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# 4. A Study of the Wave Sources of the Hiuganada Tsunamis.

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## Abstract

Four tsunamis (1931, 1941, 1961 and 1968) which were generated off Hiuganada, the east coast of Kyushu, are investigated. The source areas are located on and near the continental shelf and the directions of the major axis of source are parallel to the bathymetric line. The features of wave amplitude spectra are almost similar to each other and the predominant period is 20 min. For the 1968 tsunami, the height of tsunami at the source is of the order of 20 cm.

## 1. Introduction

The east coast of Kyushu (Hiuganada) is a region with a high level of seismic activity. Many tsunamis were also generated. Especially, a large tsunami of Oct. 31, 1662 (Musya, 1941) hit the eastern coasts of Kyushu. About 30 km of the coastline subsided and 200 lives were lost. In other cases, the magnitudes of many earthquakes associated with tsunami in this region were 7.5 or less. The moderate tsunamis of 1931 (JMA, 1931), 1941, 1961 (Takahasi and Hatori, 1961) and 1968 (Kajiura *et al.*, 1968) were observed by tide gauges at several stations in south-western Japan.

In the present paper, the following investigations are made in respect of the tsunamis which were generated off Hiuganada: 1) The estimated source area of four tsunamis are shown on a bathymetric chart to see the geographic distribution and the direction of major axis of the tsunami source. 2) To compare each tsunami, spectral analyses of the records at Tosa-Shimizu, Hososhima and Aburatsu are made. 3) From the records of the tsunamis of 1961 and 1968, the wave form at the bay mouth is inferred, based on the principle of the multiple reflection of waves. 4) For the 1968 tsunami, the sea level disturbance at the margin of the wave source is estimated by applying the ordinary refraction and shoaling coefficients.

## 2. Source area of the tsunamis

A list of tsunamis occurring off Hiuganada since 1900 is presented

Table 1. List of the Hiuganada tsunamis.

| Date | Time (JST) | | | Epicenter | | Depth km | M |
|---|---|---|---|---|---|---|---|
| | d | h | m | Lat. (N) | Long. (E) | | |
| 1931 Nov. | 2 | 19 | 03 | 32.2° | 132.1° | 20 | 6.6 |
| 1939 Mar. | 20 | 12 | 22 | 32.3 | 131.7 | 10 | 6.6 |
| 1941 Nov. | 19 | 01 | 46 | 32.6 | 132.1 | 0~20 | 7.4 |
| 1961 Feb. | 27 | 03 | 11 | 31.6 | 131.8 | 40 | 7.0 |
| 1968 Apr. | 1 | 09 | 42 | 32.3 | 132.5 | 30 | 7.5 |

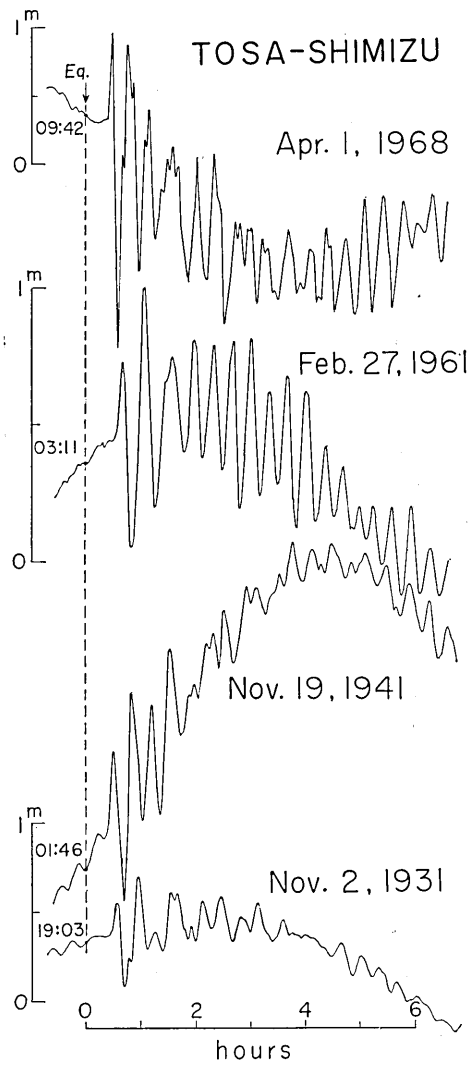


Fig. 1. Records of the Hiuganada tsunamis at Tosa-Shimizu.

in Table 1. The records at Tosa-Shimizu are shown in Fig. 1. As shown in Fig. 1, the initial motions of all tsunamis are *up* and the following fall of the initial wave of the 1968 tsunami is prominent. Double amplitudes of the 1961 tsunami as well as that of the 1941 tsunami are about 1 m and that of the 1968 tsunami is 2.4 m and is the largest of all.

The source areas of these tsunamis and the distributions of aftershocks are shown in Fig. 2 where inverse refraction diagrams are drawn from the tide stations at 1 minute intervals, but in Fig. 2 only the final wave fronts corresponding to the travel time (min) are shown. The source areas of the tsunamis of 1931 and 1941 cannot be delineated clearly because the available tide records are few. It is found that the tsunami source of 1961 lies parallel to the coast line directed in N-S, in contrast to the source of the 1968 tsunami which lies some 40 km from the Shikoku coast with the axis in E-W direction.

According to Iida's diagram (1963) which is a relation between

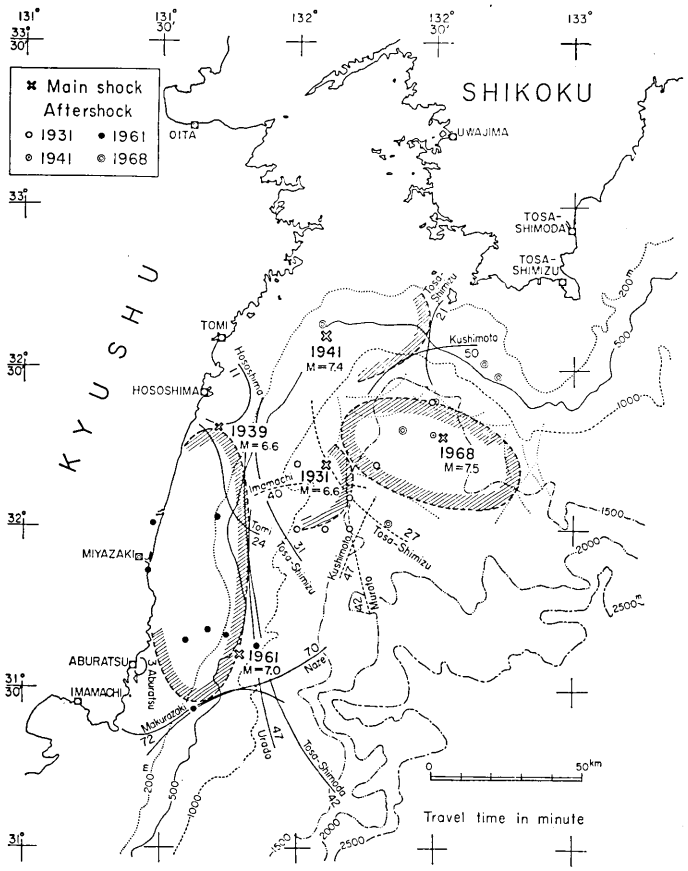


Fig. 2. Distributions of the estimated source area of the Hiuganada tsunamis and aftershocks.

the dimension of tsunami source area and earthquake magnitude, the length of 90 km for the 1961 tsunami is standard but the length of 60 km for the 1968 tsunami seems to be somewhat too short. The direction of the major axis of tsunami source is worth noticing because this region locates a cross point of the Nankaido seismic zone directed in E-W and the Hiuganada seismic zone in N-S direction. As shown in Fig. 2, the estimated tsunami source areas of 1961 and 1968 extend parallel to the Hiuganada and the Nankaido seismic zones respectively. The source areas of the tsunamis of 1931 and 1941 are located on the continental shelf, a cross point of these seismic zones. Generally speaking, each source area is located in the region which corresponds to the area of aftershock activity.

## 3. Spectra analysis

For cases of Hiuganada tsunamis of 1968, 1961, 1941 and 1931, spectral

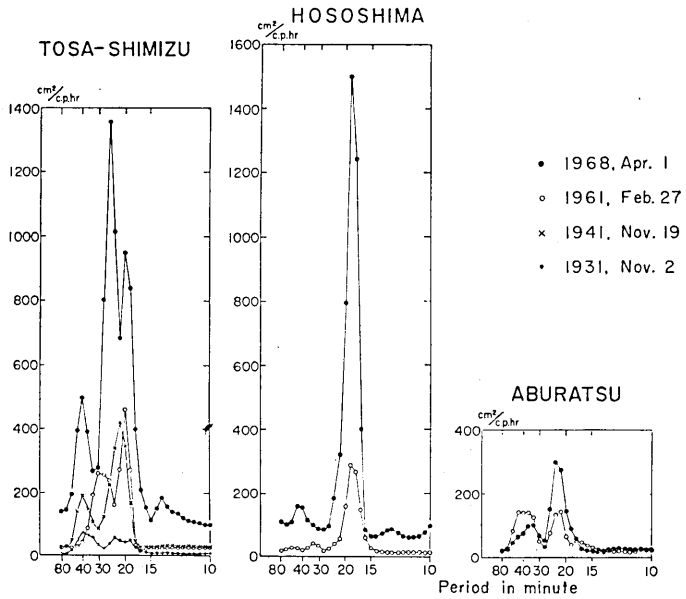


Fig. 3. Power spectra for the Hiuganada tsunamis.

analysis of tide records at Tosa-Shimizu, Hososhima and Aburatsu are made by Tukey's method. Analyzed time interval of the record is 6 hours including the initial wave. The power spectra of these records are shown in Fig. 3. It is remarkable that the features of different tsunami spectra for the same station are similar and that the frequency bands of peaks agree pretty well with each other. At the stations of Tosa-Shimizu and Hososhima, the predominant peaks fall in the band of period of 20 min and the period of 40 min is a small peak. Although it was found that the period of 40 min predominated as well as that of 20 min in the cases of the 1952 Kamchatka tsunami (Takahasi and Aida, 1963) and three tsunamis of South American origin (Hatori, 1968). From these results, large earthquakes seem to excite the longer part of seiche periods of the bay and small earthquakes the smaller period of the seiche spectrum.

In Fig. 3, the power spectrum of the 1968 tsunami is prominently larger than that of other tsunamis. At other stations, the energy of the 1968 tsunami is about 4 times, on the average, as large as that of the 1961 tsunami.

## 4. Wave form at the bay mouth

A tsunami record observed at the head of a bay contains effects of the seiches of bay and continental shelf. If we assume a bay of uniform cross section, the wave form $\eta_0(t)$ at the mouth of a bay at time $t$ can

be obtatined from the record of the wave level variation $\eta(t)$ at the head of a bay as follows:

$$\eta_0(t)=\frac{1}{2}\{\eta(t-\tau)+\eta(t+\tau)\}$$

where $\tau$ is taken $\tau=T/4$ and T the period of the fundamental seiche in the bay. By this method, the calculated waves at Onagawa for the cases of Iturup tsunamis were in fairly good agreement with the observed records at Enoshima which is located outside the bay (Hatori, 1967).

The same method is applied to the tsunamis of 1968 and 1961. For the calculation, the seiche periods of bay at Muroto and the other stations are assumed to be 10 and 20 min respectively, inferred from the data of daily observation. Figure 4 shows the records of the tsunamis of 1968 and 1961 from which the ordinary tides were eliminated and the estimated waves at the mouth of the bay. An arrow in Fig. 4 shows the occurrence time of earthquakes. Comparing the wave form of the 1968 tsunami with that of the 1961 tsunami, the following fall of the initial

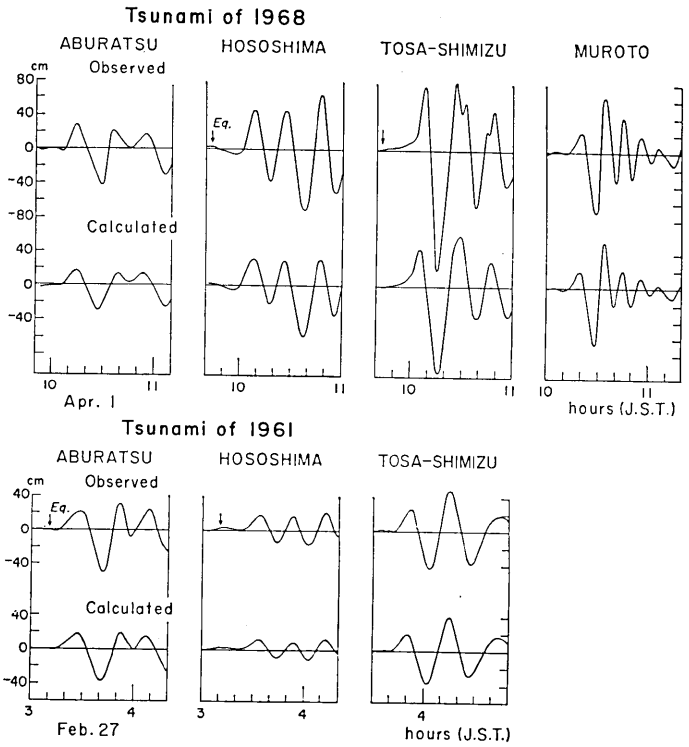


Fig. 4. Analysis of wave forms for the Hiuganada tsunamis. The observed waves: The tide is eliminated. The calculated wave: The wave forms at the mouth of the bay.

wave at Tosa-Shimizu and Muroto is prominent. For the 1961 tsunami, travel time at Aburatsu was only 3 min. Therefore, the deformation of waves due to propagation is relatively little. The estimated waves seem to be the motions of sea water on a part of the tsunami source and the calculated height at the source is 20 cm.

## 5. Sea level disturbances at the source of the 1968 tsunami

It has been confirmed that the distribution of the inundation height along the coast near the tsunami source corresponded approximately to that of the observed bottom deformation in case of the Niigata tsunami (Hatori, 1965). Taking this fact into consideration, sea level disturbances at the margin of the source are calculated from the height of the initial wave by applying the refraction and shoaling coefficients.

Wave fronts are drawn starting from the margin of the estimated source, at two minute intervals in Fig. 5. For the calculation of the refraction coefficient, the margin of the source was divided into 8.5 km widths, the coast being taken to be 5 meters deep. For the shoaling coefficient, Green's formula is applied. These factors at each region are shown in Table 2. Solid circles in Fig. 6 show values of sea level dis-

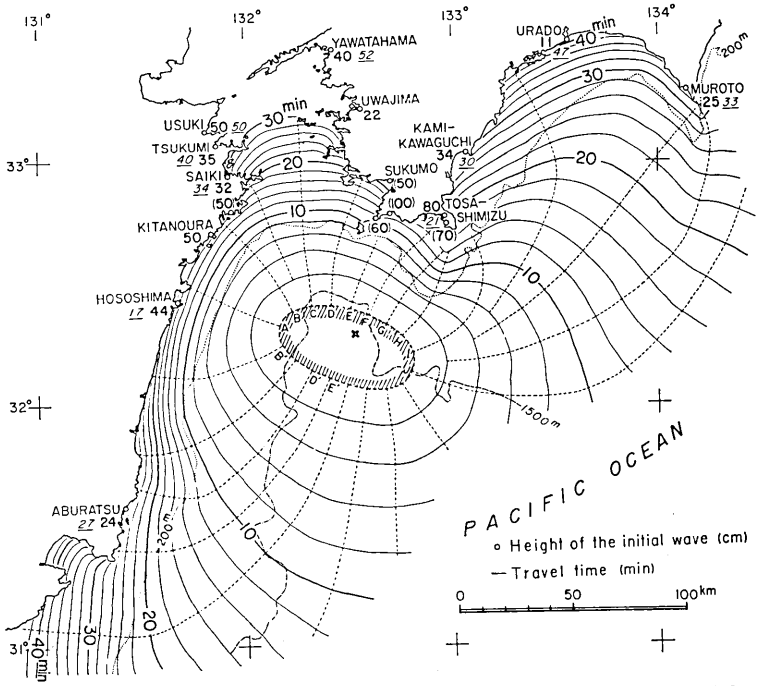


Fig. 5. Refraction diagram, distribution of the height of the initial wave (cm) and travel time (min), for the 1968 Hiuganada tsunami.

Table 2. Shoaling factor and refraction factor.

| Region | Coast | | | Margin of the wave source | | |
|---|---|---|---|---|---|---|
| | Height of the initial wave (cm) | Depth (m) | $l$* (km) | Depth (m) | $l_0$* (km) | Height of wave (cm) |
| A-B | 50 | 5 | 30 | 800 | 8.5 | 26 |
| B-C | 50 | 〃 | 20 | 1000 | 〃 | 29 |
| C-D | 40 | 〃 | 60 | 1200 | 〃 | 27 |
| D-E | (50) | 〃 | 20 | 1500 | 〃 | 19 |
| E-F | 80 | 〃 | 20 | 1600 | 〃 | 29 |
| F-G | (70) | 〃 | 10 | 1700 | 〃 | 18 |
| G-H | — | | | | | |
| H-J | — | | | | | |
| I-J | 34 | 〃 | 70 | 1500 | 1 | 68 |
| 〃 | 25 | 〃 | 90 | 1500 | 1 | 57 |
| A-B' | 44 | 〃 | 40 | 900 | 8.5 | 26 |
| D'-E' | 24 | 〃 | 26 | 1500 | 〃 | 10 |

* Width between two adjacent trajectories.

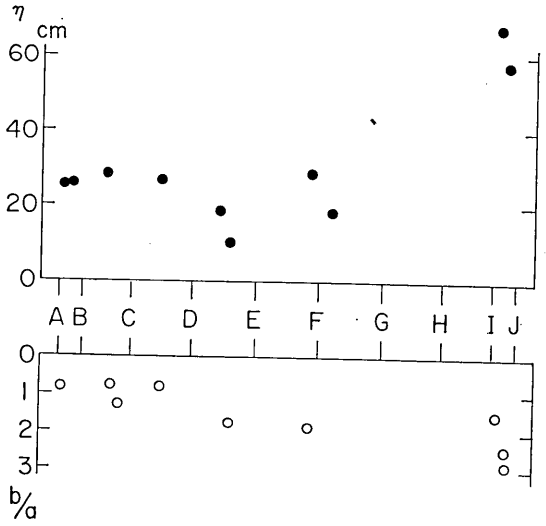


Fig. 6. Sea level disturbance (solid circle) and the ratio of the following fall of the initial wave to the first rise (open circle), around the margin of the tsunami source.

turbances at the margin of tsunami source. The average values are about 20 cm as shown in Fig. 6. On the other hand, these values of large tsunami as the Nankaido of 1946 or the Tonankai of 1944 were of the order of 1 meter (Hatori, 1966),

As above mentioned, the initial motions of the 1968 tsunami were

Table 3. Amplitude of the initial wave for the 1968 tsunami.

| Station | Initial rise $a$ | Following fall $b$ | $b/a$ |
|---|---|---|---|
| | cm | cm | |
| Aburatsu | 24 | 43 | 1.8 |
| Hososhima | 44 | 40 | 0.9 |
| Saeki | 32 | 40 | 1.3 |
| Tsukumi | 35 | 28 | 0.8 |
| Yawatahama | 40 | 30 | 0.8 |
| Tosa-Shimizu | 80 | 150 | 1.9 |
| Kamikawaguchi | 34 | 52 | 1.5 |
| Muroto | 25 | 73 | 2.9 |
| Kushimoto | 16 | 38 | 2.4 |

observed to be *up* in all cases and the ensuing falls were conspicuous. Crest-height of the initial wave $a$, following fall $b$ and the ratio of amplitude $b/a$ at each station shown in Table 3. Open circles in Fig. 6 show the ratio of amplitude $b/a$ around the margin of tsunami source. It is found that the ratio of amplitude is large toward to the east side of the tsunami source. From the features of tsunami records, the sea bottom in the south-eastern part of the source area seems to be subsided as well as the displacement of uplift.

## 6. Conclusion

The tsunami source of 1961 is located in the sea on the continental shelf, extending about 90 km in an elongated shape parallel to the coast line directed in N-S. In contrast to the source of the 1968 tsunami, the major axis of the source is 60 km in E-W direction. The average of sea level disturbance at the wave source for the 1968 tsunami is 20 cm and the sea bottom of the source area is uplift but that of the south-eastern part seems to be subsided. The features of spectra at the same station are similar for the Hiuganada tsunamis and the predominant period is 20 min.

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## 4. 日向灘津波の波源について

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日向灘に起きた4個の津波 (1931, 1941, 1961, 1968年) の波源域は陸棚またはその斜面上にあって，それぞれの余震域とおおよそ合致している．波源の長径の向きと大きさは，1961年の津波ではN-S方向に90km，1968年の津波ではE-W方向に60kmである．これらの津波は，いずれの地点も押し波で第1波が観測され，土佐清水，細島，油津の検潮記録を周期分析すると，スペクトルのピークの位置はほぼ一定して，約20分の周期が見いだされた．また1941年と1961年の津波エネルギーはおおよそ等しく，1968年の津波はこれらより4倍大きい．

1968年と1961年の津波における土佐清水，油津などの記録から，波の重複反射の理論にもとずいて，湾口における波形を算出してみた．特に1961年の油津の記録は地震後僅か3分で第1波を観測し，湾口の計算波形は波源上の1部分の水位変動を表わしているものと思われる．次に1968年の津波について，推定波源からの伝播図を作図し，沿岸の第1波の波高から波源域周縁上の水位上昇値を求めると，約20cmとなった．また波源周辺を九州から四国へ回った記録ほど，第1波の上昇の振幅に対し次の下降の振幅が大きく，波源域の南東側の海底で沈降運動があったものと考えられる．