

COMMENTS FOR THE NSF TSUNAMI WORKSHOP AT HILO,  
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By

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**1. Introduction**

While updating my list of tsunami information sources (about 3,500), I read or scanned a number of the papers and reports. A great deal is known about tsunamis (generation, transmission, runup, and effects), and how to mitigate for them. Often, however, there has been insufficient implementation and maintenance. Comments about this are in the introduction to my second report: *Tsunami Information Sources. Part 2* (April 2006); I have expanded on these herein. In Section 2 C of the report, I listed nearly 500 of the reports, articles and papers that were about Planning and Engineering Design for Tsunami Mitigation/ Protection; Adjustments to the Hazards; Damage to Structures and Infrastructures. This includes papers and reports of fluid and debris-impact forces on man-made and natural objects, and scour. In Section 2 D a few references are included about sediment scour, transport, and deposit as part of the more extensive general heading Tsunami Propagation Nearshore; Induced Oscillations; Runup/Inundation (Flooding) and Drawdown.

Much is known about what to do (or not to do), and how to assess tsunami hazard and risk. We would always like to know more. But, decisions must be made, and implemented. This can be done, and must be done, although it may be difficult. Mitigation works and procedures may affect the quality of daily life (inconvenience/ convenience), and efficiency of use of the waterfront. They involve choices, tradeoffs, and risk. They involve adjustment. They may be costly.

An example of a tradeoff is the use of seawalls. In Hawaii, in California, and perhaps elsewhere, it is difficult or nearly impossible to obtain a permit to build a new seawall (e.g., Eversole and Norcross-Nu'u, 2006). Experience in the Indian Ocean (Sumatra) tsunami of 26 December 2004 has demonstrated the usefulness of seawalls for protection from the tsunami, even where they were overtopped (e.g. BBC News, 2005; Strand and Masek, 2005). Shepard, Macdonald and Cox (1950, pp 443, 458, 466, photos in plates 12a and 30a; see Figures 1a, 1b herein) comment on the value of the strongly built concrete seawall at the Puu Maile Hospital in Hilo, HI during the 1 April 1946 tsunami, where the wave rose about 20 feet, flooding over the wall. They say: "The wall itself was undamaged, and buildings sheltered by it were undisturbed except for minor damage by flooding." Seawalls have been used in Japan for many decades (e.g. Horikawa, 1960; Togashi, 1981; Miyoshi, 1983; Kawaguchi, Itoh, and Takeuchi, 1995). There are probably other places that they should be used. They must be well designed, constructed, and maintained; they should be long (what should be the elevation of the crest [top] ?); they are usually expensive.

***This is a workshop, and I will ask questions. The first four are:***

What has been the experience with seawalls during tsunamis?

What is the present opinion about the value of seawalls for protection from tsunamis?

It seems enough is known for the adequate design and construction of seawalls; is this correct?

But, what should the elevation of the crest be? How is this established, including risk?

Damage to, or destruction of, structures and infrastructure by tsunamis, and injury and loss of life (public safety), on land

and in harbors has been documented for many tsunamis. This includes secondary damage such as oil spill, spread and fire. This information is used to plan, engineer, construct new, maintain existing, retrofit old, facilities and infrastructure; tsunami hazard mitigation. Risk analyses should be made for a particular site. Members of a community must adjust to the hazards. Evaluations must be made of the relative importance of zoning/land-management, open-space, elevation, tsunami-resistant structures, defense structures (breakwaters, seawalls, dikes, gates, forests/ groves, drainage canals), aesthetics, convenience/inconvenience to people, public education.

Details of specific components of tsunami hazards are important. These include flow characteristics (motion) of the water and the resulting scouring and sediment movement, transport and impact of wreckage, other debris, boats, automobiles, and floating objects which may include buildings not adequately attached to the foundation (e.g., Wilson and Torum, 1968, p. 366; Wiegel, 1979, p. 251). Data are available on hydrodynamic forces, hydrostatic and buoyancy forces, impact forces, scour, sediment transport and deposition; but, more is needed. ***[These are the two topics of the present workshop.]***

Much is known about how to mitigate for tsunami hazards. Whatever actions are recommended or taken include both risk and adjustment either explicitly or implicitly. Often, little or nothing is done - but it has been done in some places. Hilo, Hawaii is an example of where tsunami protection and mitigation has been planned and implemented, including utilizing a tsunami warning system, and the preparation and education of residents and visitors for evacuation and emergency response. This workshop is being held in Hilo, and it is appropriate and desirable to use it as a case study. Hilo has a commercial port, it has an urban waterfront, it has suffered major tsunami damage and loss of life, it has had a redevelopment program. Its long-term tsunami mitigation program is the result of studies and plans that started shortly after the Chile tsunami of 23 May 1960. Details are given in Section 3 herein.

## **2. Risk, Adjustment, Mitigation**

I have used the words risk, adjustment, and mitigation. As used herein, they are defined as follows.

Risk can be defined as (National Science and Technology Council, Executive Office of the President of the United States, 2005, p. 23):

"**Risk** - the probability of harmful consequences or expected losses (death and injury, losses of property and livelihood, economic disruption, or environmental damage) resulting from interactions between natural or human-induced hazards and vulnerable conditions"

**Adjustment** - According to Ayre et al. (1975, p. 104):

"The word 'adjustment,' as used here, is not meant to imply complete avoidance of risk. Some degree of risk must be acceptable, for economic reasons. Furthermore, because of the infrequent occurrence of tsunamis, information regarding their possible impact locations and runup heights is very scanty, and it must be assumed that no reasonable action can take into account all possible risk. For some locations the decision might be to make no adjustment whatever."

I recommend that this be modified by adding the term **and convenience in daily life** after the words **economic reasons**.

**Mitigation** - according to the National Science and Technology Council (2005, p. 1)

"Mitigation involves sustained actions taken to reduce or eliminate the long-term risk to human life and property based on tsunami risk assessments. This includes planning and zoning to manage development in areas particularly at risk for tsunami, embracing tsunami resistant construction, and protecting critical facilities and infrastructure."

Before continuing, I quote a statement by Horikawa and Shuto (1983) about the need for a tsunami warning system, and the preparation and education for emergency response. This is important to a community in regard to both risk and accommodation. They say:

"It is quite dangerous to believe that the violent attack of tsunami can be completely prevented by man-made structures. Based on past experience evacuation to a safe area and before tsunami attack is the best recourse for the inhabitants. It is incorrect to depend too much on the functioning of coastal defense structures."

In some regions however, the tsunami generating source is so close that almost no time is available for evacuation. In some areas, both tsunami and direct earthquake effects (shaking,

subsidence/uplift, ground-breaking [fissures], liquefaction, landslides) occur nearly simultaneously.

### 3. Hilo, Hawaii

Hilo, on the northeast coast of the Island of Hawaii, has been subjected to many tsunamis. The south and east shores of Hilo Bay are "relatively flat and at low elevations, while the west shore is a rock bluff (sic, seacliff)" (USACE, Honolulu District, 1960, p. 5). The city has a tsunami mitigation program, and a tsunami warning system and evacuation program, including warning sirens. The tsunami evacuation map for Hilo, from the Civil Defense Section of the Hilo telephone book, is reproduced on page 50 of *Designing for Tsunamis*. The present workshop is being held within the evacuation zone. A copy of this map should be given to each participant. It would be useful if the **Plan for Evacuation** were to be described by a member of the County of Hawaii civil defense staff.

"Hawaii First State to be Storm, Tsunami Ready," (*The Maui News*, Anon., 10 Dec. 2005). This announcement was made on 9 December by Director David L. Johnson of the U.S. National Weather Service, as he presented Governor Linda Lingle a plaque that recognized Hawaii as the first state to achieve the status - the **Tsunami Ready Award**. U.S. Senator Daniel Inouye of Hawaii said:

"the state had taken several steps to be better prepared for the next tsunami, including having emergency operations center in every county, a statewide siren system, evacuation maps in phone books, regular drills and public education programs."

The regional tsunami warning center for Hawaii, which serves the broader Pacific-wide function, is the **Pacific Tsunami Warning Center (PTWC)** at Ewa Beach, Oahu, Hawaii. It is operated by the U.S. NOAA's National Weather Service. The Center is part of the **Pacific Tsunami Warning System (PTWS)**. [It would be useful if this system, which has 26 international members, the Center, and their operation could be described at the Workshop by the Director, or one of the staff.]

The **Pacific Tsunami Museum** is located at 130 Kamehameha Avenue, Hilo, Hawaii. Its Homepage is <http://www.tsunami.org/>

A visit to the museum is on the agenda of this Workshop. The museum has historic photographs, videos, oral histories, artifacts, documents, scientific papers and books and an

## Interactive Hilo Bay Tsunami Map.

On 1 April 1946, a tsunami that originated in the Aleutians struck Hilo; 96 people were killed in Hilo and vicinity. Tsunamis struck Hilo on 4 Nov. 1952 (from Kamchatka) and on 9-10 May 1957 (from the Aleutians). On 23 May 1960, a severe tsunami from Chile struck Hilo, with a loss of 61 lives. Details of these tsunamis are in: *The Tsunami of April 1, 1946* (Shepard, Macdonald, and Cox, 1950); *The Tsunami of November 4, 1952 on the Island of Hawaii* (Macdonald and Wentworth, 1954); *The Tsunami of March 9, 1957 on the Island of Hawaii* (Fraser, Eaton, and Wentworth, 1959); *The Tsunami of May 23, 1960 on the Island of Hawaii* (Eaton, Richter, and Ault, 1961); *The Tsunami of 23 May 1960 in the Hawaiian Islands* (Cox and Mink, 1963).

On 27 March 1964, a large tsunami from the Gulf of Alaska struck Hilo. Other tsunamis have struck Hilo. Information on these and other tsunamis are in the Pacific Tsunami Museum.

The tsunamis mentioned above were from distant sources, and had travelled across the Pacific Ocean before reaching Hawaii. Tsunamis have been generated in Hawaii also (Cox and Morgan, 1977). The two largest locally generated tsunamis occurred on 2 April 1868 (estimated earthquake Richter magnitude 7-1/4 to 7-3/4) and 29 Nov. 1975 (earthquake Richter magnitude 7.2) (Cox and Morgan, 1977, p. 26 and p. 58). The sources of these two tsunamis were probably tectonic, associated with the coastal and underwater subsidence along a portion of the Kau-Puna Coast of the Island of Hawaii (the southeast coast); on the south and southeast flanks of Kilauea Volcano (Cox and Morgan, pp 23, 63, and 85). Subsidence of the coast was about 5 to 7 feet, earthquake of 2 April 1868 (p. 22); and as much as 6 to 11-1/2 feet, earthquake of 29 Nov. 1975 (p. 63). The "accepted tsunami runup heights" above mean sea level along this section of coast were 20 feet (+/- 2 to 5 feet) (p. 19), with a maximum of 45 feet (+/- 5 feet). Tsunami runup heights on the subsiding part of the Kau-Puna Coast, 29 Nov. 1975 event, above mean sea level at time of measurement, were 17 to 42 feet (+/- 1 foot); runup above mean sea level at time of tsunami, 19 to 48 feet (+/- 2 feet) (p. 63). At Hilo, the "accepted tsunami runup height" above mean sea level was 9 feet (+/- 2 feet) for the 2 April 1868 tsunami; 2-1/2 to 8-1/2 feet (+/- 1 foot) for the 29 Nov. 1975 tsunami (p. 61). At Hilo, during the 29 Nov. 1975 tsunami:

"...at about 0510, when the water level dropped with the recession of the first tsunami, crew members of the U.S.S. Cape Small, a Coast Guard Cutter moored in Radio Bay in Hilo Harbor, watched

their ship sink to the muddy bottom and begin to list to one side. A series of waves surged in and out of the bay at approximately 15 minute intervals, smashing some small boats and washing others onto docks; four boats were sunk and three damaged. One of the waves washed a car from the pier into the harbor..." (quoted by Cox and Morgan, 1977, p. 58, from Tilling et al., 1976).

[As an aside - The recent Hawaiian earthquake that occurred on 15 October 2006 (Magnitude 6.7, epicenter about 13 miles N (315 deg.) of Kailua-Kona (west coast of the Island of Hawaii) **did not generate a tsunami**. (Pacific Tsunami Warning Center, 15 Oct. 2006; USGS Earthquake Hazards Program, 22 Oct. 2006.)]

A photo of one of the tsunami waves (probably the 2nd) of the 1 April 1946 tsunami running up Waianuenue Street in Hilo is in Figure 2 [also in my chapter on "Tsunamis" in *Earthquake Engineering* (1970, page 283)]. Damage in Hilo from the 1946 tsunami is shown in the photos of Figs. 3a and 3b herein. Other damage is shown on page 42 of *Designing for Tsunamis*. [**More information on this monograph is given in Section 4 herein.**] Also in *Designing for Tsunamis* are photos of a bore advancing inland; page 10 and page 41. The photo on page 10 was taken about a mile east of the breakwater, in the residential area of Keaukaha. The wave reached a height of 32 feet above sea level here, and caused great damage (Shepard, Macdonald and Cox, 1950, p. 443).

What appears to be a Mach-stem moving along the seacliff at the west coast of Hilo Bay toward the mouth of Wailuku River, is shown in the photo of Figure 4. The Sugar Mill is at the center, background. For more detail about this phenomenon at Hilo, see Wiegel (1970, pp 281-284).

Most places in Hawaii reported that the 3rd or 4th wave of the 1 April 1946 tsunami was the highest on shore and did the most damage (SMC, 1950, p. 407). At Hilo, the third wave was reported to be the largest (SMC, 1950, p. 441). The water rose about 17 feet at the Wailuku River Railroad Bridge, and a span was destroyed (SMC, 1950, p. 441). A bore entering Wailuku River, probably the fourth wave, is shown in the photo of Figure 5; note the missing bridge span at the right.

A photo of a tsunami wave flowing over the seawall in front of Puu Maile Hospital, Hilo, is shown in Figure 1a (Plate 12a of SMC, 1950; see also p. 443). Figure 1b is a photo of the seawall after the tsunami, looking seaward (SMC, 1950, Plate 30a, p. 521). The tsunami height at this site was estimated to be about 20 feet.

Major damage was done to port facilities and other parts of Hilo by the 1 April 1946 tsunami (Shepard, Macdonald and Cox, 1950). Tsunami waves overtopped the 10,000-foot long rubblemound breakwater, damaging it, and destroyed sheds on the port piers, although there was little damage to the piers. Figure 6 is a photo of a tsunami wave overtopping Pier 1 (probably the 3rd wave); note the person who was lost. Figure 7 is a photo of a destroyed shed on Pier 2.

After the 1 April 1946 tsunami, a small buffer zone was created by an elevated parkway along the section of waterfront between Wailuku River and Wailoa River, seaward of Kamehameha Avenue (Fraser, Eaton, and Wentworth, 1959, p. 95). Also, a strip of land was made into a recreation and parking lot area along part of the bay front (Eaton, Richter, and Ault, 1961, p. 155). However, destroyed harbor facilities were reestablished, business operations were established on former residential sites landward of Kamehameha Avenue, and commercial outlets developed in the devastated areas (U.S. Congress, 1961, pp 23-24). The small buffer zone was ineffective, as demonstrated by the 1960 tsunami (U.S. Congress, 1961, p. 28)

Cox and Mink (1963, p. 1,204), say the following about the 23 May 1960 Chile tsunami at Hilo:

"Nearly 600 acres inland of the harbor were inundated, some of the area extending to the 20-foot contour above sea level. In nearly half of this area the destruction of buildings was almost complete...In the area of maximum destruction, only buildings of reinforced concrete or structural steel, and a few others sheltered by these buildings, remained standing - and even these were generally gutted. Frame buildings either were crushed or floated away nearly to the limits of flooding..."

According to a U.S. Army Corps of Engineers report (in U.S. Congress, 1961, p. 24): "Nearly all structures in 10 of 14 blocks along Kamehameha Avenue had been demolished."

Many photos of the damage are in *The Big Wave: May 23, 1960* (Wall and Kadooka, 1960), and in *Analysis of Structural Damage from the 1960 Tsunami at Hilo, Hawaii* (Matlock, Reese, and Matlock, 1962). Damage from the 1960 tsunami is also shown on pages 13, 29, 32, and 47 of *Designing for Tsunami*. Eaton, Richter, and Ault (1961, pp 150-155) describe the destruction and damage to buildings, contents, plumbing, automobiles and other vehicles, pavement slabs, etc. They say (p. 150):



"In the zone of total destruction, whole city blocks were literally swept clean of all buildings except those of structural steel or reinforced concrete construction and a few in the shadow zone of these."

Scientists from the Hawaiian Volcano Observatory of the U.S. Geological Survey and Hawaii National Park, with cooperation of the Hilo Police, occupied a vantage point at the north end of Wailuku Bridge to observe the 1960 tsunami "in spite of darkness" (Eaton, Richter and Ault, 1961, p. 139). The third wave was the highest. Their observations about this wave are:

"Water continued to pour out of the estuary, and its level beneath the bridge continued to drop until 1:00 a.m., when measurement with the tape showed it to be nearly 7 feet below the pre-wave water level. For a short while a strange calm prevailed as ground water cascaded from among rocks that are rarely exposed to view along the shore."

"At first there was only the sound, a dull rumble like a distant train, that came from the darkness far out toward the mouth of the bay. By 1:02 a.m. all could hear the loudening roar as it came closer through the night. As our eyes searched for the source of the ominous noise, a pale wall of tumbling water, the broken crest of the third wave, was caught in the dim light thrown across the water by the lights of Hilo. It advanced southward nearly parallel to the coast north of Hilo and seemed to grow in height as it moved steadily toward the bayshore heart of the city."

"At 1:04 a.m. the 20-foot-high nearly vertical front of the in-rushing bore churned past our lookout, and we ran a few hundred feet toward safer ground. Turning around, we saw a flood of water pouring up the estuary. The top of the incoming current caught in the steel-grid roadway of the south half of the bridge and sent a spray of water high into the air. Seconds later, brilliant blue-white electrical flashes from the north end of Kamehameha Avenue a few hundred yards south of where we waited signalled that the wave had crossed the sea wall and buffer zone and was washing into the town with crushing force. Flashes from electrical short circuits marked the impact of the wave as it moved swiftly southeastward along Kamehameha Avenue. Dull grating sounds from buildings ground together by the waves and sharp reports from snapped-off power poles emerged from the flooded city now left in darkness behind the destroying wave front. At 1:05 a.m. the wave reached the power plant at the south end of the bay, and after a brief greenish electrical arc that lit up the sky above the plant, Hilo and most

of the Island of Hawaii was plunged into darkness."

They estimated that the bore travelled about 7,000 feet from the breakwater to the shore in 2-1/2 to 3 minutes, at a speed of 40 to 45 feet per second (p. 154). Eaton, Richter and Ault (1961, pp 149-150) commented about this bore as a result of their analysis of the event:

"This evidence suggests that the height and turbulence of the bore reached a maximum in the bay between the harbor entrance and the Hilo shore and that the final flood of water into Hilo was analogous to the sheet of water that races up a beach beyond the spent breaker that propelled it."

What do the participants of this workshop think about this?

Matlock, Reese and Matlock (1962, p. 77) estimated that in the devastated area, the height of high velocity water ranged from 8 to 12 feet above ground level, travelling at 25 to 40 feet per second.

The characteristics and the effects of the 23 May 1960 Chile tsunami in Hilo, and a detailed analysis of the tsunami-induced forces on structures are in the report:

*Analysis of Structural Damage from the 1960 Tsunami at Hilo, Hawaii*, by Hudson Matlock, Lymon C. Reese, and Robert B. Matlock, University of Texas, Structural Mechanics Research Laboratory, Austin, Texas, prepared for the U.S. Defense Atomic Support Agency, Washington, D.C., Rept. DASA 1268, March 1962, 95 pp (incl. 50 photos of damage, and two large mosaics of vertical aerial photos, one prior to and one after the tsunami).

Development of Hilo's tsunami mitigation program followed the 1960 tsunami. Early documents, and the establishment of a technical tsunami advisory council are: *Analysis of Structural Damage from the 1960 Tsunami at Hilo, Hawaii* by Matlock, Reese and Matlock (1962); *A Plan for the Metropolitan Area of Hilo* prepared by Belt, Collins, and Associates in 1961/1962 (tsunamis, incl. inundation, pp 85-94 and 113-115); *Tidal Wave Emergency Evacuation Plan for City of Hilo, Hawaii*, 1962; establishment in 1962 of the *Hilo Technical Tsunami Advisory Council* and its reports to the Hawaii County Board of Supervisors (Takahasi [Chairman], Suzuki, Homma, Wiegel, and Cox).

Several studies were made during the development of Hilo's mitigation plan; see the following list. Some of the concepts were

not implemented; some concepts were.

*Hilo Harbor, Hawaii*, U.S. Congress, House of Representatives, 87th Congress, 1st Session, 1961

*Tidal Wave Emergency Evacuation Plan for City of Hilo, Hawaii*, probably by the County of Hawaii, 20 March 1962

*Protection of Hilo from Tsunamis*, by Hilo Technical Tsunami Advisory Council, to the Board of Supervisors, Hawaii County, April 1962

*Tsunami Height-Frequency Relationship at Hilo, Hawaii*, by Doak C. Cox, 1964

*Physically Feasible Means for Protecting Hilo from Tsunamis*, Third Report of the Hilo Technical Tsunami Advisory Council, to the Board of Supervisors, Hawaii County, 31 Dec. 1965

*Some Numerical Hydrodynamics for Hilo Harbor*, by Harold G. Loomis, 1966

*The Hilo Harbor Tsunami Model*, by Robert Q. Palmer and Gerald T. Funasaki, 1966; also 1967

*Study of Proposed Barrier Plans for the Protection of the City of Hilo and Hilo Harbor, Hawaii*, by Robert Q. Palmer, Michael E. Mulvihill, and Gerald T. Funasaki, 1967

*Stability of Rubble-mound Tsunami Barrier, Hilo Harbor, Hawaii*, by Adel M. Kamel, 1967

*Laboratory Study for Design of Tsunami Barrier*, by Adel M. Kamel, 1970

*Tsunami Protection for Hilo Harbor, Hawaii*, by Adel M. Kamel, 1974

*Tsunami Inundation Prediction*, by Charles L. Bretschneider and Pieter G. Wybro, 1977 (tsunami runup and inundation at Hilo and contiguous coast, p. 1,013)

*Inundation and Forces Caused by Tsunamis*, for the State of Hawaii, Tech. Supplement No. 5 to the State of Hawaii Coastal Zone Management Program, by Charles L. Bretschneider and P.G. Wybro, 1978

Many photographs referred to in this section show the tsunami

damage and destruction that has occurred in Hilo. Now let us see what has been done in Hilo as part of their tsunami mitigation strategy. Refer to the **Case Study: Hilo Downtown Development Plan**, page 27 of *Designing for Tsunamis*, Figure 8 herein. The original plan was adopted in 1974, and superseded in 1985 by the **Downtown Hilo Redevelopment Plan** under authority of Chapter 27, Flood Control, of the Hawaii County Code. Two examples are shown in photos; open space at the bay front (page 18) and an elevated restaurant (page 25).

Principle 3 in *Designing for Tsunamis* is: **Locate and Configure New Development that Occurs in Tsunami Run-up Areas to Minimize Future Tsunami Losses**. A case study is given. It is the **Hilo Downtown Development Plan** (page 27), Figure 8 herein.

One mitigation strategy by type of development given on page 24 of *Designing for Tsunamis* is:

"3) **High-Rise Hotels**. New hotels in coastal areas are typically multi-level concrete frame structures. The lower levels of these buildings can be designed for public areas such as lobbies and support uses (such as parking) for upper level rooms. In Hawaii, for example, lower levels of hotels have been designed to allow waves to pass through the ground floor parking, lobby, and service spaces, leaving upper level rooms and meeting spaces undamaged. These buildings must be designed to withstand both tsunami and earthquake forces."

The several hotels on Banyan Drive along the bay front in Hilo are of this type, I believe; including the Hilo Hawaiian Hotel, which is the workshop site. [This should be checked; were they designed and constructed in accordance with the above?] Perhaps someone from Hawaii could speak on this.

Now refer to Principle 7 in *Designing for Tsunamis*: **Plan for Evacuation**. This principle includes a section on the **Role of Vertical Evacuation in Reducing Tsunami Losses**. It is stated on page 48:

"New buildings to be designed as vertical evacuation shelters must have sufficient structural integrity to resist expected tsunami forces and earthquake groundshaking for tsunamis originating locally. Building codes and other applicable standards should ensure the tsunami and earthquake resistance of new buildings. These standards should go beyond the minimum life safety requirements of most locally-adopted codes."

This leads to the Yeh, Robertson, and Preuss (2005) report; *Development of Design Guidelines for Structures that Serve as Tsunami Vertical Evacuation Sites*. Review of this report, in turn, can be expanded by considering a case study, such as a hotel that was planned for the north shore of Oahu, Hawaii, just west of Kahuku Point.

*Structural Design Criteria for Tsunami Loads on the Kuilima Hotel: Final Report*, prepared by R.E. Lowe, of Richard R. Bradshaw, Inc., Structural Engineers, May 1971, 78 pp.

[Was this hotel built? If so, was it designed and built in accordance with the report cited above? **This should be checked.**]

More recent work on tsunami runup and inundation at Hilo has been done by Mader, Curtis, and Nabeshima (1993) and Mader and Curtis (1991).

#### **4. Designing for Tsunamis: Seven Principles for Planning and Designing for Tsunami Hazards**

Distributed throughout many reports and papers are comments and recommendations for designing for tsunami hazards. Building codes have been developed, and promulgated. Tsunami hazard maps have been developed for some area; they vary in what they depict. What can be done by a local planner or policy maker? The following publication would be useful to them. [As a disclosure, I was a member of the Expert Advisory Panel in its preparation.] This monograph is concise, illustrated with sketches and photos, and written to be easily understood.

*Designing for Tsunamis: Seven Principles for Planning and Designing for Tsunami Hazards*, prepared for the U.S. National Tsunami Hazard Mitigation Program (NOAA, USGS, FEMA, NSF, Alaska, California, Hawaii, Oregon, and Washington), March 2001, 60 pp.

[For more details, see the companion report: *Designing for Tsunami: Background Papers*, March 2001.]

The **Seven Principles** are:

1. Know your community's tsunami risk: hazard, vulnerability, and exposure
2. Avoid new development in tsunami run-up areas to minimize future tsunami losses

3. Locate and configure new development that occurs in tsunami run-up areas to minimize future tsunami losses
4. Design and construct new buildings to minimize tsunami damage
5. Protect existing development from tsunami losses through redevelopment, retrofit, and land reuse plans and projects
6. Take special precautions in locating and designing infrastructure and critical facilities to minimize tsunami damage
7. Plan for evacuation

***One product of the present NSF Workshop might be to consider this publication, and make recommendations in regard to it.***

As an example, consider Principle 4. Refer to the chart ***Design and Construct New Buildings to Minimize Damage*** on page 35 of the publication (reproduced herein as Figure 9).

Does this chart cover the subject completely?

If not, what should be added?

Should anything be deleted; if so, what?

Should some items be modified?

Look at the details in the chart. ***Note the importance of the topics of the present workshop in regard to them.*** Some of the effects or design solutions listed are: evaluate bearing capacity of soil in a saturated condition; hydrostatic forces; buoyancy (flotation or uplift forces caused by buoyancy); design for dynamic water forces on walls and building elements; design for breaking wave forces; design for debris impact; design for scour and erosion of the soil around foundations and piles; design waterfront walls and bulkheads to resist saturated soils without water in front; provide adequate drainage.

Valuable information on loads and design have been collected in reports such as:

*Development of Design Guidelines for Structures that Serve as Tsunami Vertical Evacuation Sites*, by Harry Yeh, Ian Robertson, and Jane Preuss, 2005

*Coastal Construction Manual - Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas*, FEMA, Washington, D.C.,

3rd edition, 3 vols. (FEMA 55), 2000

*Design and Construction Standards for Residential Construction in Tsunami-prone Areas of Hawaii*, by Dames and Moore, Washington, D.C., 1980

*Tsunami Engineering*, by Fred E. Camfield, 1980

*Tsunami Subcommittee Report: Draft*, Structural Engineers Association of Hawaii, October 1972, 38 pp [Note: I believe that Charles L. Bretschneider did much of the work on the section **Tsunami Wave Forces** in this report; it is thorough.]

*The Tsunami of the Alaskan Earthquake, 1964: Engineering Evaluation*, by Basil W. Wilson and Alf Torum, 1968

*Analysis of Structural Damage from the 1960 Tsunami at Hilo, Hawaii*, by Hudson Matlock, Lymon D. Reese, and Robert B. Matlock, 1962

Additional knowledge on this subject is available in papers, mostly on specific aspects. I will mention one subsequently. Useful additions to our knowledge of water motions and loads on structures will be added during this workshop.

One of the statements in Principle 4 (on page 32) is:

"Substantially constructed buildings of concrete, masonry, and heavy steel frames are likely to perform fairly well in a tsunami unless compromised by earthquake shaking. Wood-frame buildings, manufactured housing, and light steel-frame structures at lower elevations close the shoreline are likely to fare poorly in a tsunami."

This seems to be confirmed by the experience in the Sumatra (Indian Ocean) tsunami of 26 December 2004 (see the ASCE TCLEE Monograph No. 29, eds. Strand and Masek, Oct. 2005). It is also in agreement with the data in the paper by Matsutomi and Shuto (1995). It is in agreement with the experience in Hawaii during the 1 April 1946 tsunami (Shepard, Macdonald and Cox, 1950, p. 466). Also, in Alaska during the 27 March 1964 tsunami; Wilson and Torum (1968, p. 366) say that the few concrete-block and reinforced concrete structures (most buildings were wood frame) withstood the tsunami waves rather well, and cited examples. They said some of the buildings were damaged by impacts of floating boats and debris. They recommend:

"Sound reinforced-concrete construction with deep embedded foundations or solid raft foundations (foundation mats) capable of resisting scour; shear walls are desirable."

What has been the experience, and what is the judgement about this of the present workshop participants?

### 5. Tsunami Runup and Inundation; and Worst Case Scenario

Tsunami runup is not one of the topics in this workshop. There has been a workshop on this subject, and there are many papers and reports about this phenomenon. In Section 2 D of Part 2 of my report on tsunami information sources (Wiegel, April 2006), I have listed nearly 300 sources about Tsunami Propagation Nearshore; Induced Oscillations; Runup/Inundation (Flooding) and Drawdown. About 1/3 of these are about runup and inundation.

The terms tsunami runup and inundation are sometimes used differently in various publications and meetings. Eisner, Borrero, and Synolakis (2001, p. 68) write:

"As a preamble, we will define the terms **run-up and inundation**, which are sometimes misused. **Wave run-up** is the rush of water up a structure or a beach; it is called uprush. The maximum run-up is the vertical height above stillwater that the rush of water reaches as it climbs onshore. The term **inundation height** is a term often used interchangeable with run-up, but refers to either the maximum flow depth or run-up along a particular transect. Both parameters are rarely determinable in the field, although they both can be computed with MOST. Specific knowledge of the maximum wave run-up on a given beach is essential both in shore protection and in the design of coastal structures. In earlier pre-1990s studies the term tsunami height offshore was used interchangeable with run-up height. Tsunami height references are generally not useful in inundation prediction as the tsunami height varies substantially with depth, particularly in the extreme nearshore region. **Inundation** refers to the horizontal distance the wave penetrates inland. Depending on land use, either run-up or inundation are relevant, and most often both. In addition, the wave-front velocity as the wave strikes the shoreline is an important design parameter for coastal structures. An inundation computation includes prediction of runup heights, inundation distances and inundation currents. Threshold models are fairly common and compute the tsunami height at the shoreline or worse at some depth contour offshore and then project it inland to infer inundation; they are erroneously referred to as inundation models. An inundation map includes a line corresponding to the maximum



penetration of the tsunami wave triggered by the event under study."

Are these reasonable definitions? If not, how should they be modified?

[Note. The word **flooding** is used sometimes rather than the word **inundation**.]

Rather than using the elevation above the still water level at the time of a tsunami, values are commonly given as the highest level reached by the tsunami wave above a reference level such as high water level, mean sea level, or mean lower low water. **The datum must be specified.**

Many hydraulic laboratory studies have been made using solitary waves, for well known reasons. They have provided considerable insight to our understanding of tsunamis. However, tsunamis are not solitary waves (they are usually multi-wave events, as at Hilo, HI). Two papers about just one aspect of the problem, the effect of an initial drawdown followed by a rise are: "The Run-up of N-waves on Sloping Beaches," by S. Tadepalli and C.E. Synolakis (1994); and "On the Influence of the Sign of the Leading Wave on the Height of Runup on the Coast," by S.L. Soloviev and R. Kh. Mazova (1994).

What is the opinion of the workshop participants about this?

Runup/inundation maps have been made for some locations, and are being developed for others (See listings under Maps in Wiegel, 2005; 2006; Eisner, Borrero, and Synolakis, 2001; Gonzalez et al., 2001). **One of the most important specification that should be decided on in regard to their preparation and to tsunami mitigation at a site is the type of runup that is likely to occur.**

What type of tsunami is likely to occur?

Will the tsunami move onto shore like a fast rising tide, a surge, or a bore?

Do we know enough to decide this reliably?

Are sufficient data available at a particular site to judge this?

Or, if the local authorities must make a decision for adopting or upgrading a building code, or the issuance of a building permit, do they have to assume the "worst case scenario"?

If so, which is the worse case?

Perhaps there is not a single type "worst case." What quantitative information is there about this?

The words **bore and surge** have sometimes been used interchangeably, and at other times differently. I think of a bore as the fast-moving abrupt front (nearly vertical) of a tsunami, and a surge as a fast-moving front that is less steep than a bore. I ask:

What is the distinction between surge and bore for tsunamis; has it been quantified?

**Answers to these questions would be a useful product of this workshop.**

I recently read a statement that most deaths in Indonesia in the tsunami of 16 December 2004 "were caused by bodies being hurled against hard things rather than drowning" (Anon., Sept. 2006).

Is this correct?

Is this because the tsunami was moving as a bore or a surge?

What has been the experience during other tsunamis?

Refer to the recent paper "Inundation Velocities in Banda Aceh Estimated from Video Recordings of the 2004 Sumatra Tsunami," by Tsutomu Sakakiyama, Hideo Matsutomi, Sindhu Nugroho, Yoshinobu Tsuji, and Yoshikane Murakami (2006, 8 pp; this was sent to me by Dr. Sakakiyama recently, without a publication citation). Also refer to the paper "Nearshore Flow Velocity of Southwest Hokkaido Earthquake Tsunami," by A. Tsutsumi, T. Shimamoto, E. Kawamoto, and J.M. Logan (2000).

Which type of runup occurred where these observations were made?

## **6. Wave-induced Forces by a "Bore" on a Vertical Circular Cylinder**

More than fifty years ago a study was made of the forces exerted on a test pile installed in the surf zone in southern Monterey Bay, California (Snodgrass, Rice, and Hall, 1951). It was observed that, but not understood why, a **foam line** (i.e., the wave progressing shoreward just after breaking) moving past the pile exerted a larger horizontal force on the test pile than a wave that broke at the pile. This was also observed in a wave tank experiment by Hall (1957). [Note: The **foam line** appears to me to be similar to a bore.] The peak force is inertial (depends on the horizontal acceleration of the water), with a sharp spike (short duration "impact" load) in addition to the expected drag force. This has been described, and explained by Wiegell (1983), in a

manner somewhat similar to the explanation given by Goda, Haranaka and Masahata (1966, in Japanese; see Sawaragi and Nochino, 1984 for a summary in English) and Watanabe and Horikawa (1974). Additional studies have been made in the Large Wave Flume of the Coastal Research Center in Hannover, Germany, by K. Irschik, U. Sparboom, and H. Oumeraci (2005), and by Wienke and Oumeraci, 2005. I suggest that the equation and parameters in these papers be used as a basis for calculating the load on a vertical circular pile or column subject to a *tsunami moving as a bore*.

Do we have adequate quantitative data on the geometry and speed of tsunami bores to do this?

### **7. Scour on a Fringing Reef; Request for Information**

Several years ago, I did a study of the history of Waikiki Beach, Oahu, Hawaii from a coastal engineering perspective (Wiegel, 2002). This region of Oahu has a fringing reef several thousand feet wide. The sand cover on the reef is not continuous, and is not deep. Sand occurs in patches on the reef flat, and the beach is narrow (e.g., Wiegel, 2002, pp 74-76). Much of the sand on the beach at present has been brought to the beach by truck from other sources. This reef, like many others has much algae.

On three occasions, during one or more drawdowns of a tsunami, much of the reef, and on one occasion the entire fringing reef was observed to become bare. The tsunamis for which I found observations were: 14 August 1869, 1 April 1946, and 23 May 1960. A similar drawdown was likely to have occurred on 7 November 1837, based on the "tide observation" in Honolulu Harbor. The sources for these observations, and quotations, are given in Wiegel (2002, pp 21-24); with one exception. The observation of the 1869 event is from the unpublished autobiography of Harriet N.F. Deming (whose family home was at the water's edge in Waikiki), as quoted in Kanahale (1995, p. 142). The currents on the reef would have been strong, and much sediment scoured from the reef flat, carried seaward over the reef edge during the drawdown, and lost to the littoral. I think this is an important factor in the fact that there is a relatively small amount of sand at Waikiki; but I have no data. While making the study I made a search for data about tsunamis on reefs, but found little information.

What, if any, information is available about this subject?

### **8. Ports and Harbors**

This section on ports and harbors is included for several

reasons. The first is that Hilo has a port and harbor, in an open bay, with a 10-000-foot long rubblemound breakwater. It has suffered damage during tsunamis.

The second reason is that recently (2005) there have been discussions in *Civil Engineering* about the possibility (or probability ?) of damage to the Ports of Long Beach and Los Angeles, California, with substantial disagreement, as well as some agreement (Borrero, Cho, et al., 2005; Thiessen and Gioiello, 2005; Sterling, Edge, et al., 2005; Synolakis, Moore II, et al., 2005). And, in the report of the California Seismic Safety Commission, *The Tsunami Hazards and Risks to California: Findings and Recommendations on Tsunami Hazards and Risks*, one of the Findings is (2005, p. 1, with details on p. 6):

"Tsunamis present a substantial risk to the economy of the State and Nation, primarily through the impact on our ports."

[Note. This report is based on the work of the Commission's Tsunami Safety Ad Hoc Committee, which held 6 meetings and took testimony from representatives of local governments and the scientific community in California during 2005.]

It is generally recognized that the best procedure in the case of a tsunami, if adequate warning time is available, is to move the ships and boats out of a port, to sea (e.g., Committee on Earthquake Engineering Research, 1969, p. 247). An anecdote about the 1 April 1946 tsunami offshore Hilo is (Shepard, Macdonald, and Cox, 1950, p. 459):

"Boats at sea, where the waves were low and broad were of course unaffected. The master of a ship lying offshore near Hilo said that he could feel no unusual waves, although he could see the great waves breaking on shore."

In his description of the great 1896 Sanriku tsunami in Japan, in which thousands lost their lives and the destruction was devastating, Imamura (1937, p. 129) says that fishermen who were at some distance out at sea did not notice anything unusual until the next morning when they were headed to port.

In ports, many ships and boats have been severely damaged by tsunamis. As an example, in Japan and Korea during the 26 May 1983 Japan Sea tsunami, Hwang and Hammack (1984, p. 21) say:

"As the tsunami approached the shoreline and entered shallow waters, it created high water levels and strong currents. These

caused mooring lines to break and ships to capsize. Most damage to floating structures resulted when they were carried by the high water levels and strong currents toward land, where they collided with other fixed structures. During the tsunami, significant numbers of boats were damaged when they collided with piles."

In regard to port and harbor facilities, it is important to keep them maintained properly. William Herron comments on the performance difference in the Long Beach - Los Angeles Ports, between the 1960 Chile and the 1964 Alaskan tsunamis (USACE, Los Angeles District, 1986, p. 6-60. Herron said that the characteristics of the tsunamis were important; but he also said that the rehabilitation of facilities after the 1960 tsunami made them better prepared to withstand the 1964 tsunami.

The Committee on Earthquake Engineering Research (1969, p. 248) made suggestions in regard to the use of elastic shock-absorbing floating fenders; automatic constant-tensioning high-capacity deck winches for assuring taut moorings at all states of tide or water level; etc.

Owing to the construction of a new town and port of Valdez, Alaska, I am including a few details about it. This is an example of what can be done. The waterfront of Valdez was destroyed by a huge submarine slump and tsunami caused by the great Alaska earthquake of 27 March 1964 (Coulter and Migliaccio, 1966; Wilson and Torum, 1968). The waves were locally generated; they were not the major tsunami generated by tectonic displacements inshore of the Aleutian Trench in the region from Prince William Sound to Kodiak Island, which was the tsunami that affected the entire Pacific Ocean (e.g., Wilson and Torum, 1968, pp 254-294), and 358-360). The tidal range at Port Valdez is relatively large: mean tidal range 9.70 feet; diurnal range 12.15 feet; mean tide level 6.36 feet (*Tide Tables 2006*, p. 264). The destruction occurred at about low tide. The old waterfront disappeared; docks and buildings were destroyed. Most of the buildings were of light wooden frame construction (Wilson and Torum, p. 284). It had been built on the "seaward edge of a large outwash delta composed of saturated silty soil and gravel." The new town has been built at a more suitable site, about 4 miles to the northwest (Coulter and Migliaccio, 1966; Mason, Neal, et al., 1997, pp 57, 215-219).

The present Ferry and City Docks are at the water's edge of the new town, and the Small Boat Harbor is adjacent to them. Valdez has a 21-acre general cargo port. [The Richardson Highway leads north from Valdez to Fairbanks.]

In late 1982, a 700-foot-long floating prestressed concrete container dock at the commercial port became operational. This floating facility is automatically self-adjusting to the "largest tide variations," and may be moved to another site if warranted. It was constructed in Tacoma, Washington, and towed 1,600 miles to Valdez, in two 350-foot long sections (Anon., 1983). The two sections were post-tensioned together at the site. It is anchored with 8 concrete gravity anchors. Two short two-lane bridges, one near each end, provide vehicle access to the general cargo port.

Valdez is at the base of the Chugach Mountains. It is the ice-free deep water port at the terminus of the 800-mile long Trans-Alaska Pipeline (operated by Alyeska Pipeline Service Company) from Prudhoe Bay, which was build in April 1974-June 1977. The terminus is located several miles from the new town. According to Alyeska Pipeline Services Company (update 23 June 2004) all facilities at this terminus, except berths are at an elevation of 15 feet or higher (what is the datum?). There are 18 crude oil holding tanks; surrounded by reinforced earth containment dikes (2 tanks, each). These tanks are on leveled areas at 420 to 560 feet above the water (Anon., 1978). There are 4 berths; 3 are fixed platforms, and 1 floating (Anon., 1968; Alyeska 2004). The 2,600 ton steel floating berth (with 13 buoyancy chambers) was fabricated in Japan. Tests of scale models showed the berth and the hinged struts linking it to shore could easily handle design motions (**20 ft. tsunami wave**) and design horizontal loads (imposed by a berthed ship of up to 120,000 dwt) (Anon., 1978). Two photos I took of this terminal in July 1994 are in Figures 10a and 10b.

Recall the second paragraph in this section about the Ports of Long Beach and Los Angeles, and the possibility (probability?) of a severe tsunami in the future, from a hypothesized nearby underwater landslide generated tsunami. One area of agreement was the need to estimate the hazard risk in probabilistic terms. This is difficult for several reasons. One reason is that although present underwater mapping of previous slides has improved, little is known about underwater slide speeds, hence, the size of the resulting tsunami. Earlier studies of tsunami risk were for tsunamis generated in the far-field by co-seismic underwater tectonic displacements (e.g. Houston and Garcia, 1974; Houston, 1980). These are sets of two different tsunami populations.

How should sets of two different tsunami populations be treated?

After the Indian Ocean (Sumatra) tsunami of 26 December 2004, PIANC (Permanent International Association of Navigation

congresses) established **PIANC Working Group 53: Tsunami Design Criteria for Marine Structures** (Anon., July 2005). I have not seen a report by this group.

A short note about the **Protecting our Ports and Harbors Project for Oregon and Washington** appeared in the *ITS 2002 Proceedings, Session 1*, by David Stein, Sandy Eslinger, et al. (2001). A program is described that was being developed under the Oregon and Washington Sea Grant, the NOAA Coastal Services Center, and the USGS. I have not seen a follow-up about this.

Do participants of this workshop have any comments on this subject?

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## 10. Figures

1a. An early tsunami wave flooding over the sea wall at the Puu Maile Hospital near Hilo, 1 April 1946. Photo by Mrs. Pearl Welsh (Plate 12a in Shepard, Macdonald and Cox, 1950, p. 485)

1b. Sea wall at the Puu Maile Hospital, Hilo, after the 1 April 1946 tsunami. Photo by Mrs. Pearl Welsh (Plate 30a in Shepard, Macdonald and Cox, 1950, p. 521)

2. Tsunami wave (probably the 2nd) moving (surge?) up Waianauene Street, Hilo, 1 April 1946. Photo by Yoshio Shigenaga; photo courtesy Modern Camera Center, Hilo

3a and 3b. Destruction along Kamehameha Avenue, Hilo, by the Tsunami of 1 April 1946. Photos by Francis Lyman (Plate 28 in Shepard, Macdonald and Cox, 1950, p. 517)

4. Wave in form of a bore, approaching Wailuku River; looking toward the sugar mill, 1 April 1946 tsunami. It appears to be moving along the seacliff as a Mach-stem. Courtesy Modern Camera Center, Hilo

5. Bore entering Wailuku River, tsunami of 1 April 1946. Probably the 4th wave. [The Railroad Bridge span on the right was swept away by the 3rd wave.] Courtesy Modern Camera Center, Hilo

6. Tsunami wave flowing over Pier 1, Hilo, Hawaii, 1 April 1946. Note person who was lost. Photo taken by a U.S. Navy sailor. [This is also Plate 23 of Shepard, Macdonald and Cox, 1950]

7. Destruction of shed on Pier 2, Hilo, Hawaii, by 1 April 1946 tsunami. Source of photo?

8. A section through the lower downtown area from the **Hilo Downtown Development Plan** (Credit: County of Hawaii). Page 27 of *Designing for Tsunamis*, March 2001

9. Design and construct new buildings to minimize tsunami damage (From *Designing for Tsunamis*, March 2001, p. 35)

10a. Trans-Alaska Oil Pipeline Terminal (Alyeska Pipeline Service Company), Valdez, Alaska. Looking toward oil tanker loading, and crude oil tanks, from boat, 28 July 1994. Photo by Robert L. Wiegel

10b. Trans-Alaska Oil Pipeline Terminal (Alyeska Pipeline Service Co.), Valdez, Alaska. Looking down from hillside toward oil tankers loading; new Valdez is in background, 27 July 1994. Photo by Robert L. Wiegel



**Figure 1a.** An early tsunami wave flooding over the sea wall at the Puu Maile Hospital near Hilo, 1 April 1946. Photo by Mrs. Pearl Welsh (Plate 12a in Shepard, Macdonald and Cox, 1950, p. 485)



**Figure 1b.** Sea wall at the Puu Maile Hospital, Hilo, after the 1 April 1946 tsunami. Photo by Mrs. Pearl Welsh (Plate 30a in Shepard, Macdonald and Cox, 1950, p. 521)



**Figure 2.** Tsunami wave (probably the 2nd) moving (surge?) up Waianauene Street, Hilo, 1 April 1946. Photo by Yoshio Shigenaga; photo courtesy Modern Camera Center, Hilo

*a**b*

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**Figure 4.** Wave in form of a bore, approaching Wailuku River; looking toward the sugar mill, 1 April 1946 tsunami. It appears to be moving along the seaciff as a Mach-stem. Courtesy Modern Camera Center, Hilo



**Figure 5.** Bore entering Wailuku River, tsunami of 1 April 1946. Probably the 4th wave. [The Railroad Bridge span on the right was swept away by the 3rd wave.] Courtesy Modern Camera Center, Hilo





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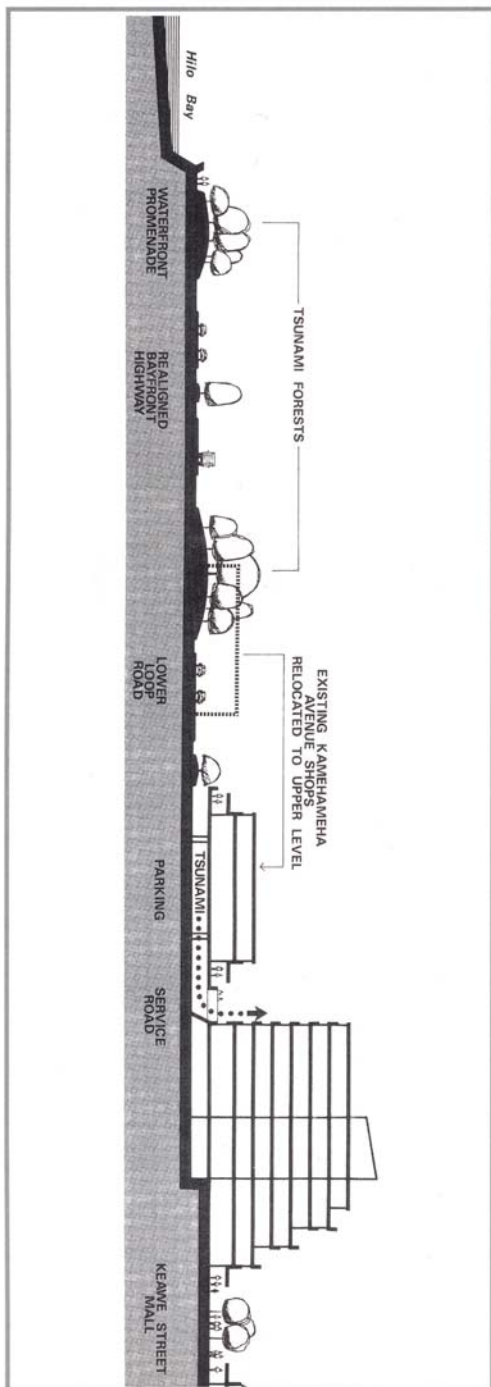
## Principle 3: Case Study

### Case Study: Hilo Downtown Development Plan

The Hilo Downtown Development Plan was adopted in 1974 to guide efforts to revitalize the downtown core of Hilo, Hawaii. The Plan established a Safety District based on the 1946 and 1960 tsunami inundation lines. All redevelopment in the Safety District was subject to urban design and building design standards. Any structure below the 20-foot elevation contour line was required to be designed to withstand the force of a major tsunami. A Parking District was also designated in the

Plan to provide parking for downtown businesses and to use parking structures as a protective barrier from a tsunami for inland structures. Parking facilities have been constructed in accordance with the Plan.

In 1985, the Hilo Downtown Development Plan was superseded by the Downtown Hilo Redevelopment Plan under the authority of Chapter 27, Flood Control, of the Hawaii County Code.



A section through the lower downtown area from the Hilo Downtown Development Plan. Credit: County of Hawaii

**Figure 8.** A section through the lower downtown area from the *Hilo Downtown Development Plan* (Credit: County of Hawaii). Page 27 of *Designing for Tsunamis*, March 2001

## Principle 4: Design and construct new buildings to minimize tsunami damage

Tsunami effects and design solutions		Phenomenon	Effect	Design Solution
P.1	Inundation		<ul style="list-style-type: none"> <li>Flooded basements</li> <li>Flooding of lower floors</li> <li>Fouling of mechanical, electrical, and communication systems and equipment</li> <li>Damage to building materials, furnishings, and contents (supplies, inventories, personal property)</li> <li>Contamination of affected area with waterborne pollutants</li> </ul>	<ul style="list-style-type: none"> <li>Choose sites at higher elevations</li> <li>Raise the building above the flood elevation</li> <li>Do not store or install vital material and equipment on floors or basements lying below tsunami foundation levels</li> <li>Protect hazardous material storage facilities that must remain in tsunami hazard areas</li> <li>Locate mechanical systems and equipment at higher locations in the building</li> <li>Use concrete and steel for portions of the building subject to inundation</li> <li>Evaluate bearing capacity of soil in a saturated condition</li> </ul>
				<ul style="list-style-type: none"> <li>Elevate buildings above flood level</li> <li>Anchor buildings to foundations</li> <li>Provide adequate openings to allow water to reach equal heights inside and outside of buildings</li> <li>Design for static water pressure on walls</li> </ul>
P.2			<ul style="list-style-type: none"> <li>Hydrostatic forces (pressure on walls caused by variations in water depth on opposite sides)</li> </ul>	<ul style="list-style-type: none"> <li>Elevate buildings to foundations</li> <li>Anchor buildings to foundations</li> <li>Design for static water pressure on walls</li> </ul>
				<ul style="list-style-type: none"> <li>Elevate buildings</li> <li>Anchor buildings to foundations</li> <li>Evaluate bearing capacity and shear strength of soils that support building foundations and embankment slopes under conditions of saturation</li> <li>Avoid slopes or provide setback from slopes that may be destabilized when inundated</li> </ul>
P.3	Currents		<ul style="list-style-type: none"> <li>Hydrodynamic forces (pushing forces caused by the leading edge of the wave on the building and the drag caused by flow around the building and overturning forces that result)</li> </ul>	<ul style="list-style-type: none"> <li>Elevate buildings</li> <li>Design for dynamic water forces on walls and building elements</li> <li>Anchor building to foundations</li> </ul>
				<ul style="list-style-type: none"> <li>Elevate buildings</li> <li>Design for impact loads</li> <li>Use deep piles or piers</li> <li>Protect against scour around foundations</li> </ul>
P.4			<ul style="list-style-type: none"> <li>Scour</li> <li>Debris impact</li> </ul>	<ul style="list-style-type: none"> <li>Elevate buildings</li> <li>Design for impact loads</li> <li>Use deep piles or piers</li> <li>Protect against scour around foundations</li> </ul>
				<ul style="list-style-type: none"> <li>Elevate buildings</li> <li>Design for impact loads</li> </ul>
P.5	Wave break and bore		<ul style="list-style-type: none"> <li>Hydrodynamic forces</li> <li>Debris impact</li> </ul>	<ul style="list-style-type: none"> <li>Elevate buildings</li> <li>Design for breaking wave forces</li> <li>Design for impact loads</li> </ul>
				<ul style="list-style-type: none"> <li>Elevate buildings</li> <li>Design for impact loads</li> </ul>
P.6	Drawdown		<ul style="list-style-type: none"> <li>Scour</li> <li>Embankment instability</li> </ul>	<ul style="list-style-type: none"> <li>Design for scour and erosion of the soil around foundations and piles</li> <li>Design waterfront walls and bulkheads to resist saturated soils without water in front</li> <li>Provide adequate drainage</li> </ul>
				<ul style="list-style-type: none"> <li>Design for scour and erosion of the soil around foundations and piles</li> <li>Use fire-resistant materials</li> <li>Locate flammable material storage outside of high-hazard areas</li> </ul>
P.7	Fire		<ul style="list-style-type: none"> <li>Waterborne flammable materials and ignition sources in buildings</li> </ul>	<ul style="list-style-type: none"> <li>Use fire-resistant materials</li> <li>Locate flammable material storage outside of high-hazard areas</li> </ul>
				<ul style="list-style-type: none"> <li>Use fire-resistant materials</li> <li>Locate flammable material storage outside of high-hazard areas</li> </ul>

**Figure 9.** Design and construct new buildings to minimize tsunami damage (From *Designing for Tsunamis*, March 2001, p. 35)



10a. Trans-Alaska Oil Pipeline Terminal (Alyeska Pipeline Service Company), Valdez, Alaska. Looking toward oil tanker loading, and crude oil tanks, from boat, 28 July 1994. Photo by Robert L. Wiegel



10b. Trans-Alaska Oil Pipeline Terminal (Alyeska Pipeline Service Co.), Valdez, Alaska. Looking down from hillside toward oil tankers loading; new Valdez is in background, 27 July 1994. Photo by Robert L. Wiegel