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OCEANOGRAPHIC FEATURES OF A SUBMARINE ERUPTION THAT DESTROYED THE KAIYO-MARU NO. 5

BY

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ABSTRACT

When Myojinsho Reef erupted in September 1952, tsunami waves were recorded several times by a self-registering wave gauge installed on the southwestern coast of Hachijo Island about 130 km from that Reef. The largest one of these tsunamis appeared on 24 September, and it is presumed that this wave caused the destruction of the KAIYO-MARU No. 5. Results of investigation of these recorded tsunami waves and other phenomena are reported.

INTRODUCTION

Since September 1952, a station for the observation of sea waves has been maintained by the Central Meteorological Observatory of Japan in the vicinity of Port Yayene on the southwestern coast of Hachijo Island (Fig. 1). The station, equipped with a self-registering wave gauge, was established with the aim of investigating the relations between wind waves or swells and atmospheric disturbances such as cyclones or typhoons. In mid-September, Myojinsho Reef erupted, and tsunamis caused thereby were recorded several times by this wave gauge. In the present paper, the results of investigations of these tsunamis are reported, together with other pertinent observations.

RESULTS OF WAVE GAUGE OBSERVATIONS

The wave gauge is of the pressure recorder type and was reconstructed from a statoscope of the type in ordinary use for recording microbarographic oscillations. The pressure change, corresponding to the rise and fall of the sea level, is automatically traced on a roll of paper at a speed of about 33 cm/hr. The device is capable of making a continuous record of waves for about 12 hours. The reducing scale

1 A surveying ship (211 tons) of the Hydrographic Office, Maritime Safety Agency of Japan.
of the instrument is about 1/70 for ordinary wind waves or swells but is somewhat less for the tsunamis in question, which have a period of about 1 min or so. A slow-leak device is attached to the instrument to eliminate waves of longer periods, such as tides.

Fig. 2 shows in tabular form the periods in which the observations were taken during the interval of 16–30 September 1952 as well as

\[ \text{In the present paper, the time of observation is always referred to the meridian of 135° E (Japanese Standard Time).} \]
Figure 2. Results of sea wave observations at Hachijo Island with a self-registering wave gauge.
eruptions of Myojinsho Reef and other unusual phenomena in this interval. The thick horizontal line segments indicate the periods in which the records were obtained by the wave gauge, and the hatched portions indicate the periods in which the tsunamis were recorded. The numerals above the horizontal line segments indicate the time (in minutes). In Fig. 2 we see that conspicuous tsunamis appeared on 16, 24 and 26 September and that something like a tsunami occurred on 23 September (see Fig. 3A, B, C, D; a normal record is shown in Fig. 3E). Since records of wind waves and swells were superimposed on those of tsunami waves, the records were smoothed so that the curves represent only the tsunami waves (see Fig. 4). The time marks shown in the above records are those obtained by interpolation. Hence possible errors in time of about ± 3 min are involved.

(A) On 16 September (see Figs. 3A, 4A), although no one witnessed eruptions, microseisms (or better, seismic surface waves) of maximum amplitude 5 µ and of period 4.1 sec were recorded at 11h52m on a portable seismometer installed at the Hachijojima Weather Station. According to seismologists, these microseisms were probably due to an eruption of Myojinsho Reef. If we assume that the velocity of propagation of these microseismic waves is several kilometers per second and that it is the same as that of ordinary seismic waves (surface waves), we may consider that the eruption occurred at about 11h52m. Since the tsunami began to occur at Hachijo Island at 12h20m, the time taken by the tsunami wave to travel from Myojinsho Reef to the observing station was 12h20m - 11h52m = 28 min. The maximum wave height of this tsunami was 56 cm.

(B) On 24 September (see Figs. 3B, 4B), a more conspicuous tsunami was recorded. The eruption which caused it was probably the one
Figure 3. Wave records at Hachijo Island. A, B and C represent tsunamis caused by the eruption of a submarine volcano at Myojinsho Reef. D shows a probable tsunami wave and E a normal record.
which also caused the disaster to the KAIYO-MARU No. 5. Since there were no survivors, no first-hand account of the eruption is reported. The tsunami began at 12h53m and the maximum wave height was 92 cm.

(C) On 26 September (see Figs. 3C, 4C), another conspicuous tsunami occurred; its maximum wave height was 71 cm and the time of its first movement was 13h03m. In this instance a ship of the Maritime Safety Agency, sent to investigate the fate of the KAIYO-MARU No. 5,

ascertained that an eruption occurred at Myojinsho Reef at 12h35m. The time taken by the tsunami wave to travel from Myojinsho Reef to the observing station on Hachijo Island was 13h03m - 12h35m = 28 min, the same value obtained for the one on 16 September.

On 23 September (see Fig. 3D), two eruptions of Myojinsho Reef at 13h12m and 13h40m were witnessed by members of the Tokyo College of Fisheries on board the SHINYO-MARU. Referring to Fig. 3D, undulations, apparently tsunami waves, began to occur at 13h50m. However, when this record is compared with those in Figs. 3A, B and C, we see that the record for 23 September differs from those for 16, 24 and 26 September in wave period as well as in wave height; that is, although at first sight the said undulations for 23 September appear to have been tsunami waves, they might have been the peculiar type of wave which appears when a typhoon or cyclone approaches, or they might have been what Munk (1949) calls "surf beats." Moreover, as regards the determination of the time of beginning of the said undulation, 13h50m, it is less clearly defined. Therefore we shall not consider here the observations obtained on this date.
TRAVEL TIME OF TSUNAMI WAVES AND MAGNITUDE OF ERUPTION

In computing the travel time of a tsunami, that is, the time taken by the tsunami wave to travel from Myojinsho Reef to the observing station, we must decide whether it is a shallow, intermediate, or deep wave and whether it propagates with phase or group velocity. Since the depth of water is 200–1400 m and the wave period 30–100 sec, and considering the relative depth (ratio of water depth to wave length), we see that the wave cannot be treated either as a deep or shallow wave (long wave); therefore it must be treated as an intermediate wave (elliptical particle orbits). If we denote the period by \( \tau \), the wave length by \( \lambda \), and the depth of water by \( d \), we have for such waves, according to the Airy theory,

\[
C = \left( \frac{g \lambda}{2 \pi} \tanh \left( \frac{2 \pi d}{\lambda} \right) \right), \tag{1}
\]

\[
C_\varphi = \frac{C}{2} \left[ 1 + \frac{4\pi d}{\lambda} \right] \frac{1}{\sinh \left( \frac{4\pi d}{\lambda} \right)}, \tag{2}
\]

where \( g \) is the acceleration due to gravity and \( \lambda = C\tau \).

It is found that, within the range of magnitude of the quantities and the distance here considered, computations by equations (1) and (2) yield the following result; the phase velocity \( C \) and the group velocity \( C_\varphi \) of the intermediate wave differ little from those of the deep water wave.

In Figs. 3A, B and C or Figs. 4A, B and C, we see that the period of the wave which first reached the observing station is about 95 sec. If we consider that this wave proceeded with group velocity, and if we compute the travel time \( t \) by the formula

\[
\frac{ds}{C_\varphi} = \sum \frac{\Delta s}{C_\varphi}, \tag{3}
\]

we have \( t = 32.1 \) min. Again, if we consider that this wave travelled with phase velocity, we have \( t = 28.5 \) min. As stated previously, the actual travel time of the wave was about 28 min as determined for 16 and 26 September. But, as noted earlier, this value has a possible error of about \( \pm 3 \) min. Consequently it is difficult to reach a definite conclusion as to whether the wave travelled with phase velocity or with group velocity. To ascertain the exact dif-
ference of travel-time within the range of wave period, water depth and distance of travel under consideration, more accurate time-marking would have been necessary.

We are also concerned with the time of occurrence of the volcanic eruption which presumably caused the destruction of the KAIYOMARU No. 5 on 24 September. If the waves shown in Figs. 3B or 4B (IX/24) are compared with those of Figs. 3A or 4A (IX/16) and 3C or 4C (IX/26), we see that the value of initial wave-period as well as the modes of variation of wave-period and wave-height are very similar. Hence it may be supposed that the travel time was about 28 min. in all cases. Accordingly, the eruption in question presumably occurred at about 24th 12h53m - 28m = 24th 12h25m ± 6m. According to the result of a SOFAR hydrophone observation made by the U. S. Navy, it is estimated that the said eruption on 24 September occurred at about 12h20m, which is in good agreement with our result.

Regarding the magnitude of the eruption, Unoki and Nakano (1953, 1953a) have made a detailed theoretical investigation which has shown that the present tsunami is a typical "Cauchy-Poisson wave" generated by a local disturbance over a limited extent of the sea surface. Assuming that the wave was generated by an initial impulse and that the radius of the disturbing source (the area to which the initial impulse was applied) was circular, it was found that the initial radius was about 2.2 km for A, B and C and that the magnitude of the initial impulse was $7.0 \times 10^8$, $11.6 \times 10^6$, and $8.9 \times 10^8$ dyne. sec/cm$^2$ for A, B, and C respectively. Again, if the initial disturbance was assumed to be an initial elevation, then the radius of the disturbing source was about 2.2 km for A, B, and C, as above, and the magnitude of the initial elevation was 6.3 m, 10.3 m and 8.0 m for A, B, and C respectively.

From navigation and communication, it is presumed that the KAIYOMARU No. 5 had not yet reached Myojinsho Reef at 10h on 24 September and that her destruction must have occurred between 10h and 13h on that same day. This information was kindly furnished by Dr. R. S. Dietz of the U. S. Navy Electronics Laboratory, San Diego, Calif.

In the first paper (Unoki and Nakano, 1953), one-dimensional treatment was given to the problem and the effect of friction was neglected, while in the second paper (Unoki and Nakano, 1953a) a two-dimensional treatment was given, with consideration of the frictional factor. Hence the values of the computed quantities for the initial impulse, etc., are not the same in both studies. Naturally the latter values are considered to be closer to reality, and the numerical values of the computed quantities quoted here are those obtained in the second paper.
Moreover, it was found that, in the tsunami of 24 September, the action of the initial impulse exerted much more effect than did the initial elevation. Furthermore, it was known that the energy of the eruption was about $3.0 \times 10^{19}$, $7.9 \times 10^{19}$ and $4.8 \times 10^{19}$ ergs for A, B, and C respectively. Thus, it is seen that the eruption on the 24th was quite violent.

THE TIME OF DESTRUCTION OF THE KAIYO-MARU No. 5 AS INFERRED FROM DEBRIS

The time of the destruction of the KAIYO-MARU No. 5 may also be inferred from the distribution of the wreckage and debris that remained afloat. From these observations, it was determined that the KAIYO-MARU No. 5 was destroyed during the afternoon of 24 September 1952, a fact which seems to confirm the result deduced from the record of the self-registering wave gauge on Hachijo Island.

In Fig. 5 the abscissa denotes the distance from Myojinsho Reef and the ordinate denotes time; the points correspond to the time and location where debris was found, and it is apparent that these points lie almost within an area limited by two straight lines. If we draw a straight line to represent as nearly as possible the distribution of these points and intersect this straight line with the axis of ordinate, we find that the time when drifting began (equivalent to the time of eruption or disaster) falls between 0h and 12h on the 24th. But if we consider Fig. 5 carefully, we notice that some flotsam, such as that indicated by (5), (7), (8) and (10), was driven relatively farther as compared with that indicated by (4), (6), etc. Since the starting time from Myojinsho Reef of all objects is considered to be the same, it is necessary to make a correction for the effect of leeway. According to Yasui (1940), the effect of leeway is expressed by the formula

$$U = k \sqrt{\frac{A}{B}} \cdot W,$$

where $U$ denotes the drifting velocity of a vessel due to the effect of wind, $W$ the velocity of wind, $A$ and $B$ the cross-sectional areas of the vessel above and below the sea surface, respectively, taken in a plane perpendicular to the direction of drift, and $k$ a certain constant. If $U$ and $W$ are measured in cm/sec, the value of $k$ is 0.03. The value of the ratio $A/B$ will differ for different flotsam, but in the present

*Here it is assumed that the KAIYO-MARU No. 5 was destroyed in close proximity to Myojinsho Reef.
Figure 5. Drifting distance of erupted materials and wreckage from the KAIYO-MARU No. 5 relative to time of drifting. 1. Wooden box, soy keg, angular timber, log, pieces of cork, and numerous timbers. 2. Surveying buoy. 3. Surveying log. 4. Wood from a sampan stern, and a piece of cork. 5. Rack of a sampan, life buoy, and a piece of wood from a vegetable container. 6. Fragment of a life buoy. 7. Fragment of bulwark. 8. Crossbar of bed from operator’s room. 9. Four kegs. 10. Part of environs of boat. 11. Part of compass bridge deck. A. Piece of comparatively new wood. B. Volcanic ashes and solidified substances. C. Sulphur and pumice. (Note: Flotsam “A” was picked up by a fishing boat, and it is uncertain whether or not this is part of the KAIYO-MARU No. 5 wreckage.)
case we take, as an approximation, $A/B$ as a constant and equal to $\frac{1}{2}$ for all the flotsam concerned.

By means of weather charts published by the Central Meteorological Observatory of Japan, the wind velocity and direction over the area considered were estimated; and by using equation (4), the effect of leeway was eliminated. In Fig. 6, the small white circles represent the positions where the items of flotsam were actually picked up.
Figure 7. Chart of streamlines of the ocean current, drawn from the estimated positions of flotsam with the effect of leeway eliminated.
If the effect of leeway were nonexistent and if the flotsam had been carried by the general current alone, wreckage would have been found at the positions indicated by the black circles in Fig. 6.

Fig. 7 shows the streamlines of the ocean current in the area concerned; these were drawn from the estimated positions of flotsam after the effect of leeway had been eliminated. Unfortunately the direction of the current is somewhat obscure near 139° 50' E and 31° 00' N because of the fact that there was at that time a stationary front in this vicinity. Since some of the flotsam was situated on the northern side and some on the southern side of the front, some errors were unavoidably introduced when the effect of leeway was calculated.

With the effect of leeway eliminated, Fig. 8 is drawn to show the "travel-time curve" of Fig. 5 with corrected values; the values of time and distance correspond to the black circles in Fig. 6. In Fig. 8 we see that the items of flotsam are distributed more or less regularly along a straight line. If we read the value of time at the point where this straight line intersects the time axis, then the starting time of the driftages from Myojinsho Reef occurred during the afternoon of the 24th (about 18h, we venture to say).

Since there are probably some errors in our estimated values of wind direction and velocity over the sea (the values adopted for $k$ and $A/B$ in the formula $U = k \sqrt{A/B} \cdot W$) and of the positions where the flotsam was found, we cannot draw a more detailed conclusion than this from the travel-time curve method used above.

Again we note that the above discussion is based on the assumption that the flotsam came from close proximity to Myojinsho Reef. If the KAIYO-MARU No. 5 met with disaster at some point far apart from Myojinsho Reef, then a major correction would have to be made in our calculations and conclusions. However, at present there is nothing which seems to contradict our assumption. At any rate, the above result of driftage investigation is not inconsistent with the result inferred from the record of the self-registering wave gauge on Hachijo Island. Moreover, if we calculate the velocity of the ocean current from the travel-time curve in Fig. 8, we have approximately 0.7 knot, which is in fairly good accord with the result of observations taken hitherto in this vicinity (Hydrographic Office of Japan, 1948; see also Hanzawa, 1953).

As noted earlier, it is not certain that flotsam "A" in Fig. 5 is a part of the wreckage of the KAIYO-MARU No. 5. Again, it is not certain that the erupted materials "B" and "C" in Fig. 5 were ejected from Myojinsho Reef at the time of the eruption which destroyed the KAIYO-MARU No. 5. Hence, in Fig. 8, A, B and C are omitted.
Figure 8. Drifting distance relative to time, corrected for the effect of leeway.
ACKNOWLEDGMENT

In conclusion, we wish to express our thanks to members of Hachijojima Weather Station who obtained wave records for us, to the observers and crew of the CHIKUBU-MARU, at whose personal risk data in the danger zone were obtained, to Dr. K. Suda, director of the Hydrographic Office, Maritime Safety Agency of Japan, who kindly gave additional data concerning the disaster of the KAIYO-MARU No. 5, and to Dr. K. Wadati, director of the Central Meteorological Observatory of Japan, for his encouragement and advice. Similar thanks for helpful information and suggestions are due Dr. Y. Kawabata of the Central Meteorological Observatory of Japan, Dr. C. Tsuboi of Tokyo University, and Dr. R. S. Dietz of the U. S. Navy Electronics Laboratory, San Diego, California. And the authors pray heartily for the heavenly bliss of the investigators and crew on board the KAIYO-MARU No. 5 whose precious lives were lost in the southern sea of Japan in the interest of science.

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APPENDIX

Although these data and observations have no direct bearing on the disaster of the KAIYO-MARU No. 5, we have added them here for the record.

The CHIKUBU-MARU, a weather ship of the Central Meteorological Observatory of Japan, was navigating in waters near Myojinsho Reef from 15h to 19h on 21 September 1952 on her passage from Torishima to Tokyo, at which time her crew witnessed an eruption at Myojinsho Reef about 17h 35m. Their observations on that occasion are noted herewith. Fig. 9 shows the positions of their stations, the numeral in brackets denoting the time of observation.

(1) APPEARANCE OF THE ERUPTION
15h20m; odour of sulphur noted about 22 nautical miles SSE from Myojinsho Reef.
15h50m; intense odour of sulphur noted about 17 nautical miles SSE from the Reef.
16h10m; column of white smoke trailing westward was seen on the horizon NNW from the ship, about 13 nautical miles from the Reef.
16h22m; from the sea surface at the foot of the column of white smoke, a column of black smoke shot upward to a height of about 200 m; this dispersed and turned white subsequently.
16h30m; on the sea surface, west of the ship, a stream of yellowish green sulphide spread SSW in the shape of a belt from the direction of Myojinsho Reef.
17h35m; column of deep black smoke belched upward from the steam and white smoke, and several seconds later a column of fire appeared.
17h38m; this same column of black smoke attained a height of more than 5000 m, and a large quantity of incandescent lava fell into the sea. The surface of the sea swelled up, and the diameter of this swollen portion increased to about 740 m almost instantly.
17h40m; volcanic ashes fell from the sky on the deck of the ship, which was then about 5000 m SE from the point of eruption; when these ashes struck the observers' cheeks, the men felt pain, and in the interest of safety, the ship retreated northeastward at full speed.
Figure 9. Observation stations occupied by the CHIKUBU-MARU.
Fig. 10 shows the temperature, chlorinity, and dissolved oxygen values of the surface water at each station. The water temperature at stations 6–11, close to Myojinsho Reef, was 27.8°, which is somewhat higher than the temperatures at more distant stations. Apparently this higher temperature was partly due to the heating of the water by various substances ejected from Myojinsho Reef which were carried southward by currents.
The chlorinity values for stations 1–9 are somewhat less than those for stations 13–16. The cause of this discrepancy is not clear at present, but a part of it may be explained qualitatively; possibly water of low salinity spurted from Myojinsho Reef together with other substances, flowed southward with the ocean current, and, by mixing, diluted the surface sea water.

As for the distribution of the dissolved oxygen, no particular tendency is noted.

(3) Floating Mineral Substances and Plankton

Floating mineral substances and plankton organisms from each 100 cc sample of surface-water were examined by the following method. The catch in each water sample was concentrated into 2 cc with a centrifuge, and 0.5 cc of this sample was then examined through a microscope. Brown volcanic dust, presumably small fragments of pumices, were abundant in all samples; a small quantity of pyroxene crystals was also included. Heavier volcanic dusts probably sank rapidly. The quantity of floating mineral substances was greatest at stations 6–11, close to Myojinsho Reef, and least at eastern stations 12–16.

Furthermore, the quantity of plankton organisms was small, amounting to approximately 40 individuals per litre even in samples that were comparatively rich in population. The intercellular substances of organisms such as *Rhizosolenia calcar-avis*, *Coscinodiscus* sp., *Trichodesmium thiebaudii* and *Pyrocystis pseudonoctiluca*, had disappeared completely. The scarcity of plankton in the surface water near Myojinsho Reef may have been caused by the injurious action of the eruptive efflux and the subsequent sinking of plankton to lower layers. However, the data are too scanty for definite conclusions.

According to data from observers aboard the Tokyo College of Fisheries boat *Shin'yō-Maru* on 23 September, surface chlorinity of the sea adjacent southward of Myojinsho Reef was especially low; H. Niino, a member of the party, suggests that this may have been due to mixing of low salinity water which issued from Myojinsho Reef during its eruption with adjacent water.