject to stream flooding, and a zone along the coast subject to marine flooding.

One of the stream-flood zones is comprised by the floodways; the other consists of the rest of the floodplain. Following federal usage (Flood Insurance Administration, 1976) the marine-flood-hazard zone has been referred to in an explanatory publication (Oahu Dev. Conf., 1976) as the Coastal High Hazard District, although this terminology does not appear in the Towill Corp. report.

In the establishment of a marine-flood-hazard zone, consideration should appropriately be given to the combined hazards of tsunamis, storm waves, and storm surges. Hawaii is relatively immune from storm surges. Hawaii is relatively immune from storm surges, so that these may be disregarded in zoning for insurance purposes. On most Hawaiian coasts the hazard from large tsunamis, those with average recurrence frequencies of one per century or less, extends farther inland than the hazard of storm waves of similar frequencies, although for higher frequencies the extent of storm-wave hazard is greater on many coasts. Hence on most coasts, but perhaps not all, the hazard of tsunami inundation should determine the limits of the marine-flood-hazard zone. In
any case, it appears, from the Towill Corp. report and other documents, that the limits of the marine-flood-hazard zone, as proposed for use in the federal flood insurance program, have been determined on the basis of the tsunami hazard alone. Hence, this zone will be referred to in this report as the proposed tsunami hazard zone as well as the Coastal High Hazard District.

I began the study leading to this paper, when certain misapplications of historic tsunami data came to my attention in the environmental impact statements on a few coastal developments. The misapplications were attributed to criteria being used to define the tsunami hazard zone for the federal flood insurance program.

First drafts of this paper, equivalent essentially of what is now the body of the paper, consisted of a brief critique of the methods used to outline tsunami hazard zones. In the appendices, which were added later, I have tried to suggest alternative ways of using or improving on these methods, and as a basis for possible improvements have discussed the desiderata and available information in greater detail.

Various drafts of this paper have been submitted for review to Ronald Pulfrey of the U.S. Army Corps of Engineers, to Arthur Muraoka of the City and County of Honolulu Department of Land Utilization, to several members of the joint NOAA-University of Hawaii tsunami research effort at the Hawaii Institute of Geophysics, and to other persons who have been involved in tsunami runup measurement programs in the past. Their criticisms have resulted in the corrections of several factual details. However, I must take full responsibility for the conclusions expressed in the paper. A report by Taniguchi (1973) describing a hydrodynamic method for projecting tsunami heights came to hand after I had distributed the last draft of this paper for review. Hence I must take entire responsibility for my comments on the hydrodynamic means of analysis, its present limitations, and its potentials.

This paper deals exclusively with the marine flood hazard, and almost exclusively with the tsunami hazard, and not with the other hazards recognized in the proposed flood hazard district.

Previous tsunami hazard zoning

Prior to 1961, the only approach to a definition of a tsunami hazard zone in Hawaii was the indication by the U.S. Coast and Geodetic Survey that, on tsunami warning occasions, the coasts should be evacuated to an elevation of 50 feet above sea level. Although the indication was repealed by County Civil Defense Agencies, this evacuation limit criterion was not generally known by residents of the coastal zone. In 1961, recognizing that a definitive evacuation zone should be established, and that the 50-foot criterion would result in far more extensive evacuation than was justified, or could even be accomplished, the newly established Tsunami Research program of the Hawaii Institute of Geophysics (HIG) identified what were called Potential Tsunami Inundation Areas (Cox, 1961).
As recommended by the HIG, the boundaries of these areas were subsequently adjusted slightly by the State Civil Defense Division and County Civil Defense Agencies to make them more easily identifiable by the public, and the resulting Tsunami Evacuation Areas were adopted for use in the tsunami warning system. Maps of these areas have been for many years published in annual telephone directories (eg. Hawaiian Telephone Co., 1976).

The limits of potential tsunami inundation were based on the recorded runup heights and inundation limits of four tsunamis, those of 1 April 1946 from the eastern Aleutian Is., 4 November 1952 from Kamchatka, 9 March 1957 from the central Aleutian Is., and 22 May 1960 from Chile. The potential limits were not considered, however, as tight envelopes about the recorded heights and inundations. It was recognized that tsunamis from different source areas and with different periods, even if of no greater magnitude, would have inundation limits differing from, and in some areas lying inland of those of the tsunamis for which records were available.

After trial of several models, a simple model of potential tsunami inundation was adopted which was based on assumed tsunami energy levels just offshore, and assumed rates of energy dissipation and reflection with distance inland. In general a +50-ft. energy level was adopted at the -10 ft. msl contour, and it was assumed that the energy surface would have a 1 percent downward inland slope. The construction is illustrated in figure 1. However, a 30-ft. energy level was adopted for coasts facing southwestward, a direction from which significant tsunamis had not been historically recorded; a correction was made for the effects of extensive shallow water deeper than 10 feet; and modifications were introduced to account for effects at bays with narrow mouths.

Fig. 1 Typical inundation pattern in a valley fronted by a dune ridge and reef, showing means of construction of limit of potential inundation. (From Cox, 1961)
The resulting limits were found to lie somewhat inland of all recorded inundations except at a few places where tight envelopes about the recorded observations had to be substituted for the model results.

**Proposed tsunami zoning**

The official report prepared for the federal flood insurance program on Oahu (Towill Corp., 1976) discusses the establishment of the tsunami hazard zone as follows:

The method for deriving the tsunami inundation limits for various frequency of occurrences was proposed in a short report entitled, "Tsunami Studies for Oahu, Hawaii." This report was coordinated through the following departments of the City and State.

**City - Oahu Civil Defense Agency**
- Department of Public Works
- Department of Land Utilization
- Building Department

**State- Department of Land and Natural Resources**

It was indicated in the report that this method of determining tsunami inundation limits may be refined by future studies. No adverse comments were received for use of this tsunami method in the Flood Insurance Study on this basis.

A copy of the cited short report entitled "Tsunami Studies for Oahu, Hawaii" (Towill Corp., 1975) was kindly supplied me by the U.S. Army Corps of Engineers. The following discussion of the methodology is based on that earlier report because that report provided more detail than the official report.

The historical records on which the proposed tsunami hazard zone were based were runup heights recorded in a Catalog of Tsunamis in the Hawaiian Islands (Pararas-Carayannis, 1969) for the same four tsunamis as those used by the HIG, plus the tsunami of 27 March 1964 from Alaska. The envelope of these runup heights, neglecting certain heights that were considered non-representative, and considering the nature of tsunami exposure in filling in gaps, was considered as a "shoreline elevation profile." The profile and data points used in its definition are shown on a diagram in the 1975 report and also in the official 1976 report.

Runup-height/probability curves were constructed for seven coastal areas based on the records of the 5 tsunamis above noted, and for Honolulu on the basis of 43 annual values recorded since 1837 in the Hawaiian Catalog. By reference to these, and to an additional 139-year runup height/probability curve for Hilo, it was estimated that the equivalent of a "shoreline elevation
profile" for a 100-year tsunami would be 1.25 times the height of the profile established on the basis of the 5-tsunami record.

The results of using a 1 per cent downward inland slope, as adopted in the HIG report, were compared with the results of using a more elaborate computation based on roughness and the nature of tsunami runup that was proposed by Taniguchi (1973) for use in the County of Hawaii. Since the results were similar, the simple 1 per cent slope criterion was applied to the 100-year shoreline height profile to define the inland limits of the tsunami hazard zone.

The resulting maps of the hazard district are now being reviewed, and samples have been published (ODC, 1976).

General rationale for differences

For several reasons, the boundaries of the proposed Coastal High Hazard District should be expected to differ from the HIG potential tsunami inundation limits and limits to the Civil Defense tsunami evacuation areas.

1. The HIG lines were intended to serve as a basis for definition of the limits to which persons should evacuate the coast on occasions of tsunami warnings, and the Civil Defense lines were drawn to serve directly as such limits. The now-proposed lines are intended to serve as the boundary for a district within which there are restrictions as to land use and structural design. The HIG and Civil Defense limits were not associated with any explicit tsunami inundation frequency, but in consideration of public safety should have reflected a frequency of less than once in 100 years. The now-proposed lines refer explicitly to 100-year events. It is therefore expectable that the evacuation limits should lie somewhat farther inland than the limits to special controls of land use and structural design (particularly as it is now recognized that the evacuation need only be from lower floors of substantial high buildings).

2. The HIG and Civil Defense lines were drawn when only 14 years of tsunami height record were available for most coastal areas, and before the longer records of Honolulu and Hilo had been compiled. Thirty years of record are now available for most coastal areas of concern, and tsunami-height probability relations have been established for 139-year records at Honolulu and Hilo. Reasonably reliable extrapolation from the periods of record to 100-year events, or events of even lower frequency, is thus possible now.

3. Considerable study of tsunamis and their effects has been made since 1961, and should be expected to result in better definition of the limits of probable inundation.

Considering the different functions intended to be served by the Civil Defense tsunami evacuation area and the now-proposed coastal hazard district, it seems appropriate that there be differences in detail between the criteria used in defining the two types of zones. However, it seems clear that zones
reflecting any particular hazard should be based on common historical data, particularly when the pertinent historical data are so limited as is the case with tsunamis. Without compelling reason to the contrary, it would also seem that the analytic methodologies in the case of zones defined for various purposes should be similar even though there would be differences in some standards.

In the light of increases in the period of historical record and the level of understanding of tsunamis, it is clearly appropriate to reexamine the HIG-Civil Defense methodology for tsunami zone delineation. However, the methodology most recently proposed should not be free from critical review. The fact that the Coastal High Hazard District based on this methodology has been proposed for adoption in the near future justifies a high priority for the criticism of this latter methodology.

Criticism of proposed boundary criteria

In several respects the criteria that have been used to determine the boundary for the Coastal High Hazard District are questionably appropriate, and in one particular they are based on an erroneous assumption.

1. Clearly erroneous in principle, and perhaps most misleading in effect, is the assumption that the envelope of recorded runup heights defines a profile of wave height (or head), with reference to mean sea level, at the shoreline ("shoreline elevation profile"). There are actually three assumptions involved: i) that the runup heights were measured at the shoreline; ii) that the runup heights were measured from mean sea level; and iii) (implicitly) that the runup heights are direct indications of incident tsunami wave energy.

Very few, if any, of the runup heights of the tsunamis of 1946, 1952, 1957, or 1960 were measured at or near the shoreline. They actually represented the elevations of debris, damage, swash marks, etc., at points inland, and in many cases at the limits of inundation. The equivalent heights at the shoreline would thus in general be higher by 1 per cent of the distance from the point of measurement to the shoreline, if the 1 per cent slope were applicable. As recorded, the runup measurements of a tsunami have referred to heights above tide level at the time of arrival of the tsunami, not to heights above sea level.

The erroneous treatment of the recorded runup heights results in seaward displacement of the 100-year inundation limit seaward from its proper position, and may even result in its placement seaward of the inundation limit of a historical tsunami, as is indicated by the example illustrated in figure 2. The assumptions used in this example are shown in table 1, together with values calculated by the proposed (Towill) criteria, and corrected values. In this example, the maximum runup is assumed to have been measured from mean sea level. The error would be even larger than indicated if the maximum runup have been measured from a higher tide level.
Explanation: Maximum historic inundation limit
Maximum historic shoreline head
100-year shoreline head
100-year inundation limit
Proposed construction line
Corrected construction line

Figure 2. Example of estimation of tsunami inundation limit illustrating differences between proposed and corrected methods

Table 1. Example of assumed and calculated values in estimation of tsunami inundation limit illustrating differences between proposed and corrected methods

**Assumptions**

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Max. historic runup height</td>
<td>10 ft., msl</td>
</tr>
<tr>
<td>Location of historic runup height</td>
<td>At limit of inundation</td>
</tr>
<tr>
<td>Ground slope</td>
<td>2% upward inland</td>
</tr>
<tr>
<td>Tsunami head slope</td>
<td>1% downward inland</td>
</tr>
<tr>
<td>Max. historic inundation extent</td>
<td>500 ft., msl</td>
</tr>
</tbody>
</table>

**Calculated values**

<table>
<thead>
<tr>
<th>Calculated value</th>
<th>By proposed method</th>
<th>Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. historic shoreline head</td>
<td>10 ft., msl</td>
<td>15 ft., msl</td>
</tr>
<tr>
<td>Max. 100-yr. shoreline head</td>
<td>12.5 ft., msl</td>
<td>18.8 ft., msl</td>
</tr>
<tr>
<td>100-yr. inundation extent</td>
<td>417 ft. inland</td>
<td>627 ft. inland</td>
</tr>
</tbody>
</table>
The significance of the implicit assumption that runup heights are direct indicators of incident tsunami energy will be discussed later.

2. The criteria make no specific allowance for differences in the patterns of runup and inundation resulting from differences between the directions of approach and periods of possible future tsunamis and those of the tsunamis of record. The differences in pattern may be substantial. For example, the greatest recorded tsunami height at Haena, Kauai was that of the major 1946 tsunami from the eastern Aleutian. The height of that tsunami at Wainiha was lower, and the heights at Hanalei lower still. Yet the smaller magnitude 1957 tsunami from the central Aleutians, resulted in a record 53 ft. runup at Wainiha, and in considerable damage at Hanalei where no damage had occurred since about 1910.

The need for allowance for differences in pattern is considerably less now, when 30 years of record is available for most coasts, and 139 years of record for Honolulu and Hilo, than it was in 1961. The use of the 1.25 factor for estimating 100-year heights from local historical maximum heights may eliminate the need, but this should be reconsidered.

3. The criteria make use of recorded tsunami runups as published in the Hawaiian tsunami catalog rather than as available in original publications or as compiled in manuscript maps at the Hawaii Institute of Geophysics.

4. In the criteria, certain runup heights were eliminated as not representative. A height recorded on an undeveloped promontory, for example, might legitimately be regarded as unrepresentative of runup heights on the adjacent developed coastline, but few recorded heights can be considered unrepresentative of the effects of a tsunami in the adjacent area. The grounds for rejection of any recorded height should be carefully reviewed.

5. The Hilo runup height/probability plot used in the criteria is one presented by the Corps of Engineers in 1973. No reference is made to a plot issued by the HIG on the basis of an exhaustive study of the Hilo tsunami history (Cox, 1964), or an analysis of Wiegel (1964, pp. 95-108) based on the same study. The results of the three should be compared.

6. In the derivation of the criteria, the simple 1 percent energy-loss rate derived by Cox has been compared with the slopes estimated by Taniguchi, but there is no mention of an applicable slope estimation method proposed by Bretschneider and Wybro (1975). The Bretschneider and Wybro method and that of Taniguchi actually apply to runup height slopes, not total energy height slopes.

Actual definition of Coastal High Hazard District

It is not clear at the moment whether the boundary of the tsunami hazard zone used as the Coastal High Hazard District will actually be defined by the criteria used in determining where it lies on the ground or by a set of maps. The advantages and disadvantages of the two modes of formal definition have
been discussed by the Environmental Center in the case of the boundaries of the Special Management Area established under the Shoreline Protection Act (Cox et al, 1975 pp. 24-27).

Even if the actual definition is to be by maps, it is essential that the criteria used in the preparation of maps proposed for adoption be as accessible as the maps themselves, and that final criteria corresponding to the boundaries on the adopted maps be formalized. There is likely to be considerable objection to the location of the boundary in detail, particularly by property owners hoping to escape the controls that will affect land use and structural design within the District. Defense against charges that the location of the boundary in any particular area is arbitrary and capricious will require that the boundary be based on standardized and accepted criteria.

A strong case can be made that the criteria should not be limited strictly to those based on the tsunami hazard discussed in previous sections, at least if the definition of the boundary of the Coastal High Hazard Zone is to be by maps. The exact location can never be defined by map position alone, because of scale limitations, and the boundary determination will be simplified if the boundary as defined by the hazard criteria is subject to minor adjustment to allow coincidence with surveyed or easily recognized features such as street center lines, property lines, etc.

Conclusions

Before the proposed Coastal High Hazard District boundaries are adopted, the criteria on which they are based should be reconsidered. Particularly suspect is the treatment of tsunami runup heights as if they were heights at the shoreline.

The criteria used in determining the proposed boundaries of the Coastal High Hazard District should be as accessible for review as the maps showing those limits, and the criteria used in determining the boundaries finally adopted should be formally documented.

The boundaries should be subject to minor adjustment before final adoption to allow them to coincide with surveyed or easily recognized features.

References


Appendix A: Further detailed comments

Desiderata for determining potential tsunami inundation

The inland limits of a tsunami hazard zone in any area should represent the inland limit of tsunami inundation (or of inundation to some prescribed depth) expectable in that area over an extended period. For warning evacuation purposes, and apparently for the purposes of the National Flood Insurance Program, it is the limit of inundation that is sought (and not the limit of inundation to a depth of, say, 1 foot or 2 feet).

Rigorous determination of the expectable limit of inundation in the area could be made only if records of the extent of successive inundations in the area were available over a period several times as long as that for which the determination was to be made. For the purposes of the National Flood Insurance Program the determination is to be made for a period of 100 years, and for tsunami warning system purposes the determination should be made for a period at least that long. However records of tsunami inundations are not available for any Hawaiian coastal area for anything even approaching a 100-year period.

Historic tsunami inundation records

There are some published records of the limits of inundation of a few tsunamis in a few areas, notably Hilo. Undoubtedly some additional scattered and generally unpublished but trustworthy records exist. Both the published and unpublished records may provide some guidance in estimating the expectable extent of tsunami inundation over an extended period.

Except at Hilo, however, the records of historic inundation extents are entirely too short and fragmentary to serve as a base from which maximum expectable extended-period inundation limits could be extrapolated, even if extrapolation of inundation/probability curves were appropriate. Inundation limits would not be directly amenable to probability extrapolation except in a region of uniform ground slope. Hence the maximum expectable extended-period inundation limits must be estimated from some other measures or indicators of maximum expectable extended-period tsunami energy incident along the coastline.

Means of synthesis in general

The two methods used or proposed for tsunami hazard-zone definition are both essentially methods for synthesizing the expectable extended-period limits of tsunami inundation. The method which I used (Cox, 1961) to delineate potential tsunami inundation areas for warning evacuation purposes may be characterized as using a single tsunami height/probability function common to all incident coastal areas. The methods now proposed (Towill Corp., 1975) to delineate the tsunami hazard zone for the purposes of insurance and control of
land use and structural design may be characterized as using a specific tsunami-height/probability function for each coastal locality. Both methods have been based on records of tsunami heights measured along Hawaiian coastlines.

In principle, other methods might be used, for example one based on tsunami magnitude/probability and tsunami period/probability functions specific to each generating area from which tsunamis affect Hawaii.

To start from a record of sufficient length to allow reliable frequency analysis, this method would have to begin with long-term records of earthquakes in generating areas. It would have to involve estimating tsunami magnitude and tsunami periods from earthquake magnitudes; determining through hydrodynamic analysis the relation between the tsunami magnitude and period and the tsunami energy incident on Hawaiian coasts for every combination of generating areas and Hawaiian coastal areas; synthesizing from these determinations the long-term maximum incident tsunami energy expectable in each coastal area; and estimating from these energies the corresponding tsunami inundations. Progress is being made in the development of the necessary analytic techniques, but the combination is far from ready for application.

Hence, attention must be focussed on the empirical Hawaiian data that lend themselves to the common height/probability function method, the locality-specific height/probability function method, or variants of these. The relationships between total shoreline head, runup height in the inundation area, and runup height at the limit of inundation have certain implications as to methods for estimating shoreline tsunami heads from measured runups heights, and estimating inundation limits from estimated shoreline heads. These implications will be discussed later. It is first necessary to discuss the nature of the tsunami runup records available and their relation to incident tsunami energy.

Tsunami runup and incident tsunami energy

It must be recognized that the estimation of tsunami inundation from any measure or indicator of incident tsunami energy can be only approximate. The relationship between incident energy and inundation is non-linear and subject to both site-dependent and tsunami-dependent sources of variation. For a tsunami with uniform incident energy the extent of inundation would vary from place to place depending on ground slope and roughness and the surface configuration above and below sea level. At the same place, the inundation of tsunamis of equal incident energies would vary with the direction of tsunami approach and the period of the incident tsunami waves.

Incident tsunami energy is not directly measurable. For comparison with runup heights, incident wave energies may be expressed as heads above sea level in linear terms. However runup heights can serve only as indicators of incident energies, rather than direct proxies. The runup height of a wave moving inland is a measure of the total energy of the wave only at the limit of inundation, where the velocity and depth of water are zero. At any point seaward of this limit, the combination of potential head and pressure head.
are indicated directly by the height of the wave, but the third component, of head, the velocity head is not indicated by the wave height.

The sum of potential and pressure head could be measured at the shoreline, or at points between the shoreline and the inundation limit, by the runup of the wave on a pole or rod offering little resistance to the flow. However, the velocity head could be measured only if the velocity of flow could be measured throughout the depth of inundation.

The rate of dissipation of energy of a tsunami is extremely small in the open ocean, and reflections of energy are significant only where substantial changes in depth occur within distances that are on the order of the wave length or smaller. However both dissipation and reflection become very important as the waves of a tsunami move into shallow water and onto land. Through the combination of dissipation and reflection, assuming no convergence or divergence, the head at the shoreline must decrease inland, reaching a minimum at the inundation limit. At some places the runup heights measured for a tsunami have been found to increase inland. Again assuming no convergence or divergence, an increase indicates that the rate of dissipation and reflection of energy was more than offset by the conversion of velocity head to potential and pressure head.

**Hilo and Honolulu historic records**

It would be fairly simple to translate the maximum height of tsunami runup above sea level expectable over an extended period to the maximum extent of tsunami inundation over the same extended period if the former were known. Records of tsunami runups in Hawaii are available since 1819. However, at only two places, Hilo and Honolulu Harbor, are runup records sufficiently long and complete to have made long-term runup/probability analysis seem worthwhile. The records at both places date from 1837 and thus cover a period of nearly 140 years.

The Hilo record is the more complete. However, within the Hilo area there has been a considerable range of runups for each historic tsunami comprehensively surveyed, and there may be a considerable range of potential tsunami runups. The runups recorded for the Hilo area were not all measured in the same part of the area. Furthermore, the extent of protection of the Hilo area has changed over time, for example by the construction of the breakwater. Hence the record is not strictly homogeneous. As a basis for direct estimation of the potential limits of tsunami inundation, the Hilo runup records are of doubtful utility. However, as a basis for estimating potential tsunami runup, the Hilo record is probably the best available in Hawaii and possibly the best in the world, and several analyses of this record have been made (Cox, 1964; Wiegel, 1964; Corps of Engineers, 1973).

The Honolulu record, which is less complete but probably more homogeneous, has also been analyzed (Towill Corp., 1975). Except at Honolulu and Hilo, the maximum tsunami runup or head expectable over an extended period must be estimated from short-term records of historic runups.
Historic runup elsewhere: Data sources

Systematic recording of tsunami runup for Hawaiian coastal areas other than Hilo and Honolulu harbor began in 1946. On Oahu, the runups of the 1946, 1952, 1957, 1960, and 1964 tsunamis were measured (to the extent they were measurable) in many coastal areas. A comprehensive file of the records is maintained at the Hawaii Institute of Geophysics.

As tabulated in the Hawaiian tsunami catalog compiled by Pararas-Carayannis (1964), the runup heights from this file have been reduced to meters and their locations are indicated by geodetic coordinates. The joint tsunami research effort at the Hawaii Institute of Geophysics has recognized the need for systematic publication of the entire file of records. Plots, on a scale of 1/62,500, of the measurements, in feet, have been prepared for the publication (Loomis, in press).

A comparison of the catalog tabulation and these new plots for a sample of the Oahu coast indicates differences in location, differences in height, and either omissions or erroneous insertions of measurements in one source or the other. To be used in as important a process as the definition of a tsunami hazard zone for evacuation or for flood insurance purposes, the runup heights should be checked against original sources, unless the discrepancies between the Loomis plots and Pararas-Carayannis tabulations are reconciled by such checking and corrected.

Historic runups elsewhere: Datum planes

The runups for each of the tsunamis of 1946, 1952, 1957, 1960, and 1964 were generally measured from tide level at the time of measurement but corrected to height above tide level at the time of the tsunami. Adjustment to convert the runup to height above mean sea level may be derived from tide conditions at the time of each of these tsunamis as summarized by Loomis (in press). The corrections are shown in table A-1 only to the nearest foot because the measurements themselves are of no greater accuracy.

Table A-1. Adjustments to correct recorded runup measurements to msl runup heights

<table>
<thead>
<tr>
<th>Tsunami</th>
<th>Tide at arrival time</th>
<th>Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1946</td>
<td>0.5 ft m11w, falling</td>
<td>- 1 ft.</td>
</tr>
<tr>
<td>1952</td>
<td>1.0 ft m11w, falling</td>
<td>0 &quot;</td>
</tr>
<tr>
<td>1957</td>
<td>2.5 ft.m11w, falling</td>
<td>+ 1 &quot;</td>
</tr>
<tr>
<td>1960</td>
<td>high tide</td>
<td>+ 1 &quot;</td>
</tr>
<tr>
<td>1964</td>
<td>0.5 ft m11w, rising</td>
<td>0 &quot;</td>
</tr>
</tbody>
</table>
None of the runup measurements were made at the shoreline. Except where the inundation did not reach the beach berm, no runups were measured on beach fronts. In the case of each of the tsunamis occurring from 1946 through 1960, and probably in the case of the 1964 tsunami as well, many of the runups were measured at the limit of inundation of the tsunami, or so close to it as to be essentially equal to elevations of that limit. Where the inundation was extensive, however, the runups were often measured on buildings, trees, etc., between the beach berm (or its equivalent on a rocky coast) and the limit of inundation, and, according to memory, usually within a few hundred feet of the berm. Where there were dunes with lower land inland, the runups were commonly measured on the seaward side of the dunes, or at the limits of inundation where the water swept round the dunes to flood the lower land in back. In a few places, more than one runup was recorded along a profile transverse to the shoreline.

Unfortunately the exact locations of the runup measurements are not identified in the HIG map file; in general they were not recorded in the publications on which the map file is based; and probably in most cases they were not identified in the field notes or field maps. Several of the field maps are or were stored at HIG, but most of the field notes would be difficult or impossible to recover. If a runup measurement corresponded to the elevation of the ground within, say, 300 feet of the shoreline, it can reasonably be assumed that it corresponded to the elevation of the runup limit. Otherwise, in the absence of an identification of this location, the most reasonable simple assumption would be that the runup was measured, say, about 200 feet inland of the shoreline.

(From averages of measurements during summer and winter conditions on 27 beach profiles plotted in Moberly and Chamberlain, 1964 (Hawaiian Beach Systems, HIG 64-2, Appendix A) it appears that the average distance from the mean-sea-level shoreline to the inland limit of annual beach instability for Oahu beaches is about 115 feet. The average distance to the edge of land vegetation may be assumed approximately equal to that distance, on rocky as well as beach shorelines. A runup height that was not measured at or near the limit of inundation may be assumed to have been measured within 100 feet inland of the vegetation line and hence, on the average about 200 feet from the mean-sea-level shoreline.)

The synthesis problem

The problem then consists of synthesizing the long-term limits of tsunami inundation, along the entire coast of an inland like Oahu, from the meager and scattered records of historic inundations for a few places, the long-term but not strictly homogeneous records of tsunami runup at Honolulu and Hilo, and the much more numerous but also non-homogeneous short-term records of historic runups elsewhere. This synthesis requires a combination of probability extrapolation from short to long period records; translation of runup heights to total heads; translation from heights or heads to horizontal inundation extents;
projection from heights or heads measured in one part of inundation area to another part; and geographic interpolation, extrapolation or generalization, from areas where inundations or runups were recorded to other areas.

Some comments may be made as to the order in which the analytic processes should be undertaken in the synthesis. The inundation limits in an area would not be directly amenable to probability extrapolation, even if there were a record of inundations over several decades in that area, unless the ground slope were uniform. Similarly, geographic extrapolation or interpolation from areas of known inundation limits could not be used to determine limits in which there were no inundation records unless the ground profiles were nearly identical. Hence, the geographic interpolation, extrapolation, or generalization and the probability extrapolation should be applied to the runup or related height measurements or estimates, to determine some sort of long-term expectable profile at the shoreline or offshore, and the long-term expectable inundation limits should be determined from that profile.

**Probability extrapolation**

Little need be said here about the processes of probability analysis as applied to the long-term tsunami runup records of Hilo and Honolulu. In principle the determination of rare-event probabilities is quite complicated (see for example Wiegel, 1964 or Loomis, in press). However, the procedures used by Cox (1964), Wiegel (1964), and Towill Corp. (1975) are probably adequate to the problem of interest.

The problem of probability extrapolation of the short-period runup records, available from place to place along the shoreline, merits further discussion. The records at most places are but 30 years long, and extrapolation to recurrence intervals of 100 years is, at best, uncertain. The use of the runup/probability function from the long-term Hilo records for extrapolation from the short-term records seems much more reasonable than reliance on the runup/probability functions suggested by the short-term records themselves. The extrapolation is reasonable, however, only at localities where there is a runup recorded for each of the five significant tsunamis since 1946, or where there is very little probability that any missing measurements would have exceeded recorded measurements.

Even if runup measurements were available for every historic tsunami on some single profile transverse to the shoreline, the runup heights could not be considered strictly proportional to shoreline heads, or to the horizontal extents of inundation, unless the ground slope along the profile were uniform, and unless the runup heights had all been measured at the inundation limits, the runup heights had been measured at distances from the shoreline proportional to the tsunami heads, or the rate of conversion from velocity heads to potential and pressure were exactly balanced by the rates of energy dissipation and reflection (runup heights having zero slopes inland). Hence an attempt should be made to adjust the runup measurements to make them homogeneous, for example by converting them to shoreline heads.
No recorded measurements should be omitted from the analysis without cogent reason.

**Geographic interpolation or generalization**

Interpolation between points at which long-term expectable heights can be directly estimated is justified only where the onshore and offshore terrain is essentially similar between the points. At the time of the HIG estimation of potential tsunami inundation limits (Cox, 1961), there were no points at which expectable long-term heights had been determined. Hence generalization from the entire record of runup heights for all points seemed essential. Now, perhaps, reasonable estimates of expectable long-term heights can be made for points with sufficiently close spacing to substitute interpolation for generalization. If this is indeed the case, the use of interpolation to redetermine the limits of potential tsunami inundation for evacuation purposes may be as justifiable as to determine the limits for insurance purposes.

**Height projection**

Two general methods have been used to estimate the rate of height loss or head loss with inland inundation of a tsunami wave: a generalized empirical method which I employed (Cox, 1961), and a theoretical hydrodynamic method employed by Taniguchi (1973) and by Bretschneider and Wybro (1975).

My 1961 description of the generalized empirical method is reproduced in Appendix B to this report. As will be seen by reference to that description, the method of estimation applied to the total head, not the runup height, and I estimated that the head inland would be less than the head at the -10 ft. contour by 1 per cent of the distance inland from the -10 ft. contour. I made no attempt to distinguish the effects of variable ground slope and roughness, or of variable wave length and character. Since the head loss was assumed uniform, the 1 per cent loss would be just as applicable to the head at the shoreline.

It should be noted that the assumed uniform 50-ft. and 30-ft. heads at the -10 ft. contour, and the allowances for the effects of reefs and channels, are not pertinent to a system for determining potential inundation limits that is based on potential shoreline heads. The potential shoreline heads should already reflect the variation in offshore conditions.

The Taniguchi (1971) and Bretschneider and Wybro (1975) methods are essentially identical to each other. Salient characteristics are as follows:

1. Both apply directly to the estimation of runup heights rather than total heads, although Taniguchi has provided a means to translate runup heights to heads;

2. Both take into account the effects of surface roughness;
Both are based on the assumption that the ground is level between the shoreline and the limit of inundation;

Both differentiate between the effects of bore and non-bore inundation;

Neither takes into account the effects of differences in wave length or period;

Both assume that all of the wave energy is dissipated by friction and none is reflected back from the inundation area.

With the assumption that the ground is level between the shoreline and the limit of inundation, one may assume that the ground elevation is anywhere from sea level to the runup height above sea level at the inundation limit. The choice within this range is critical to the results, as is indicated by the following example based on the Taniguchi method. Assuming a head at the shoreline of 15 feet, an inundation-limit runup height of 10 feet, a roughness equivalent to a value of Manning's n of 0.02, and Froude number's of 2 for bore inundation and 1 for non-bore inundation, the inundation distances for various ground elevations would be shown in table A-2 and figure A-1.

Table A-2. Example of variation of inundation distance with ground elevation

<table>
<thead>
<tr>
<th>Case</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground level, feet</td>
<td>0</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Inundation distance, bore, feet</td>
<td>145</td>
<td>96</td>
<td>7</td>
</tr>
<tr>
<td>Inundation distance, non-bore, feet</td>
<td>954</td>
<td>801</td>
<td>528</td>
</tr>
</tbody>
</table>

With the level-ground assumption, the calculated runup height envelope, as well as the head envelope, must continuously slope downward inland, whereas observations indicate, that over ground sloping upward inland, the actual runup height envelope may slope upward inland.

The effects of neglect of the wave length or period may be suggested by intuitive reference to the runup behavior of waves of longer and shorter period than tsunamis. A semi-permanent rise in the level, or even a tide with 24 or 12 hour period would result in flooding to the height of the rise in the sea even at distances many hundreds of feet from the shoreline, whereas a storm wave with the same height would be dissipated close to the shoreline.

The effects of back reflection are difficult to envision but surely important.
Figure A-1. Example of variation of inundation distance with ground elevation: 3 non-bore cases
Shoreline head -- 15 ft. msl.
Runup at inundation limit -- 10 ft. msl.
Diagrams in Bretschneider and Wybro report indicate that the average runup slope for a bore with initial height above ground of 20 ft., assuming $n = 0.20$, would be about 1%, but the average runup slope for a non-bore wave with the same initial height would be only 0.26%. However, considering the effects of neglected factors, these slopes must be regarded as subject to considerable uncertainty.
Appendix B: 1961 Criteria for delineating potential tsunami inundation areas

The general features in the pattern of runup and inundation that have persisted through all of the recorded tsunamis indicate that the availability or probability of inundation is most critically dependent on the rate and direction of approach of the tsunami wave, as evidenced by the effects of smooth surfaces and areas of buildings and trees. However, for simplicity and expediency it was decided that a first step toward a rational approach would be to reduce the effects of roughness, altitude, and orientation to a single parameter, the relation between runup height, and width of the zone across which the waves would move from some arbitrary starting point in the ocean. To allow for the effect of the reefs, the arbitrary starting point chosen was the 10-foot depth below mean lower low water, which could readily be interpolated from inshore bathymetric contours shown on many of the newer U.S. Geological Survey topographic quadrangles of the islands. It was found by trial that an assumed 50-foot runup height for zero width with a one percent decline with distance traversed, would provide an estimate of potential width of inundation and height of runup that appeared reasonable when compared with the records. The principles involved in the construction are shown in figure 1.

On the southwestern shores of the Islands, although the resulting estimates of runup and inundation seem reasonable enough for practical purposes, the average runup heights on the southwest coasts, particularly in Honolulu, and the demonstrated effectiveness of tsunami from the north and east, they were clearly overpredicted height of waves. In view of the tremendous practical problems in the evacuation of urban areas on the southwest coasts, particularly in Honolulu, and the demonstration of tsunami from the southwest, other similar criteria were tried for the southwestern areas. The most suitable was an assumed 30-foot runup height for zero width, with again a one percent decline in width traversed.

The same criteria were found to apply best in the vicinity of bays and harbors where the breadth of the troughs are sufficiently wide to permit much tsunami energy to enter the Bay, considering its area.

Along a few coasts on Oahu areas of reef of considerable width but at depth greater than 10 feet appear to be effective in reducing the height of the waves. Figure 2 indicates the relation between runup heights and width from the minus 10-foot to the minus 20-foot contour as well as from the shoreline to the minus 10-foot contour. The potential inundation boundaries were improved in the areas of considerable width of deeper reef by considering that the runup reduces to zero at the 10-foot and 20-foot contours below mean sea level in excess of 1000 feet would have half as much effect in reducing runup height as widths traversed at the 10-foot contour.

Some inundation and runup may be expected at the in inundation areas in the deepest bays and harbors—those in which, by the criteria discussed above, there would be no effects. Considering the records in places like Honolulu, Pearl Harbor and a number of estuaries, it seems safe to consider generally that such effects would reach a maximum height of 4 feet above mean sea level where they would not be estimated higher by the other criteria. Arbitrarily it has been assumed that the water will not inundate an area more than 400 feet wide in such places.
Diagrams illustrating the construction of the limits of potential inundation in typical coastal areas by the use of these criteria are shown in figure 3.

In a few areas the historical records indicate that the normal criteria would not provide a sufficient margin of safety. In Hilo and Kahului, particularly, the area actually inundated by the May 1960 tsunami was in places wider than the potential inundation area estimated by the normal criteria. The boundaries of the potential inundation areas in these places were adjusted to afford an appropriate margin of safety and then checked with geophysicists familiar with the behaviour of the tsunami in those places. Less important special adjustments were made on the outer shores of Wainiha Bay, Kauai, because of extreme heights measured there in 1957 by E. D. Broadbent; at Hawiitillili, Kauai, because of excessive heights at the head of the bay in 1946; along the estuaries connecting with Kahaka Bay, Waialua, Oahu, because of bore development there in 1952 and 1957; at Iroquois Point, west of the Pearl Harbor entrance on Oahu, because of excessive heights measured there by
A. K. Cornelison in 1960; in the Spreckelsville and Maliko areas on Maui, because of excessive inundation there in 1946 and 1960; and at Hakalau, Hawaii, because of excessive inundation in 1946.

Altogether, the areas which may be considered potentially liable to inundation are:

I. On northwest, northeast, and southeast coastlines, for tsunami of distant origin from any direction; and on designated southwest coastlines for tsunami from the south or west:

A. All areas between the shoreline and the intersection with the ground of a surface declining inland with a slope of 1 percent from a height of 50 feet above mean sea level:

1. At the 10-foot contour below mean lower low water; or

2. At bays, estuaries, harbors, or canals with narrow channels, lines connecting the segments of the minus 10-foot contour across the channels where they are 2,000 feet or less in width or across the 2,600-foot width of the channel into Kaneohe Bay, or

3. Where the submarine slopes seaward of the minus 10-foot contour is slight, lines drawn seaward from the minus 10-foot contour at a distance from it equal to half of the excess of the local distance from the minus 10- to the minus 20-foot contour over 1,000 feet.

B. All additional areas less than 4 feet above mean sea level and within 400 feet of the shore of the ocean or tidal bodies such as a bay, harbor, estuary, or canal.

C. A few additional areas in which the historical record indicates liability to inundation at: Wainiha (figure 4) and Nawiliwili (figure 5), Kauai; Wailuku (figure 6), Oahu; Kahului (figure 8), and Spreckelsville (figure 9), and Maliko (figure 10), Maui; Hakalau (figure 11) and Hilo (figure 12), Hawaii.

II. On designated northwest coastlines for tsunami of distant origin from the south or west:

A. Areas defined as in section I.A, but using a 30-foot instead of a 50-foot height offshore.

B. Areas defined as in I.B.

C. An additional area at Iroquois Point (figure 7), Oahu, in which the historical record indicates liability to inundation.

Maps have been prepared outlining these areas on the islands of Kauai, Oahu, Maui, and Hawaii (appendix), except along clify or uninhabited coasts. Where studies have not delineated areas more closely, it is recommended that the area of potential inundation be considered, as previously:

A. Unanalyzed coastal areas less than 50 feet above mean sea level.

(Note: Of the figures showing exceptional areas, only figs. 6 and 7 showing cases on Oahu are reproduced here).
Fig. 6 Potential tsunami inundation areas at Waialua, Oahu.

Fig. 7 Potential tsunami inundation areas at Iroquois Point, Oahu.
Appendix C: Suggestions as to procedure

Introduction

The time constraints on the adoption of a Coastal High Hazard District may be such that the proposed boundary of this District must initially be adopted essentially as now mapped. The public hearings, which I understand are required, may bring to light evidence that the boundary in some localities is improperly located. However, it is expectable that owners of coastal property, reflecting their individual (and particularly short-term) interests, will urge seaward, rather than landward revisions of the boundary. Hence, landward relocations of the initial boundary are unlikely to be proposed by the general public, and seaward relocations, no matter how logical, may well be resisted. For this reason, consideration should be given to delaying the adoption of the District for a few months in order to improve the criteria used to define its boundary and to revise the boundary using the revised criteria.

Suggestions for revision prior to adoption

The following suggestions are made for immediate revision of the Coastal High Hazard District boundary criteria and boundaries prior to adoption:

a) Use all runup and inundation records on file at the Hawaii Institute of Geophysics.

b) Determine actual location of runup measurements where possible. In the absence of actual location identifications, assume runup heights were measured 200 feet from the shoreline.

c) In the absence of indicators of velocities associated with runup heights, assume that runup heights above tide level were essentially as great as total head above tide level.

d) Estimate shoreline head above tide level from each runup measurement on the basis of relationship between shoreline head, distance inland, and head loss. In the absence of a better relationship assume a 1% slope of head upward between measurement point and shoreline.

e) Correct historic shoreline heads above tide level to shoreline msl heads. The effect of the combination of steps b) through e) will be the application of conversion adjustments to any measurements whose actual locations are not known, in accordance with table C-1.

f) Collate all historic shoreline heads estimated from step e) that pertain to essentially the same coastal locality, and determine the maximum, if it is reasonably certain that no unestimated historic shoreline head would be greater. (In actual practice, it will generally be determinable by inspection which of the several runup heights recorded for a locality will yield the maximum historic shoreline head for that locality, and to make the necessary adjustments to that height alone and not to the rest.)
Table C-1. Adjustments to convert recorded runup measurements of uncertain locations to shoreline heads

<table>
<thead>
<tr>
<th>Tsunami</th>
<th>Adjustment for tide level</th>
<th>Projection from point of measurement to shoreline</th>
<th>Total adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1946</td>
<td>-1 ft</td>
<td></td>
<td>+1 ft</td>
</tr>
<tr>
<td>1952</td>
<td>0 ft</td>
<td></td>
<td>+2 ft</td>
</tr>
<tr>
<td>1957</td>
<td>+1 ft</td>
<td>+2 ft</td>
<td>+3 ft</td>
</tr>
<tr>
<td>1960</td>
<td>+1 ft</td>
<td></td>
<td>+3 ft</td>
</tr>
<tr>
<td>1964</td>
<td>0 ft</td>
<td></td>
<td>+2 ft</td>
</tr>
</tbody>
</table>

- g) Estimate the maximum local extended-period shoreline head from each local historic shoreline head determined in f) using an appropriate probability extrapolation factor. (For estimation of 100-year maximum heads from a historic record of 30 years, the factor used by Towill Corp. is 1.25.)

- h) Use the relationship between shoreline head, distance inland, and head loss (1% of distance in the absence of a better relationship) to estimate extent of inundation for each head estimate in g) from intersection of head loss line with ground.

- i) Along coasts of essentially constant or gradually changing offshore and onshore topography, estimate extent of inundation between points estimated in b) by intersection with ground of head surface determined by relationship and in d) and h) and shoreline head profile points interpolated between points estimated in g).

- j) Plot the maximum expectable 100-year limits of tsunami inundation on maps of suitable scale.

- k) Allow public review and challenge of both the criteria used in preparing the maps and the maps. In particular, welcome any public contributions of local records that would modify the estimated position of the maximum expectable 100-year limits. However, resist any attempts to relocate the estimated limits seaward on the basis of short-term records without extrapolation to long-term probability.

Suggestions for the longer term

The above suggestions relate to improvements that could, I believe, be made in a few months. The results will still be less precise than is justified considering the importance of regulation of uses of the potential tsunami...
inundation areas, and the importance of avoiding overregulation. The following suggestions relate to further improvements that probably cannot be accomplished in a few months.

a) Review more carefully the recorded runup and inundation records and attempt to pin down further the locations of measurements.

b) Extend the hydrodynamic methodology for height projection to include the effects of wave period, back reflection, and typical topographies. (I expect that the analytic precision will not justify independent analysis of the height profiles for each coastal locality. However, it may be that an algorithm for computer computation may be devised of sufficient generality to justify independent calculation on the basis of local topography and roughness.)

c) Adjust runup height measurements using the results of a) and b).

d) Revise probability analyses and probability extrapolation methods, as may be appropriate in the light of adjustments to runup height and inundation measurement using the results of a) through c).

e) Using the result of a) through d) revise the boundary criteria and boundaries for both the Coastal High Hazard District and the tsunami evacuation area.

f) Consider the establishment of zones of differential risk with corresponding different land-use and design controls and perhaps different extents of evacuation.
Appendix D: Datum planes and shorelines

As noted in the discussion of the datum planes used in recent historic measurement programs (p. 14) corrections of as much as a foot may be required to adjust the recorded heights to the common datum plane of mean sea level. Obviously, height to be used for predictive purposes must be expressed with respect to some common datum plane. It seems clear that the common datum plane, in the case of heights used in determining the limit of potential tsunami inundation, should be mean sea level because the elevations shown on topographic maps of Hawaii published by the U.S. Geological Survey or based on Geological Survey leveling data are elevations above mean sea level. For consistency, the shoreline, as used in this report, is the line of mean sea level.

Confusion may well arise from the usage of other reference levels and shorelines. For example Taniguchi's (1975) illustrations indicate usage of mean lower low water as a reference level. Datum planes and shorelines commonly referred to in Hawaii are summarized in the following table.

Table D-1. Datum planes and shorelines in Hawaii

<table>
<thead>
<tr>
<th>Datum plane</th>
<th>Elev. above msl, ft.</th>
<th>Shoreline</th>
<th>Dist. av. inland from msl ft.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>0 to approx. +15</td>
<td>&quot;kahakai&quot;</td>
<td>0 to approx. +210</td>
</tr>
<tr>
<td>mean high water</td>
<td>+0.8</td>
<td>line of mean high water</td>
<td>+11</td>
</tr>
<tr>
<td>mean sea level</td>
<td>0</td>
<td>line of mean sea level</td>
<td>0</td>
</tr>
<tr>
<td>mean lower low water</td>
<td>-0.8</td>
<td>line of mean lower low water</td>
<td>-11</td>
</tr>
<tr>
<td>tide level (contemporaneous)</td>
<td>+1 ft.</td>
<td>contemporaneous tide line</td>
<td>+14</td>
</tr>
</tbody>
</table>

*Based on 14% beach slope

None of the datum "planes" are true planes. Even mean sea level (the mean level of the sea and its inland equivalent the surface of the geoid) is an irregular roughly spherical surface. Other tide levels, including mean high water and mean lower low water, are even more irregular. Relative to mean sea level, the slopes of mean lower low water and mean high water are insignificant in Hawaii, at least in the context of tsunami problems, but on coasts with very high tides cannot be neglected. Contemporaneous tide levels slopes are also insignificant in Hawaii in the context of tsunami problems, although contemporaneous tide levels are even less regular than mean tide levels. Mean lower low water is the datum plane commonly used for bathymetric charts and in coastal engineering work.
Even though mean sea level is the usual datum plane for land topographic maps and in land engineering work, the shoreline shown on Geological Survey topographic maps is the intersection of mean high water with the ground, the mean high water line. Although the levels of mean sea level, mean lower low water, and mean high water do not vary significantly with time if the means are computed over (or adjusted to) a sufficiently long period, the horizontal positions of the lines of these "planes" may vary from time to time as the result of coastal emergence or submergence, and more commonly and very significantly as the result of shoreline advance and retreat on beaches. The horizontal position of the contemporaneous tide line varies, in addition, of course, with the tide level.

In Hawaiian cadastral surveying, the conventional shoreline is not defined by a tide level but by the normal annual limit of wave uprush as marked by debris lines and the seaward limits of land vegetation. Such a line, corresponding to the "kahakai" in traditional Hawaiian usage, is now legally defined as the usual seaward limit of private property. Although the elevation of the kahakai above sea level varies considerably from place to place, the horizontal position of the kahakai is much more stable than the horizontal position of any tide line.

Although mean sea level seems clearly the most appropriate common datum plane for the expression of heights, and although the mean sea level line is used in this paper as the reference shoreline, the use of auxiliary reference surface and lines may be helpful if the definition of potential tsunami runup and inundation becomes more precise than is now justified. In the hydrodynamic method for projecting heights inland, for example, the actual or an assumed ground level must be used. The ground level of some coastal planes is about the same as the elevation of the kahakai, but the average height of most coastal planes within the limits of tsunami inundation is greater than the height of the kahakai, and the height of some, back of dune ridges, is lower. On many coasts use of an assumed surface of uniform slope would be preferable. The best estimate, of course, would be based on the actual ground profile.

Horizontal distances from the mean sea level shoreline generally differ from distances from the mean high water shoreline by only about 10 feet. However, for precision the actual differences should be used. For some purposes, inland distances from the kahakai may be more useful, but corrections will always be necessary for conversion.