Evaluation of Potential Hazards from Lava Dome Collapse on Mt. Unzen-Fugen-dake

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The Unzen Restoration Work Office, Ministry of Land, Infrastructure, Transport and Tourism (hereinafter referred to as MLIT) has continued to observe the lava dome formed on Mt. Unzen-Fugen-dake by the eruption activities after 1990. To date, major changes have not been seen, but in the 14-year period between 1997 and 2011, approximately 1 meter-long southeastward displacement has been observed. Possibility of collapse of the lava dome due to its own weight, rainfall, or earthquakes and so on suggests the necessity for measures against such collapse. This study was conducted to grasp the range of the impact of the collapse of the lava dome as basic data for taking comprehensive measures against its collapse. In this study, five cases of lava dome collapse of different scales were assumed. And the range of the impact of each case was estimated by numerical simulation. The continuum model was used as the simulation model, and the law of resistance of Takahashi's pyroclastic flow equation was used. Since there is no past example of a comparable lava dome collapse, the data for the pyroclastic flows deposit that occurred in 1991 on Mt. Unzen-Fugen-dake was used for correction. The authors obtained knowledge of the area of the impact of the collapse of the lava dome from this study.

Keywords: sector collapse, debris avalanche, monitoring, lava dome

1. INTRODUCTION

Due to the eruption activities in the period between 1990 and 1995, a large amount of ejecta (about 170 million m^3 of pyroclastic flows deposit and about 100 million m^3 of lava dome) has been produced and has been deposited around the summit of Mt. Unzen-Fugen-dake. As pyroclastic flow deposit may cause debris flows, The Unzen Restoration Work Office, MLIT has undertaken the erosion control enterprise. To prevent accidents due to rock falls at the construction site, the lava dome is being observed continuously. Currently, a continual displacement accompanied by creep due to gravity or to the cooling and resultant contraction of the lava dome has been observed. I

Sector collapse in a volcanic body formed mainly by ejecta may cause a large-scale, high-speed debris avalanche as seen in the collapse of Mt. Bandai in Japan in July 1888 and Mount St. Helens in USA in May 1980, and may cause a hazard(Inokuchi, 2006). As methods for assessing the impact of a debris avalanche, various models such as the energy cone model, the dry particle flow continuum model(Takahashi et al., 1995), and the distinct element model(Yamada et al., 2011) have been studied, but there are few studies that quantitatively simulate the characteristics of blocks falling during being crushed into finer particulars.

In this study, the authors examined a method for quantitatively assessing the impact of the collapse of the lava dome to obtain data used for risk management.

2. FORMATION AND CURRENT SITUATION OF THE LAVA DOME

The lava dome which constitutes the summit Mt. Unzen-Fugen-dake was formed by eruption activity between 1990 and 1995. A unit of lava ejecta is called a "lobe." When a lobe grows to a certain size, lava starts to erupt from another crater and forms a new lobe. The lava in Mt. Unzen-Fugen-dake is dacitic and high in viscosity. Therefore, thick, tongue-shaped lobes were formed. Destabilization in the process of the formation has caused partial collapse, which often generated rock fall and pyroclastic flows. Finally, 13 lobes were formed in total, and some lobes remain. The lava dome of these lobes was named the "Mt. Heisei Shinzan Lava Dome." The structure of the lobes in the lava dome is shown in **Fig. 1.**

On the other hand, pyroclastic flows deposit piled up in the flow range in an unstable state, which made the area prone to sediment discharge. As a result, a series of debris flows occurred and caused heavy damage to Shimabara, located downstream of the volcano. The erosion control project has been promoted by the Unzen Restoration Work Office, MLIT. From possibility of rock fall and partial collapse, the lava dome has been observed for the safety control under construction. In the 14-year period between 1997 and 2011, approximately 1 meter-long southeastward displacement has been observed in part of the lava dome (P8) as shown in **Fig.2**. Possibility of lava dome collapse is suggested.

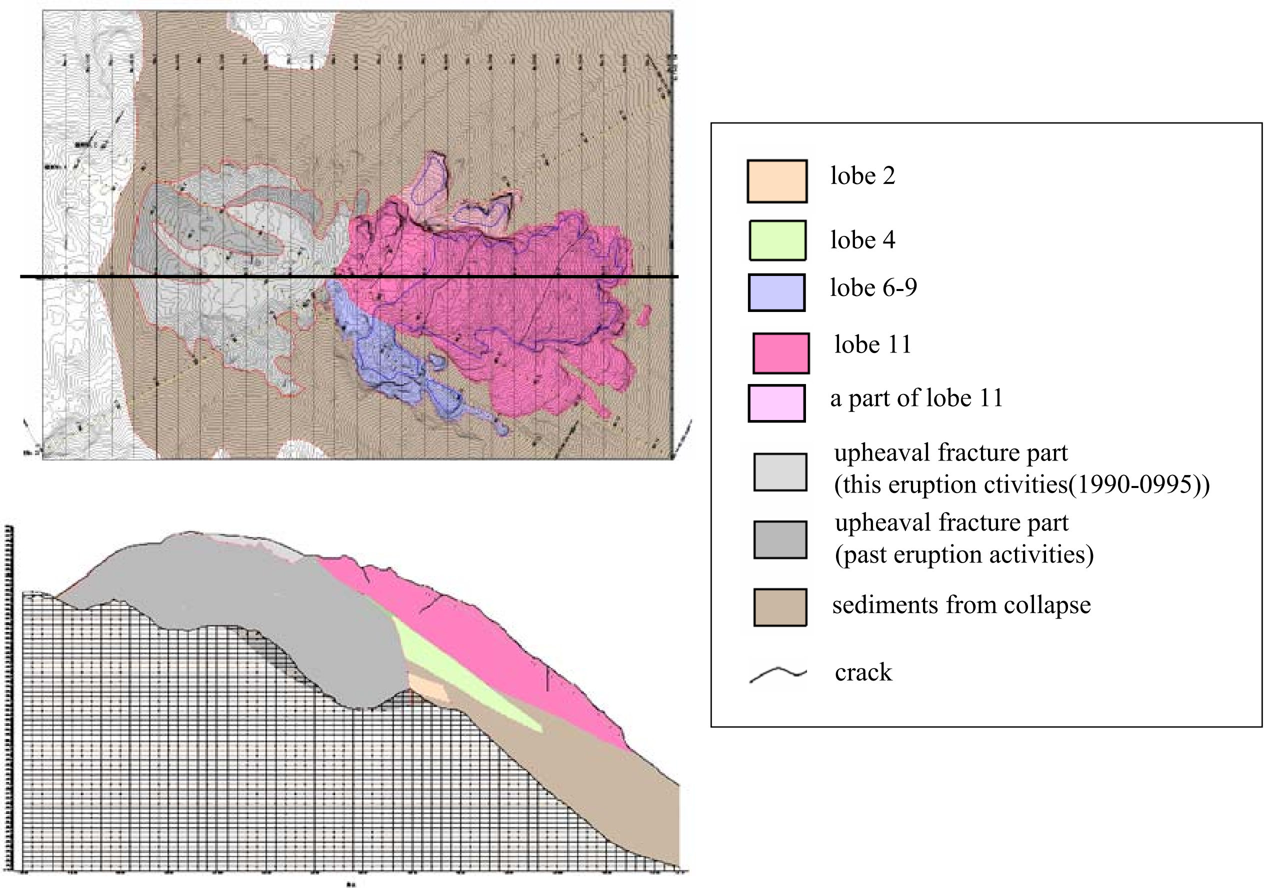

Fig.1 Structure of the Lava Dome (upper: Plane View, lower: Cross-section View along the Thick Line
(The inside is an estimated view.)

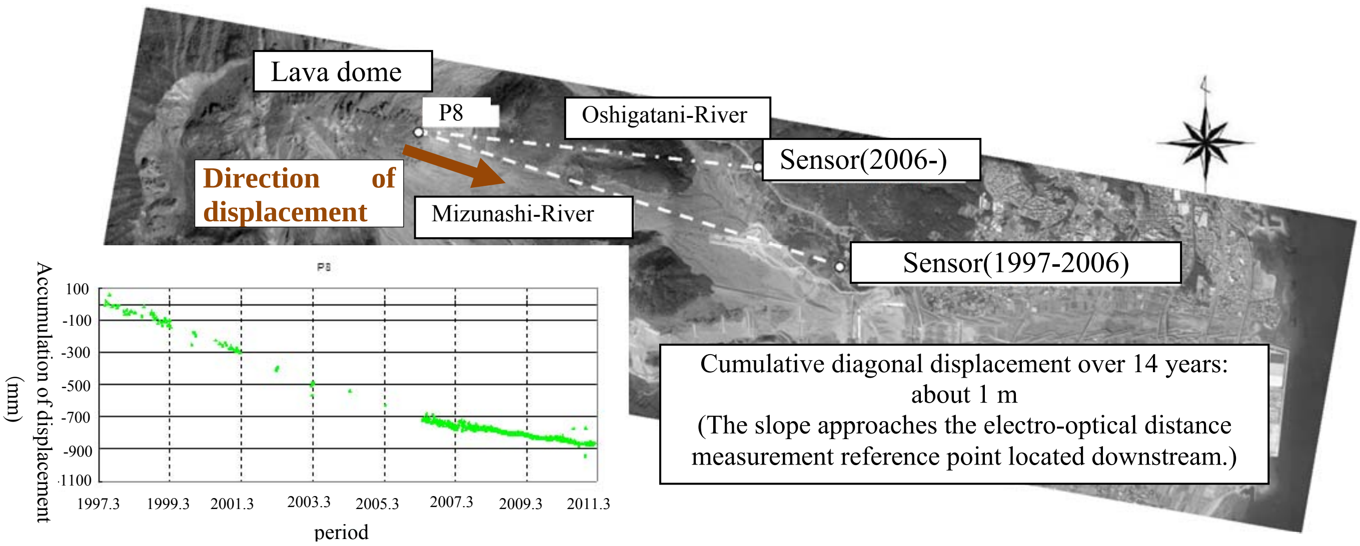

Fig.2 Location and Displacement of the Lava Dome

3. VERIFICATION OF THE STABILITY OF THE LAVA DOME

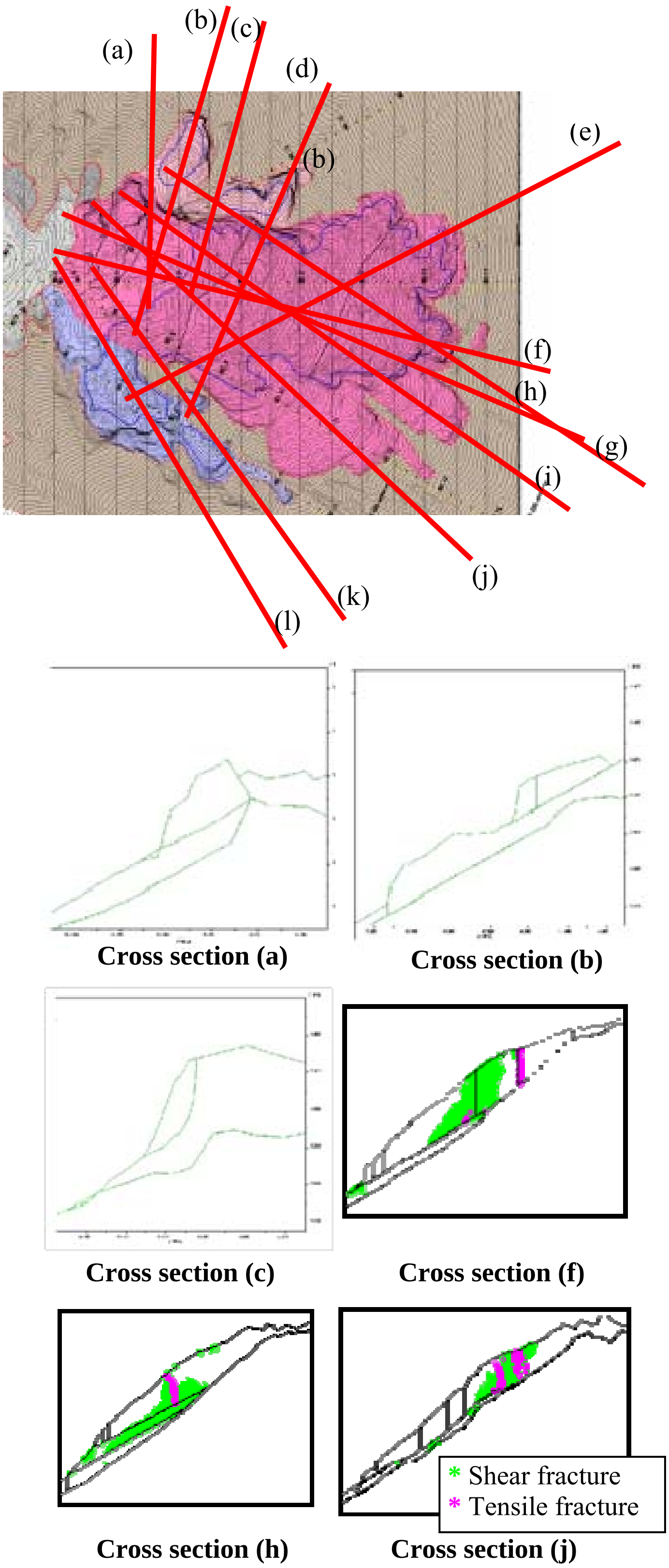

Fig.3 Locations of the Cross Sections Analyzed and Distribution of Shear Fractures

Table 1 Physical properties of lava dome

classification	physical property				
	Young's modulus (E) (kN/m^2)	ultimate tensile strength (σ_t) (kN/m^2)	Poisson's ratio (ν)	adhesive force (c) (kN/m^2)	internal frictional angle (φ) (°)
substratum	1.0×0^{10}	4900	0.3	4900	64
massive lava	4.5×10^{6}	300	0.3	1785	57
sediments from collapse	1.5×10^{5}	300	0.4	400	55
porous lava	4.5×10^{6}	300	0.35	350	20
assumed boundary (for example, boundary between lobe and other lobe)	4.5×10^{6}	240	0.3	240	24

The authors estimated which area in the lava dome was prone to fracture and how the lava dome collapsed. A two-dimensional numerical analysis method that can calculate the displacement of the masses of rock and the internal stress which occur with gravity, earthquake, water pressure, and can also simulate influence of crack(distinct element method: DEM) was used. Cross sections used for the analysis were set in such a way that the whole area of the lava dome could be covered. The physical property of the lava dome was set up based on previous investigation and a test result. The physical property was classified and set as substratum, massive lava(upper part of lava dome), sediments from collapse, porous lava(lower part of lava dome), assumed boundary((boundary between porous lava and sediments from collapse). Physical properties is shown as **Table 1.**

The set cross sections and the analytical results are shown in **Fig. 3**. In the northern cross sections (a) to (d), tensile or shear fractures were not observed. Other hand, in the eastern or southeastern cross sections (f) to (l), a tendency was observed to develop a tensile fracture on the inside due to the lava in the relatively uniformly sloping slip surface being pulled downward by gravity.

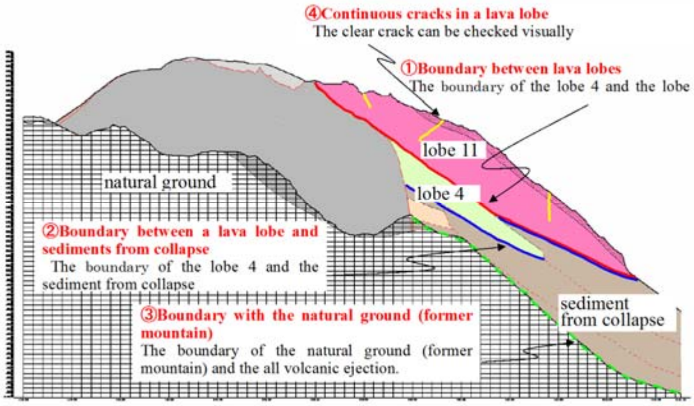

Fig.4 Locations of Assumed Collapse Sections

Table 2 5 Collapse Cases of Different Scales

Case	Collapse form	Basis for estimating collapse location	collapsing volume (10^6 m^3)
1	Collapse from the crack in the lower part of lobe 11	Visual confirmation of the crack	7.68
2	Collapse below the crack in the mid-slope of lobe 11	Result of stress analysis	10.24
3	Collapse above the boundary between lobe 11 and lobe 4	Boundary between lobe 11 and lobe 4	17.92
4	Collapse above the boundary between lobe 4 and talus	Boundary between lava lobes	32.00
5	Collapse in the boundary with the original ground before the eruption	Boundary between the original ground and the all volcanic ejection	53.76

4. ASSUMPTION OF LAVA DOME COLLAPSE CASES

4.1. Collapse Mechanism Viewed from the Formation Process

The authors estimated the form of lava dome collapse.

Generally, weathering, rock deformation due to creep, and other physical properties are cited as causes of lava dome collapse, but these phenomena take a long period. The lava dome in Mt. Unzen-Fugen-dake has not yet shown any remarkable deformation. Thus, it was assumed that the lava dome would collapse from the boundaries where "discontinuous surface" is observed. The authors think that "discontinuous surface" is observed in the following four boundaries:

1) **Boundary between lobe 11 and lobe 4(clinker)**
2) **Boundary between a lobe and talus**
3) **Boundary between the original ground (former mountain) and the all volcanic ejection by this eruption activities**
4) **Continuous cracks in a lava lobe**

The four boundaries is shown in **Fig.4**.

4.2. Assumption of Collapse Cases

Based on these four boundaries, the authors assumed five cases of lava dome collapse of different scales as shown in **Table 2** and **Fig.5**.

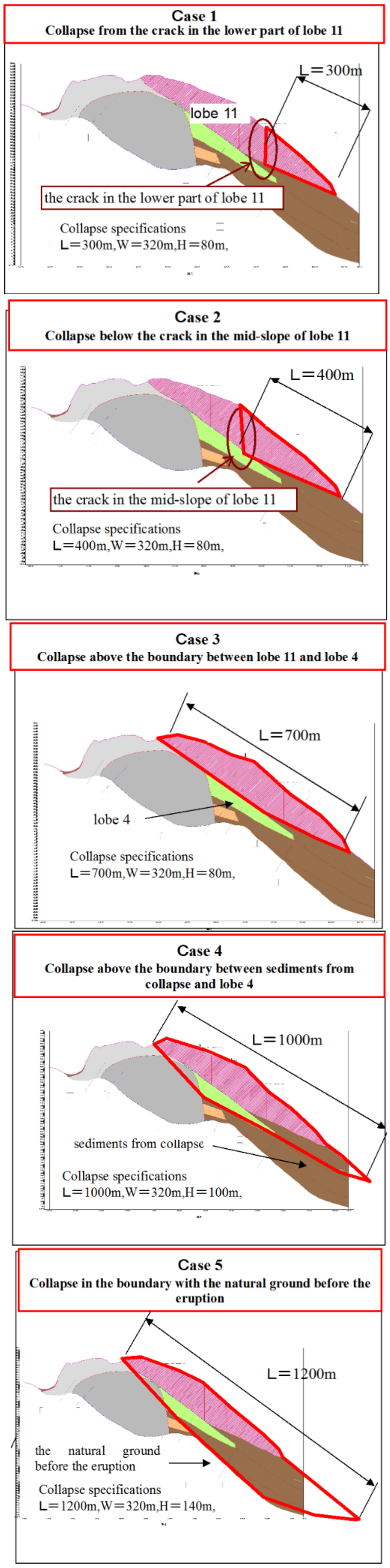

Fig.5 Locations of Collapse Sections of 5 Collapse Cases of Different Scales

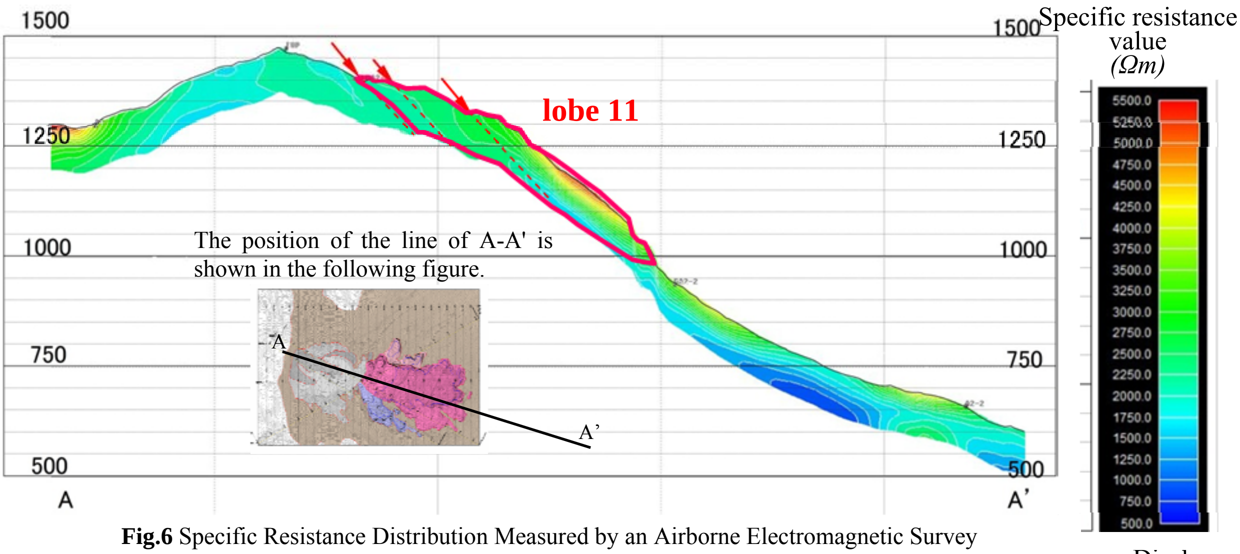

Fig.6 Specific Resistance Distribution Measured by an Airborne Electromagnetic Survey

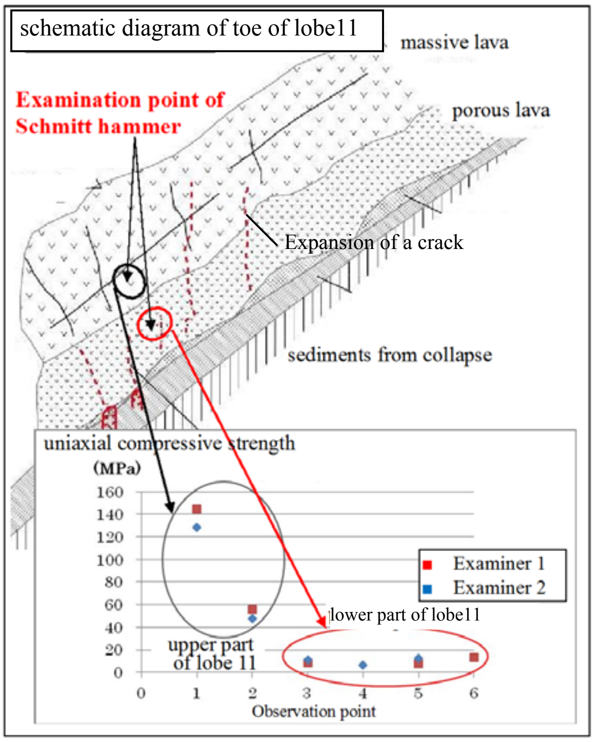

Fig.7 Strength Test Using a Schmitt Hammer

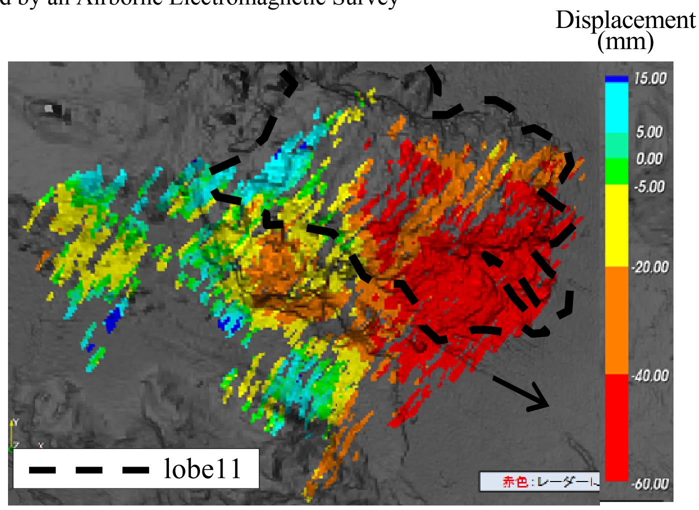

Fig.8 Displacements Observed by a Synthetic Aperture Radar (2011.11.18 - 2012.12.17)

The authors estimated the most likely of these five cases to occur based on the observation results shown below.

Fig. 6 shows the distribution of specific resistance values measured by an airborne electromagnetic survey using a helicopter. According to this figure, high specific resistance values are observed in the toe of lobe 11. As a high specific resistance value indicates that the lava in that area has become significantly loose, the toe of lobe 11 is thought to correspond to this.

Fig. 7 shows the results of a strength test using a Schmitt hammer conducted on the toe of lobe 11. The unconfined compressive strength shows that a lower part is weaker than the upper part.

Fig. 8 shows a displacement distribution obtained by a ground-based synthetic aperture radar. This figure shows displacements in the direction of the arrow. In the toe of lobe 11 or the lower part of the slope, relative downward displacements (approximately 40 mm to -60 mm over a 13-month period) have been observed.

According to these results, the authors confirmed that the compression strength of boundary of lobe 11 is relatively weak and the displacement of the lobe 11 is relatively large. Therefore, the authors determined that the possibility of occurrence of case 1 to 3 is higher.

By the way, the temperature of emission of gas around the lava dome suggests that the lava dome has become cool. It is assumed that the collapse of the lava dome is unlikely to cause pyroclastic flows, and collapsed blocks will be crushed to cause a debris avalanche.

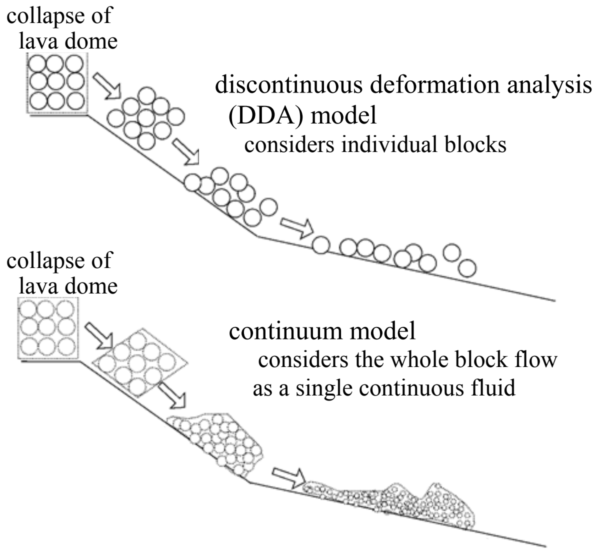

Fig.9 Concepts of the Discontinuous Deformation Model and the Continuum Model

Table 3 Comparison between DDA Model and the Continuum Model

	DDA model	Continuum model
Reproducibility of debris avalanches	The stress, strain, slip, contact force, and motion of blocks are calculated based on the geometric form, loading conditions, and material constant of individual blocks and the mechanical material constant of the contact site.	The model proposed by Takahashi can represent crushing of blocks into fine particulars after collapse and distinguish particular flow state from fluidized state according to the particular size. The law of resistance is also changed.
Evaluation	Reproducible	Reproducible
Versatility of parameters	Various parameters, such as friction angle, adhesion, viscosity coefficient, Poisson ratio, and energy damping ratio at the time of block contact, can be used for detailed setting.	Different parameters can be set depending on the state (particular flow state or fluidized state) flexibly according to actual phenomena.
Evaluation	Versatile	Versatile
Calculation time	It takes an immense amount of calculation time when the number of blocks is increased, and in practice, it can only be used with a rough model with a small block count (or a model with fewer than 200 blocks that are 100m in diameter).	It takes from several hours to several days for calculation.
Evaluation	Takes long calculation time	Takes short calculation time
Past record of use	It has not been used to estimate lava dome collapse or other large-scale phenomena (It is commonly used in research levels with a data count of 10 to 100).	It was used by Takahashi, et al. in June 3, 1991 to sort out values used to simulate the block stream from the pyroclastic flow in Mt. Unzen-Fugen by calculation.
Evaluation	No past record of use	Has past records of use
Overall evaluation	Not employed	Employed

5. ASSESMENT OF THE IMPACT OF DEBRIS AVALANCHES

5.1. Examination of Methods for Impact Assessment

A numerical simulation model was used as the method of assessing the impact of debris avalanches. There are two types of models to represent a debris avalanche: one is the discontinuous deformation analysis model (DDA), which considers individual blocks in calculation, and another is the continuum model, which considers the whole block flow as a single continuous fluid in calculation. Comparison of these two methods is shown in **Fig.9** and **Table3**. In estimations using the discontinuous deformation analysis model, a tendency was observed that downward flows stop in the mid-slope with a small particular count, and downward flows reach further with a larger particular count. This is probably because the collision of particulars promotes downward flows. It is believed that the phenomenon can be simulated reliably by further increasing the particular count close to the actual scale. However, as the current computer capacity takes time to make calculations for a massive amount of particulars, this model is not practical. This time, the continuum model was employed in view of calculation time, past records of use, and so on.

5.2. Selection of a Basic Equation

It is assumed that when the lava dome collapses, large-size blocks become fine particulars as particulars collide with each other or the ground while they flow down the slope. Currently, there is no model available that can accurately simulate such a phenomenon. Thus, it was decided to use Takahashi’s pyroclastic flow equation (Takahashi, 2006), which takes into account the fact that particulars become finer and the law of resistance is changed accordingly. Takahashi’s equation assumes two flow states: particular flow state in which particulars are relatively large in size and fluidized state . When particulars become finer and the average particular size reaches a certain value or smaller, the flow state changes. In particular flow state, resistance due to the skeletal structure in the fluid and resistance due to bottom friction occur, whereas in fluidized state, only resistance due to bottom friction occurs.

■ Law of resistance in particular flow state

$$\tau_{bx} = \alpha_s \rho_m g H_f \cos\theta_x \tan\phi + \rho_m f U_f \sqrt{U_f^{\,2} + V_f^{\,2}} \quad (1)$$

$$\tau_{by} = \underbrace{\alpha_s \rho_m g H_f \cos\theta_y \tan\phi}_{\text{Resistance in the fluid due to the skeletal structure}} + \underbrace{\rho_m f V_f \sqrt{U_f^{\,2} + V_f^{\,2}}}_{\text{Resistance due to friction between the fluid and the bottom}} \quad (2)$$

τ_{bx} and τ_{by} : Bottom shear force in x and y directions

α_s : Ratio of static pressure to total pressure. Specified in concentration

ρ_m : Pyroclastic flow density

g : Acceleration of gravity

H_f : Flow depth of the main body

θ_x, θ_y : Gradient of sedimentary layer surface in x and y directions

ϕ : Internal friction angle

f : Coefficient for bottom resistance

U_f, V_f : Flow rate in x and y directions

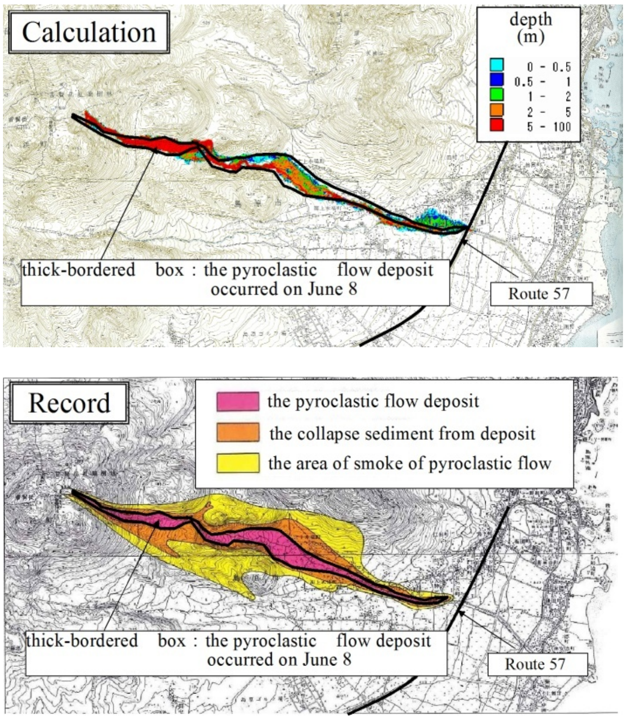

Fig.11 Comparison Between Reproduction by Calculation (Top) and Record (Bottom)

■ Law of resistance in fluidized state

$$\tau_{bx} = \rho_m f U_f \sqrt{U_f^{\,2} + V_f^{\,2}} \qquad (3)$$

$$\tau_{by} = \underbrace{\rho_m f V_f \sqrt{U_f^{\,2} + V_f^{\,2}}}_{\text{Resistance due to friction between the fluid and the bottom}} \qquad (4)$$

f : Coefficient for bottom resistance (different from that for particular flow)

5.3. Development of Parameters by Reproduction by Calculation

Since there is no past example of a comparable lava dome collapse, the data for the pyroclastic flow that occurred on June 8, 1991 was used for correction. As shown in **Fig. 11**, the parameters were adjusted by reproducing the phenomenon by calculation so that the reach of the flow generally coincides with the record.

5.4. Numerical Calculation

Calculations were made with these calculation conditions for the above five cases. The results are shown in **Fig. 12**.

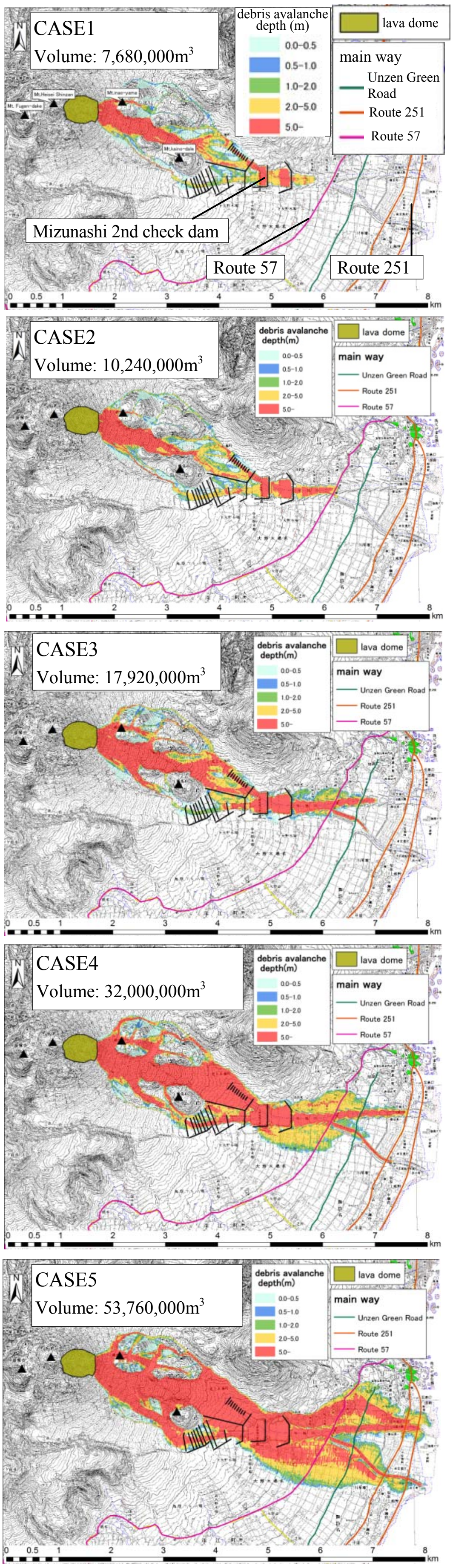

Fig.12 Calculation Results

6. ASSESSMENT OF THE IMPACT OF THE COLLAPSE OF THE LAVA DOME

In cases 1 and 2, flooding did not occur in the downstream settlement. In case 3, two meters deep or less flooding occurred in a narrow range upstream Route 57. In case 4, five meters deep or less flooding occurred in a wide range from Mizunashi 2nd check dam to the broad farm road. In case 5, 10 meters deep or less flooding occurred in a wide range from Mizunashi 2nd check dam to Route 251.

Thus, there is a possibility that the lava dome collapse will cause damage to the settlement in case 3 among the 3 cases likely to occur, and this suggests the need to take countermeasures. In cases 4 and 5, which are less likely to occur than case 3, there is a possibility that the collapse of the lava dome will cause damage to a wide range. Since these two cases require large-scale countermeasures to be taken in facilities, the range of impact obtained in this study should be used as a basis for developing a hazard map to help evacuate residents.

7. CONCLUSION

The authors obtained knowledge of the range of the impact of the collapse of the lava dome from this study.

It is assumed that when the lava dome collapses, large-size blocks become fine particulars as particulars collide with each other or the ground while they flow down the slope. Thus, it was decided to use Takahashi’s pyroclastic flow equation, which takes into account the fact that particulars become finer and the law of resistance is changed accordingly. As a result of simulation of Takahashi’s equation, in case 3, which is the likely to occur among five assumed cases, there is a possibility that the collapse of the lava dome will cause damage to the settlement and this suggests the need to take countermeasures. In cases 4 and 5, which are less likely to occur than case 3, there is a possibility that the collapse of the lava dome will cause damage to a wide range. The range of impact obtained in this study should be used as a basis for developing a hazard map to help evacuate residents.

The range of the impact of the collapse of the lava dome was estimated, but to use this data to assist safe evacuation, it must be decided when to evacuate. Although the lava dome has been observed on a continuous basis, specific observation values have not been established that indicate an increased risk of collapse and the time to evacuate. It is necessary to continue observation to accumulate data and establish criteria for determining when to evacuate. It would be effective to observe the lava dome by different methods instead of relying on a single observation method.

In the future, it is important to grasp changes of the lava dome by different observation methods, assess the potential of the collapse of the lava dome based on the observation results, and build a system that works to help safe evacuation.

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