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5. *On the Tsunamis along the Island of Hawaii.*

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1. Introduction

The Hawaiian Islands are situated at the center of the circum-Pacific seismic zone. The Island of Hawaii has, therefore, suffered severe damage from tsunamis. Forty-one tsunamis have occured during the last 140 years[1], as shown in Fig. 1. These tsunamis originated along the coast of Sanriku (Japan), Kamchatka, Aleutian, Peru, Chile and Hawaii.

The tsunami, propagated toward the islands situated in mid-ocean, produced many effects such as diffraction and refraction. In the case of the tsunami on April 1, 1946 K. Hidaka and S. Hikosaka[2] calculated the distribution of wave-heights along the coast of Kauai Island, Hawaii, on the basis of Proudman's theory of diffraction of tidal waves by a circular island. S. Homma[3] theoretically discussed, the behavior of a tsunami passing around a circular island, where the effect of the insular

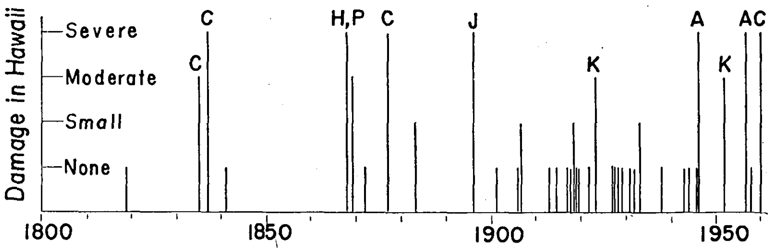

Fig. 1. Historical tsunami in Hawaii. Height of an ordinate indicates degree of damage in Hawaii. Epicenter of earthquakes; A: Aleutian, C: Chile, H: Hawaii, J: Japan (Sanriku), K: Kamchatka, and P: Peru.

1) The Hilo Tribune-Herald, Ltd. K. HORIKAWA, "Tsunami Phenomena in the Light of Engineering View-point," *Rep. Chilean Tsunami, Field Inv. Comm. Chilean Tsunami,* (1961), 136.

2) K. HIDAKA and S. HIKOSAKA, "Note on the Hawaiian Tsunami of April 1, 1946," *Journ. Oceanogr. Soc. Japan,* **5** (1949), 28, (in Japanese).

3) S. HOMMA, "On the Behavior of Seismic Sea Waves around Circular Island," *Geophys. Mag., Centr. Meteorolog. Obs.,* **21** (1950), 199.

Table 1. List of the Island of Hawaii showing wave-heights, in feet above mean lower low water, for the tsunamis. Data for 1896 from Honolulu Press (1897), for 1933 from Jaggar (1933), for 1946 and 1952 from Macdonald et al. (1947, 1954), for 1957 from Fraser et al. (1959), and 1960 from Eaton et al. (1961).

Locality	Sanriku 1896	Sanriku 1933	Aleutian 1946	Kamchatka 1952	Aleutian 1957	Chile 1960
Hilo	8	2~3	28~30	0~9	8~13	13~19
Keaau			24	0	8	12
Honolulu landing						14
Cape Kumukahi					3	3
Pohoiki			9		7	6
Opihikad						6
Kaimu			20		10	13
Kalapana			18	3	7	7
Halape				0		5
Punaluu	12		13	0	7	11
Honuapo	12		14		7	17
Kaalualu	12					17
South Point			20		10	9~13
Milolii			2		5	3
Hookena	8		8	4	7	7
Honaunau			7		6	5
Kauualoa	30					
Napoopoo	30	17.5	9	4	7	16
Keauhou	30		13	3	7	12
Kahaluu						8
Kailua	8 (30)		11	2	5	8
Kawaihae			12	<2	5	9
Mahukona			14		7	4
Upolu Point			20		8~11	7~9
Pololu Valley			34~55		15~32	10~12
Waipio Valley			40		23	8
Honokaa			28		10	6
Laupahoehoe			30		10	7
Hakalau			37		10	9
Honomu			37		11	12
Pepeekeo			27		12	5
Onomea			34		17	11
Papaikou			35		9	9

slope was taken into account. K. Iida and Y. Ohta[4] explained the distribution of tsunami heights of the 1960 Chilean tsunami along the coast of Kii peninsula in S. W. Japan, assuming the peninsula as a cylindrical island.

On the Island of Hawaii, wave-heights of the 1896[5] and 1933[6] Sanriku tsunamis, Japan, have been reported. Wave-heights of the 1946[7], 1957[9] Aleutian tsunamis, the 1952[8] Kamchatka tsunami, and the 1960[10] Chilean tsunami have been surveyed in detail as shown in Table 1.

The present paper discusses the relation between the wave-heights along a circular island expected from Homma's theory and the distribution of observed wave-heights of the above-mentioned tsunamis along the coast of the Island of Hawaii.

2. Distribution of wave-height on the Island of Hawaii

As to the distribution of wave-height on the Island of Hawaii, J. P. Eton et al.[10] have shown the graphic comparison of the regional wave-height pattern for the 1960, 1957 and 1946 tsunamis.

Homma's model assumes a cylindrical island as shown in Fig. 2. The resultant amplitude P at various points on the coast has been obtained as follows:

$$P=\left|\sum_{n=0}^{\infty}\frac{2\alpha_n}{\alpha_n+1}A_n\cos(n\theta)\right|,$$

where

$$\alpha_n=\sqrt{n^2+1-\tau^2}\ ,$$

4) K. IIDA and Y. OHTA, "On the Height of the Chilean Tsunami on the Pacific Coasts of Central Japan," *Rep. Chilean Tsunami, Field Inv. Comm. Chilean Tsunami,* (1961), 108.

5) ANONYMOUS, "Summary of the Report on Tsunami in Hawaii." *Earthq. Invest. Comm.* **11** (1897), 37 (in Japanese).

6) T. A. JAGGAR, "Tsunami or Earthquake Tidal Wave of March 2, 1933," *Volcano Letter Hawaii,* **397** (1933).

7) G. A. MACDONALD, F. R. SHEPARD and D. C. COX, "The Tsunami of April 1, 1946, in the Hawaiian Islands," *Pacific Science,* **1** (1947), No. 1.

8) G. A. MACDONALD, C. K. WENTWORTH, "The Tsunami of November 4, 1952, On the Island of Hawaii," *Bull. Seismol. Soc. America,* **44** (1954), 463.

9) G. D. FRASER, J. P. EATON and C. K. WENTWORTH, "The Tsunami of March 9, 1957, on the Island of Hawaii," *Bull. Seismol. Soc. America,* **49** (1959), 79.

10) J. P. EATON, D. H. RICHTER and W. U. AULT, "The Tsunami of May 23, 1960, On the Island of Hawaii." *Bull. Seismol. Soc. America,* **51** (1961), 135.

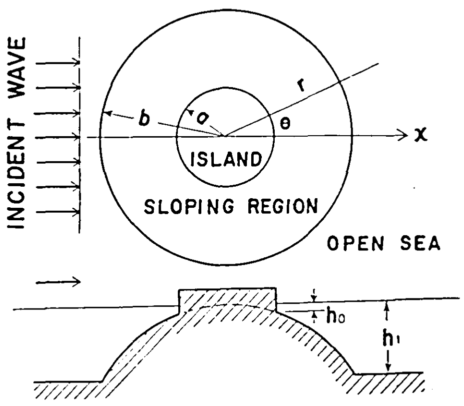

Fig. 2. Model of a circular island.

$$A_n=\frac{2\varepsilon_n}{\pi}(-i)^{n+1}\frac{\rho}{\rho^{\alpha_n}U_n(\tau)+\dfrac{\alpha_n-1}{\alpha_n+1}\rho^{-\alpha_n}V_n(\tau)} ,$$

$$U_n(\tau)=(n+1)H_n^{(2)}(\tau)-\tau H_{n+1}^{(2)}(\tau)-\alpha_n H_n^{(2)}(\tau) ,$$

and

$$V_n(\tau)=(n+1)H_n^{(2)}(\tau)-\tau H_{n+1}^{(2)}(\tau)+\alpha_n H_n^{(2)}(\tau) .$$

The following assumptions are made: $b=200$ km, $h_1=4$ km, $\rho=b/a=\sqrt{h_1/h_0}=3$, and $\tau=\sigma a/\sqrt{gh_0}=\sigma b/\sqrt{gh_1}\fallingdotseq100/T$ (σ is the angular speed of the plane incident wave). Values of the amplitude and the phase difference of individual mode of oscillation was calculated for the case of $\tau=6$, 4 and 2 or $T\fallingdotseq17$, 25 and 50 min.

Next, this theory was applied to explain the behavior of 1896, 1946, 1952, 1957 and 1960 tsunamis on the Island of Hawaii. The directions of incident waves were taken from the report of 1946, 1957 and 1960 tsunamis by J. P. Eaton et al., and those of 1896 and 1952 tsunamis were taken from a map of the seismic sea wave warning system of U. S. C. G. S.[11] as shown in Fig. 3.

The island is divided into multiples of ten degrees, starting from the direction of the incident wave, the origin being taken at the center of the island as shown in Figs. 4 to 8. In Figs. 4 to 8, the black points indicate the locations of Hilo and Napoopoo. The wave-height H_0 is taken at the opposite side of the island to the incident wave.

11) J. M. SYMONS and B. D. ZETLER, "The Tsunami of May 22, 1960 as Recorded at Tide Stations, Preliminary Report," *U. S. of Commerce, Coast and Geodetic Survey* (1960).

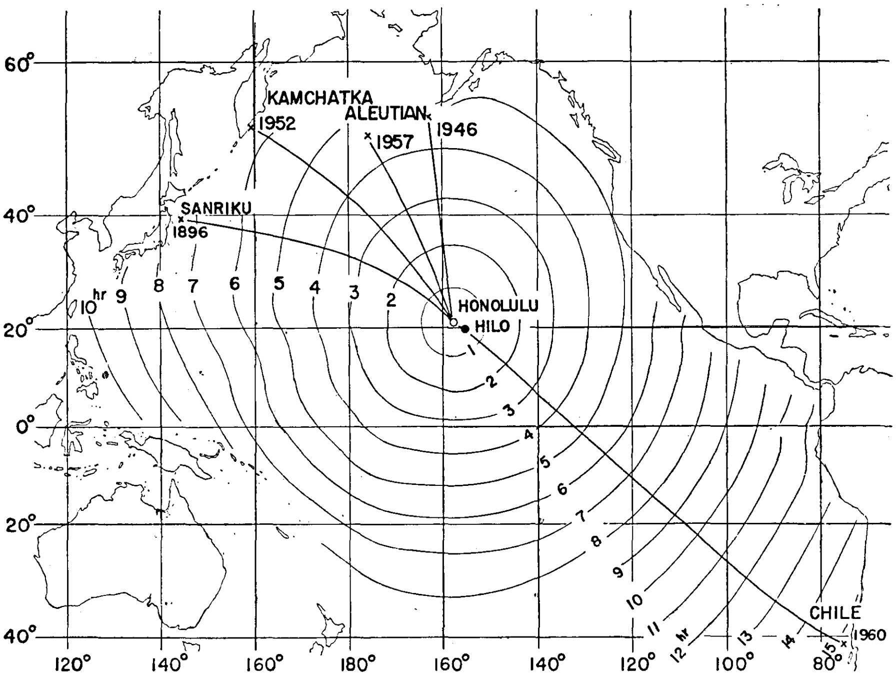

Fig. 3. Map of the tsunami warning system. Data from U. S. C. G. S.

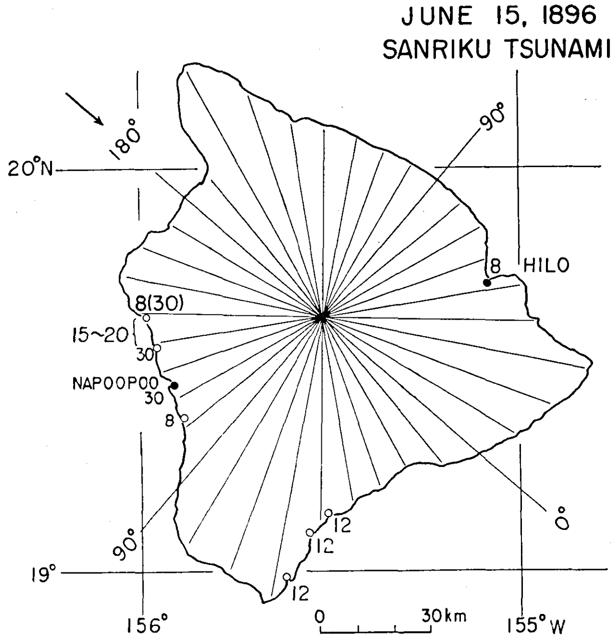

Fig. 4. Wave-height, in feet above mean lower low water, for the tsunami of June 15, 1896.

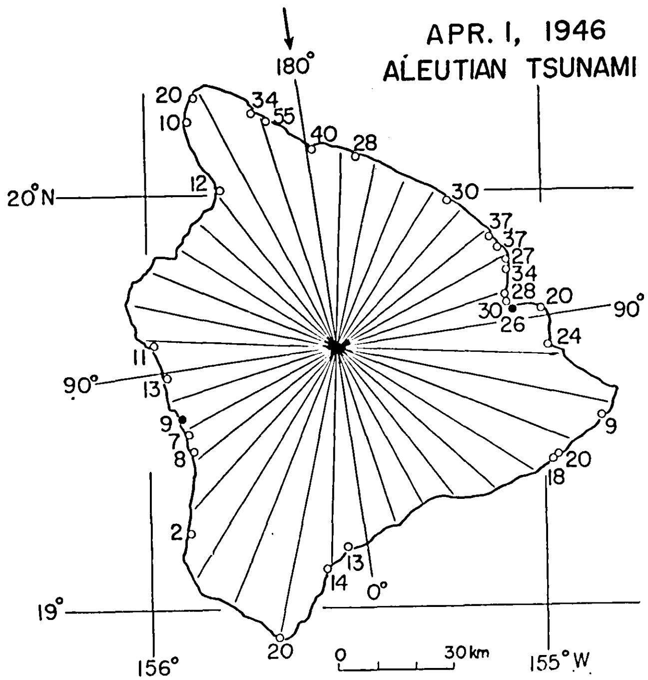

Fig. 5. Wave-heights in feet above mean lower low water for the tsunami of April 1, 1946.

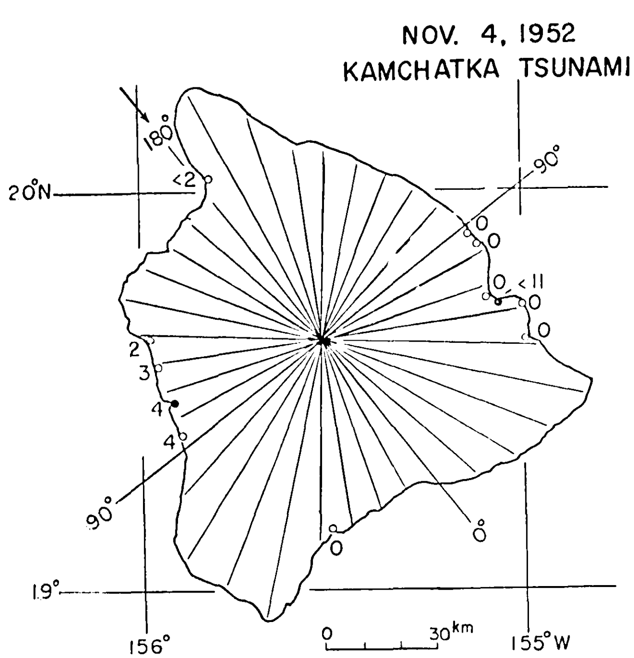

Fig. 6. Wave-heights in feet above mean lower low water for the tsunami of Nov. 4, 1952.

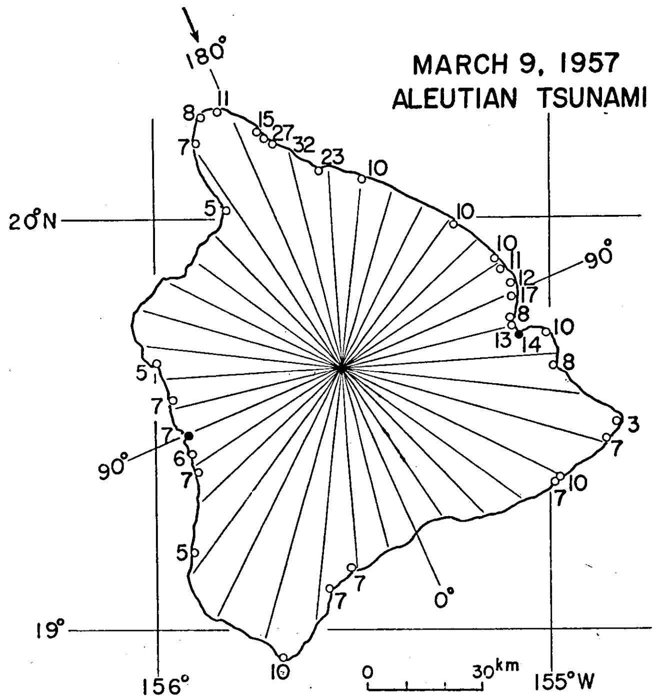

Fig. 7. Wave-heights, in feet above mean lower low water for the tsunami of March 9, 1957.

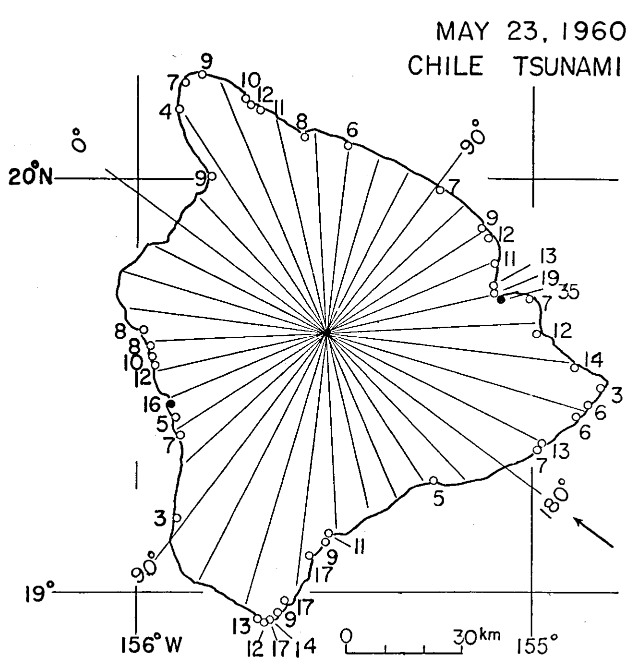

Fig. 8. Wave-heights, in feet above mean lower low water for the tsunami of May 23, 1960.

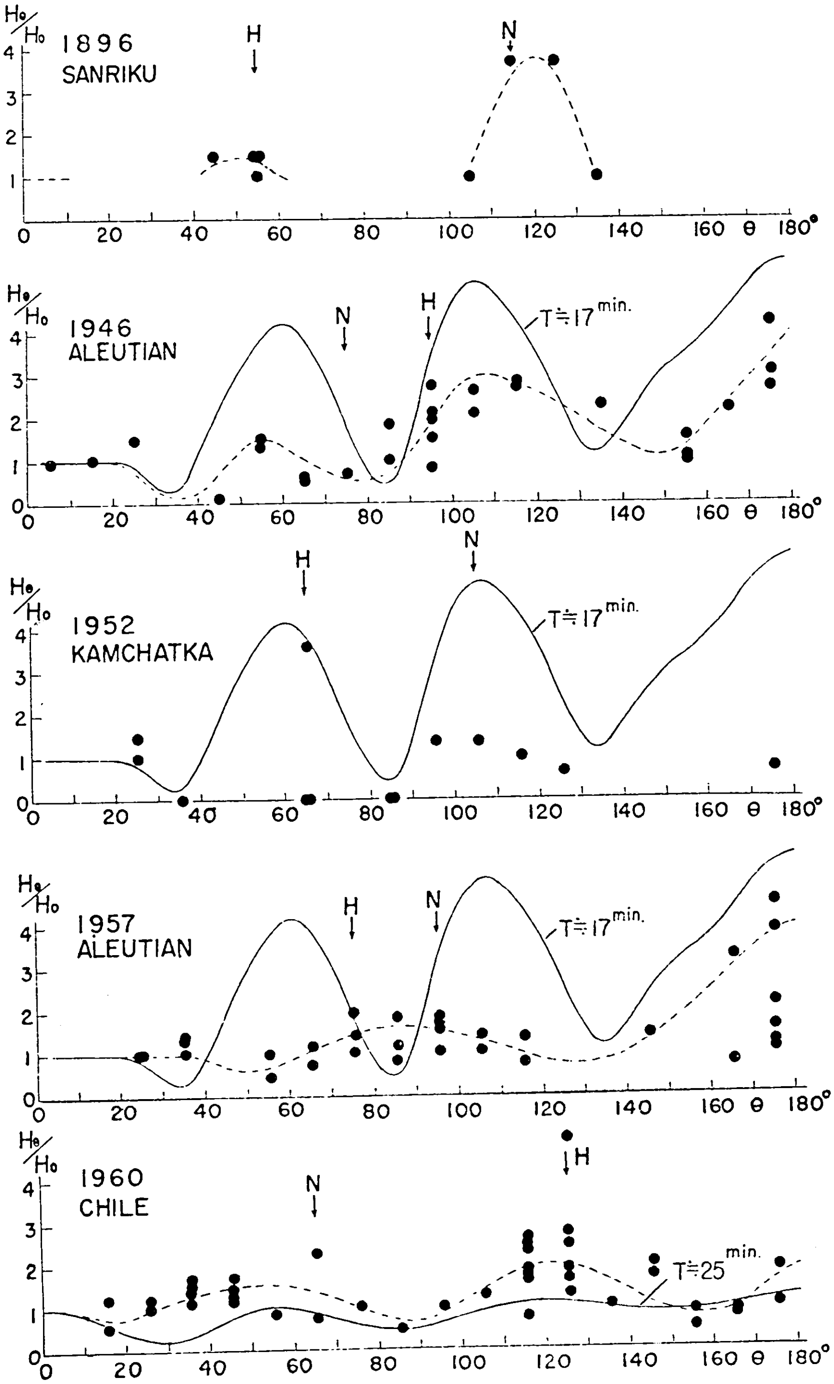

Fig. 9. Distribution of wave-height ratios at various points on the coastline. H_0: Wave-height at rear side of the island; See Table 2. Full line: Theoretical value, Broken line: Observed line.

Wave-height ratio H_θ/H_0 at various points on the shore line are shown in Fig. 9. In the figure, full lines show theoretical values with period $T \fallingdotseq 17$ and 25 min. In theory, the variation is fairly remarkable, especially when T is small. For the case of $T \fallingdotseq 17$ min, the amplitude in the vicinities of $\theta = 35°$ and $85°$ are less than that of the incident wave, while at $\theta \fallingdotseq 60°$, $110°$ and $180°$ they are 5 or 6 times larger than the latter. Table 2 shows the data observed at Hilo. Theoretical values seem roughly similar to the observed values in these periods except for the 1957 Aleutian tsunami. The former is larger than the latter in wave-height ratio H_θ/H_0.

As shown by arrows, wave-heights at Hilo and Napoopoo are large for every tsunami. In past tsunamis, these areas have often suffered severe damage. The wave-height increase by diffraction and refraction should be warnings for future tsunamis.

As shown in Table 2, wave-length L is calculated on the basis of the period and celerity of waves estimated from tide-gauge records at Hilo. The radius of the Island of Hawaii is assumed to be $a = 66$ km. At azimuth angles $\theta = 50° \sim 60°$, $110° \sim 120°$ and $180°$ wave-height ratio H_θ/H_0 was calculated for different tsunamis. Fig. 10 shows the relation

Table 2. List of tsunamis at Hilo.

Date	Epicenter	M	H_0*(m)
1896 June 15	39.6°N 144.2°E	7.6	2.4
1946 April 1	53.5 N 163.0 W	7.4	3.9
1952 Nov. 4	52.5 N 159.0 E	8.2	0.9
1957 March 9	51.3 N 175.8 W	7.8	2.1
1960 May 23	41.0 S 73.5 W	8.4	2.1

* H_0: Wave-height at rear side of the Island of Hawaii.

Date	The 1st Wave-height A(m)	Period T(min)	Travel Time (h m)	Distance $R \times 10^3$ km	Velocity $V \times 10^3$ m/min	Wave Length L(km)	a/L
1896	—	18*	—	6.0	13.4	241	0.274
1946	—	15**	4 51	3.8	13.1	197	0.335
1952	1.33	19	6 37	5.4	13.6	258	0.256
1957	1.11	18	4 54	3.9	13.3	239	0.276
1960	1.50	34	14 56	12.4	13.8	468	0.141

* By record at San Francisco.
** By record at Honolulu.
$a = 66$ Km.

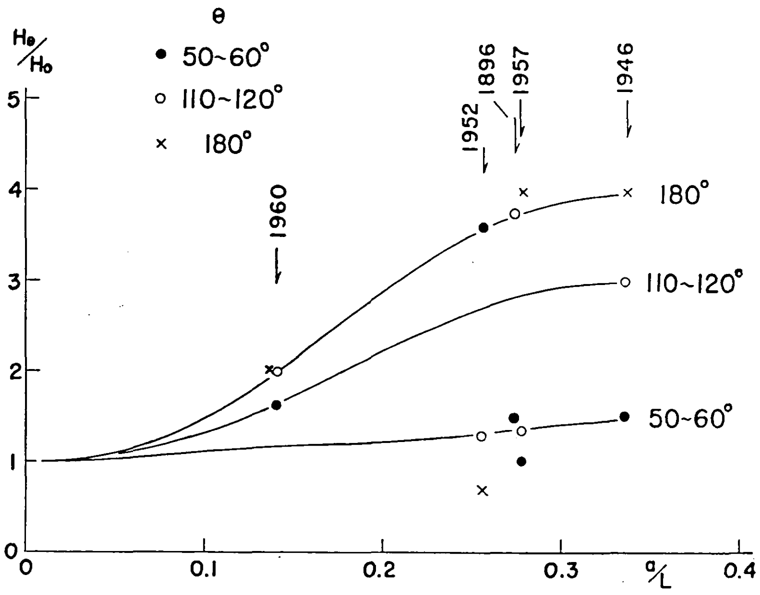

Fig. 10. The relation between a/L and H_θ/H_0.

between a/L and H_θ/H_0. As shown in Fig. 10 when the wave-length of an incoming tsunami is less than the radius of the island, wave-height ratio increases at azimuth angles $\theta=50°\sim60°$, $110°\sim120°$ and $180°$, and these wave-heights become 1.5, 3, and 4 times respectively. No difference of wave-height can be observed between the left hand and the right hand of an incident wave.

3. Conclusions

The tsunamis discussed in this paper, caused severe damage on the Island of Hawaii and it seems that the incident directions of these tsunamis are indicative of future tsunami in Hawaii. Abnormal wave-heights may be explained by the action of diffraction and refraction.

The author hopes that the present paper will be useful in planning various preventive measures against future tsunamis. The relation between the tsunami energy and the distribution of wave-heights on the Island of Hawaii will be investigated in the future.

In conclusion, the author thanks Prof. R. Takahasi for his guidance and encouragement in the carrying out of this study. His thanks are also due to Assist. Prof. K. Kajiura for his valuable help and advice in the preparation of the manuscript.

5. ハワイ島における津波について

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ハワイ諸島は環太平洋の地震帯に囲まれた地理的条件から，これまでしばしば津波に見舞われ，過去140年間に41回にもおよぶ記録がある．この内，特に甚大な被害を与えた津波の浪源は三陸沖，カムチャツカ沖，アリューシャン沖，ペルー沖，およびチリ沖である (Fig. 1).

大洋に点在する島に伝わる津波は，波の回折，屈折の影響が大きく，これまで幾つかの理論的考察がある．日高・彦坂 (1949) は円筒形の島におよぼす長波の回折を計算し，1946年の津波におけるハワイの Kauai 島の波高分布と理論値とを比較し，本間 (1950) は円形の島で，海底傾斜を考慮にいれ計算を行つた (Fig. 2). また飯田・太田 (1961) は1960年のチリ津波における紀伊半島の波高分布を検討した．

ハワイ島においては，1896年および1933年の三陸津波をはじめ，1946年および1957年のアリューシャン津波，1952年のカムチャツカ津波および1960年のチリ津波については，島の周囲に沿つて詳細な津波の波高が測定されている (Table 1). これら実測の波高分布と，本間の理論とを比較検討して，ハワイ島における津波の回折，屈折の影響を考察した．

まず EATON ら，および U.S.C.G.S. の資料から各津波の入射角を決定し，次にこの入射波を基準にして，Fig. 4～8に示すごとく，島のほぼ中心を原点に 10° ごとに，放射状に分割する．入射波に対し，島の反対側の波高 H_0 を基準にとり，沿岸各点の波高比 H_θ/H_0 と入射角 θ との関係を求めた (Fig. 9). 本間の理論値によると，津波の周期 $T=17$ 分のとき波高は，$\theta \fallingdotseq 60°$, 110° および 180° が大きく，$\theta=35°$ および 85° が小さく求められているが，これに対応する Hilo の検潮記録からの周期 (Table 2) と比較したとき，理論値と実測値とは図に示すように，1957年のアリューシャン津波を除き，およそ傾向が一致し，理論値が大きい値を示している．Fig. 9 で Hilo および Napoopoo の位置を示したように，いずれの津波においても，他地点よりも波高比が大きい．この両地域の異状波高は湾の副振動以外に，津波の回折，屈折による影響で波高が増大すべき位置に存在することは注目に値する．

次に Fig. 9 の波高比大なる各津波の入射角 $\theta=50°$～60°, 110°～120°および 180° に着目し，Hilo にて観測した周期並びに伝播速度から津波の波長 L を求め，ハワイ島の半径 $a=66$ km と仮定して，各津波について H_θ/H_0 と a/L との関係を求めた (Fig. 10). 図に示すように，島の半径に比し，波長の短い津波では波高比は増大する．入射角 $\theta=50°$～60°, 110°～120° および 180° において，最大の波高比はそれぞれ 1.5, 3, および 4 倍にも達する．その他，入射波の右回り，あるいは左回りによる波高の差異は認められなかつた．