Sustainable Sand Mining Management in Merapi Area Using Groundsills

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Synopsis

Mt. Merapi is one of the most active volcanoes in the world and located at 30 km north-northeast from Yogyakarta, Indonesia. A large amount of sediment supply from Mt. Merapi area is serious threat to people, but works also as an important natural resource for people. Thus, the sediment from the volcano has given both advantages and disadvantages. Sustainable sediment management is urgently required to mitigate the sediment disasters and provide the people with benefits. It is considered that sand mining activity and installation of groundsills can be used as one of the tools to control the sediment disasters and the regional development. In this study, we discussed the basic management concepts of sand mining and groundsill installation for such sustainable sediment management.

Keywords: Mt. Merapi, sediment, resources, disaster, sustainable management

1. Introduction

1.1 Mt. Merapi activities

Mount Merapi shown in **Fig. 1** is one of the most active volcanoes in the world. It erupted once 3 years, major eruption occurred at an interval of 9 years, and also has actively produced huge sediment. The produced sediment has caused many disasters, and threatening local residents. Pyroclastic flows have run down during the last 100 years toward all directions the slope of Mt. Merapi (Voight, et al., 2000 and DGWR, 2001b), but they have occurred most on southwest slope during 37 years from 1961 to 1997. The occurrence of pyroclastic flows in 1998 and 2001 was limited on the western slope. However, in the eruption on June 2006, the pyroclastic flows took place in Gendol River and Woro River (Mananoma, et al., 2006) and the direction changed towards southeast. Many debris flows have occurred for long years. The total number of debris flows recorded from 1931 to 1996 is more than 500 times in almost all the rivers on the slope of Mt. Merapi (DGWR, 2001b).
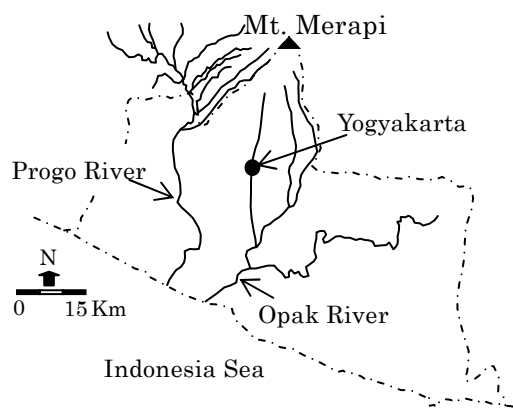
Fig. 1 Location of Mount Merapi

The volcanic materials are deposited at the slopes of the Mt. Merapi. The specific gravity of the deposited sediment is between 2.65 and 2.70 and the content of silt is 0.06% to 1.40%. Therefore, it has good quality for construction (Sutikno, 2003). Due to the increase in sand consumption, the total amount of the sand mining activity has been increased rapidly.

Meanwhile, the lower Progo River which is originated at the Mt. Merapi has been affected by the material from its eruptions. In this paper, we discussed sustainable sand mining in the Merapi area with considering sediment production, socio economic condition and the river bed variation in the lower Progo River. Recently, the bed degradation occurred at the lower Progo is very serious because due to sand mining activities. On the other hand, the sand mining activities is difficult to be stopped due to socio economic condition. Based on the view, we propose the sustainable sand mining management.
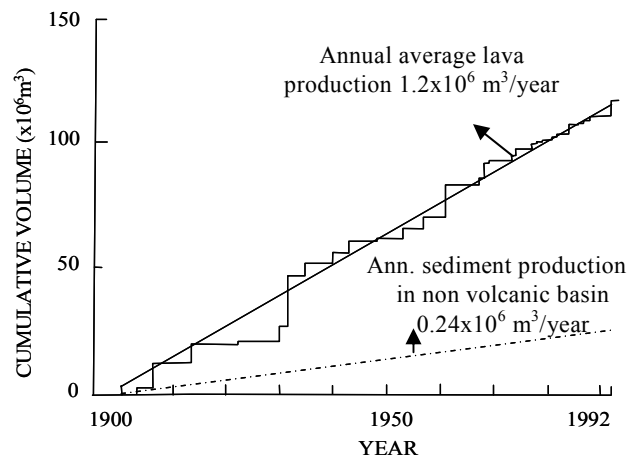
1.2 Sediment production

The sediment production shown in **Fig. 2** is from both volcanic active basin and non-volcanic basin. The lava production data from 1890 to 1992 have been compiled by Siswowidjoyo et al., (1995). **Fig. 2** shows that the production volumes of individual eruptive events are varied widely from less than 1 million m^3 to more than 20 millions m^3. The annual average lava production rate is approximately estimated at 1.2 millions m^3. The sediment production from non-volcanic basin is estimated at 20% of the sediment production from volcanic active basin (DGWR, 2001b), therefore, the annual average sediment production is equal to 0.24 million m^3. Thus, the annual average sediment production rate from Merapi Volcano (volcanic active basin) and non-volcanic basin is 1.44 millions m^3.

2. Sand mining activities
2.1 Current situation

In addition to threaten people and asset in the downstream, the sediment is important resources for people. The sand mining volume in the foothills (upper area) of Mt. Merapi in 2000 was estimated at 5-6 x $10^6 m^3$/year. The sand mining persists not only in the foothills of Mt. Merapi but also in the lower reach of river channel, especially in the Progo River. In the Progo River, the sand mining activities are concentrated in the lower reach area. The mining rate in the Lower Progo is estimated at about 2,933m^3/day or 1.07x$10^6 m^3$/year.

Recently, sand mining activities is very intensive. No sediment supply flows into the lower

Fig. 2 Sediment production from Mt. Merapi

Progo River. The consequence is river bed degradation occurred in this area. The bed degradation at the Srandakan Bridge, Bantar Bridge, and Kebonagung Bridge are 7.39 cm/year, 28.9 cm/year and 31.1 cm/year, respectively (DGWR, 2001a). Uncontrolled sand mining has caused serious problems in the watershed such as unstableness of sediment control facility, bridge and irrigation intake by digging nearby, channel and riverbank instability due to riverbed degradation in the downstream, and destruction of aquatic and riparian habitat due to natural and artificial sediment armoring.

2.2 Sediment balance

The current situation of sediment balance in Mt. Merapi area shown in **Fig. 3** is influenced by sediment production, sediment mining and sediment discharge to sea. According to DGWR report, the hydrological and topographical conditions in the lower Progo River as follows; the annual average discharge is 83.1m^3/s. The mean diameter of bed material is 1 mm, the average river width is 200 m, and the average bed slope is 0.0015. Under this condition, the total sediment discharge in the lower Progo River, Q_s, is estimated at 1.46 millions m^3/year using Ashida and Michiue's bed load transport formula (Fujita and Sasahara, --). This result shows annual average sediment discharge is almost equal to annual average sediment production rate. Therefore, the sediment output balances with the sediment input. If the bed material is not removed by sand mining, bed

degradation does not occur. If sand mining activities in the upper reach does not turn down, it means no sediment supply into the lower reach continues for a long term. Under this condition, the slope is decreased from 0.0015 until the static equilibrium state of sediment transport is reached. Finally, the slope is estimated to be 0.000156.

3. Necessity of sand mining activities

3.1 Socio-economical condition

The reasons why the sand mining activities are excessive depend on the socio-economical condition of local people in surrounding Mt. Merapi area. First, the reason is the poverty and employment. Generally, inhabitants in Merapi area are farmer and husbandry as well as sand miner. The ratio of those small scale farmers who own less than 0.5 ha amounts to 91% of total agricultural household (DGWR, 2001c). The percentage of poor house holders in the sub districts in the area is from 17.5 % to 82.5%. The second reason is the population changes. Based on data from Public Work Agency (2005), the population density in the Mt. Merapi ranges from 558 to 1045 persons/km^2 and the lowest is in Cangkringan sub district. The average annual growth of population in the area ranges from 0.7 to 1.3%/year (DGWR, 2001c). The population growth of the sub district in Sleman is shown in **Fig. 4**. The figure shows that the acceleration of population changes in mountainous area is larger than the others. The figure shows that the acceleration of population changes in mountainous area is larger than the others. The acceleration of population changes in mountainous area is larger than others, especially after the economic crisis at 1997 due to; first, feel safety provided by sabo works, second, regional development, such as transportation access and irrigation facilities associated with sabo works, third, resources such as forest, agriculture land and sand material.

3.2. Questionnaire survey

In order to know the socio-economical condition and people's awareness of the produced sediment by Mt. Merapi, a questionnaire survey has been conducted in April to June 2008. The numbers of respondent are 113, 45, and 122 in upper (rural), middle (urban), and lower area (rural), respectively. Because the sediment related disasters/problems relatively occurs more intensive in upper area and lower area, the number of respondent in both areas is more than in the middle area. The survey location consists of 6 sub districts, 9 villages and 31 sub villages. The survey area is shown in **Fig. 5**. The contents of questionnaire are regarding
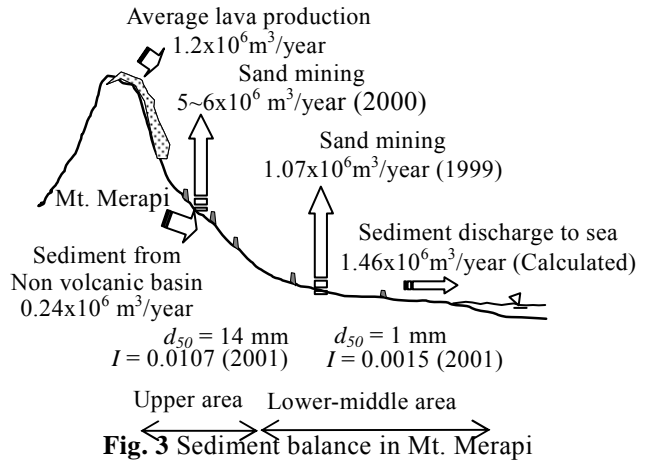

Fig. 3 Sediment balance in Mt. Merapi
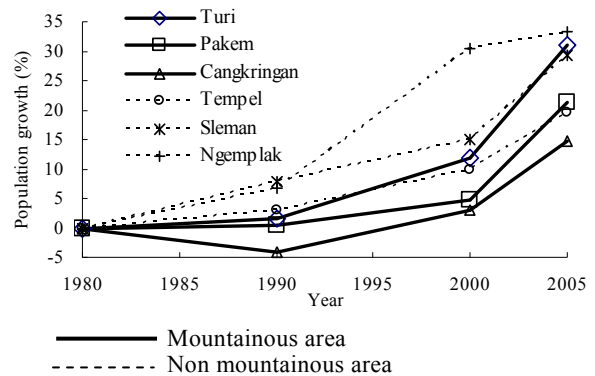

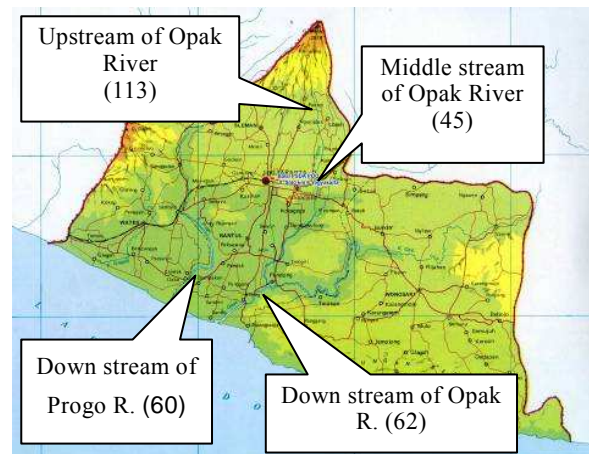**Fig. 4** The population growth of selected sub district in Sleman district

Fig. 5 The area of questionnaire survey

649

socio-economical condition, hazard perceptions of inhabitant and perception on river function as well as environment condition.

The questionnaire results are summed and presented as percentages and are drown as a series of bar charts. We explored the socio-economic condition of inhabitant through questions related to education background, job of house hold and family income. The result of education background of inhabitants is shown in **Fig. 6.** The figure describes that the percentage of education background of inhabitant under senior high school level at lower Progo, lower Opak, middle Opak and Gendol (upper Opak) are 41.6%, 50%, 53% and 62.8%, respectively. It indicates that the education background of inhabitant in upper area is lowest if it is compared to the other areas. The monthly income of inhabitant is shown in **Fig. 7.** Based on the result, it shows that the monthly average income of inhabitant at lower Progo, lower Opak, middle Opak and Gendol (upper Opak) are 1, 1.15, 1.17 and 0.8 millions rupiah, respectively. It indicates that people in upper area has the lowest income. Hence, that are some reasons why the sand mining activities to be active, especially in upper area of Mt. Merapi.

Fig. 8 shows the inhabitant opinion related Mt. Merapi eruption, it is resources or disaster. Most inhabitants have opinions that Mt. Merapi eruption creates both disaster and resources. In fact, inhabitants near Mt. Merapi who have an opinion that Mt. Merapi as disaster are less than others. Hence, local people think that Mt. Merapi eruption provides some resources for them. **Fig 9** shows the inhabitant opinion related river function. Commonly, local people think that the river function is as water resources, especially for water irrigation. However, almost inhabitants in lower and upper area have an opinion that the river function is as sand resources.

3.3 Sand mining impact on socio-economical condition

The sand mining activities have given some advantages for rural/local people and local government. **Table 1** shows the impacts of sand mining activities. Sand and gravel material in Mt. Merapi offer many benefits such as employment
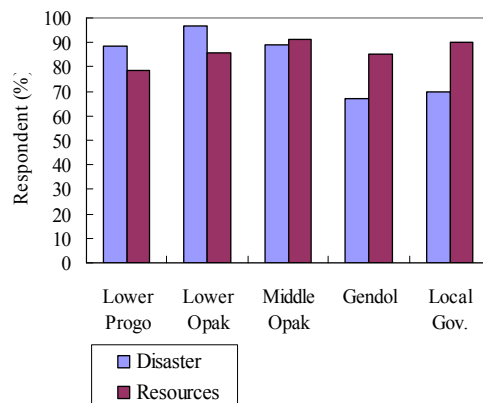
opportunity, and an increase in economical benefit to farmers. Total number of mining worker in Mt Merapi area amounts to about 21,000 man/day.
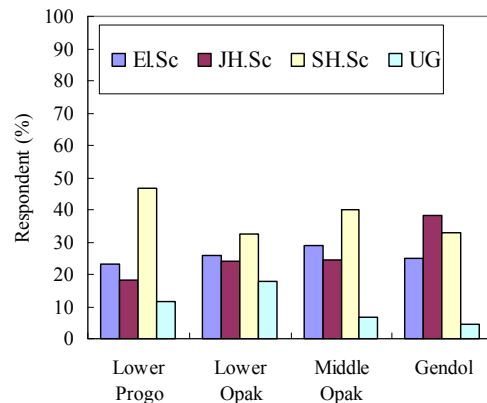
Fig. 6 The education background of inhabitants
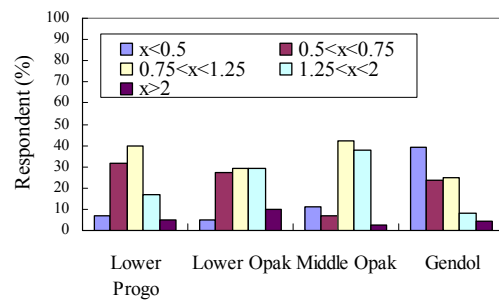
Fig. 7 The monthly income of inhabitant (million rupiah)

Fig. 8 The inhabitant perception of Mt. Merapi eruption

Table 1 Sand mining workers, annual sand mining volume and annual tax income

|	Magelang	Sleman	Klaten
Employers/day	13,340	2,476	5,206
Sand mining vol. (m³)	5,118,720	334,800	710,280
Annual tax (million Rp.)	8,847	10,696	6,216
Annual sand mining tax (million Rp.)	868	117	29
Tax ratio (%)	9.81	1.10	0.46
Tax per unit vol. (Rp./m³)	169.57	349.46	40.83
Regulation tax (Rp./m³)	575-775	405-525	1,750-3,250

The sand mining activity has also given an additional income tax for local government and the ratios of sand mining tax to total tax is 0.46% to 9.81%. It means that exploitation of sand and gravel material provides rural areas with considerable opportunities for economic development. The sand mining tax is important for Magelang district, but no so important for Klaten district.

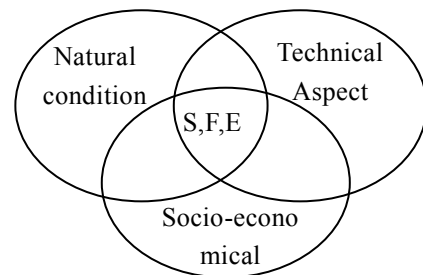## 4. Concept of Sustainable Sand Mining Management

Based on the background of socio economical condition, the sand mining activities is difficult to be stopped, even if it also must be controlled. We attempt to propose such sediment management. **Fig.10** shows that the proposed management considers natural condition, socio-economical and technical aspects. The management is attempted to have effect (effective) for socio-economic condition, be able to done (feasible) and be able to maintained (sustainable). Sustainable, in this paper, means the sand mining activities can be maintained with consider sediment production (natural condition), resources utilization for supporting socio-economical and environment conservation as well as disaster mitigation. In this method, the basic concepts of such sustainable sediment management using sand mining and groundsills are proposed.

Sand mining management is one of the methods to control sediment discharge in Mt Merapi area. The view point in sustainable sand mining is how to determine the allowable sand mining volume in upper area around Mt. Merapi. Determining the allowable sand mining volume, the following steps are necessary. **Fig. 11** shows the steps determining the allowable sand mining volume. First, the designed bed slope in the lower reach, i_{bd}, is decided. In consequence of first step, it is necessary to estimate how many groundsills must be installed for degradation measurement. If the designed bed slope is much less than the original bed slopes, the number of groundsills is larger. Next step, sediment discharge to sea, Q_{s1}, is calculated for the designed bed
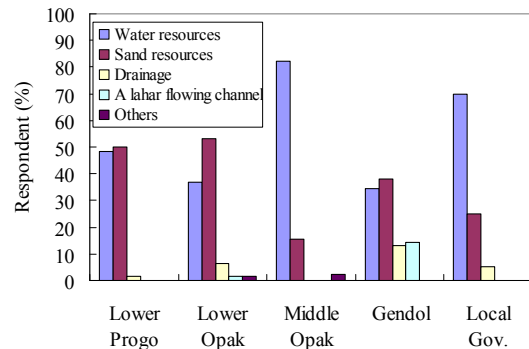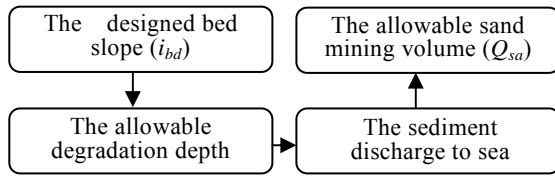

Fig. 9 The inhabitant perception of river function

E: Effective for local condition
F: Feasible
S: Sustainable

Fig. 10 Considered aspect of sediment management

Fig. 11 Flowchart to determine the allowable sand mining volume, Q_{sa}
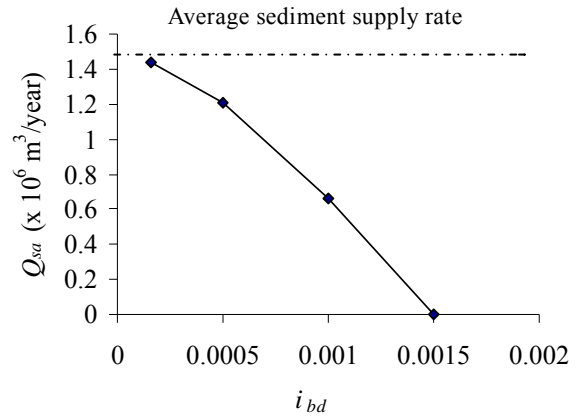
slope. Finally, the allowable sand mining volume, Q_{sa}, can be calculated upon the design sediment supply rate, Q_{spd}, and the sediment discharge to sea as follows.

$$Q_{sa} = Q_{spd} - Q_{s1} \qquad (1)$$

Assumed that Q_{spd} is equal to Q_{spm} ($1.44 \times 10^6 \text{m}^3/\text{year}$), Q_{sa} becomes $Q_{spm} - Q_{s1}$. For instance, if the designed bed slope is 0.0015, the sediment discharge to sea, Q_{s1}, is $1.46 \times 10^6 \text{m}^3/\text{year}$. Thus, under this condition, the allowable sand mining volume is around zero. In the other case, if the designed bed slope is 0.0010, the sediment discharge to sea is $0.78 \times 10^6 \text{m}^3/\text{year}$, and therefore the allowable sand mining volume is estimated at $0.66 \times 10^6 \text{m}^3/\text{year}$. Relation between i_{bd} and the allowable sand mining volume, Q_{sa}, is shown in **Fig. 12**. In the Mt. Merapi area, the maximum allowable sand mining volume is limited to $1.44 \times 10^6 \text{m}^3/\text{year}$ that is sediment resources annually provided from Mt. Merapi volcanic and non volcanic area on average.

By the controlled sand mining activity, an extra empty of capacity in the sediment reservoirs is useful to contribute the rural economy and control the river bed elevation in lower reach. However, the lava production rates of individual eruptive events vary widely from less than 10^6 m^3 to more than $20 \times 10^6 \text{m}^3$. Therefore, the sediment supply rate, Q_{supply}, from the Mt Merapi also changes very much. Thus, it is very important to determine the maximum allowable sediment discharge in the lower Progo River, Q_{s2}, for each of the designed bed slope. Q_{s2} is defined as sediment discharge that causes the designed bed slope to return to the original bed slope. Relation between i_{bd} and Q_{s2} is shown in **Fig. 13**. If Q_{supply} is less than or equal to

Q_{s2}, a series of groundsill is never buried with sediment. But if Q_{supply} is much bigger than Q_{s2}, this condition will cause severe aggradations. For instance, if a huge eruption occurs with the sediment production rate of $20 \times 10^6 \text{m}^3/\text{year}$ like 1930, it is predicted that the bed slope changes from the designed bed slope to 0.0086. This condition is quite danger for the lower reach. In order to reduce the predicted sediment disasters, the excess sediment supply should be controlled by the

Fig.12 Relation between the allowable sand mining volume, Q_{sa}, and the designed bed slope, i_{bd}
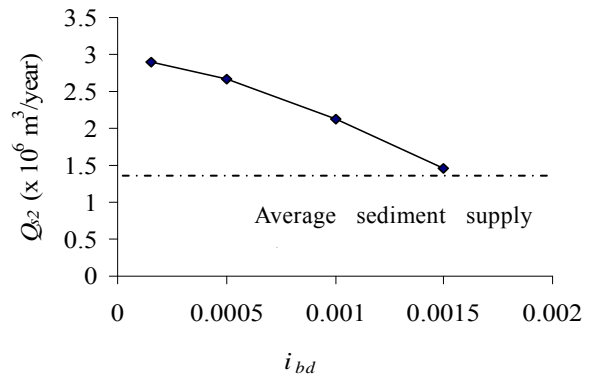
Fig.13 Relation between the allowable sediment supply, Q_{s2}, and the designed bed slope, i_{bd}

structural measurement such as sand pockets. For sustainable sand mining management, it is important to release the sediment deposit from the sand pocket at a rate of Q_{sa}. Considering the actual situation of the volcanic activities in Mt. Merapi, a buffer zone such as a sand pocket is required in the deposition area of pyroclastic flows/debris flows for sustainable sediment management.

5. Sustainable sand mining management using groundsills

Sand mining management concept is discussed in **Chapter 4**. However, the concept is established under equilibrium sediment transport condition. In this chapter, one dimensional bed deformation analysis is used as a tool to manage sediment and performed for the lower reach of the Progo River. Two management concepts on the sand mining and the groundsill installation are discussed.

5.1 Simulation model

The basic equations of the one dimensional bed deformation analysis are shown as follows. The used model is the standard well-used one dimensional bed deformation model. Mass and momentum equations of water are as follows.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{2}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) = -gA\frac{\partial z}{\partial x} - gAI_e + \frac{\partial}{\partial x}\left(A\sigma_{xx}\right) \tag{3}$$

where, t is the time, x is the coordinate along the longitudinal direction, A is the cross-section area of water, Q is the water discharge in main channel, g is the gravity, ρ is the water density, z is the water surface elevation, I_e is the energy slope and σ_{xx} is the turbulence stress.

Ashida and Michiue's formula is used for the estimation of sediment transport rate. Equation of continuity of sediment discharge is:

$$B_w\frac{\partial z_b}{\partial t} + \frac{1}{1-\lambda}\frac{\partial Q_b}{\partial x} = 0 \tag{4}$$

where, B_w is the channel width, λ is the porosity of bed material, z_b is the riverbed elevation.

5.2 Hydraulic conditions

The simulation is carried out using the averaged geometric and hydraulic characteristic values of the lower reach of the Progo River. These data are the same as the data used in **Section 2.2**. The calculation length is 30 km. Normal water depth is used for the downstream boundary conditions. The initial grain size of bed material is used 2 types, namely uniform sediment and sediment mixture, referring to DGWR report.

Calculations are performed under 6 conditions for each sediment type. The initial longitudinal bed geometry is drawn in **Fig. 14**. In Case 1, initial bed lope is 0.0015 and 3 groundsills are installed on the original bed. The height of each groundsill is 2.7m and the longitudinal interval between groundsills is 9km. Under this groundsill install condition, the designed bed slope becomes 0.0012. Supplied sediment discharge is the equilibrium sediment transport rate with the slope 0.0012 (= 0.0338m³/s). In Case 2, the hydraulic condition is the same as that in Case 1 except for the installation level of groundsills. The crest of groundsills has the same level as the bed surface. When the bed has been degradated because of sand mining and so on, groundsills will be installed as Case 1 to increase the bed surface. When the initial bed level should be kept, groundsills will be installed as Case 2. Cases 3 and 4 will be used for the discussion on the installation order of groundsills. Only 1st groundsill is installed as an initial condition in Case 3 and the 2nd groundsill and the 3rd groundsill are installed after 1 year and 2 years, respectively. The other hydraulic condition is the same as that in Case 1. Only 3rd groundsill is installed as an initial condition in Case 4 and the 2nd groundsill and the 1st groundsill are installed after 1 year and 2 years, respectively. The other hydraulic condition is the same as that in Case 1. Bed variation characteristics under large sediment supply conditions are discussed using Cases 5 and 6. The initial bed slope between groundsills is 0.0012. In Case 5, the supplied sediment discharge during the first year is the same as the sediment discharge in the 1930's huge eruption (= 0.790m³/s).
Supplied sediment discharge in the following 4 years is the equilibrium sediment transport rate with the slope 0.0012. In Case 6, the supplied sediment discharge during the first year is the two times as the equilibrium sediment transport rate with slope 0.0015 (= 0.0463m³/s x 2). Supplied sediment discharge in the following 4 years is the equilibrium sediment transport rate with the slope 0.0012.

5.3 Results and discussion

Fig. 15 (a) shows the temporal change of bed geometry in Case 1. The bed deformation between

groundsills is very fast and bed slope becomes mild with time. Bed level at 18km from the downstream end decreases with time in the first year and increases in the following years. **Fig. 16** (a) shows the temporal change of the sediment transport rate between the 2nd groundsill and the 3rd groundsill in Case 1. The figure indicates that the bed at 18km is degraded until 8 months, because the sediment transport rate at 18km is more than sediment transport rate at 19km. These results indicate that the bed deformation between groundsills in the first year is the adjustment process of bed geometry to the local flow condition. On the other hand, after 8 months, sediment deposition takes place at 18km due to the effect of the upstream sediment supply conditions. The sediment transport rate at 10km is still smaller than the equilibrium sediment transport rate with the bed slope 0.0012 (= 0.0338m^3/s) at 5 years. Hence, approaching to the equilibrium state takes very long time under this condition.

Fig. 15 (b) shows the temporal change of bed geometry in Case 2. The bed degradation in the downstream of 3rd groundsill is invisible after 1 year. This result indicate that the effect of small sediment supply condition (= 0.0338m^3/s) propagates to downstream very slowly. Here, let me try to use the very slow propagation velocity to decide the installation order of groundsills. In Case 2, the 3 groundsills are installed at time as the initial condition. However, in order to save budget (including interest for the budget), we had better construct only one groundsill first and the others are constructed at the following appropriate year. **Fig. 16** (b) shows the temporal change of the sediment transport rate on 3 groundsills in Case 2. Sediment transport does not decrease on the 2nd groundsill and the 1st groundsill until 2 years and 4 years, respectively. As a result, if installation of crest of groundsill is the same as the bed surface to keep the original bed, not to increase the original bed, installation of the 2nd groundsill can be done at the 2 years and installation of the 1st groundsill is at the 4 years. It is economical that the groundsills are installed from upstream to downstream.

Fig. 15 (c) and (d) show the temporal change of bed geometry in Cases 3 and 4. Comparing among Cases 1, 3 and 4, bed degradation at the
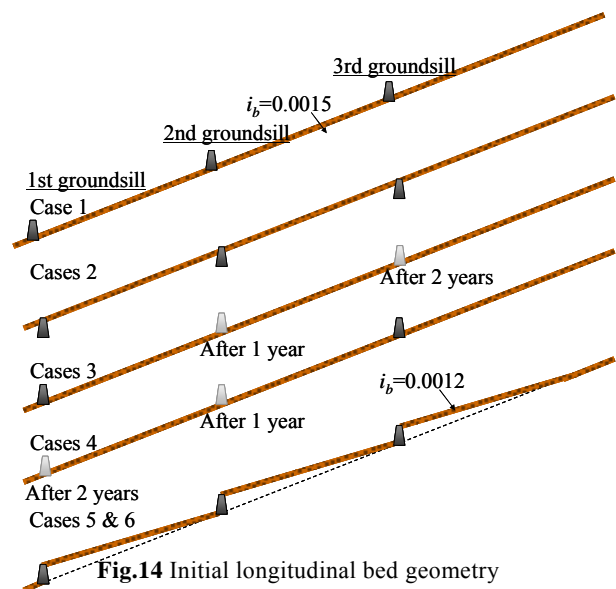

Fig.14 Initial longitudinal bed geometry

downstream of groundsills (ex. 18km and so on) is suppressed in Case 3. Hence, the groundsills in Case 3 are the most stable and the depth of the basement under the bed can be shallow. As a result, the construction costs of groundsills can be saved. **Fig. 16** (c) shows the temporal change of the sediment transport rate at the downstream end. In order to minimize the impact of groundsill construction on the ecosystem of the downstream of groundsills, the decrease range of sediment discharge should be smaller. From the view point of this, Case 3 has the smaller temporal change of sediment discharge (initial sediment transport is 0.0457m^3/s). Hence, when groundsills are installed to increase the bed level (the crest of groundsills is higher than the bed surface), it is safe for human being, plants and animals that the groundsills are installed from downstream to upstream. As discussed using **Fig. 12**, the sediment discharge with the original bed slope can be one of the allowable maximum sediment discharge for sediment disaster prevention. As shown in **Fig. 2**, huge amount of sediment is supplied to rivers when the volcano is erupted.

Fig. 15 (e) shows the temporal change of bed geometry in Case 5. Bed elevation from 25km to 30 km becomes very high after 1 year and overbanked sediment flood is expected. After 5 years, all the groundsills are filled with sediment and the slope becomes larger than 0.0015. Of course, these results depend on the upstream sediment supply condition. However, the data of the

(a) Case 1

(d) Case 4

(b) Case 2

(e) Case 5

(c) Case 3

(f) Case 6
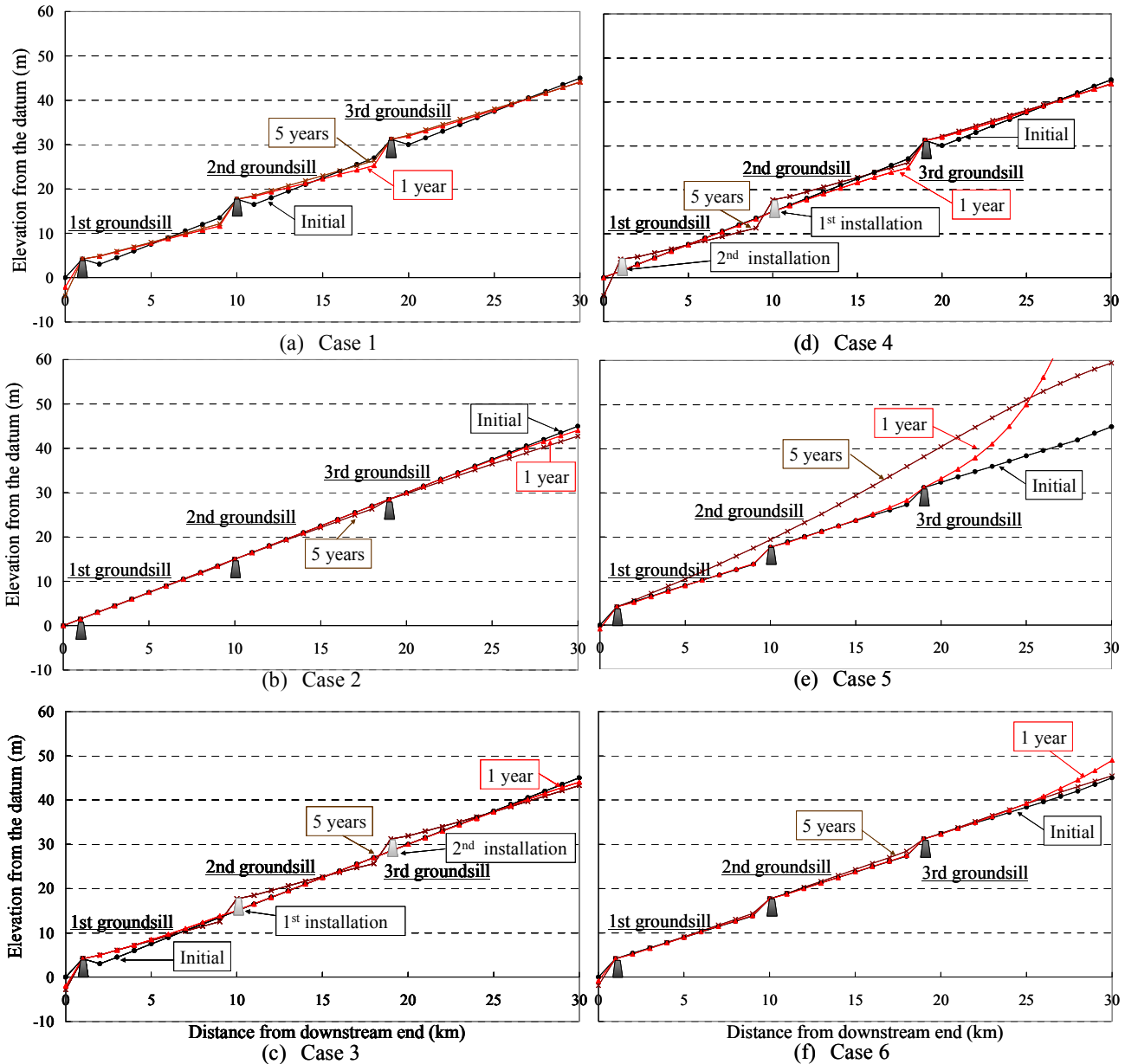
Fig. 15 Temporal change of bed geometry

upstream of the Progo River is not enough to discuss the propagation characteristics of sediment supply by the volcanic eruption . Hence, the above mentioned sediment supply condition is applied as an example here. **Fig. 15** (f) shows the temporal change of bed geometry in Case 6A. As shown in **Fig. 15** (f), the bed deformation around the groundsills is very small because of the decrease in the sediment discharge peak during the propagation process to downstream. Hence, the allowable maximum discharge is underestimated, when the equilibrium conditions is assumed. As a result, the two times as the equilibrium sediment transport rate with the slope 0.0015 can be flowed without filled

with groundsills.

6. Conclusion

(1) In this study, sediment supply from mountainous area is considered as natural resources, and the basic concepts of sustainable sediment management assisted by sand mining and sabo works are discussed.

(2) In fact, sediment mining brings non-negligible economic effects to people and local government in Mt. Merapi area.

(3) On the other hand, uncontrolled sand mining forms sever bed degradation and damages to ecosystem in the lower river. Furthermore, the

budget for river regulation works is restricted.

(4) It is considered that the suggested management concepts can be used for helping to determine the politics on the sand mining and the groundsills and sand pockets installations.

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(a) Case 1

(b) Case 2

(c) Downstream sediment discharge in Cases 1, 3 and 4
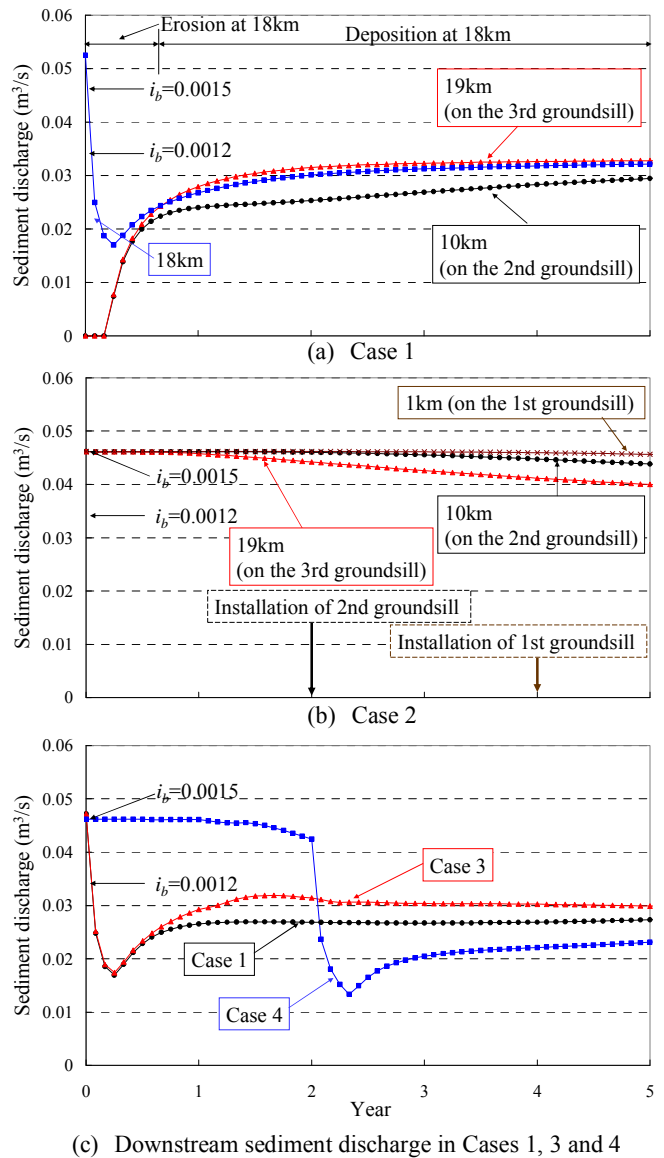
Fig.16 Temporal change of sediment transport rate

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656

床固めを使用したメラピ地域における持続可能な砂利採取管理

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要　旨

　メラピ火山はインドネシアのジョグジャカルタの北北東30kmに位置する世界で最も活動的な火山の１つである。メラピ火山から大量に流出する土砂は，周辺の人々に多大な脅威を与えている。しかし、これらの土砂は周辺の人々に対して，重要な自然資源としての役割も果たしている。したがって，火山からの流出土砂にはメリット，デメリットの両者が包含されている。人々の利益を守り，土砂災害を軽減する持続的な土砂管理が緊急的に求められている。床固めの導入と積極的な砂利採取は，災害の軽減と地域的な開発の１つのツールとして用いられるものと考えられる。本研究では，このような持続的な土砂管理に対する床固めの導入と砂利採取に着目し，その基本的な管理の概念について議論する。

キーワード:メラピ火山，土砂，資源，災害，持続可能な管理