Geomorphologic features of large-scale submarine debris-avalanche along Japan coast

—Comparison of Oshima-Oshima Volcano in Hokkaido and off Kaimon Volcano in southern Kyushu—

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Abstract

Ninety percent of all tsunamis are generated by earthquakes; however, the remaining 10% are caused by meteorite collisions, volcanic activity, and submarine landslides. Submarine landslides occur due to slope instability, and large-scale submarine landslides can generate very large tsunamis. Therefore, from the viewpoint of disaster prevention, it is important to clarify the generation mechanism and features of submarine landslides. In this research, we compared the features of submarine landslides generated in two different regions, and we calculated their volumes. The first environment is a debris avalanche that occurred by the collapse of a volcanic body; the debris flowed into the sea and generated the Kanpo Tsunami along the Sea of Japan in 1741 in the case of Oshima-Oshima Volcano southwest off Hokkaido in the Japan Sea. A hummocky topography was found from the sea floor at the northern part of Oshima-Oshima, it is assumed to be the debris avalanche in 1741. In the second place, a submarine landslide exists from the continental shelf margin southwest of the Satsuma Peninsula in the southern part of Kyushu up to a depth of 320 m. We calculated the volume of the submarine landslide, and the volumes of the two landslides were similar ($\sim 2 \text{ km}^3$). However, those distributions and morphology are significantly different. We clarified that these differences are caused by the difference in the environment (topography, width of head wall, collapsed materials, *etc.*).

Key words : submarine landslide, debris avalanche, Oshima-Oshima, Kaimon

1. Introduction

Ninety percent of all tsunamis are generated by earthquake deformations, but the remaining 10% are caused by meteorite falls, volcanic activity, and submarine landslides (Imamura, 1998). Although there has been considerable research on earthquake tsunamis, landslide tsunamis are still not clearly understood. Submarine landslides are caused by the collapse of a volcanic body with volcanic activity, or by slope failure occurring on an unstable slope (*e.g.*, a continental shelf slope). Large amounts of volcanic debris avalanche deposits have been discovered in the sea floor around volcanic islands such as the Hawaii Islands, the Canary Islands, and Ritter Island (Lipman, 2006; Garcia, 2006; Masson, 2002; Ward and Day, 2003; *etc.*). The debris avalanche generated by the 1640 Hokkaido Komagatake Volcano eruption in Japan flowed into Funka Bay; the resulting tsunami surged toward Usu Zenkoji on the opposite bank and more than 700 people were killed (Katsui *et al.*, 1975). Debris avalanche deposits were discovered offshore of Hokkaido Komagatake Volcano, and their distribution reportedly had a volume of $0.92 - 1.2 \text{ km}^3$, maximum width of 15 km, and distribution area of 126 km^2 , and the deposits flowed 20 km from the crater (Yoshimoto *et al.*, 2003). Mayuyama,

which lies to the east of Unzen Volcano, collapsed due to the earthquake that resulted from the 1792 volcanic activity. The resulting debris avalanche flowed into the sea, and a large-scale tsunami was generated. This tsunami surged toward the Kumamoto side on the opposite bank and claimed 15000 victims (Tsuji and Murakami, 1997). The tsunami caused by the collapse of Mayuyama was simulated by Sasahara (2004), and a tsunami run-up elevation of more than 25 m was obtained at Futsu in the Shimabara Peninsula. The tsunami generated in Toya Lake by the sector collapse of the Usu Volcano was simulated immediately a day after the eruption began in 2000 (Satake, 2001). On the other hand, Storegga submarine landslide is known off the western coast of Norway as a huge slope failure. The Storegga submarine landslide released about 8150 years ago. It caused tsunami along Iceland, Shetland and Scotland (Smith, *et al.*, 2004). And also, some statistical researches were conducted on the collapse of the continental shelf slope. McAdoo *et al.* (2000) searched for a submarine landslide by using side scan sonar and sea beam in four different regions of the continental shelf slope around North America (active margin, non-active margin, *etc.*), and they obtained statistics using geomorphic characteristics. Reportedly, several morphological features of a submarine landslide were distributed in the region of about 4° , where the inclination of the continental shelf slope was comparatively

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gradual. A submarine landslide in the continental shelf slope around the North Atlantic was similarly investigated by Hühenerbach and Masson (2004), who reported that the landslide was mostly generated on a comparatively gradual continental slope of about 5° . According to both reports, collapses on the continental shelf slope occurred on slopes that had a comparatively gradual inclination; reportedly, it is possible that slope failure is generated at an inclination of about 1° . Similarly, an active submarine landslide was reported on a western continental shelf slope offshore of the Satsuma peninsula, which is located to the west of the region investigated in this study (Iwabuchi, 2006). A large-scale submarine landslide of volcanic or non-volcanic has the possibility to suddenly generate a tsunami. Therefore, in order to prevent disasters, it is important to clarify the morphological features of these submarine landslides and their generation mechanism. However, submarine landslides show different features based on the ambient environment (*e.g.*, volcanic body collapse and continental shelf slope collapse) and the collapse materials. Therefore, we considered two different cases in this research. One case is the debris avalanche deposits of Oshima-Oshima, which is located on the western part of Hokkaido, as an example of a volcanic island. The other case is a submarine landslide on the continental shelf margin on the offshore part of the Satsuma Peninsula in the southern part of Kyushu. We compiled the distribution of the submarine landslide; in addition, we estimated the collapse volumes and compared them as different condition.

2. Research method

In this research, we used bathymetric data collected by the Japan Coast Guard around Oshima-Oshima in 2000 and around the southern part of Kyushu in 2006. These data were obtained using a SeaBeam2000 multi-beam sounding device, which can collect very detailed data at a resolution of tens of meters. Data on the neritic region were obtained from the Japan Coast Guard's "Basic bathymetric data of littoral region." In addition, side-scanning images obtained by IZANAGI at the Ocean Research Institute, University of Tokyo, were used to confirm the debris avalanche block in the northern part of Oshima-Oshima. We created a grid with a lattice interval of 5" (about 150 m) from the multi fan-beam data by using Generic Mapping Tools (GMT), and we reconstructed the topography before sector collapse by using a technique similar to that used by Satake and Kato (2001). The process of recon-

struction was as follows. ①We estimated the area of collapse and sediment from detailed bathymetry and side scan images. ②Only data on the collapsed region were removed and re-interpolated from surrounding data using the surface function of GMT. ③Only data on the sedimentary region were removed and re-interpolated from surrounding data by using GMT. By considering the difference between the two topographic datasets, the volumes of the slide and sediment areas were estimated. The volume of the volcanic body was calculated by 3D analysis of the function in Arc GIS (created by ESRI).

3. Topography

3.1 Oshima-Oshima island

Oshima-Oshima is located in the southwest region off the Hokkaido Oshima Peninsula in the Sea of Japan. Moreover, Oshima-Oshima makes contact with the Matsumae plateau, and the Okushiri ridge is divided into parts along north-south on the east side (Fig. 1). Oshima-Oshima is composed of triple volcanic body, and it was formed in the following order: Higashiyama, Nishiyama, and the central cone. It is a strato-volcano that alternately erupted andesitic lava, basaltic lava, and pyroclastics while it develops (Katsui and Yamamoto, 1981). The last known activity period of this volcano is 1741–1790, a period that came after 1500 years of dormancy. The most violent activity of this volcano occurred on August 29, 1741, when Nishi-

Fig. 1 Location map of Oshima-Oshima. Dotted line indicates area of Fig. 2

yama collapsed. The debris avalanche flowed into the sea and generated the Japan Sea Tsunami. The hummocky topography that was formed by the debris avalanche deposits can be observed in the sea to the north of Oshima-Oshima (Fig. 2). Canary Islands also collapsed in a similar way, and the debris avalanche deposits in that case were confirmed to have formed a hummocky topography at the bottom of the sea (Masson *et al.*, 2002). The head wall of Oshima-Oshima continues up to a depth of 1100m, and a hummocky topography exists below a depth of 1100 m. We use the word "head wall" as composite term of main scarp and slide surface at the source area in case of a subaerial landslide. Therefore, we premised that the collapsed region was shallower than 1100 m and that the sedimentary region was deeper than 1100 m for calculating sediment volumes. Moreover, the inclination of each grid point was calculated from a grid that shows the topographical map around Oshima-Oshima (Fig. 2). The plot of the inclination is shown in Fig. 3. This figure shows that Oshima-Oshima gradually slopes downward to the bottom of the sea before reaching a conversion point at 1500 m, where rapid inclination in the subaerial region occurs. It is considered that the volcanic body of Oshima-Oshima continues downward to at least 1500 m. The very gradual inclinations from the coastline to a depth of 200 m indicate the continental

shelf in the western part of Oshima-Oshima. Further, the very gradual inclinations from a depth of 1000 m indicate the smooth terrace in the Matsumae Plateau. The region where the debris avalanche deposits are deposited from a depth of 1100 m to 2200 m has an inclination of 10° to 40° , slopes greater than the ambient slope.

3.2 Kaimon submarine landslide

We find bends of contours off Satsuma Peninsula, Kyushu (Fig. 4). As a result of detailed topographic analysis, those bends of contours turned out submarine landslide. Deposits from the Kaimon submarine landslide are located in the southern part of the Satsuma Peninsula, and as Kaimon Volcano, which exists in the subaerial region. Kaimon Volcano is a stratovolcano

Fig. 2 Topography and bathymetry around Oshima-Oshima. Contour interval is 20 m. The coordinate system is WGS 84

Fig. 3 The inclination plot around Oshima-Oshima

Fig. 4 Location map around study area. Dotted line indicates area of Fig. 5

formed by alternate eruption of lava and scoria over 3000 years after 4000 BP years, and the volcano has a lava dome (Ishikawa, 1979). The Kaimon submarine landslide is distributed from the continental margin to a depth of 320 m in the southern part of Kaimon Volcano (Fig. 5). The continental shelf in this region has a wide and very gradual slope of $1-2^\circ$. However, the steep cliff that has collapsed at the continental shelf margin is distributed from depths of 140 m to 200 m off the southeastern part of Kaimon Volcano. The width of

Fig. 5 Topography and bathymetry off Kaimon Volcano. Dotted line indicates the toe of estimated collapse area (case 1 and 2)

Fig. 6 Reconstructed bathymetry around Oshima-Oshima before collapse

Fig. 7 Difference between Fig. 2 and Fig. 6. The contour interval is 40m. The dots indicate the sedimentary area. The slashes indicate the collapsed area

the bent steep cliff is about 10 km; it is considered to be a head wall of the submarine landslide, which is covered by Kaimon Volcano. Therefore, there is a high possibility that the submarine landslide is older than the present Kaimon Volcano.

4. Reconstruction of submarine landslide

4.1 Volume of Oshima-Oshima debris avalanche

We reconstructed the topography before sector collapse by a technique similar to that employed by Satake and Kato (2001) using bathymetric data (Fig. 6). We defined the boundary of the collapsed region and the sedimentary region as a depth of 1100 m from bathymetric data and side scan images. A small block of debris avalanche was found in the side scan images (the size was smaller than about 100 m as compared to the hummocky topography). Therefore, we defined the range of block distribution as the limit of the sedimentary area (Fig. 2). The resulting reconstructed topography around Oshima-Oshima before the collapse is shown in Fig. 6. In the reconstructed map, the debris avalanche deposits disappeared in the northern part of Oshima-Oshima. The reconstructed stratovolcano with an apron slope similar to that of the southern part of Oshima-Oshima is shown in Fig. 6. The volume of the volcanic body was calculated by using reconstructed data. We defined the base of the volcanic body as a

Fig. 8 (a) and (b) : Reconstructed bathymetry before collapse. The solid lines indicate the region of submarine landslide. (c) and (d) : Comparison with Fig. 5. The dots indicate the sedimentary area. The solid contour indicates difference with Fig. 5, and interval is 5m

depth of 1500 m, because this depth was the conversion point of inclination (Fig. 3). However, as for the western part of Oshima-Oshima borders the Matsumae Plateau at a depth of 1100 m, we determined the base of the volcanic body at a depth of 1100 m in the western part of Oshima-Oshima. We estimated the volcanic body above this base as the volcanic volume and calculated the volcanic volume. The total volume of Oshima-Oshima Volcano was found to be about 127 km³. Moreover, the volume of the Oshima-Oshima debris avalanche was calculated from the difference between the two topographic datasets: recent data and reconstructed bathymetric data (Fig. 7). Each volume was calculated from the product of the difference in the altitude at the grid point and the lattice area of the grid. The total volume of sedimentary debris avalanche was 2.2 km³, and the maximum thickness was 160 m in

front of the collapsed region. The volume of the collapsed region was 2.1 km³; it corresponded well with the sedimentary volume. Moreover, the areas of the collapsed and sedimentary regions were 20 km² and 220 km², respectively (Fig. 2). Therefore, the average thickness of the sedimentary region was about 9 m.

4.2 Volume of Kaimon submarine landslide

We also reconstructed the topography before the collapse for the Kaimon submarine landslide using a technique similar to that used for Oshima-Oshima. We presumed two cases for the collapsed area from the topography of the continental shelf: the northern continental shelf inclines to the south; the depth contour is along the east-west direction (Fig. 5). On the other hand, it inclines to the southwest in the eastern part of area; there, the depth contour has direction from north-northwest to south-southeast (Fig. 5). The head

scarp exists between western and eastern continental shelf. Therefore, it is estimated to incline gradually westward around the head scarp before collapse. However, the head scarp is bent with a width of 10 km. We presumed and reconstructed two collapsed cases (Fig. 8) : in case1, there is a smooth contour before the collapse (Fig. 5 – case 1) while in case 2, the bent shape is already present before the collapse (Fig. 5 – case 2). The head wall aligned southward changes to have a gradual slope that continues to the west, similar to the ambient continental shelf in case 1 in Fig. 8 (Fig. 8 – a). The landslide topography from the collapsed region to the southwest also disappears, and it changes to have a gradual slope that is inclined westward, similar to the ambient topography. On the other hand, the collapsed region was also reconstructed, and it showed a bent gradual slope in case 2, where the bending was presumed to be present (Fig. 8 – b). Moreover, we compared the reconstructed grid data with present bathymetric grid data to calculate the volume of the collapsed and sedimentary areas (Fig. 8 – c, d). The result showed that the volume of the collapsed and sedimentary regions in case1 was 1.81 km³ and 2.05 km³, respectively. Fig. 8 – c shows that the front of the collapsed region is eroded, and the total of the eroded and collapsed values is 1.93 km³. The volume of the collapsed and sedimentary regions in case 2 is also 0.93 km³ and 2.1 km³, respectively; the collapsed value including the eroded volume in front of the collapsed region is 1.75 km³ (Fig. 8 – d). The areas of the sedimentary and erosion regions are 187 km² and 142 km² in case 1 and 181 km² and 148 km² in case 2, respectively. Therefore, the average thickness is about 10 m. Moreover, the sedimentary region begins at a depth of 280 m (Fig. 8 – c, d).

5. Discussion

The volumes of the Oshima-Oshima debris avalanche and the Kaimon submarine landslide are similar in scale, about 2 km³. However, the form and distribution of the debris avalanche deposits differ significantly in these two regions. The debris avalanche deposits pile up to a large thickness of 160 m in front of Oshima-Oshima, and they concentrate over a range near the collapsed region. On the other hand, the sediment of the Kaimon submarine landslide piles up over a very small thickness and is widely distributed when compared with the Oshima-Oshima debris avalanche.

We compared the features of the two regions. In the case of Oshima-Oshima, the blocks of debris avalanche

are distributed up to a depth of 2200 m, and the horizontal distance from the collapse head wall to the limit of the block is 24 km. The relative elevation of the debris is 2900 m from the top of the collapsed region to the limits of the blocky sediment. These values were used for the coefficient of dynamic friction (H/L) of the debris avalanche. H/L is the ratio of the maximum perpendicular distance (H) to the maximum horizontal distance (L) of the source and the limit of the sediment. The average H/L of the volcanic debris avalanche is about 0.1 and that of large debris avalanche is 0.05 (Siebert *et al.*, 1987; Ui, 1983; *etc.*). For example, Hokkaido Komagatake debris avalanche which is similar condition with case of Oshima-Oshima indicates 0.06 (Yoshimoto, 2003). The H/L of Oshima-Oshima is about 0.12. The width of the collapse head wall is 2 km, but the maximum width of the sedimentary area is 15 km. On the other hand, the Kaimon submarine landslide has a very small value, 0.008. The maximum horizontal distance from the collapsed head wall on the continental shelf to the limit of the sediment is 25 km (L). Further, the maximum perpendicular distance is only 200 m (H), because the sediments are distributed in a depth range 120 m to 320 m. The coefficient of dynamic friction of Oshima-Oshima showed a similar average value to that of the volcanic debris avalanche, but the Kaimon submarine landslide showed a very small value of 0.008. The difference in the sedimentary distribution is caused by different factors: the difference in the collapsed region, the topographic environment, the width of the head wall, collapse mechanism and the collapsed materials that is volcanic or not. The width of the head wall is only 2 km in the case of Oshima-Oshima; however, it is 10 km in the case of the Kaimon submarine landslide, five times the width in the case of Oshima-Oshima. The distributions of sediments are also different in the two regions. In the case of Oshima-Oshima, the debris avalanche deposits spread laterally with a maximum width of 15 km in the sea. On the other hand, the sediment does not spread laterally in the Kaimon submarine landslide; it flows straight to a depth of 320 m, maintaining the width of the head wall (10 km). This difference is caused by topography and speed between debris flow and turbidity current. The head wall curves and continues to a depth of 1100 m in the case of Oshima-Oshima. In short, lateral movement is limited by the head wall until a depth of 1100 m. In addition, about 40 percent of the Oshima-Oshima collapse occurred in the subaerial region. In other words, the speed of the de-

bris avalanche rapidly reduced when it flowed into the sea. It goes straight if the speed is high like turbidity current, however it extends to lateral when the speed reduce. Therefore, the Oshima-Oshima debris avalanche spread laterally after flowing into the sea. On the other hand, it is considered that speed was high in the case of the Kaimon submarine landslide, because distribution of sediment is even.

When we considered mechanisms of transportation, the debris avalanche created currents similar to sediment gravity flow into the sea. In general, sediment gravity flow is divided into 4 types (turbidity current, fluidized sediment flow, grain flow, debris flow). Those flows show that coarse grains settle toward the base of the flow, and their speed and density reduce. When the shear stress can no longer overcome the friction, the layer of colliding grains stops moving. (Bouma, 1962). In physics, the speed, density, and particle size of the sediment gravity flow are considered as important parameters that determine fluid flow. For instance, the run-out distance increases with the speed and density. In addition, fine particles flow longer than coarse particles under similar conditions. The coarser the particles, the closer to the source they would be, and the finer the particles, the more extensive and even they would be in thickness (Laval *et al.*, 1988). Oshima-Oshima debris avalanche is estimated that is composed of large volcanic blocks; however Kaimon submarine landslide is composed of smaller particles such as sand and silt. As a result, very thick sediments (large block) were deposited in front of the source region in the case of Oshima-Oshima. On the other hand, in the case of the Kaimon submarine landslide, the sediment spread evenly in thickness. Those morphological features are influenced by transportation mechanism of sediment which is different between 2 regions. We can estimate difference of transportation mechanism from those morphological features. Oshima-Oshima debris avalanche was transported by debris flow. On the other hand, Kaimon submarine landslide was transported by turbidity current. The morphological features of submarine landslide are decided by geological condition (topography, material *etc.*) and transportation mechanism.

6. Conclusions

We compared morphological features of Oshima-Oshima debris avalanche with Kaimon submarine landslide sediment. In the case of Oshima-Oshima, collapsed sediment is thickest in front of the collapsed

area, however in the case of Kaimon submarine landslide, the collapsed sediment spreads evenly in thickness. Those differences are caused by differences of component material: Oshima-Oshima is composed of large volcanic rock; on the other hand, Kaimon submarine landslide is composed of small particles such as sand and silt. Therefore, Oshima-Oshima's flow mechanism is debris flow; whereas, Kaimon submarine landslide's flow mechanism is turbidity current. As a result, different sediment distributions were made by different flow mechanisms.

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