Sediment Run-Out Processes and Possibility of Sediment Control Structures in the 2013 Izu-Ohshima Event

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Typhoon No. 26 in 2013 attacked the Izu-Oshima Island with record heavy rainfall and caused a disaster resulting from landslides and mud flows. This extreme event is the motivation of our study on how we evaluate hazardous zones at risk of mud flows and how we design structural and non-structural measures accordingly. The present study describes sediment runout processes, mud flow control by means of a guide wall, and a method to evaluate topological conditions in which landslides and mud flows avalanche into unexpected areas. The landslides took place in the western slope of Izu-Oshima, which is only about 2500m wide. Analyses on phase shifting from solid to liquid as well as on mobility of the soil masses suggest that the soil masses released by the landslides transformed directly into mud flows, and that the mud flows developed in size through sediment erosion in their run-out processes. The predicted results by means of a numerical model based on depth-integrated governing equations of sediment-water mixture flow suggest that mud flows could be controlled well using a guide wall, which shows a high possibility of mud flow control using a storage structure with a guide wall. In addition, we propose a simple method to evaluate topological conditions to judge whether mud flows will enter unexpected areas, which will provide a key to identify hazardous zones including even those that have been missed out conventionally.

Key words: sediment induced disaster, debris flow, mud flow, sediment control structure, hazardous area

1. INTRODUCTION

Izu-Oshima is a volcanic island, located 120 km south of Tokyo, with Mt. Miharayama volcano, which constitutes the Fuji-Mikurajima volcanic chain. Severe rainfall due to Typhoon No. 26 (Wipha) hit the island on 15 and 16 October 2013, and triggered many thin-surface layer landslides in the western slope of the island. The released sediment formed mud flows, which attacked parts of Motomachi town, claiming 39 victims and causing serious damage to private and public property. Damage was particularly heavy in Kandachi district of the town. This event suggests that still more study is needed on how to mitigate disaster damage from the viewpoints of natural and social sciences. As far as physical aspects found involved in this disaster are concerned, further study should be done on the following themes:
(a) Multi-events such as landslides, mud flows resulting from the landslides, and overflow with numerous drift woods.
(b) Critical rainfall conditions, a classic, unsolved and yet important theme, for an occurrence of sediment-related disaster.
(c) Mud flow behavior on the island’s slope with several small ridges, where the flow field is laterally flat because stream channels have not yet fully developed morphologically. Overflow takes place easily in such an undeveloped stream channel because its flow capacity is likely to be much less than mud flow discharge. Similarly, it is important to study how to extract hazardous zones in the flow field that is steep and laterally flat.
(d) Constitutive relations on mud flows composed of volcanic ash.
(e) Run-out processes and treatment of drift woods in the flow field.
(f) Extreme rainfall in its intensity, depth and area, and its influence on physical phenomenon.
In the Izu-Ohshima disaster, the districts located in the steep, laterally flat area were damaged heavily. Such areas usually draw less attention in identifying hazardous zones because debris flows are considered not to come into areas where streams or torrents are not formed clearly and thus, countermeasures against debris flows and mud flows have been conducted, focusing on sediment behavior in relation to streams and torrents.

The present study mainly addresses study themes (c) and (d) listed above, and describes sediment runout processes, focusing on the transformation from landslides to mud flows that has been observed in the Izu-Ohshima event. The study also presents a numerical model to explain the runout processes and its application to investigate a possibility of mud flow control by means of artificial structures. In addition, discussions are made on a simple method to evaluate whether a mud flow passes over topological ridges.

2. SEDIMENT RUNOUT PROCESSES

2.1 Outline

On 15 and 16 October 2013, Typhoon No. 26 advanced northeast over the Pacific Ocean on the eastern side of Japan, resulting in extreme rainfall in a long, narrow strip stretching from Izu-Ohshima to the Bousou peninsula. Figure 1 illustrates the rainfall data observed at two rain gauge stations, Oshima and Kitanoyama, which are only 3.7 km apart [Kanae, 2014]. Both accumulated rainfall depth and rainfall intensity measured at Oshima station are about twice as large as those at Kitanoyama despite that these data were measured at the closely adjacent stations. In addition, Ohshima’s data show that severe rainfall exceeding 100 mm/h continued for several hours, and the accumulated rainfall reached over 500 mm at around 2 am on the 16th. Local residents said that abnormal events had begun since then.

Seismic events were analyzed using seismometer records in relation to occurrences of landslides and mud flows [Inokuchi et al., 2014]. The analyzed data suggested five signals possibly related to sediment movement events, which are also illustrated in Fig. 1. It shows that sediment movements such as landslides and mud flows took place at least five times as far as the seismometer signals are concerned.

Photo 1 shows some features of the landslides and associated mud flows that occurred on the mountain side of Motomachi area, and suggests that the landslides took place with a thin surface layer sliding down the laterally flat slopes and masses of

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**Fig. 1** Characteristics of rainfall due to Typhoon No. 26 on 15 and 16 October 2013. The seismic signals are illustrated also along the temporal axis for convenience [Kanae, 2014]
the released sediment turned into mud flows. The mud flows seem to have increased its size by eroding the surface sediment layer of the slopes. Such mud flow behavior may have been recorded by the seismometer. In this photo, several ridges are illustrated for chapter 4 with white circles 1 to 4.

**Figure 2** shows a longitudinal bed profile of the Ohkanazawa torrent from the mouth to the mountain slope. The slope part steeper than 30 degrees is connected to the torrent reach. Most of the landslides took place in such steep slopes located at altitudes of 400 to 500 m and thus, a large amount of sediment released by the landslides was supplied to the torrent where the bed slope ranges from 15 to 20 degrees.

In general, soil masses delivered to such steep channels hardly stop their motion if they are saturated by water. Correspondingly, we assume that the mud flows in Izu-Ohshima were formed right in the middle of the run-out processes over the slopes, which will be discussed from a different...
point of view in following sections.

2.2 Transformation from landslides to mud flows

Flows with sediment transportation can be classified into four types, as illustrated in Fig. 3: normal flow with bedload (bottom left), debris flow (top left), flow with bed-loads and suspended loads (bottom right), and mud flow (top right). Flow with bed-loads, in which pore water pressure within the bed layer is not influenced by sediment motion, changes monotonically into debris flow with increase of bed slope [Egashira et al., 1997]. When the particle size of bed sediment decreases, turbulent suspension will take place. In this stage, pore water pressure is influenced by suspended sediment resulting from turbulent suspension. When the bed slope increases in flow with suspended sediment, mud flow will be formed, in which the bedload layer is overlaid with the turbulent suspension region as shown in the top right drawing of Fig. 3 [Egashira et al., 1994].

A field survey conducted in the damaged area found that sand and fine sand with a mean diameter of 0.5 mm were dominant in the transported material as well as in sediment composing the mountain slopes [Takebayashi et al., 2014; Wakai et al., 2014]. Figure 4 shows a typical grain size distribution that is reproduced by the authors of the present study, referring to the data of Wakai et al. [2014]. Assuming that the surface layer of a slope is saturated by water and that sediment particles finer than $d_f$ mix with pore water, the fluid phase of a total body can be estimated by:

$$c_{fp} = \lambda + p_f c_s \quad (\lambda + c_s = 1)$$  \hspace{1cm} (1)

where $\lambda$ is the porosity, $c_s$ is the sediment concentration of the surface layer, $p_f$ is the composition ratio finer than $d_f$, and $c_{fp}$ is the ratio of the fluid phase.

$$c_{fp} + c_{sp} = 1$$  \hspace{1cm} (2)

where $c_{sp}$ is the ratio of the solid phase that is the same as the solid phase concentration. The mass density of the fluid phase is given by:

$$\rho = (\lambda \rho_w + p_f c_s \sigma) / c_{fp}$$  \hspace{1cm} (3)

where $\rho_w$ is the mass density of water and $\sigma$ is the mass density of fine sediment particles.

Although the porosity in the surface layer of the slope has not been investigated, the solid phase concentration within the total body can be estimated using reasonable ranges of these parameters such as: $\lambda = 0.4$, $c_s = 0.6$ and $p_f = 0.2\sim0.4$. Thus, equations

![Fig. 3 Flow patterns with sediment transportation](image-url)
(1) and (2) yield the solid phase concentration of \( c_{sp} = 0.36\sim0.48 \). In addition, using the values of \( \sigma = 2.65 \, \text{g/cm}^3 \), \( \rho = 1 \, \text{g/cm}^3 \) and \( \phi = 37^\circ \) (= internal friction angle of sediment), the critical bed slope for a soil mass or flow body to stop its motion is estimated to be 13 to 8 degrees. These estimated values for \( c_{sp} \) and the critical bed slope suggest that a soil mass delivered to a torrent, such as Ohkanaawaza (Fig. 2), cannot cease its motion and changes into mud flow, and that the mud flow can increase its size in the erosion process even if there is no water supply to the soil mass or to the flow.

### 3. MUD FLOW CHARACTERISTICS AND THEIR CONTROL

#### 3.1 Mud flow characteristics

Figure 5 shows a mud flow model, created by referring to the results of section 2.2 and other studies on debris flows [Egashira et al., 1994; 1997]. The laminar flow region, in which flow is characterized by fluid viscosity, sediment size and concentration, and the internal friction angle of sediment (particle-particle contact), is formed in the bottom region and overlaid with the turbulent flow region. The external force acting on the fluid body should be equal to the resisting force at the bed surface, which yields a ratio of the laminar flow depth to the total depth:

\[
\frac{h}{h_t} = \frac{((\sigma/\rho_w - 1)c_1 + 1)\tan \theta}{(\sigma/\rho_w - 1)c_1\{\tan \phi + (1 - c_1/c_2)\tan \theta\}}
\]  

where \( c \) is the sediment concentration in the turbulent layer, \( c_1 \) is the sediment concentration in the laminar layer, \( h_t \) is the depth of the laminar layer, and \( h \) is the total flow depth. By means of analogy to the thickness of the bed-load layer, \( c_s \) could be estimated as:

\[
c_s \cong (c_1 + c)/2
\]  

Although we have no reliable method to predict the sediment concentration, \( c \), in the turbulent layer, \( c \) must be correlated to \( \rho c_\# \) as well as to the washloads.

#### 3.2 Governing equations of mud flow

The landslides and associated mud flows can be described well by means of depth integrated 2-D governing equations if the flow resistance and the erosion-deposition rate are given properly. The mass conservation equations for flow body and sediment within the flow body are described respectively:

\[
\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = E
\]  

(6)

\[
\frac{\partial c_h}{\partial t} + \frac{\partial c_{uh}}{\partial x} + \frac{\partial c_{vh}}{\partial y} = E
\]  

(7)

Momentum conservation equations are described as:

\[
\frac{\partial hu}{\partial t} + \frac{\partial huu}{\partial x} + \frac{\partial hv}{\partial y} = -gh\frac{\partial z_b}{\partial x} - \frac{1}{\rho_m} \frac{\partial P}{\partial x} - \frac{\tau_{bx}}{\rho_m}
\]  

(8)

\[
\frac{\partial hv}{\partial t} + \frac{\partial hvv}{\partial x} + \frac{\partial hv}{\partial y} = -gh\frac{\partial z_b}{\partial y} - \frac{1}{\rho_m} \frac{\partial P}{\partial y} - \frac{\tau_{by}}{\rho_m}
\]  

(9)

The mass conservation equation of bed sediment is:

\[
\frac{\partial z_b}{\partial t} = -\frac{E}{c_s \cos \theta}
\]  

(10)

where \( h \) is the flow depth, \( u \) is the \( x \)-component of flow velocity, \( v \) is the \( y \)-component of flow velocity, \( E \) is the erosion rate, \( c \) is the depth average sediment concentration defined by:
\[ \bar{c} = \left\{ (c_1 h_i + c(h_i - h_s))/h_i \right\} \]

Where \( h_s \) is the bed elevation, \( \tau_{bs} \) is the \( x \)-component of bed shear stress, \( \tau_{bs} \) is the \( y \)-component of bed shear stress, \( \theta \) is the bed slope, and \( P \) is the total pressure defined as:

\[ P = \int_{z_0}^{z_0 + h} \rho_m g \cos \theta dz \]

Where \( \rho_m \) is the mass density of mudflow body.

The erosion rate is formulated by Egashira [2011] as follows:

\[ E/\sqrt{u^2 + v^2} = c_e \tan(\theta - \theta_e) \]  \hspace{1cm} (11)

Where \( \theta_e \) is the equilibrium bed slope given by:

\[ \tan \theta_e = \frac{(\sigma / \rho - 1)c_s}{h_i} \frac{h_i}{h} \tan \phi \]

\[ \frac{(\sigma - 1)(c - (c - c)h_i/h) + 1}{h} \]  \hspace{1cm} (12)

Since \( \theta \) is the local bed slope, erosion takes place in the region with \( \theta > \theta_e \), and deposition occurs otherwise.

The bed shear stress could be evaluated by means of analogy with the friction law of debris flow:

\[ \tau_h = \tau_y + \rho_f f(u^2 + v^2) \]  \hspace{1cm} (13)

where \( \tau_y \) is the yield stress and \( f \) is the friction factor.

3.3 Numerical prediction of mud flows in damaged area with a countermeasure

A numerical model for mud-flow run-out processes is studied by Takebayashi et al. [2014] using the governing equations described in the previous section. We employ this model to investigate issues in controlling mud flow by the use of a guide wall. The topology of the damaged area is illustrated in Fig. 6. The computational grid size is specified as \( \Delta x = 15 \) m in the west-east direction and \( \Delta y = 12 \) m in the north-south direction. The potential erosion depth, which is defined as the thickness of a sediment layer to be eroded, is specified as \( D_{ep} = 0.5 \). Its thickness is responsible for the developing process of mud flow. Since several problems still remain unsolved concerning with constitutive relation and associated friction law, we assumed that the sediment concentration was constant as \( c_s = c = 0.4 \) and the relative depth as \( h_i/h = 0.4 \), and evaluated the bed shear stress using \( \tau_y = \rho_f f(u^2 + v^2) \) \((f = k^2/4 = 0.035)\), which is similar to the approach taken by Julian and Paris [2010] to conduct numerical computations.

The surface soil layer that corresponds to the potential erosion depth is assumed to be saturated with water. Experimentally, a landslide with the size...
of 45 m long in the east-west direction, 36 m long in the south-north direction, and 0.5 m thick is provided at three places to initiate mud flows.

Figures 7 and 8 show the final stages of the erosion and deposition processes with and without the guide wall, respectively. These suggest that mud flows will not enter the damaged area and a large amount of sediment will deposit on the upstream side of the guide wall if the mud flows are controlled as expected.

Figure 9 shows the temporal changes of mud flow discharge at the several cross-sections illustrated in Fig. 6. These results show that the simulated mud flows developed by sediment erosion from Sec. 40 to Sec. 60, and decreases towards Sec. 80 due to sediment deposition.

These results suggest that mud flows could be controlled well by means of a sediment storing structure with a guide wall.
4. TOPOLOGICAL CONDITIONS FOR MUD FLOW TO PASS OVER RIDGES

There are topological ridges in the damaged area, as marked by the white circles in Photo 1. A flow field can be very complex due to the existence of ridges, which can be misleading in identifying hazardous zones; we often assume that mud flows will not pass over ridges and thus areas downstream of the ridges are safe from the hazard. In the Izu-Oshima case, however, the soil masses or the mud flows passed over the ridges, as illustrated in Photo 1. It is very important to evaluate whether mud flows will climb over topological ridges for implementing countermeasures against sediment induced disasters.

4.1 Linear equation for mud flow

Figure 10 is a schematic diagram of a 1-D mud flow. Assuming that non-linear terms can be neglected and referring to the mud flow model by Egashira et al. [1994], the momentum conservation equation is simplified as follows:

\[
\frac{d}{dt} (\rho_m h \Delta x v) = \rho_m h \Delta x g \sin \theta - (\sigma - \rho) c g h \Delta x \cos \theta \tan \phi - \rho_m f v^2 \Delta x
\]  
(14)

Where \( \rho_m \) is the mass density of water and sediment mixture:

\[
\rho_m = \sigma \rho + \rho (1 - \sigma)
\]

In addition, neglecting the deformation due to sediment erosion and deposition, equation (14) can reduce to:

\[
\frac{dv}{dt} = g \sin \theta - \frac{(\sigma / \rho - 1) c g \cos \theta h t}{(\sigma / \rho - 1) c + 1} \tan \phi
\]

\[- \frac{f}{h} v^2 \]

(15)

This is an equation of motion for the mass-point system, which is very similar to the equation for soil masses released by slope failures [Egashira and Ashida, 1985]. Using the spatial coordinate \( x \) instead of time \( t \) by means of transformation, \( dx = v(t) dt \) and introducing non-dimensional variables such as \( v' = v / \sqrt{gh} \) and \( x' = x / h \) equation (15) yields:

\[
v' \frac{dv'}{dx} = b - f v'^2
\]  
(16)

where \( b \) is the difference between the driving force and Coulomb’s shear force defined by:

\[
b = \cos \theta \left[ \tan \theta - \frac{(\sigma / \rho - 1) c h t}{(\sigma / \rho - 1) c + 1} \tan \phi \right]
\]  
(17)

Equation (16) has an analytical solution for the flow over a constant bed slope:

\[
v' = \left[ v_0' e^{-2 \beta \phi} + \frac{b}{f} (1 - e^{-2 \beta \phi}) \right]^{1/2}
\]  
(18)
discussion. The flow should stop somewhere on the slope where \( b \) has a negative value, \( b < 0 \) Assuming the upper slope of \( \theta_u \) is long enough for a flow to gain a steady velocity, and assuming the kinetic energy of the flow is conserved at the inflection point between the two slopes, the run-out distance is obtained from (18) with \( v = 0 \).

\[
x_s' = -\frac{1}{2f} ln\frac{b_d}{b_u - b_d}
\]  

(20)

where \( x_s' \) is the run-out distance from the inflection point, defined as \( x_s' = x_f / h \), and \( b_u \) and \( b_d \) are defined as equation (17) for the upper and down slopes, respectively.

Figure 12 is a schematic diagram to discuss whether a flow climbs over a ridge. If the run-out distance is longer than the length, i.e., \( x_c \), from the bottom to the peak of a ridge, the flow will go over the peak while it will stop at a ridge if \( x_c \) is longer than the run-out distance. This can help make a preliminary judgment whether a flow climbs over a ridge by comparing \( x_c' \) and \( x_s' \).

Figure 13 shows the critical lines given by (20) with \( x_c' = x_s' \). These curves are computed using \( \phi = 35^\circ \), \( f = 0.04 \), \( c = 0.4 \) and \( h_f / h = 0.4 \). The left side area of each curve indicates a flow could climb over a ridge, which means the length of the slope illustrated in Figure 12 is shorter than the run-out distance \( x_s \). The run-out distance is a function of the flow depth, friction factor and parameters included in \( b \), and is predicted easily with (20).

Ridges No. 3 and No. 4 marked on Photo 1 are at most 0.5 meters high. Assuming that slope gradients \( \theta_u \) and \( \theta_d \) are 8 and -4 degrees, respectively, (20) or Figure 13 yields:

\[
x_s' = 2.25.
\]

This value for the non-dimensional run-out distance means that a mud flow thicker than 3.2 m could pass over these two ridges because the length of slope \( x_c \) is 7.2 m (\( = 0.5 / \sin 4^\circ \)).

5. CONCLUDING REMARKS

We have learned several important issues from the Izu-Ohsima sediment related disaster in 2013. Sediment runout processes, sediment control and mud flow behavior within a complex field were chosen for discussions. The results are summarized as follows:

(1) Analysis of the sediment runout processes suggests that the soil masses released by the landslides transformed directly into the mud flows, which developed in size from eroding the surface soil layer. The idea of phase-shifting from solid to
fluid is introduced to explain the high mobility and developing process of the mud flows.

(2) The simulated results of mud flows suggest that mud flows could be controlled with artificial structures such as sediment detention dams and guide walls.

(3) We proposed a simple formula, deriving from a linear equation for momentum conservation, to evaluate whether mud flows will pass over topological ridges. The proposed method may be a powerful tool to extract hazardous zones in areas having similar geomorphic characteristics of the mountain area in Motomachi of Izu-Ohsima. However, we need to test its validity using field data and 2-D numerical simulations.

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REFERENCES

Egashira, S. (2011): Prospects of debris flow studies from constitutive relations to governing equations, Journal of Disaster Research, Vol. 6, No. 3, pp. 313-320.

Egashira, S. and Ashida, K. (1985): The dynamic behavior of a soil block on slope, International Symposium on Erosion, Debris Flow and Disaster Prevention, Tsukuba, Japan, pp. 249-254.

Egashira, S., Satoh, T. and Chishiro, K. (1994): Effect of particle size on the flow structure of sand-water mixture, Annuals, Disaster Prevention Research Institute, Kyoto Univ., No. 37B-2, pp. 359-369 (in Japanese with English abstract).

Egashira, S., Miyamoto, K. and Itoh, T. (1997): Constitutive equations of debris flow and their applicability, Proc. 1st International Conference on Debris Flow Hazards Mitigation, ASCE, pp. 340-349.

Inokuchi, T., Ueno, M., Kanae, S., Inagaki, H., Nihei, Y., Shimizu, Y. and Sato, T. (2014): Izu-Ohsima disaster resulted from severe rainfall associated with Typhoon-26, October in 2013, Joint Research Report by JSCE, JGS, JSE and JLS, March, 2014, Sec. 5.1 (in Japanese).

Julien, P.Y. and Paris, A. (2010): Mean velocity of mud flows and debris flows, Jour. Hydraulic Eng., Vol. 136, No. 9, pp. 676-679.

Kanae, S. (2014): Izu-Ohsima disaster resulted from severe rainfall associated with Typhoon-No. 26, October in 2013, Joint Research Report by JSCE, JGS, JSE and JLS, March, 2014, Sec. 5.1 (in Japanese).

Takebayashi, H., Egashira, S. and Fujita, M. (2014): Horizontal two dimensional analysis of mud flow occurred in Izuoshima island on October 2013, Advances in River Engineering, JSCE, Vol. 20, pp. 391-396 (in Japanese with English abstract).

Wakai, A., Uchimura, T., Araki, K, Inagaki, H. and Gotô, S. (2014): Izu-Ohsima disaster resulted from severe rainfall associated with Typhoon-No. 26, October in 2013, Joint Research Report by JSCE, JGS, JSE and JLS, March, 2014, Sec. 5.3 (in Japanese).

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