CHAPTER 2

HILO HARBOR TSUNAMI MODEL - REFLECTED WAVES SUPERIMPOSED

Robert Q. Palmer
Michael E. Mulvihill
Gerald T. Funasaki
U. S. Army Engineer District, Honolulu
Corps of Engineers, Honolulu, Hawaii

ABSTRACT AND ACKNOWLEDGMENT

The city and harbor of Hilo, located on the northeast coast of the island of Hawaii, have been severely damaged by numerous tsunamis. Physical features which play an important role in the formation of tsunami bores at Hilo are the submarine ridge formations in deep water outside the bay mouth and the nearly vertical cliffs along the Hamakua coast which reflect the tsunami wave into the harbor. The purpose of this paper is to discuss the Hilo Harbor Tsunami Model and this reflected wave and its effects.

The tests described and the resultant information presented herein, unless otherwise noted, were obtained from research conducted under the Hilo Harbor Model Study of the United States Army Corps of Engineers by the Honolulu Engineer District. The permission granted by the Chief of Engineers to publish this information is appreciated.

INTRODUCTION

The Hawaiian Islands, encompassed by the circum-Pacific belt of seismic and volcanic activity (Wilson, Webb, and Hendrickson, 1962), are highly vulnerable to tsunami attacks. Hilo harbor (figure 1), the second largest port in the State of Hawaii, is situated on the northeast coast of the island of Hawaii. The location of the triangularly shaped bay at Hilo makes this port city very susceptible to tsunamis from the eastern half-circle of the seismic belt which extends from the Aleutian Islands down to the west coast of South America. Historical records since 1819 indicate that there have been 42 damage causing tsunamis in Hilo, 7 of which inflicted very severe damages (U. S. Army Engineer District, Honolulu, 1962). There have been over 150 fatalities and $50 million in damages during the last 20 years. The 2 most recent devastating attacks in the Hilo area occurred on April 1, 1946, and May 23, 1960.

The April 1, 1946, tsunami (MacDonald, Shepard, and Munk, 1947) was caused by a submarine earthquake on the northern slope of the Aleutian trough, which registered about 7.5 on the Richter scale. The waves traveled southward across the Pacific to Hawaii with an average speed of approximately 490 MPH, a wave length of nearly 100 miles, and a wave height of less than 2 feet in the open sea. It is estimated that the first wave of the tsunami train entered Hilo harbor at approximately 7:00 a.m. The observed interval between waves was 15 minutes. The runup of the third and highest wave was said to have reached 26 feet above MLLW along the Hilo waterfront. The inundation extended 1/2 mile inland and covered an area of 0.4 square mile between the Wailuku River and

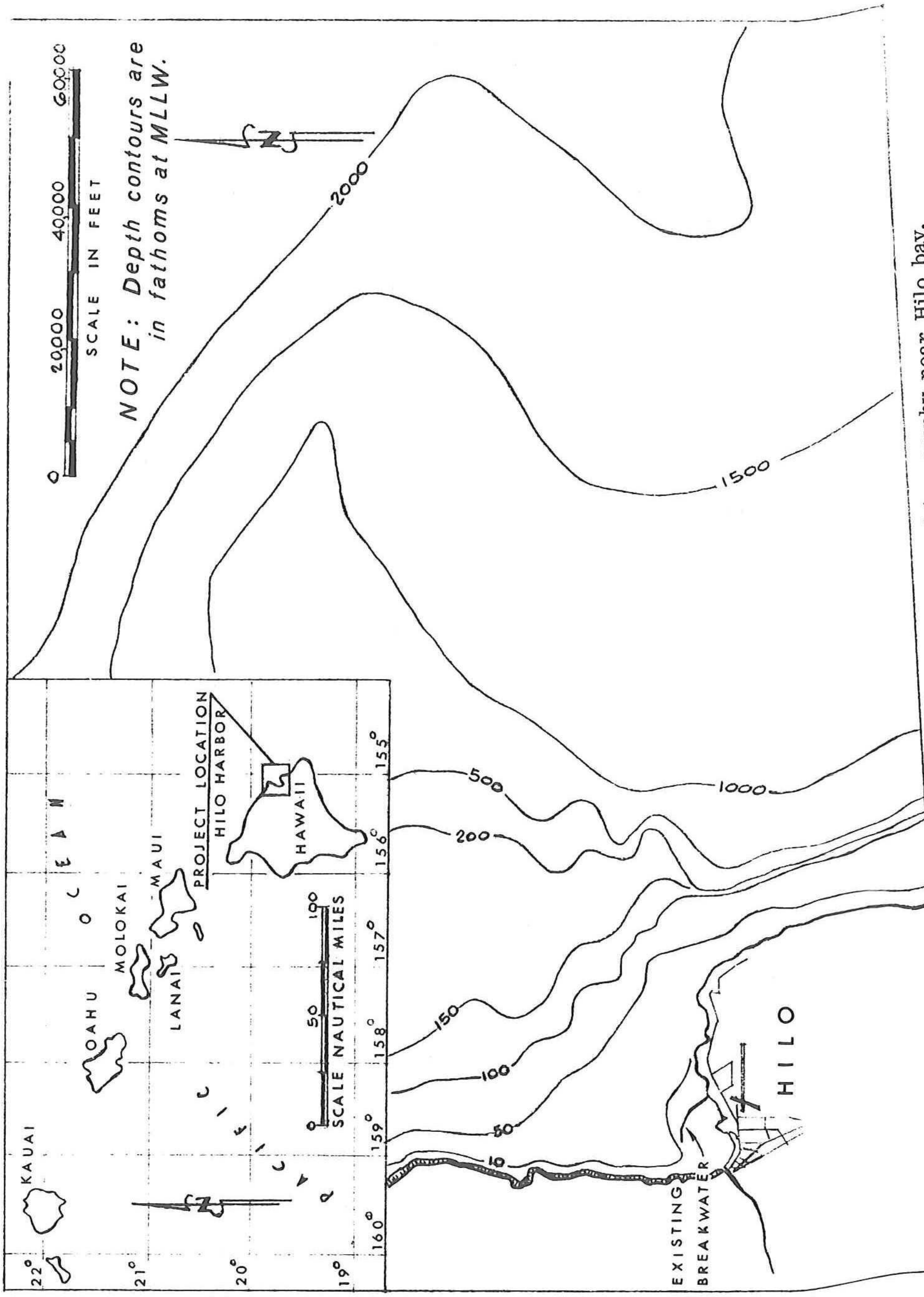

Figure 1 Location of Hilo harbor, Hawaii, and topography near Hilo bay.

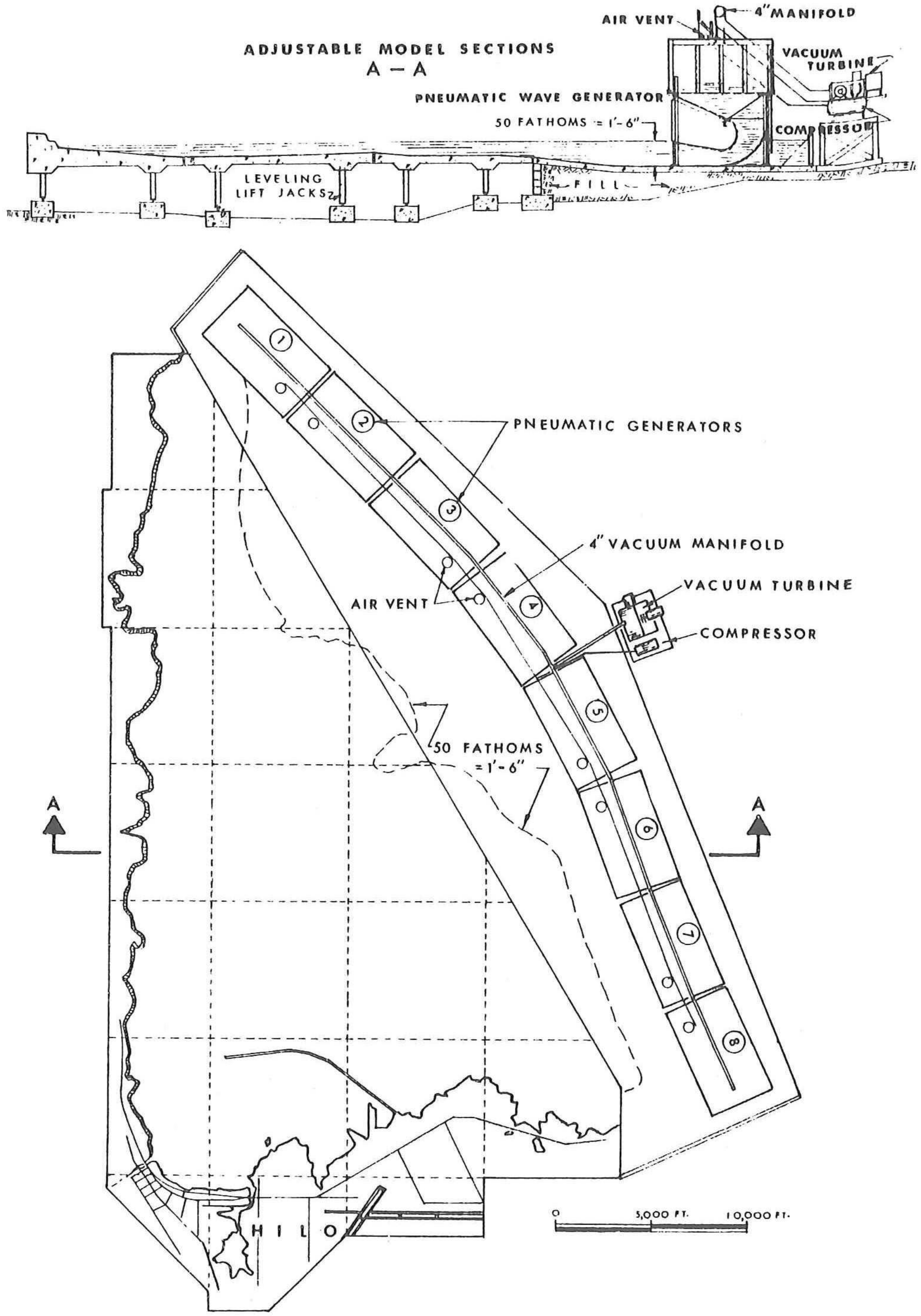

Figure 2 Hilo harbor model.

Waiakea Peninsula with the average height around 22 feet. At the mouth of the Wailuku River, the water rose about 17 feet, destroying the railroad bridge and carrying one of the steel spans 750 feet upstream. At the root of the breakwater near the pier area, the water rose 29 feet, and at pier No. 1 a measurement was taken at 27 feet. The 2-mile-long breakwater was 60 percent destroyed down to a depth of 2 to 3 feet below sea level. This disaster at Hilo resulted in $26 million in property damages and 96 lost lives.

The May 23, 1960, tsunami (Eaton, Richter, and Ault, 1961) originated off the coast of Central Chile where 10 days of violent earthquakes caused extensive destruction during the latter part of May. It is believed that on May 22, one of the quakes, which registered 8.5 on the Richter scale, generated the tsunami wave train which struck the Hilo waterfront 15 hours later causing runup in excess of 30 feet above MLLW. The average water height from Wailuku River to Waiakea Peninsula was 23 feet, and the extent of runup exceeded the limit of the 1946 tsunami. The inundated area which included all of Waiakea Peninsula was approximately 50 percent greater than in 1946. The water height at pier No. 1 was 13 feet with measurements taken at the root of the breakwater reaching 16 feet. However, the breakwater, which was rebuilt after the 1946 tsunami, suffered only minor damage. The post-tsunami report revealed that in spite of a warning system 61 lives were lost in Hilo with property damages in excess of $22 million.

THE MODEL

The catastrophic losses of the 1960 tsunami reemphasized the urgent need for some form of tsunami protection for the city and harbor of Hilo. In November of 1960 (U. S. Army Engineer District, Honolulu, 1960), Congress authorized the tsunami protection project and provided funds for advanced engineering and design. This very difficult problem was further complicated by the dearth of knowledge concerning the generation and behavior of tsunamis in general, and the distinctive affinity this phenomenon has for bore formation at Hilo in particular. Because of the nature of the problem, the United States Army Corps of Engineers, charged with the detailed study, concluded that the best approach in arriving at a feasible plan of protection was to conduct hydraulic model studies. Pilot models (Housley, 1965; Shen, 1965) were used to explore model distortion, orientation, and tsunami generators. Conferences were held with outstanding authorities in this field to determine the critical parameters for designing the model to insure accurate results. Based on the recommendations made at these conferences, the Chief of Engineers decided to construct a model of Hilo bay only, which limited the scope of construction to approximately 30 square miles of prototype area. Provision was made to expand the model to include four times the ocean area if this became necessary. The model (figure 2), constructed of concrete and contoured down to a depth of 50 fathoms at the bay mouth, was built to a distorted scale of 1:600 horizontally and 1:200 vertically. Its shape is that of a right triangle with sides measuring 63 and 96 feet. A pneumatic type wave generator was selected to create a solitary wave to reproduce the tsunami bore in Hilo harbor.

The model construction was initiated by the Honolulu Engineer District in March 1964, and 5 months later, the model was completed and operational. The State of Hawaii facility, which houses the Hilo Harbor Model, has been named the "Look Laboratory of Oceanographic Engineering" after the late James K. K. Look, a civil engineer of the Honolulu Engineer District who lost his life in Hilo seeking vital engineering data during the 1960 tsunami.

Initial calibration of the model and pneumatic generators was begun in August 1964. Adjustments were made for the variation in roughness of the land and submarine areas reproduced on the model. The basic concept of the model calibration was to duplicate the actual conditions which occurred in Hilo during the several tsunamis for which prototype data were available. After examination of the data, testing was aimed at duplicating the following three basic conditions:

a. High water marks (elevations to which the wave rose at specific locations along the waterfront and harbor).

b. Limit of inundation (line showing extent to which the tsunami runup occurred).

c. Marigrams (time history of wave action at a location).

Because of the unpredictability of wave actions at the Hilo waterfront and harbor, testing to verify the model became a trial-and-error process. A slight change in the wave input significantly affected most of the key points in the model.

In calibrating the model by duplicating prototype conditions, the waves for the various tsunamis tested were also being verified and programmed for repetitive testing of proposed barriers. Four months were required to develop the waves for the 1946, 1952, 1957, and 1960 tsunamis. A two-wave sequence was used to simulate the largest wave in the tsunami train and the drawdown of the water in the harbor prior to its attack.

During the course of the testing program, two conferences were held to discuss tsunami behavior in the model. Among the consultants who attended the conferences were: Dr. Garbis H. Keulegan, former director of the National Hydraulics Laboratory of the Bureau of Standards; Dr. William G. Van Dorn, Scripps Institution of Oceanography; Dr. Basil W. Wilson, Science Engineering Associates; and Robert L. Wiegel, assistant dean of engineering, University of California. The recommendations on test procedure offered at these conferences were incorporated into the model testing program. The consultants agreed the test results indicated that the model had attained an acceptable degree of similitude; i.e., that the characteristics of the wave were realistic and the wave actions in the harbor were representative of the prototype tsunami. Also, two design waves for the testing of tsunami barriers were selected. Due to the high intensity (8.5) of the generating earthquake, the 1960 tsunami was selected as being of design magnitude from the direction of South America. The magnitude of the 1946 tsunami was increased by

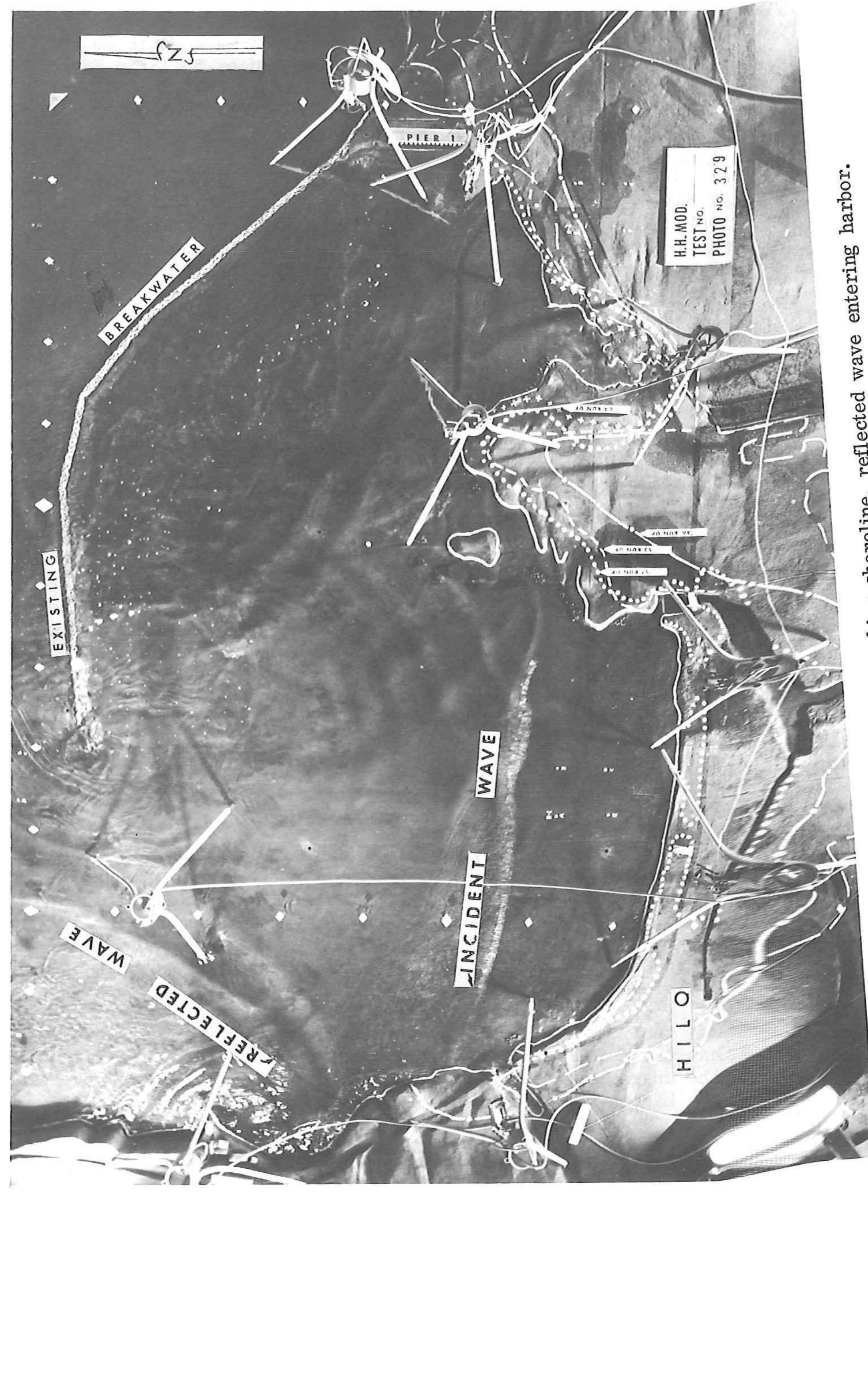

Figure 3a Incident wave approaching shoreline, reflected wave entering harbor.

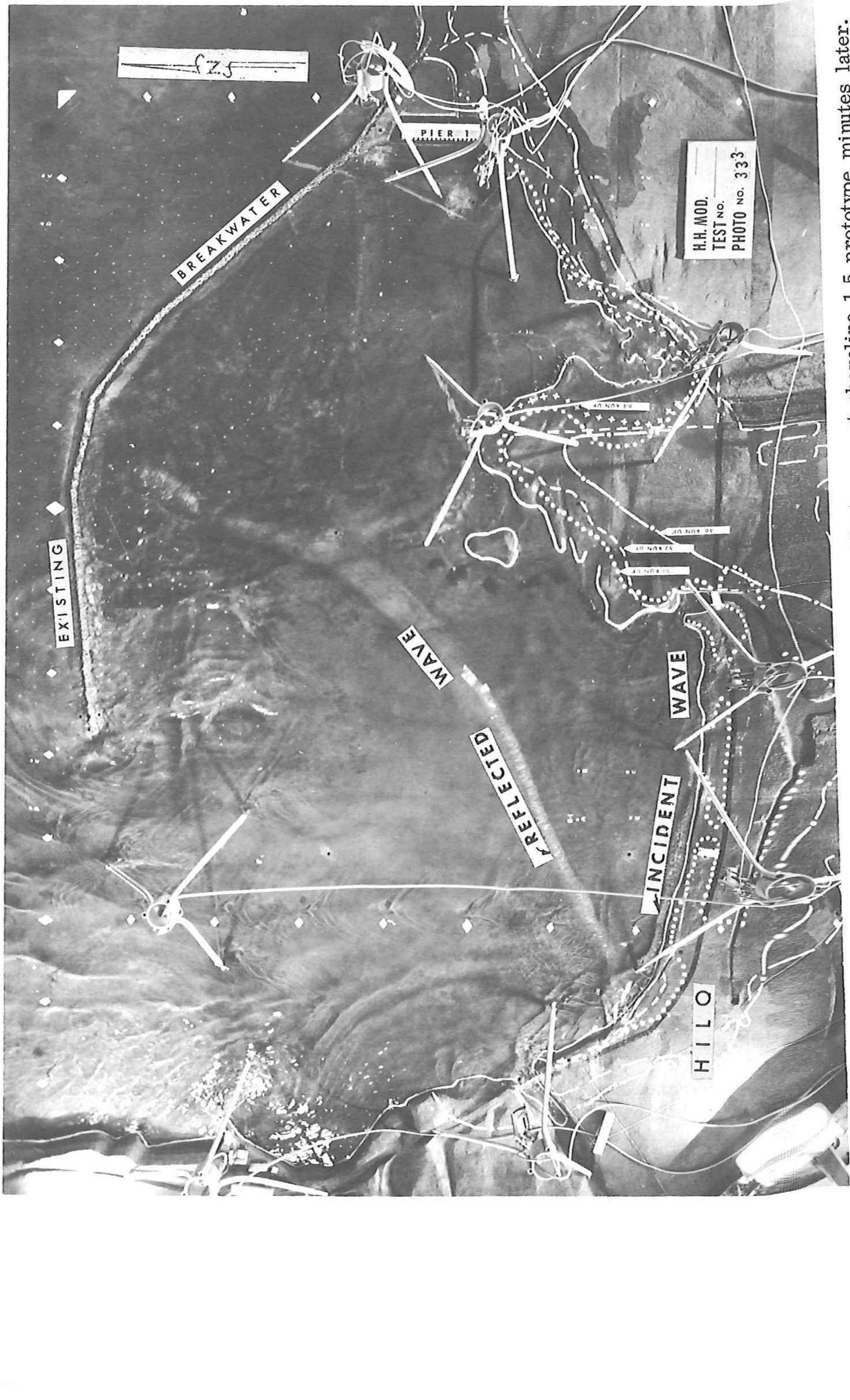

Figure 3b Reflected wave superimposing on incident wave at shoreline 1.5 prototype minutes later.

25 percent because an earthquake of greater magnitude than 7.5 (1946 condition) could very possibly occur off the Aleutian Islands.

THE REFLECTED WAVE

During the model verification tests, the reflected wave (figure 3) off the nearly vertical Hamakua cliffs emerged as a significant cause of tsunami bore formation in Hilo harbor. The occurrence of this phenomenon was suspected by Munk (1957) in his report on the Hilo seawall. In his analysis of the tsunami problem at Hilo, Munk commented that his estimated theoretical wave heights at the shoreline might be larger if reinforced by the reflected wave off the Hamakua cliffs.

Investigation after the 1960 tsunami produced a witness, Mr. McLaren Child, who was attempting to navigate his boat out of Hilo harbor during the tsunami. Mr. Child, a resident of Hilo, stated that when he was in the vicinity of the harbor entrance, his boat was struck by two major waves, about 2 minutes apart. Since the period for this tsunami was established at approximately 15 minutes, these two major waves could very possibly have been an incident wave and the reflected wave.

Wiegel (1963) conducted pilot model tests on a 1:15,000 undistorted scale model of Hilo and vicinity. During these tests, he observed a reflected wave which became independent of the incident wave and "moved as a high wave running on top of the water which had diffracted into the harbor as the incident wave." Wiegel's findings further indicated the evolvement of a Mach stem type phenomenon which, because of its strength, became independent of the reflected wave.

In 1963, Palmer (co-author) and Alfred Barona of the Honolulu Engineer District collaborated on a refraction study of both the 1946 and 1960 tsunami wave fronts to determine their theoretical propagation into Hilo harbor. These analyses (figure 4), which traced the movement of the incident and reflected wave fronts at 1 minute intervals, indicate that there is a concentration of wave energy at the Hilo waterfront. The diagrams also show that the incident wave precedes the reflected wave into the harbor by approximately 2 minutes. The direction of the wave front just prior to running up on the land correlates well with the data reconstructing water movement in the runup zone after the 1960 tsunami.

The amount of experimental data dealing solely with the reflected wave was limited by the scope of the model study. Visual observations and recorded data of wave heights at various points in the harbor clearly indicated that the reflected wave was a major factor in aggravating the tsunami action in Hilo harbor. During the course of the verification tests, it was observed that the angle of wave generation would affect the angle of the reflected wave. This angle was adjusted until the high water marks in the harbor were acceptably duplicated.

As a separate term paper project for a course in ocean engineering at the University of Hawaii, Funasaki (co-author) ran a series of tests in the model to investigate behavior of the reflected wave. This study attempted to show the effect of the angle of incidence on the reflected

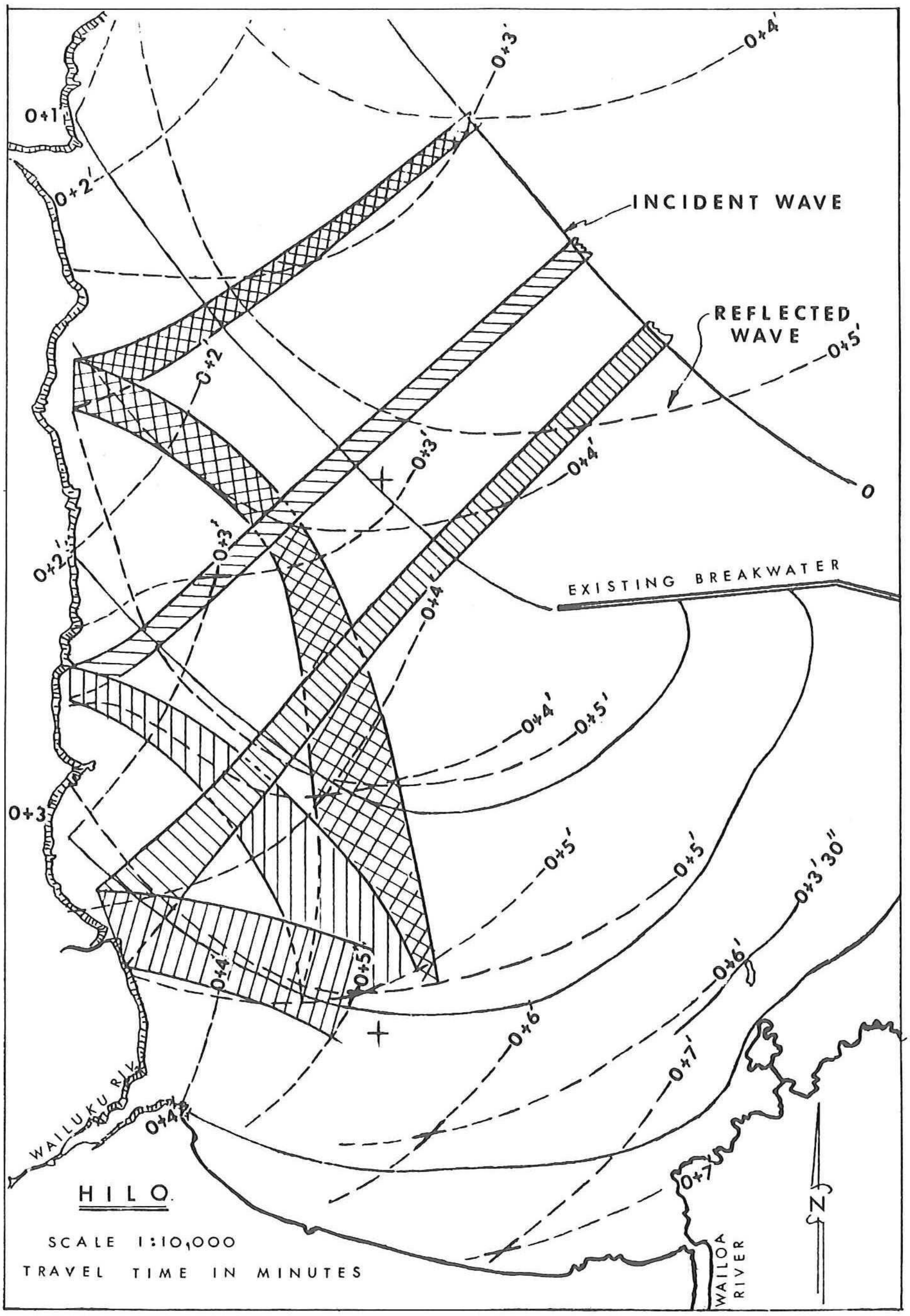

Figure 4 1960 tsunami refraction diagram.

wave entering Hilo harbor, and to determine the extent of incident wave amplification by the reflected wave at the shoreline. The results of these tests indicate that the critical approach direction of a tsunami into Hilo bay may have an incident angle of approximately 80 degrees (N. 80° E.) at the mouth of the bay since the reflected wave heights entering the harbor were highest from this direction. The tests for all directions indicate that the time interval between the incident and reflected waves at the harbor entrance was about 1-1/2 to 2 minutes (prototype), which verifies Mr. Child's testimony that his boat was struck by two major waves about 2 minutes apart as he was attempting to leave the harbor during the 1960 tsunami. The results also showed that the angle of incidence did not make an appreciable difference in the extent of incident wave amplification at the shoreline. For a constant wave input, the increase in wave height was approximately the same from all directions. The amplification varied from 55 to 150 percent of the incident wave height for wave inputs based on differential heads of 0.5 foot to 2.5 feet (half foot increments) in the pneumatic generator chambers. The time interval between the incident and reflected waves at the shoreline became less as the angle of incidence decreased. The results for the test with an incident angle of 20 degrees showed that the reflected and incident waves combined to form a single amplified wave at the shoreline.

CONCLUSION

Up to the present time, model investigations and post-tsunami papers on the problem at Hilo indicate that a combination of three bathymetric conditions causes the tsunami devastation at Hilo. First, the submarine ridge formations outside the bay mouth refracts the tsunami wave into the bay. Second, the triangular configuration of the bay, with Hilo at the apex, has a compressive effect on the wave. Third, the reflected wave off the cliffs superimposes on top of the incident wave in Hilo harbor. These three factors have played the vital roles in the tsunami attacks at Hilo.

The most important result of the Hilo Harbor Model Study has been the fact that the complex phenomenon of tsunami bore formation was acceptably duplicated and the problem was shown to be susceptible to solution in an hydraulic model.

Following the completion of similitude tests for the 1946 and 1960 tsunamis, testing of numerous barrier plans was undertaken. Since the studies of the various plans are still being conducted, discussion on this matter will not be presented at this time.

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