

CHAPTER ONE HUNDRED EIGHTY ONE

REEF RUNWAY WAVE PROTECTIVE STRUCTURE, HONOLULU INTERNATIONAL AIRPORT, OAHU, HAWAII, STABILITY PERFORMANCE EVALUATION

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Abstract

An inspection survey of the Reef Runway Wave Protective Structure at the Honolulu International Airport was accomplished in 1982 to assess the performance of the dolos and rock armored structure to date. The inspection showed the structure to be performing adequately considering that the design wave conditions were experienced.

Introduction

In 1972, the State of Hawaii began construction of an offshore runway at the Honolulu International Airport. This project, called the Reef Runway, was undertaken to alleviate aircraft noise and safety concerns over metropolitan Honolulu, provide more flexibility for aircraft takeoff and landings, and increase airfield capacity. The project encompasses dredged fill on 1,240 acres of offshore coral reef with a 16,100 foot-long wave protective structure, a 12,000 foot-long by 200 foot-wide runway, 1,350 feet of apron and clear zone bordering the runway, and taxiways and service roads which connect the runway to shore. The protective structure is of rubblemound construction and armored with 4 and 6 ton dolos concrete units along the deepwater sections. Figure 1 shows a General Plan view of the Reef Runway at the Honolulu International Airport. The project was the subject of environmental controversy, and was held up for approximately one year due to various court actions. Finally, the U.S. Supreme Court allowed the project to proceed after declining to hear appeals from environmental groups on the adequacy of the Environmental Impact Statement. In 1975, the Reef Runway protective structure was completed, and in 1977, the Reef Runway was dedicated and operational. The Reef Runway was named one of the Ten Outstanding Engineering achievements of 1977 by the National Society of Professional Engineers, and one of Outstanding Projects of 1977 by the American Society of Civil Engineers. The Federal Aviation Administration also elected the Reef Runway an Environmental Excellence Award.

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In mid 1982, a detailed inspection of the Reef Runway protective structure was initiated by Edward K. Noda & Associates for the Reef Runway Managing Consultant at the request of the State of Hawaii. The survey was undertaken as a precautionary measure to assess the performance of the structure to date. In view of the controversy which has developed as to the viability of existing stability criteria for concrete armor units in rubblemound structures, stemming from the breakwater failure at Port Sines on the Atlantic coast of Portugal in 1978, the results of the survey were expected to serve as verification of the design criteria as well as to provide a baseline data set for future inspection and maintenance surveys. The inspection revealed no significant damages, and the protective structure was found to be performing as designed. The evaluation of the stability performance of the wave protective structure was two-fold. First, the physical condition of the structure was assessed to determine the percent damage to the armor units. Second, the wave conditions to which the structure has been subjected to date were evaluated to determine whether the design wave criteria were experienced. This paper summarizes the results of the inspection and stability performance evaluation of the Reef Runway protective structure.

Reef Runway Protective Structure Design

The basic design criteria for the Reef Runway wave protective structure was developed by Tetra Tech of Pasadena, California, in 1972 for the Reef Runway Managing Consultant, the Ralph M. Parsons Company.

Oceanographic Design Criteria

Tetra Tech recommended a design stillwater elevation of +3.0 feet above Mean Sea Level (MSL) based on evaluation of the following factors:

- *Set-up due to wind stress components
- *Water level increase due to atmospheric pressure reduction associated with storm centers
- *Wave set-up due to breaking waves
- *Astronomical tide

It is interesting to note that the highest tide recorded to 1981 was 2.39 feet above MSL. The Mean Higher High Water (MHHW) level is 1.08 feet above MSL.

The design wave criteria was based on the maximum possible wave height, H_{max} , that could theoretically exist at the toe of the structure. For the deepwater dolos-armored section, the maximum wave height was given by:

$$H_{max} = (0.73 + 5.6 S)D \quad (1)$$

where:

S = the ocean bottom slope seaward of the toe
 D = the total water depth at the toe

Thus, the design wave height varied as a function of the local bottom slope and water depth along the toe of the structure, and the highest computed H_{max} was 25.2 feet at Station 116+00. To determine the maximum wave height for the shallow water section fronted by fringing reef, S, in the above equation, was set to zero.

Tetra Tech also reviewed and evaluated previously measured and hindcasted storm events to verify that waves as large as H_{max} could physically be generated in the region, and concluded that 25 foot waves could be expected to occur once in ten years.

Armor Stability Criteria

Primary armor design for stability was evaluated using the Hudson equation:

$$W = \frac{w_r H^3}{K_D (S_r - 1)^3 \cot \phi} \quad (2)$$

where:

W = weight of individual armor units (lbs)
 w_r = unit weight of the armor unit (lbs/ft³)
 H = design wave height at the structure (ft)
 S_r = specific gravity of the armor unit relative to seawater = (w_r/w_w)
 w_w = unit weight of seawater = 64 lbs/ft³
 ϕ = angle of the structure face measured from horizontal
 K_D = stability coefficient (varies primarily as a function of the shape of the armor units, roughness of the armor units, and degree of interlocking obtained in placement)

The layer thickness of the primary armor units is given by:

$$t = n k_t (W/w_r)^{1/3} \quad (3)$$

where:

t = thickness of primary armor layer (ft)
 n = the number of units comprising the armor layer thickness
 k_t = layer coefficient (varies as a function of the type of armor unit)

Finally, the density of units in the primary armor layer is given by:

$$N = n k_e (1 - P/100) (w_r/W)^{2/3} \quad (4)$$

where:

N = the number of armor units per square feet of surface area

P = the average porosity of the primary armor layer (%)

For the exposed deepwater section of the wave protective structure, various primary cover layer designs were assessed and designs completed for five alternative protection schemes. In the competitive bidding process, Hawaiian Dredging and Construction Company was the low bidder, and chose a design consisting of 4 and 6 ton dolos concrete armor units. It has been recognized that rubblemound structures can accept some level of damage and still remain stable. In view of this, and the acceptability of a degree of risk associated with the recurrences of significant storm events, the stability coefficient K_D was selected to yield an acceptable damage level of 4% and 2% for the 6 and 4 ton dolos trunk sections, respectively. Tests conducted by the USAE Waterways Experiment Station (Davidson & Markle, 1976) indicate that stability is affected only when random breakage exceeds 15% and cluster breakage exceeds 3 units. Table 1 summarizes the stability criteria adopted for the final design of the dolos covered sections.

Table 1. Stability Criteria for Dolos Armor
(Sta 85+00 to 131+50)

	Breakwater Head	Trunk Sections	
	Sta 85-86	Sta 110-120	All other
Nominal weight of units	6 ton	6 ton	4 ton
Unit weight, w_r	147 lb/ft ³	147 lb/ft ³	147 lb/ft ³
Design wave height, H_{max}	13.8 ft	25.2 ft	<18 ft*
Cot structure slope	2.25	1.5	1.5
Stability coefficient, K_D	6.8	64	32
Allowable damage	0%	4%	2%
Layer thickness, t	11.3 ft	11.3 ft	9.9 ft
Number of units thick, n	2	2	2
Layer coefficient, k_e	1.3	1.3	1.3
Density of armor units, N	.055/ft ²	.055/ft ²	.075/ft ²
Porosity of armor layer, P	60%	60%	60%
Crest elevation above MSL	16 ft	20 ft	16-20 ft

*While maximum wave heights were typically less than 18 feet, within a short reach maximum wave heights to 19.3 feet can be expected.

The armor layer extends down to the toe of the structure, where the maximum water depth is 27 feet below MSL at

Station 116+00. Figure 2 depicts typical cross sections for the protective structure. Figure 3 depicts the relative dolos dimensions and Table 2 lists the design dimensions for the 4 and 6 ton units, based on a unit weight of 147 lb/ft³ for concrete.

Table 2. Design Dimensions for Individual Dolos Units

	Nominal Weight of Units	
	4 ton	6 ton
Volume = 0.16 C ³	54.9 ft ³	81.9 ft ³
Overall dimension, C	7 ft	8 ft
Waist dimension, B = 0.32 C	2' 1"	2' 5"
Fluke dimension, A = 0.20 C	1' 5"	1' 7"
Fillet dimension, D = 0.057 C	5"	6"

Inspection and Damage Assessment

The inspection survey was performed during the period July 1982 through January 1983, and involved a visual, photographic and underwater reconnaissance of the entire Reef Runway protective structure. Although a major portion of the structure is fronted by shallow reef which facilitated the inspection, approximately 7,000 lineal feet is in deeper water sometimes exceeding 25 feet. Inspection of the underwater regions of the deepwater sections were hampered by poor visibility water conditions, resulting in three months of delay from September to December 1982 before conditions improved sufficiently to enable completion of the survey.

A total of 301 dolos armor units were damaged out of a total of 18,009 units originally placed, yielding an overall damage of 1.67% to the primary armor cover. An estimated 71 out of the 4,317 6-ton units placed and 230 out of 13,692 4-ton units placed were broken or displaced, yielding damages of 1.64% for the 6-ton and 1.68% for the 4-ton units. Table 3 provides a detailed damage assessment. The number of dolos placed per various reaches are estimated based on the total number of dolos known to have been placed and the percent of square footage covered within the given reach, assuming reasonably uniform density of placement for given dolos size.

Since the water depth at the toe varies considerably over short distances, the maximum design wave height and actual K_D vary within given reaches of a specified nominal dolos size. For the head section to Sta 86+00, the design K_D of 6.8 is slightly conservative over the actual K_D of 6.6; however, the actual damage is greater than the no-damage design criteria. For Sta 110+00 to 120+00 which also utilized 6 ton dolos, the design K_D of 6.4 is

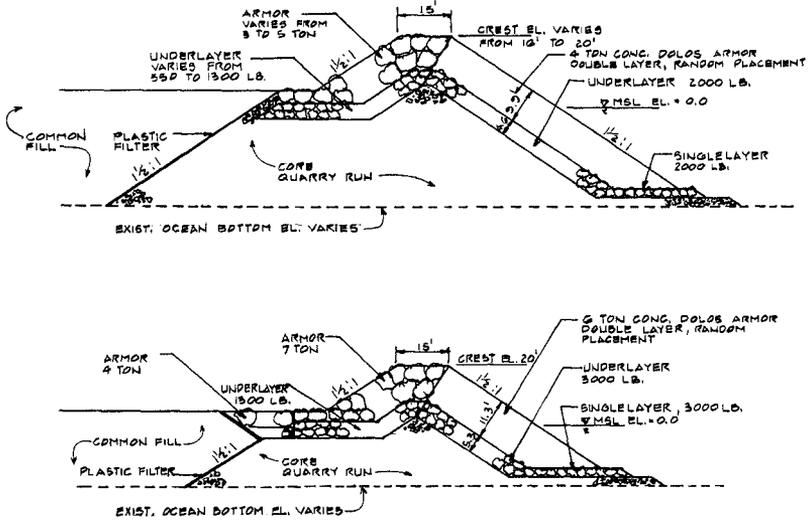


FIG.2 TYPICAL DOLOS ARMOR PROTECTIVE STRUCTURE SECTIONS
(Not To Scale)

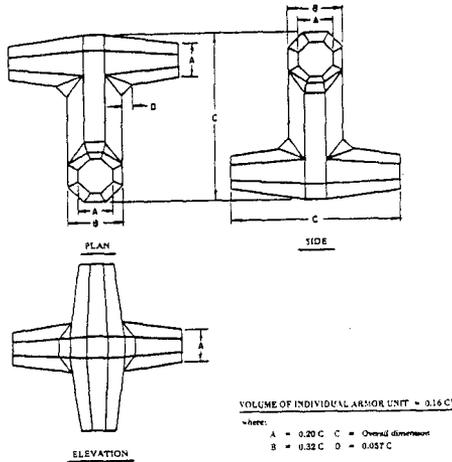


FIG.3 RELATIVE DOLOS DIMENSIONS

Table 3. Damage Assessment of Dolos Armor Units, Reef Runway Wave Protective Structure
(Based on 1982 Inspection)

Station Location		No. of Damaged Dolos			Dolos	Design	Stability Coef. K _s		No. Dolos	Percent Damage	
From	To	U/Water	A/Water	Total	Size	H _{max} (ft)	Design	Actual	Placed	Design	Actual
Breakwater Head		2	0	2	6T	13.8		6.6			
85+00	86+00	6	2	8	6T	13.8		6.6			
Head	86+00	8	2	10	6T		6.8	6.6	1,234	0%	0.81%
86+00	88+64	16	5	21	4T	13.8-12.7		14.8-11.5			
88+64	91+64	22	8	30	4T	12.7-16.8		11.5-26.6			
91+64	95+25	31	6	37	4T	16.8-19.3		26.6-40.4			
95+25	96+25	14	4	18	4T	19.3-18.5		40.4-35.6			
98+25	101+25	12	6	18	4T	18.5-15.4		35.6-20.5			
101+25	104+25	14	4	18	4T	15.4-15.2		20.5-19.7			
104+25	107+25	13	9	21	4T	15.2-13.1		19.7-12.6			
107+25	110+00	13	6	19	4T	13.1-15.1		12.6-19.3			
86+00	110+00	135	47	182	4T		32	11.5-40.4	9,510	2%	1.91%
110+00	113+25	12	4	16	6T	15.1-20.2		12.9-30.9			
113+25	116+25	9	1	10	6T	20.2-25.2		30.9-59.9			
116+25	120+00	28	7	35	6T	25.2-16.1		59.9-15.6			
110+00	120+00	49	12	61	6T		64	12.9-59.9	3,083	4%	1.98%
120+00	125+25	19	5	24	4T	16.1-11.8		23.4- 9.2			
125+25	128+25	7	4	11	4T	11.8-16.8		9.2-26.6			
128+25	131+50	10	3	13	4T	16.8- 9.3		26.6- 4.5			
120+00	131+50	36	12	48	4T		32	4.5-26.6	4,182	2%	1.15%
TOTAL		228	73	301					18,009		1.67%
6 ton Total		57	14	71					4,317		1.64%
4 ton Total		171	59	230					13,692		1.68%

similarly conservative over the actual range of K_D ; and in this reach the actual damage overall is well within the 4% design damage criteria. For the reaches with 4 ton dolos, the actual K_D sometimes exceeded the design K_D of 32; however, the actual damage overall was within the 2% design damage criteria.

For those reaches with 4 ton dolos, the actual K_D is as high as 40 in one area. However, test results (Zwamborn, 1980) indicate that for the design packing density, the K_D of 40 is still within the envelope of data for 2% damage. For a relative packing density of 0.075 units/ft² $\times V^{-2/3} = 1.08$ for the 4 ton dolos, the test data indicate a minimum K_D of 16, mean K_D of 25.5, and maximum K_D of 41. The data indicates an optimum double-layer packing density of 0.9 to 1.0 $V^{-2/3}$, with corresponding mean K_D of 32 to 28. The design packing densities of 0.055 units/ft² $= 1.04 V^{-2/3}$ for the 6 ton dolos and 0.075 units/ft² $= 1.08 V^{-2/3}$ for the 4 ton dolos would indicate less stability than optimum. In fact, Darling (1976) indicates that the required packing densities resulted in a three-layer cover, with a large percentage of the total 1.4% breakage during placing operations resulting from trying to fit the top layer of dolos.

In general, the damaged units were found scattered randomly throughout the structure, and the primary armor cover appeared to retain its original integrity. The broken dolos were intermixed with the unbroken units, and a few units were displaced from the structure. However, it was difficult to determine where the displaced units came from. Figures 4 and 5 show typical damages to the dolos.

During the period when the survey was delayed due to poor visibility water conditions, Hurricane Iwa struck the Hawaiian Islands. Both above water and underwater inspections indicated no evident additional damage as a result of the storm. Apparently, most of the damage to the dolos occurred prior to the wave attack from Hurricane Iwa.

Wave Evaluation

In order to provide a credible assessment of the performance of the Reef Runway wave protective structure, an evaluation of the types and magnitudes of the largest waves to have attacked the structure following completion of construction in the fall of 1975 to the completion of the inspection survey in January 1983 was accomplished. Figure 6 depicts the general location of the project site within the Hawaiian Islands, and Figure 7 shows the site in relation to adjacent facilities along the south coast of Oahu. Three distinct wave types have attacked the structure during this period:



FIG.4 TYPICAL DOLOS BREAKAGE (6-TON UNITS AT STA 119+25)



FIG.5 TYPICAL DOLOS BREAKAGE (4-TON UNITS AT STA 128+50)

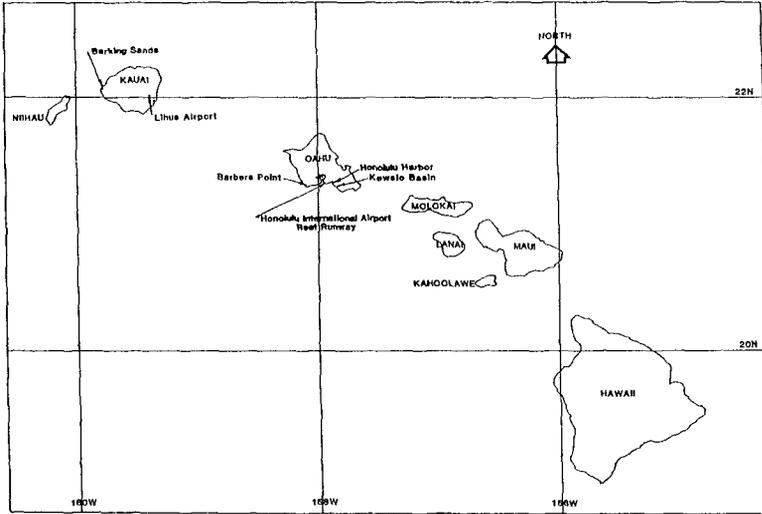


FIG. 6 MAP OF THE HAWAIIAN ISLANDS SHOWING THE PROJECT SITE LOCATION

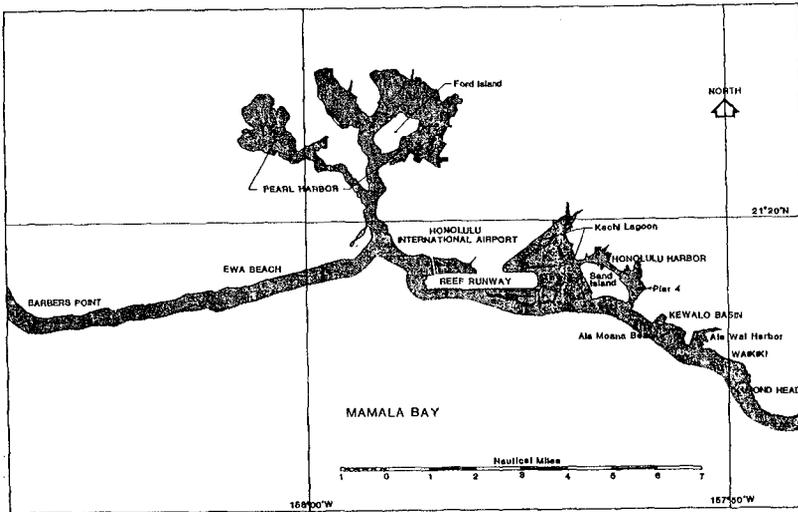


FIG. 7 VICINITY MAP OF PROJECT SITE ON SOUTH SHORE OF OAHU

- *Locally generated "Kona" storm waves
- *Southerly swell generated by Southern Hemisphere storms
- *Hurricane Iwa waves

Kona Storm waves and Southerly swell

Nov 24, 1975 storm: South and southeast winds generated estimated maximum surf of about 6 feet at Ala Moana. Although winds were not particularly strong at the Honolulu International Airport, estimated 25 to 30 mph winds generated waves large enough to wash a 118-foot fishing vessel aground at the entrance to Honolulu Harbor. A 41-foot Coast Guard rescue boat trying to help the fishing vessel ran aground nearby.

Feb 5-6, 1976 storm: This was a major storm which generated large southwest waves offshore the Reef Runway for about two days. Peak gust at Lihue Airport, Kauai, was 46 mph from the southwest. The average wind speed at Honolulu International Airport was 17.5 mph, with the fastest mile of 26 mph. Although the wind data at Honolulu Airport did not indicate exceptionally strong southwest winds, the waters southwest of the Reef Runway did experience strong Kona winds. Estimated surf was about 6 feet at Ala Moana.

Jan 8-10, 1980 storm: Up to that time, this storm caused the greatest monetary loss ever recorded in the State. Heavy rains, Kona winds, high waves, and two tornadoes accompanied the passage of two successive cold fronts. Wind gusts of 100 mph were recorded on Mt. Haleakala, Maui. Honolulu International Airport recorded gusts of 52 mph. The long duration of strong winds generated high waves which battered the south and west shores of all the islands. Estimated maximum surf was about 6 feet at Ala Moana, with surf to 15 feet reported in other areas. Bretschneider (1984) reports hindcast deepwater significant wave heights of 29 feet with significant period of 13.5 seconds.

Southerly swell: During the summer months, large swell from Southern Hemisphere storms frequently cause high surf conditions along the southern shores of the Hawaiian Islands. The following are occurrences of estimated high surf conditions:

- *July 27-28, 1976: 8 feet
- *July 29, 1976 : 7 to 9 feet, max 10-12 feet
- *May 25, 1977 : 8 feet

Hurricane Iwa waves

On November 23, 1982, the most destructive storm in Hawaiian history, Hurricane Iwa, struck the Hawaiian

Islands. Hardest hit were the islands of Niihau, Kauai, and Oahu, where storm surge and waves inundated the southern coast of Kauai and the leeward and portions of the southeast coast of Oahu. Statewide storm-related damages exceeded \$310 million.

A hindcast analysis of the expected hurricane waves at the Reef Runway was accomplished utilizing the significant wave approach by Bretschneider (1970, 1972a, 1972b, 1976). The hurricane parameters used in the hindcast are as follows:

Central Pressure, P_c = 28.6 inches Hg (measured)
Pressure depression, ΔP = 1.32 inches Hg
Radius of maximum wind, R = 20 nautical miles
(estimated)
Latitude, ϕ = 22 degrees
Average forward speed, V_F = 20 knots

Figure 8 shows the track of Hurricane Iwa, where the storm center passed within 110 to 120 nautical miles of the Reef Runway at its closest point of approach. The hindcast indicated maximum significant wave heights of 39.8 feet with wave period of 13.3 seconds, and expected significant wave heights offshore the Reef Runway of about 31 feet associated with sustained winds of 35 knots. Bretschneider (1984) suggests that the radius of maximum wind was probably as large as 50 nautical miles, with hindcast maximum significant wave heights of 41 to 43 feet and periods of 14.2 to 14.7 seconds. Based on his hindcast analysis, expected significant wave heights offshore the site were on the order of 35 feet.

No instrument measurements are available to confirm the hindcast wave heights. However, the US Navy reported that its guided missile destroyer USS Goldsborough was hit by a "30 foot" wave about 2 miles offshore the entrance to Pearl Harbor at 4:30 pm, on 23 November 1982, which killed a crew member on the forward deck and washed a second crew member overboard. While direct wave measurements are not available, wind speed measurements at the Honolulu International Airport confirm the hindcast 35 knot sustained wind speeds.

Measurements of the rise in water level elevation due to the passage of Hurricane Iwa are also available. Data from gage measurements in Kewalo Basin, approximately 3 miles from the Reef Runway, indicates that the difference between measured water levels and predicted tide levels was a maximum of 41 inches (3.4 feet) due to the storm. The design water level for the Reef Runway wave protective structure was 3.0 feet above MSL.

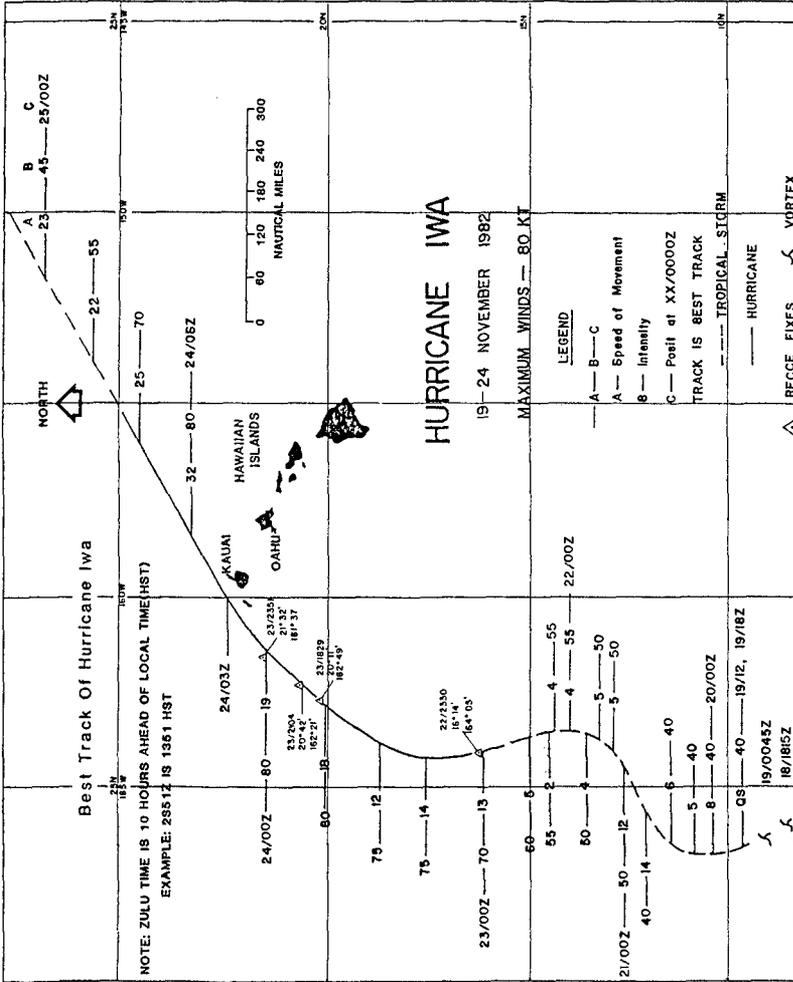


FIG. 8 TRACK OF HURRICANE IWA, NOVEMBER 1982

Summary and Conclusions

A visual and photographic inspection of the wave protective structure for the Reef Runway, Honolulu International Airport, has been performed to assess the present physical state of the structure. The performance of the protective structure was assessed by reviewing the basic design criteria and design practices utilized for construction, and evaluation of the maximum waves which have attacked the structure.

A review of the design procedure for the wave protective structure performed in 1972 indicates that the design practice implemented for the Reef Runway protective structure is still consistent with present day techniques. Hindcasts of the wind-generated waves from Hurricane Iwa indicates that significant wave heights of up to 35 feet would be expected offshore the Reef Runway located approximately 110-120 nautical miles from the hurricane center. Comparison of these hurricane hindcast waves with the design maximum breaking waves along the exposed deepwater sections of the protective structure shows that Hurricane Iwa most probably generated maximum design wave conditions for the structure.

The design water level for the wave protective structure was 3.0 feet above MSL, and water level measurements at Kewalo Basin during Hurricane Iwa indicate a maximum measured rise of about 36 inches above MSL. When analysis is performed subtracting expected tidal fluctuations from measured water level, a maximum water level rise due only to Hurricane Iwa is calculated at 41 inches.

In general, the Reef Runway wave protective structure is in very good condition. The exposed deepwater section protected by 4 and 6 ton dolos concrete armor units has undergone the most severe wave attack and is the only major region where wave damage is evident. Underwater and above water visual inspection surveys were performed both prior to and after wave attack from Hurricane Iwa. These inspections indicate that no visually discernable damage to the dolos armored sections occurred due to Hurricane Iwa wave attack.

A numerical count of broken dolos by station locations was performed and the results show that 301 units were found broken, comprising about 71 each 6-ton units and 230 each 4-ton units. At the completion of construction in late 1975, 4,317 each 6-ton and 13,692 each 4-ton dolos units were installed yielding a percent damage of 1.64% for the 6-ton and 1.68% for the 4-ton units, with an overall damage percentage of 1.67% for all dolos installed.

The design criteria utilized a 2% damage level for the 4-ton dolos, a no-damage criteria for the 6-ton dolos at the

breakwater head, and a 4% damage level for the 6-ton dolos along the trunk section. Comparison of this design damage level versus the existing damage indicates that the structure is performing adequately following the design wave attack.

Underwater visual inspections show that the dolos protected deepwater sections remain integrally intact, and that broken dolos parts generally still remain imbedded in the structure cover layer. At Station 88+00 is the only area which was noted to have a small void region on the slope face with some broken dolos sighted 10-15 away from the structure toe.

Historically, scale-model experiments of dolos protected rubblemound structures indicate that the stability characteristics increase with small levels of damage. The reason is attributed to the condition that under wave attack, usually by relatively smaller waves than the design waves, units which were placed in an unstable position would either move and break or would be displaced off the structure, thereby resulting in a small percent damage. Those units not broken or displaced would nest and stabilize, thereby developing greater interlocking stability with a consequent capability to remain stable under the design wave attack. This condition is believed to have occurred for those sections of the Reef Runway protective structure utilizing dolos armor units. Following construction, wave attack from Kona storm waves and Southern Hemisphere generated swell, generally smaller than the design wave heights, served to increase stability by increasing the as-constructed interlocking capability of the random placed dolos units, with the inherent consequences of suffering a small level of damage. It is believed that the overall 1.67% dolos damage level noted during this survey occurred prior to wave attack from Hurricane Iwa. With an increased stability capability, the dolos armored structure was able to withstand wave attack from Hurricane Iwa with no increase in damage as compared to prior visual surveys.

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