Sediment discharge by storm runoff from a creek on
Merapi volcano

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Abstract
Observation of storm runoff, suspended sediment and debris flow, and topographical surveys of the channel at the Bebeng River on the southwestern slope of Merapi volcano for 3 years since 1991, have clarified the characteristics of the low runoff coefficient for storm runoff, the large flux of suspended load, and the conditions of debris-flow occurrence, motion and deposition. Estimated annual sediment discharge through the observation site consists of 167,000 m³ of debris flows and 47,000 m³ of total load. Comparison of sediment transportation at three volcanic torrents on Mount Yakedake, Mount Unzen in Japan and Mount Merapi indicates a trend where the frequency and scale of debris flows, and the amount of sediment yield at a specific volcanic torrent generally decreases exponentially with the time after the last effective eruption. For example, annual depth of sediment yield or sediment discharge might be expected to decrease from the initial rate of $10^1$ to $10^2$ mm/year following the eruption to $10^1$ mm/year in less than several years, and finally approach $10^0$ mm/year in less than a few decades.

Key words: Sediment discharge, Erosion rate, Volcanic torrent, Debris flow, Suspended sediment

Introduction
Volcanic eruption dramatically increase the intensity of sediment discharge and the frequency of debris flow. Post-eruption erosion of volcanic slopes has been studied at many volcanoes, including Mount Usu (Chinen, 1986), Mount Sakurajima (Shimokawa et al., 1987), and Mount St. Helens (Collins et al., 1986). A common qualitative or quantitative finding is that erosion rate or sediment discharge drastically decreases with time after eruption. But most of the results have been derived from measurement at stakes at partial slope on tephra or along transverse cross sections of stream channel, so that it is difficult to estimate total sediment discharge from drainage basin with those data, additionally time length of the observation of those studies are only 4 years at the longest.

In order to clarify the present processes of sediment discharge and the total sediment flux at Bebeng River on Mount Merapi, we observed debris flows and floods, and repeated topographic surveys in the stream channel. Then we compared our data with the results from Mount Unzen (Suwa et al., 1994b) and Mount Yakedake (Suwa et al., 1989) to evaluate the temporal change in sediment discharge from volcanic torrents for longer time interval over several decades. The study slopes and observation sites of flows at 3 volcanoes are shown in Fig. 1.

Mount Merapi is an active volcano which generates pyroclastic flow hazards every few years, and thereby facilitates the subsequent phenomena of debris flows. These pyroclastic flows result from the collapse of lava domes. Recently major pyroclastic flows occurred on the southwestern slope of Merapi volcano in 1969 and 1984 (Furuya, 1989). Other pyroclastic flows were observed on the same slope from February 2, 1992 to 1993 (Hiratsuka, 1992). The disastrous pyroclastic flow on the 22nd of
November 1994 killed 29 and injured 95 peoples along a river on the southern slope of Mount Merapi. Subsequent debris flows were reported and are being studied (Lavigne et al., 1995).

Observation of debris flows at the Bebeng River

The frequency of debris flows and flooding on the Putih River was very high just after the 1984 pyroclastic flow, but it has decreased rapidly in rather short time (Shimokawa et al., 1995). Considering the present situation of frequent debris flows in the Bebeng River, we executed an intensive observation of debris flows and suspended sediment, along with topographic surveys of the creek and intermittent observation of sidewall erosion since December 7, 1991.

Two video observation systems were installed at two observation sites as shown in Fig. 2. The system consists of two video cameras: one is an interval shot camera for taking one second motion picture intermittently every 5 minutes, and the other is a trigger shot camera to take a motion picture of a debris flow. This second camera starts operating when the ground vibration detector measures the ground vibration acceleration exceeding 10 gal (=cm/sec²), as induced by a debris flow.
Results of debris-flow observation

More than 10 debris flows occurred since December 7, 1991. Unfortunately, the trigger cameras missed many debris flows and floods due to darkness of night and various problems with the video systems.

In the afternoon of the 8th of January 1992, debris flows were triggered by a rainstorm as shown in Fig. 4. Repetition of many surges of debris flows and the lateral migration of the flow channel, which was accompanied by the alternating processes of scouring and deposition of debris, were clearly found in the video record. Recently the channel reach in the view field above the dam BE-D8 has been the deposition slope for small to middle scale debris flows. The mean longitudinal slope angle there is about 2.9 degrees. Due to this condition, the flow moved in the lateral direction as shown in Fig. 3. Almost all the flows were hyperconcentrated flows or flows whose lower layer is the collective flow of debris and whose upper layer is the tractive flow of debris; this is different from a typical debris flow in which the concentration of debris is nearly constant throughout the flow depth under the condition of fully developed mixture. The scale of this debris-flow discharge was not so big, but the amount of debris transported was very large, containing many boulders.
A heavy rainstorm induced a middle-scale debris flow on the evening of the 10th of December 1993. Though the trigger cameras missed recording this flow, two dominant surges are confirmed to have occurred from the record of the interval shot camera. The first surge was estimated from the video record to have passed between 16:15 and 16:20. The second might have occurred between 17:20 and 18:20 from the strong rainfall intensity and removal of a huge amount of debris from the visual field of the camera.

**Hydrologic condition for debris-flow occurrence**

Fig. 4 shows a relationship between debris-flow occurrence and temporal change in rainfall intensity every 10 minutes. In many cases, the time of debris-flow occurrence coincides well with the time of strongest rainfall intensity, permitting a short time delay due to the transit of debris flow from the position of debris-flow occurrence and debris-flow measurement. In these cases, the rapid increase of runoff due to heavy rainfall erodes the gully bed deposits and grows into a debris flow. Most of debris flows on volcanic slopes start like this (Suwa, 1988, 1989, 1992, 1993; Suwa et al., 1989).

In a few other cases, as found on the 28th of November 1985 and on the 24th of November 1991, debris-flow occurrence is delayed remarkably from the time of peak rainfall intensity. Two explanations are possible for this fact. One is that the delay can be ascribed to the spatial difference between the observation point of rainfall and the position of debris-flow occurrence. This condition is possible by the movement of the rainfall zone and/or locality of rainfall intensity. Another is the formation of a natural dam from a landsliding of gully sidewall and its subsequent break up. For instance, a toppling type landslide from a sidewall occurred just after the 8 January 1992 debris flow and completely blocked the torrent with deposits more than 2000 m³; later this natural dam was completely removed by a following large flood (Suwa et al., 1994).

Permeability of volcanic slopes is generally so large that, without heavy rainfall, water flow is usually absent at the stream channel above the distal fan. Only heavy rainstorms might be able to generate an effective runoff which increases flow rate to entrain debris particles one after another and grows into a debris flow. With the intention of studying the background condition for the generation of surface runoff, in-situ tests of permeability were carried out on the mountain slopes and on the lateral banks along the Bebeng River, the Kamikamihori gully, and on Mount Unzen. Permeability of the deposits layer on the slopes along the Bebeng River and the Kamikamihori gully took rather larger values of $10^{-2}$ to $10^{-3}$ cm/sec than the values of $10^{-5}$-$10^{-7}$ cm/sec on Mount Unzen.

Fig. 5 shows the condition of rainfall intensity which triggered debris flows at Mount Merapi, Mount Unzen and Mount Yakedake, where andesitic and dacitic lava are common. The intensity is rather larger at Mount Merapi than that at the other two mountains. Debris flows seem to occur easily at Mount Unzen, where eruptive activity was still high even at the end of 1994 and it finished in March 1995. The last eruption at Mount Yakedake was in 1962. Rainfall condition for debris flow initiation seems to depend on many factors such as the size of the mountain, time lapse from the last eruptive activity, the relative elevation of the observation point and so on. Among them, the time lapse from the last eruption may have the strongest effect in restoring the infiltration capacity of the slope to reduce the runoff coefficient, affecting the change in sediment discharge from the basin. Further discussion will be held in the final section of this paper.
Observation and estimation of suspended sediment

At 800 m elevation of Bebeng River, water is always turbid in the rainy season, even on a fine day. At the high water stage during and just after a squall, transportation of debris by traction and suspension is very active. Even in such cases where the flow is not a type of debris flow but only a flood, the volume of suspended sediments transported is always significant.

Turbid water samples were taken at both low and high water stages to get a relationship between concentration of suspended sediment and runoff discharge. Table 1 shows some examples of the observed hydraulic condition of the flow and concentration of suspended sediments.

The stream usually increases in discharge (i.e. a gaining stream) and suspended sediment concentration at the low water stage in the section of the Bebeng River below the position \( y=1950\text{m} \) (altitude is 920m). An example of the low water stage in Fig. 6 shows an

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Date</th>
<th>Time</th>
<th>Position ( y )-coord. (m)</th>
<th>Concentration of suspended sediment (g/litre)</th>
<th>Flow rate (m³/sec)</th>
<th>Mean velocity (m/sec)</th>
<th>Mean depth (m)</th>
<th>Width (m)</th>
<th>Slope angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 Dec</td>
<td>14:34</td>
<td>120</td>
<td>32.9</td>
<td>0.067</td>
<td>0.48</td>
<td>0.11</td>
<td>1.2</td>
<td>3.24</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>40.7</td>
<td>0.20</td>
<td>0.74</td>
<td>0.14</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>14:44</td>
<td></td>
<td>37.9</td>
<td>0.28</td>
<td>0.92</td>
<td>0.11</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>14:49</td>
<td></td>
<td>43.5</td>
<td>0.40</td>
<td>0.89</td>
<td>0.14</td>
<td>3.1</td>
<td>2.93</td>
</tr>
<tr>
<td>5</td>
<td>4 Dec</td>
<td>14:46</td>
<td>120</td>
<td>18.5</td>
<td>0.56</td>
<td>1.43</td>
<td>0.11</td>
<td>3.5</td>
<td>2.68</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>14:51</td>
<td></td>
<td>21.7</td>
<td>0.10</td>
<td>1.2</td>
<td>0.06</td>
<td>4.1</td>
<td>5.6</td>
</tr>
<tr>
<td>7</td>
<td>5 Dec</td>
<td>11:42</td>
<td></td>
<td>13.4</td>
<td>0.08</td>
<td>1.0</td>
<td>0.08</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td>23.9</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6 Relationship between the concentration of suspended sediment and water discharge along the river on 7 December, 1992.
empirical indication that both concentration of suspended sediment and discharge would increase in downstream direction. In general, the concentration of suspended sediments has a close relationship with discharge of stream.

Based on the whole data set (Suwa et al., 1995), the concentration of suspended sediment $C$ ($m^3/m^3$) at the observation site at the dam BE-D8 can be estimated, allowing for an error margin up to 50%, with the empirical regression curve

$$C = 10^{-4} \times 10^{(\log Q + 1.83)/0.52}$$

(1)

where $Q$(m$^3$/sec) is discharge of the stream above the dam BE-D8, and correlation coefficient $r = 0.64$. Eq. (1) is applicable when $Q$ is within the range of 0.15 to 50m$^3$/sec. Generally the functional relationship is not strictly unique between the concentration of suspended sediment $C$ and flow rate $Q$.

A kind of hysteresis is known to exist in the relationship, then two different empirical equations may be expected on the increasing and the decreasing stage of hydrograph. Although, the accuracy of estimation for the suspended sediments concentration of each flood might not be very good due to the hysteresis and also due to unpredictable factors such as sudden sediment supply to the flow from sidewall landsliding, higher reliability may be expected when the integrated quantity from each storm-runoff event is discussed.

**Estimation of sediment discharge by storm runoff**

Hydrographs of storm runoff were deciphered from the visual data from the 5 minute interval operation camera. Discharge $Q$ (m$^3$/sec) at the dam BE-D8 can be calculated as

$$Q = BhV$$

(2)

where $B$ (m) is the width, $h$ (m) is the mean depth and $V$ (m/sec) is the mean velocity of the water flow. Mean velocity $V$ can be written as

$$V = k_1L$$

(3)

where $L$ is the horizontal travel distance of the water flow in the air from the spillway of the dam. Provided the mean velocity can be estimated from Chezy’s formula of river flow, mean velocity can be given as

$$V = k_2h^{1/2}$$

(4)

and then the mean depth can be estimated with the formula from Eqs. (3) and (4)

$$h = k_3L^2$$

(5)

where $k_1$, $k_2$ and $k_3$ are the constants. Deciphering the mean width $B$ and the travel distance $L$ from the video record, flow rate $Q$ was calculated to give the hydrograph as shown in Fig. 7.

The catchment area of the Bebeng River for the observation point is estimated to be 5.0km$^2$ on the map with a scale of 1 to
Table 2 shows the direct runoff coefficient and the transportation of suspended sediment for 12 examples of storm runoff. The peak runoff coefficient in the table was calculated as the ratio of the instantaneous peak depth of runoff to the hourly depth of rainfall just before the appearance of peak runoff. The values of direct runoff coefficient from 5 to 30% are not very large when compared with those at the Yakedake volcano. The total amount of suspended sediment for each flood was calculated by time integration of the flux of suspended sediment through the whole cross section of the flow. Concentration C can be estimated using the empirical Eq. (1) from the discharge Q at the dam.

The annual flux of suspended sediment might be evaluated by the above mentioned method. But it is not possible to get all the desired storm runoff data because of the lack of night time data. Instead of actual observation of storm runoff, the depth of direct runoff can be estimated by the following method.

Based on the observation data such as in Table 2, the direct runoff coefficient $f_d$ for each rainstorm can be estimated (allowing for an error up to 100%) with an empirical regression curve,

$$f_d = 10 \left( \frac{R_{\text{max}} - 140}{200} \right)$$

where $R_{\text{max}}$ (mm/h) is the peak intensity of hourly rainfall, and $r = 0.59$.

Then the depth of direct runoff $R_d$ is the product of the total depth of rainfall and direct runoff coefficient $f_d$. Also based on the observation data such as in Table 2, the total volume of suspended sediment $V_s$ (m$^3$) for each flood can be estimated with an empirical regression curve,

$$V_s = 10 \left( \frac{(R_d + 7.24)}{2.18} \right)^{1.09}$$

where $R_d$ is the depth of direct runoff and $r = 0.78$. Attention should be paid to the fact that any level of correlation for the regression curves (1), (6) and (7) is not very high. The following estimation is based on these correlation levels. Calculation using 165 flood data points from all of the heavy rainfalls from

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Beginning of rainfall</th>
<th>End of rainfall</th>
<th>Total depth of rainfall</th>
<th>Peak of 10 minutes rainfall</th>
<th>Depth of direct runoff</th>
<th>Depth of direct runoff coefficient</th>
<th>Peak discharge</th>
<th>Mean concentration of suspended sediment</th>
<th>Total volume of suspended sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982</td>
<td>Dec 1</td>
<td>14.10</td>
<td>18.30</td>
<td>18.30</td>
<td>18.30</td>
<td>18.30</td>
<td>18.30</td>
<td>18.30</td>
<td>18.30</td>
<td>18.30</td>
</tr>
<tr>
<td>1983</td>
<td>Jan 10</td>
<td>14.30</td>
<td>18.50</td>
<td>18.50</td>
<td>18.50</td>
<td>18.50</td>
<td>18.50</td>
<td>18.50</td>
<td>18.50</td>
<td>18.50</td>
</tr>
</tbody>
</table>
December 1991 to November 1993 (with a rainfall intensity not less than 5mm/10 minutes or an hourly intensity not less than 10mm/hour) gives the amount of sediment transport as summed in Table 3. The annual volume of suspended sediments transported by these floods amounted to more than 36,000m³/year. The flux of bed load is known to be in the range from 10 to 50% of the suspended load (Statham, 1977 etc.). Assuming the flux of bed load is 30% of suspended load, the flux of total load amounts to more than 47,000m³/year.

Evaluation of mass wasting

In order to clarify the processes of mass wasting and to evaluate the annual volume of mass movement, transverse cross sections and a longitudinal cross section, as shown in Fig. 2, were measured twice a year in a perpendicular coordinate system. Changes in the cross sections showed some variety over time. Figs. 8 and 9 show the remarkable uplift of gully bottom in the whole study reach above the dam BE-D8, due to the repetition of debris flows and floods. Construction of a new dam BE-D8 seems to have greatly affected this deposition process.

Significant undercutting of the sidewall occurred at many sites during a big flood or a debris flow, especially on the outer side of the winding channel. After such undercutting, a landslide or a debris fall might be promoted by decrease in slope stability. As for sidewall erosion, one of the most active slopes, from which a huge amount of debris has collapsed, is the right sidewall on the cross section.
Sediment discharge by storm runoff

Although the slopes and gully bottom of the Bebeng River above an altitude of 1400 meters are presently rather stable, without any devastation, and vegetated by moss, weeds, and small trees, sediment discharge due to debris flows and floods at the observation site amounts to a huge volume. Repeated topographic surveys could not find any process of downcutting in the gully. Therefore, undercutting on the sidewalls and debris supply from the consequent slides of sidewalls in the reach between the altitudes 800 meters and 1400 meters are the main source for the sediment discharge. The supply of huge amounts of debris from many landslides at the sidewalls between the altitudes 950m and 1400m was confirmed with many photographs (Tsuchiya, 1994). It was found that the pyroclastic flows of November 1994 which ran down the Boyong River also singed some portion of the headwaters of Bebeng River. This devastated condition will have some significant effect on the sediment discharge from that time on.

Deposition on the channel bottom have occurred all over the survey reach above the Dam BE-D7 for the two years since December 28, 1991. An annual deposition rate of 167,000m$^3$/year was evaluated from the change in the longitudinal and the transverse cross sections shown in Table 4 as the least yearly volume, most of which was brought by debris flows. This rate is somewhat underestimated, because some amount of sediments are being removed every day by active sand mining.

The annual rate of total sediment discharge is 214,000m$^3$/year, evaluated at the Bebeng river observation site which consists of a 167,000m$^3$/year debris-flow discharge and a 47,000m$^3$/year total-load discharge. Here the bulk volume was evaluated assuming the porosity of deposits to be 0.3.

### Discussions and conclusions

Observation of storm runoff, sediment transport, and topographic surveys at the Bebeng River on Merapi Volcano from 1991 to 1994, and the comparison with the sediment discharge at Mount Yakedake and Mount Unzen yielded the following results. At Bebeng river,

1. More than 10 debris flows occurred from December 1991 to July 1994. The annual volume of deposits by debris flows in the 3 km long reach above the dam BE-D7 amounted to 167,000m$^3$.

2. Debris movement on the headwater slopes above the altitude 1400m has recently been inactive. Source materials for debris flows were being supplied with landsliding of the sidewalls in the reach at an altitude between 950m and 1400m.

3. Landsliding would often occur due to the undercutting of the sidewall on the outer side of winding channel by the repetition of floods and debris flows. These slides sometimes form a natural dam in the narrow channel section to block the stream. All of these deposits would easily be washed away by a following flood or debris flow.

4. In many cases, the time of debris flow coincided with the time of strong rainfall intensity. In a few cases, the debris flow was delayed 20 or so minutes from the time of peak rainfall intensity. Two explanations might be possible for the latter case: the spatial distance between the observation point of

<table>
<thead>
<tr>
<th>Cross section</th>
<th>$T_5$</th>
<th>$T_4$</th>
<th>$T_3$</th>
<th>$T_2$</th>
<th>Dam BE-D8</th>
<th>$T_1$</th>
<th>Dam BE-D7</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-coordinate (m)</td>
<td>2071</td>
<td>1831</td>
<td>845</td>
<td>304</td>
<td>110</td>
<td>78</td>
<td>-275</td>
<td></td>
</tr>
<tr>
<td>Bottom width of channel (m)</td>
<td>30</td>
<td>73</td>
<td>71</td>
<td>122</td>
<td>80</td>
<td>60</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Mean depth of deposition (m)</td>
<td>2.1</td>
<td>0.9</td>
<td>1.9</td>
<td>2.1</td>
<td>0</td>
<td>1.9</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Volume of deposits (m$^3$)</td>
<td>21,300</td>
<td>98,100</td>
<td>146,600</td>
<td>24,100</td>
<td>5,300</td>
<td>38,400</td>
<td>333,800</td>
<td></td>
</tr>
</tbody>
</table>
rainfall and the position of debris-flow occurrence, or the formation of a natural dam from a landslide and its subsequent collapse. In the former case, a rapid appearance of storm runoff erodes the bottom deposits to grow into a debris flow.

(5) Rough estimation of the flux of suspended sediment from discharge of the stream is possible with an empirical regression curve for the Bebeng River observation site.

(6) After the coefficient of direct runoff for heavy rainfall was roughly estimated from the peak of hourly rainfall with an empirical regression curve, the volume of suspended sediment transported by each flood was also empirically estimated from the depth of direct runoff. Assuming the volume of bed load is 30% of suspended load, the total load amounts to at least 47,000m³/year.

(7) The total rate of sediment discharge of 214,000m³/year is evaluated at the observation site. This rate consists of 167,000m³/year by debris flows and 47,000m³/year by total load.

Conditions of sediment transportation at the three volcanic torrents can be compared with each other as in Table 5.

(8) There are remarkable differences in the total bulk volume of sediment transportation \( V \) and the frequency of debris flow \( F \). Many factors are considered to affect \( V \) and \( F \). Among them, the time after the last effective eruption \( T \) is the most significant, which would decrease the runoff coefficient to reduce the discharge of storm runoff. Then the macroscopic capacity of sediment transportation by surface runoff would decrease. From the comparison of the specific amount of sediment transport \( S_v \), a general relationship is expected where \( S_v \) would decrease exponentially with the time \( T \) after the last eruption of the volcano which was effective on that torrent. Considering the results of this study and the erosion rates in other study sites (Chinen, 1986; Shimokawa et al., 1987; Collins et al., 1986), the annual depth of sediment yield or sediment discharge might be roughly expected to decrease from the initial rate of \( 10^1-10^2 \) mm/year following the eruption, to \( 10^1 \) mm/year in less than several years, and finally approach \( 10^0 \) mm/year in less than a few decades.

### Table 5 Comparison of sediment discharge and hydro-geomorphological condition at three volcanic torrents

<table>
<thead>
<tr>
<th></th>
<th>Mt. Yakedake</th>
<th>Mt. Merapi</th>
<th>Mt. Unzen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kamikamihori gully</td>
<td>Bebeng river</td>
<td>Mizunami river</td>
</tr>
<tr>
<td>Altitude of mountain top (m, a.s.l.)</td>
<td>2445</td>
<td>2911</td>
<td>1473</td>
</tr>
<tr>
<td>H : Relative hight between the top and the observation site (m)</td>
<td>865</td>
<td>2100</td>
<td>1392</td>
</tr>
<tr>
<td>Full length of the stream (m)</td>
<td>2500</td>
<td>14000</td>
<td>7600</td>
</tr>
<tr>
<td>Stream length to the observation site (m)</td>
<td>1500</td>
<td>6000</td>
<td>5000</td>
</tr>
<tr>
<td>Mean inclination of the stream (°)</td>
<td>20.7</td>
<td>9.9</td>
<td>10.9</td>
</tr>
<tr>
<td>Mean inclination of the stream to the observation site (°)</td>
<td>29.9</td>
<td>19.3</td>
<td>15.5</td>
</tr>
<tr>
<td>Inclination of the stream at the observation site (°)</td>
<td>7</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>A : Catchment area for the observation site (km²)</td>
<td>0.83</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>P : Mean of annual precipitation (mm)</td>
<td>2800</td>
<td>4500</td>
<td>3100</td>
</tr>
<tr>
<td>Year of the last activity of effective eruption</td>
<td>1962</td>
<td>1984</td>
<td>1990-1994-</td>
</tr>
<tr>
<td>T : Time after the last effective eruption (years)</td>
<td>33</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>K : Permeability in the surface layer of the slope (cm/sec)</td>
<td>( 10^{-2} ) - ( 10^{-3} )</td>
<td>( 10^{-2} ) - ( 10^{-3} )</td>
<td>( 10^{-3} ) - ( 10^{-5} )</td>
</tr>
<tr>
<td>F : Frequency of debris flow (/year)</td>
<td>0.7</td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>V : Total bulk volume of sediment transportation (x10³ m³/year)</td>
<td>0.5</td>
<td>20</td>
<td>210</td>
</tr>
<tr>
<td>( S_v ) : Specific amount of sediment transportation (x10² m³/km²·year)</td>
<td>0.6</td>
<td>4</td>
<td>17.5</td>
</tr>
<tr>
<td>Annual depth of sediment yield (mm/year)</td>
<td>6</td>
<td>40</td>
<td>175</td>
</tr>
</tbody>
</table>
Acknowledgments

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