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Sediment Production from Weathered Bedrock in Winter Season - Field Observation and Numerical Simulation

SEDIMENT PRODUCTION FROM WEATHERED BEDROCK IN WINTER SEASON - FIELD OBSERVATION AND NUMERICAL SIMULATION -

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A field observation was conducted to elucidate mechanisms of freeze and thaw action and following sediment production on a bare slope in Tanakami Mountains, southern part of Shiga Prefecture, Japan. During the observation period (December, 2004 – April, 2005), air, surface and subsurface (10, 25, 50 cm depth) temperatures were continuously measured with 10 min interval. Sediment which was produced on the bedrock was collected and weighted once in a week from a plot area (plot 1). For another plot area (plot 2), sediment was left on the bedrock until the end of the observation period. From the observation results, it was indicated that freeze and thaw action occurred repeatedly, and frozen zone (temperature < 0 ˚C) reached to a depth of 10 cm. The sediment production occurred due to the active freeze and thaw action, and stopped at the end of the observation period when the freeze and thaw cycle also stopped (April, 2005). Total amounts of the sediment production on plot 1 and 2 were 108 and 44 kg/m2/year respectively. This difference indicates that sediment cover on the bedrock surface mitigated the effect of freeze and thaw action. These observed results were simulated by a thermal conductivity analysis method. Comparison between observed and simulated results suggested that multiple experiences of the freeze and thaw cycles are necessary for the bedrock to become sediment. It was confirmed that the estimation of the sediment production due to freeze and thaw action is possible by this numerical simulation method.

Key Words : *sediment production, freeze and thaw action, model simulation, bare slope, surface cover*

1. INTRODUCTION

In Japan, sediment production due to freeze and thaw cycle in winter season and following slope erosion supplies nearly constant amount of sediment to the stream channels every year. Therefore, it is one of the important sediment input to the sediment flow system, although its amount is not huge. It is supposed that the similar kind of sediment production is occurring in any other countries except for tropic regions.

Some studies regarding to the sediment production due to freeze and thaw action have been published (e.g., Suzuki and Fukushima, 1989; Sawada and Ashida, 1986; Fujita et al., 2005; Okunishi et al, 2000). Suzuki and Fukushima (1989) investigated the sediment production on a few different bare slopes in Tanakami Mountains, Shiga Prefecture, and reported that approximately constant amounts of annual sediment production (i.e., 5,000 ~ 10,000 m^3/km^2/year) were observed on these slopes. They supposed that the cause of this constant annual sediment production was the constant effect of freeze and thaw cycle on bedrock of the slopes in winter season. Sawada and Ashida (1986) had measured the sediment production on the slopes

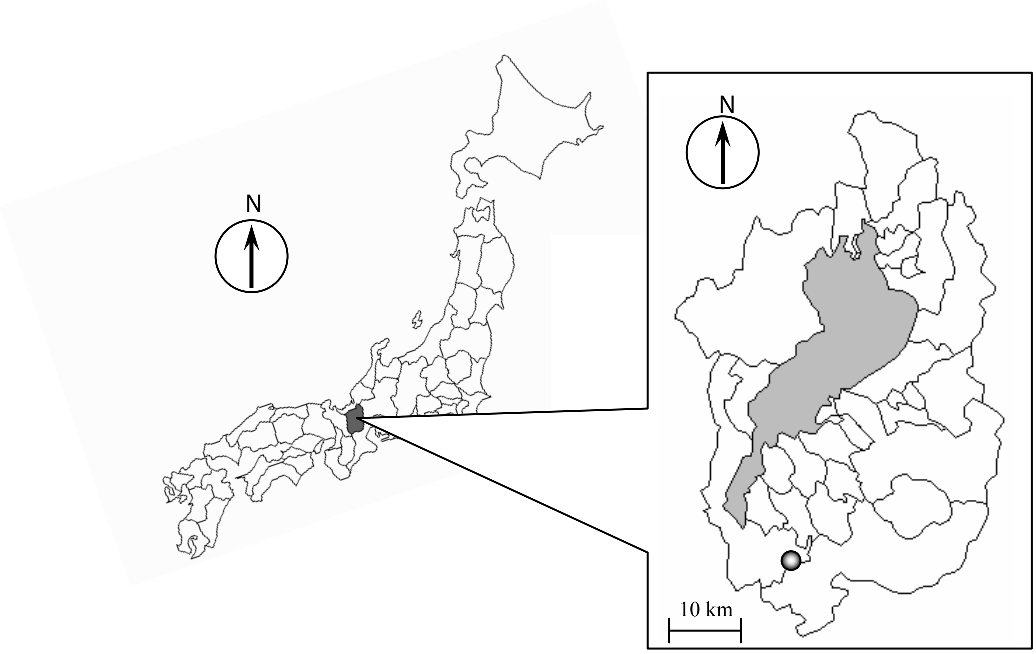

Fig. 1 Observation site in Tanakami Mountain, southern part of Shiga Prefecture

which have various geology and slopes in the Takahara-river basin with high frequency (once in a week) for several years. Fujita et al. (2005) analyzed relationships of the observed sediment production by Sawada and Ashida (1986) with rainfall or with effect of the freeze and thaw action. From the analysis, they found that the sediment production had high correlations with the repetition number of the freeze and thaw cycles during the winter and early spring seasons, and with the rainfall intensity (mm/hr) during the summer and autumn seasons. These correlations, they concluded, indicated there was a certain process of the sediment production in winter season due to freeze and thaw cycles and washout of these sediments by rainfall in summer season. Although these previous study observed the eroded sediment down from the slopes, they did not consider detail of bedrock granulation into sediment due to freeze and thaw action. Even in a study by Okunishi et al. (2000) in which they tried to conduct detailed observation for the freeze and thaw action, only quantitative results were presented.

Mathematical analysis may be another effective approach investigating the freeze and thaw action. Method of thermal conductivity analysis in the ground has been already developed, and applied to many cases (e.g., Japanese Geotechnical Society, 1994; Chen et al., 1998). However, almost all these applications were not to the bedrock layer but to soil layers, and even in the application to the bedrock layer by Ishiyama et al. (1996) the sediment production due to freeze and thaw action was not investigated.

In this research, we conducted a detailed observation on a bare slope in Tanakami Mountains, southern part of Shiga Prefecture, to reveal the practical phenomenon of freeze and thaw action and the following sediment production on the weathered bedrock. Furthermore, we developed a simple simulation model of the thermal conductivity as well as the bedrock granulation, and applied it for the observed results to elucidate the mechanisms of the sediment production due to freeze and thaw action on weathered bedrock.

2. FIELD OBSERVATION

(1) Observation site

Tanakami Mountains, located in southern part of Shiga Prefecture (Fig. 1), were famous for its vegetation less condition until 100 years ago, and the beginning of the Sabo works in Japan. Today, the vegetation have been recovered on many slopes, however, some bare slopes still remain. On Jakujyo-Rachidani slope, one of the remaining bare slopes, we conducted the field observation. The slope is facing to the north direction, and has 34 degree gradient. Bedrock of the slope, which consists of granite, is highly weathered and easy to break into granular sediments. Before the observation, the bedrock was covered by thin sediment layer (less than 10 cm) derived from the granite bedrock, and the boundary between the bedrock and sediment layer was obvious.

(2) Method

The observation was carried out from December 2004 till April 2005. After the sediment layer was swept away from the bedrock surface, an area (0.6 m in length, 1.8 m in width) was partitioned by plastic board to prevent the sediment moving across the boundaries, and divided into two plots in the middle

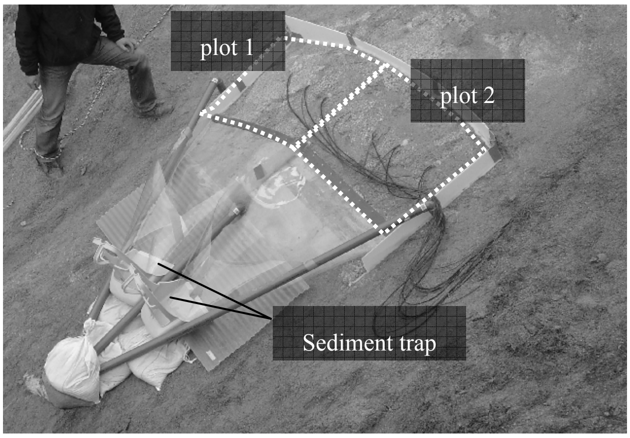

Fig. 2 Equipment for the observation on the bare slope

of the area (Fig. 2). The left and right side plots are called "plot 1" and "plot 2" respectively, and each plot has 0.56 m^2 surface area. At down-slope end of each plot, sediment traps were set up to collect the sediment flowing from each plot. In the bedrock of each plot, three holes were made perpendicular to the slope to the depth of 10, 25 and 50 cm, and thermocouple sensors were inserted. Air temperature, bedrock surface temperature, and subsurface temperatures (10, 25, 50 cm in depth) were measured with 10 min interval during the observation period. The sediment produced from plot 1 was collected and weighted almost once in a week. On the other hand, the sediment produced from plot 2 was left during the observation period, and all the sediment was collected and weighted at the end of the observation period (April 17, 2005). Although the sediment sampling was stopped at the end of observation period, the temperature measurement has been continued.

(3) Results of field observations

a) Temperature changes

Changes of the air and surface temperature are shown in Fig. 3. As a long term tendency of temperature changes, air and surface temperatures showed daily fluctuations and gradually increased from middle of March. The temperatures go down to sub-zero many times for more than four months, from December 2004 to the beginning of April 2005. The lowest air temperature was -6.8 degree C during the observation period. These results indicate that the temperature condition was sufficient for freeze and thaw action taking place. Almost constant surface temperature (0 degree C) for several days at the beginning of January 2005 was due to snow cover. This observed record indicates that the surface cover conditions greatly affect on the freeze and thaw action.

Changes of subsurface temperature (10, 25 and 50 cm from the surface) in plot 1 and 2 are shown in Fig. 4 and 5, respectively. These figures indicate that the temperature at deeper level tends to be higher and smaller fluctuation in both plots. Comparing the plots, differences are very small but the temperature in plot 1 is slightly lower than plot 2. This small difference is important for depth of 10 cm, because the temperature in plot 1 went down to sub-zero temperature but in plot 2 it kept above zero temperature. This difference was due to the different treatment for sediment layer in plot 1 and 2, and indicates again that the surface cover conditions affect the temperature changes.

b) Sediment productions

Change of sediment production in plot 1 is shown in Fig. 6. Contrasting this figure with Fig. 3, it is obvious that the active sediment production occurred during the period when the air and surface temperatures frequently went down and up across the zero degree C and no sediment production was observed after the temperatures kept above zero degree C in April. These results confirm that the sediment was produced by the effect of freeze and

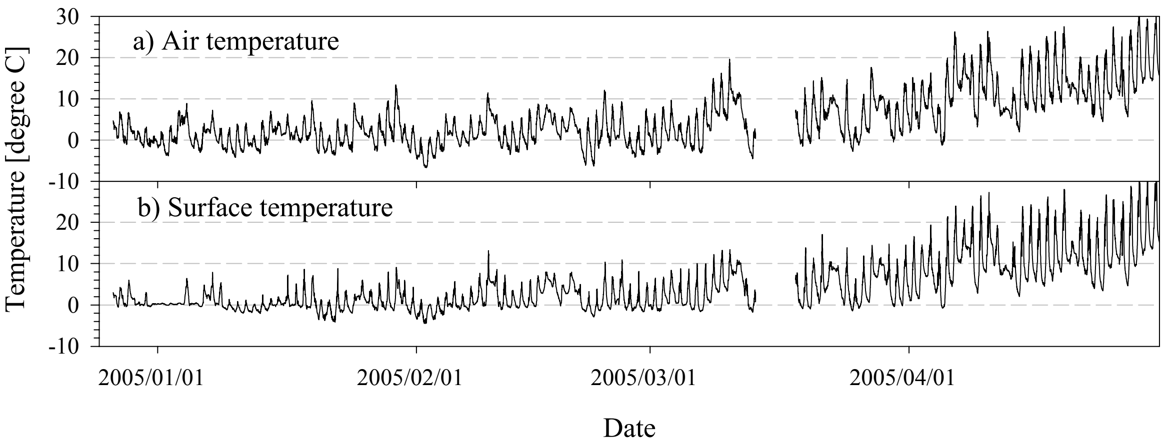

Fig. 3 Changes of air and surface temperatures

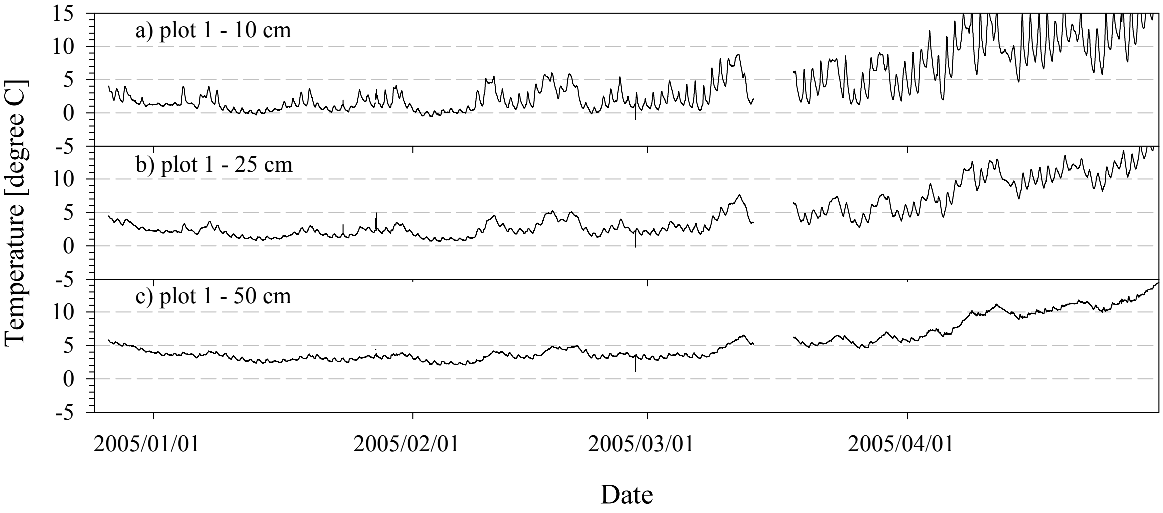

Fig. 4 Changes of subsurface temperatures in plot 1

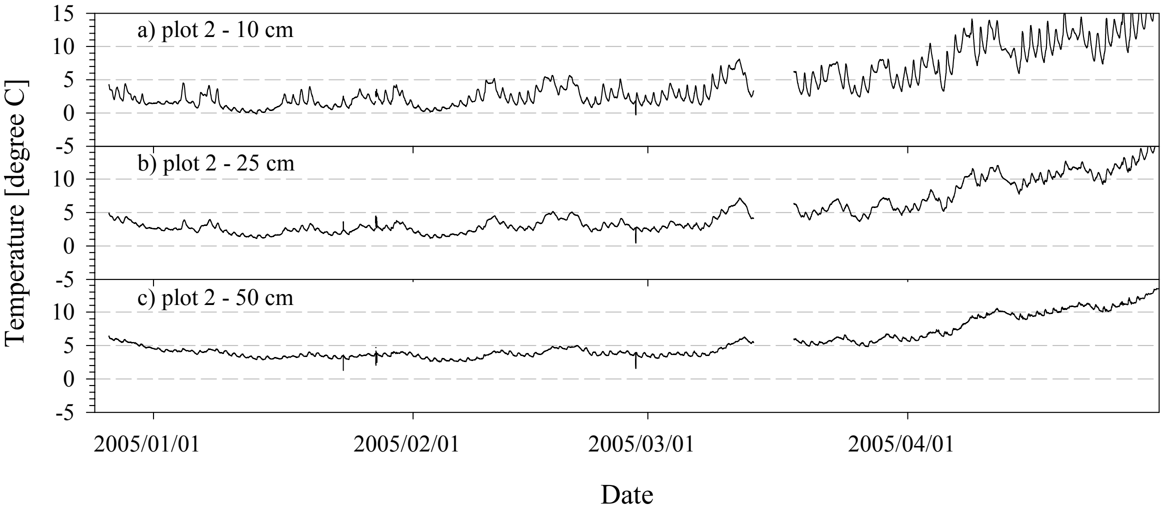

Fig. 5 Changes of subsurface temperatures in plot 2

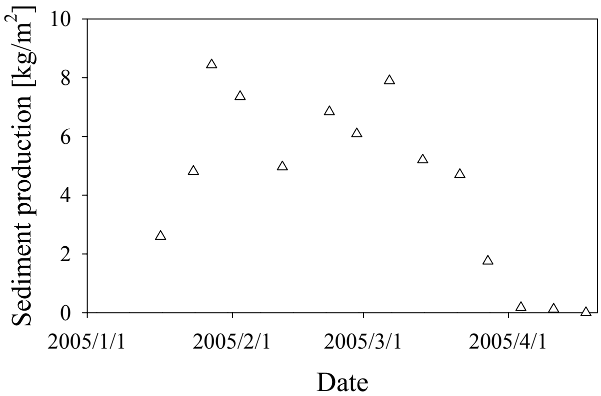

Fig. 6 Changes of sediment production on plot 1

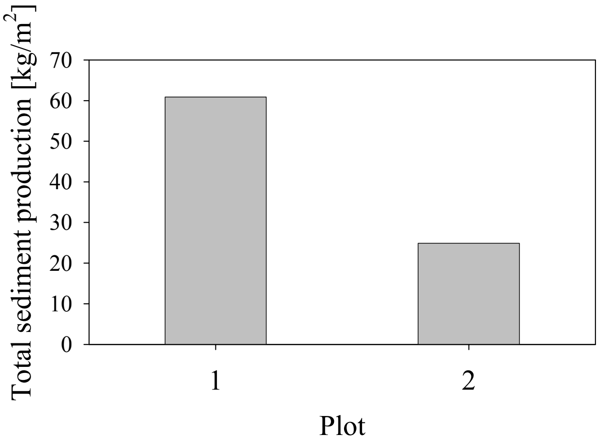

Fig. 7 Comparison of total sediment production between plot 1 and 2

thaw action in middle winter.

Total amount of the sediment production in plot 1 and sediment production in plot 2 which was collected and weighted at the end of the observation period (April 17, 2005) are shown in Fig. 7. The total sediment production in plot 1 is much larger than that in plots 2; the difference is nearly double. The difference of the total sediment production is due to the condition of sediment cover above the bedrock between plots 1and 2. Because the sediment which was produced on the bedrock surface is removed once in a week in plot 1, and the bedrock surface was exposed to the atmosphere, then heat directly exchanged between the air and the bedrock surface. On the other hand, because the sediment was left on the bedrock surface during the observation period in plot 2, the sediment functioned as a buffer layer for the thermal conductance. This difference made the effect of freeze and thaw cycle on the bedrock in plot 2 smaller than that in plot 1, and the total amount of sediment in plot 2 also smaller than that in plot 2. Therefore, it is conceivable that if a slope is steep enough to exceed the angle of repose for the produced sediment, amount of the sediment production is larger than it from a gentler slope. Supposing the porosity of the sediment $\phi = 0.48$ and density ρ = 2.65 g/cm^3, the total sediment productions in plot 1 and 2 are converted into 44,000 and 18,000 m^3/km^2/year, respectively. Although these values are larger than the previous observation by Suzuki and Fukushima (1989) which is 5,000 - 10,000 m^3/km^2/year, they are reasonably consistent because the effect of freeze and thaw was larger in the present observation by sediment removal from the bedrock surface than in the previous one.

3. MODEL SIMULATIONS

(1) Thermal conductivity analysis

To analyze the freeze and thaw action with the water flow within the weathered bedrock, it is necessary to consider both thermal conduction and water infiltration in porous media simultaneously. Basic equations for one dimensional thermal conductance and water infiltration are shown below.

$$\frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + \rho_i L_w \frac{\partial \phi}{\partial t} = \rho c \frac{\partial T}{\partial t} \quad (1)$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial \theta}{\partial z}\right) - \frac{\rho_i}{\rho_w}\frac{\partial \phi}{\partial t} \quad (2)$$

Where, T is temperature, θ is volumetric water content, ϕ is volumetric ice content, λ , c , D , ρ are thermal conductivity, heat capacity, water diffusivity, and density of bedrock, respectively, ρ_i and ρ_w are density of ice and water, respectively. When the temperature T > 0 degree C, the volumetric ice content ϕ is constantly 0, then the equation (1) and (2) can be solved independently each other. When T < 0 degree C, however, ϕ is not constant anymore, then the equations (1) and (2) depends each other. Under such condition, relationship between non-freezing water content and temperature is necessary to solve the equations (1) and (2) simultaneously. We employed the empirical relationship proposed in a previous study by Jame & Norum (1980) shown below.

$$\begin{aligned} &T = 0.0 && (0.35 \le \theta) \\ &T = (\theta - 0.35)/0.6 && (0.05 \le \theta < 0.35) \\ &T = (\theta - 0.583) \times 60 && (0.025 \le \theta < 0.05) \\ &T = -2.0 && (\theta < 0.025) \end{aligned} \quad (3)$$

Recent hydrological research indicates that the weathered bedrock has water permeability, and infiltrates rainwater into itself (Kosugi et al., 2006; Katsura et al., 2006). However, because hydraulic conductivity of bedrocks is generally small comparing to it of soils, we assumed it to be negligible (D = 0) in the analysis. Therefore, equation (2) was simplified into following form,

$$\frac{\partial}{\partial t}\left(\rho_w \theta + \rho_i \phi\right) = 0 \quad (4)$$

This equation expresses the water mass conservation. Thermal properties of the bedrock, λ, c were obtained by averaging every materials, i.e., rock, water, ice and air, which are components of the weathered bedrock. The equations (1), (3), and (4) were simultaneously solved by Finite Element Method.

(2) Model for sediment production

In this study, a simple sediment production model considering history of freeze and thaw cycles which bedrock experience was proposed. An example of the thermal conductivity analysis, (a) change of the surface temperature as an input data

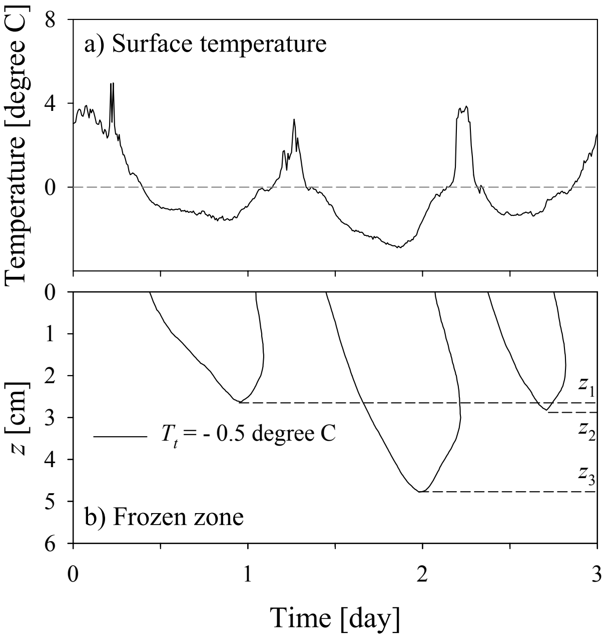

Fig. 8 Examples of a) surface temperature as the input data, and b) simulated frozen zone assuming threshold temperature T_t = -0.5 degree C.

and (b) calculated change of frozen zone within the bedrock, is shown in Fig. 8. In the figure, threshold temperature for the frozen state, T_t, was assumed to be -0.5 degree C. In this example, frozen zone reached to a depth $z = z_1$ at first night and disappeared on the next day. Similarly, it reached to

$z = z_3$ and z_2 ($z_1 < z_2 < z_3$) at second and third night, respectively, and disappeared on following days. According to this history of the freeze and thaw cycles, the bedrock experienced three times of freeze and thaw cycles in a range $0 < z < z_1$, twice in a range $z_1 < z < z_2$, and ones in a range $z_2 < z < z_3$. If experience of only one freeze and thaw cycle induces the granulation of the bedrock, all range $0 < z < z_3$ become sediment. On the other hand, if experience of three freeze and thaw cycles are necessary for the bedrock granulation, only a range $0 < z < z_1$ become sediment.

After removal of the granulated range $0 < z < z_1$, such as a case of plot 1 in the field observation shown in the previous chapter, the experiences of freeze and thaw cycle in the range $z_1 < z < z_2$ and $z_2 < z < z_3$ are recorded and following experiences will added to them. As noted above, the experience of freeze and thaw cycle N_{ft} and the threshold temperature for freezing zone T_t are the important parameters in this model.

(3) Calculation conditions

One dimensional calculation was conducted for the subsurface zone ranging $0 < z < 10$ m. A constant temperature 10.17 degree C, which is estimated by averaging the measured temperature at $z = 50$ cm for a year, was given to the bottom boundary, and the actually measured surface temperature was given for the surface boundary. For the vacant period of the surface temperature (March 3 - 18, 2005), a suitable pattern was substituted. Although calculated period

was supposed to be one year prior to the end of the observation period (April 17, 2005), the surface temperature was not measured for period before the observation started (December, 2004). Therefore, measured surface temperature from April to December, 2005 was substituted. The calculation time interval was 10 min, which is consistent with the observation interval. All the parameters used in the model calculation are listed in Table 1.

(4) Results of model simulation

a) Temperature changes

Comparison between observed and simulated temperatures for plot 2 is shown in Fig. 9. For all depth, long-term tendency of the observed temperature is well simulated by the model calculation. However, there seem to be some detailed disagreements between them. During the period when the surface temperature went down below zero (see Fig. 3), the daily fluctuation is not shown in simulated temperature for the depth of 10 and 25 cm, and the simulated temperature increase tends to delay compared with the observed temperature. The less daily fluctuation during the freezing period is also seen in the observed temperature, and may be due to the mitigation effect by latent heat of water freezing and thawing. Because this effect was over rated in the model simulation, much lesser daily fluctuation may be calculated. Similar less fluctuation of temperature is also seen for the depth of 50 cm. These disagreements between the observed and simulated temperature may be due to some simplification of the model, such as the ignorance of water flow within the weathered bedrock and the relationship between the non-freezing water content and temperature in a previous study was used in substitution for the simulation. Although the simulated temperature change showed some disagreement with the observed result, it is confirmed that the overall tendency of temperature change was well simulated by the present model.

Table 1 Parameters for the simulation

Parameter	Value	
λ_{rock}	3.0	J/m/K/s
λ_{water}	0.582	J/m/K/s
λ_{ice}	2.255	J/m/K/s
λ_{air}	0.024	J/m/K/s
c_{rock}	921.0	J/kg/K
c_{water}	4186.0	J/kg/K
c_{ice}	2093.0	J/kg/K
c_{air}	1006.0	J/kg/K
L_w	332.8	kJ/kg
θ_s	0.48	
$\theta + \phi$ (constant)	0.40	

b) Sediment productions

Simulated change of sediment production with fixed N_{ft} (= 1) and three different T_t (= 0.0, -0.5 and -1.0 degree C) are shown in Fig. 10a. On the other hand, simulated change of sediment production with fixed T_t (= -1.0 degree C) and three different N_{ft} (= 1, 5 and 10) are shown in Fig. 10b. Indeed the simulated sediment production decrease as T_t to be lower, it was too much overestimated comparing to the observed sediment production (Fig. 10a). Although other conditions were employed (i.e., lower T_t or lower thermal conductivity c), the

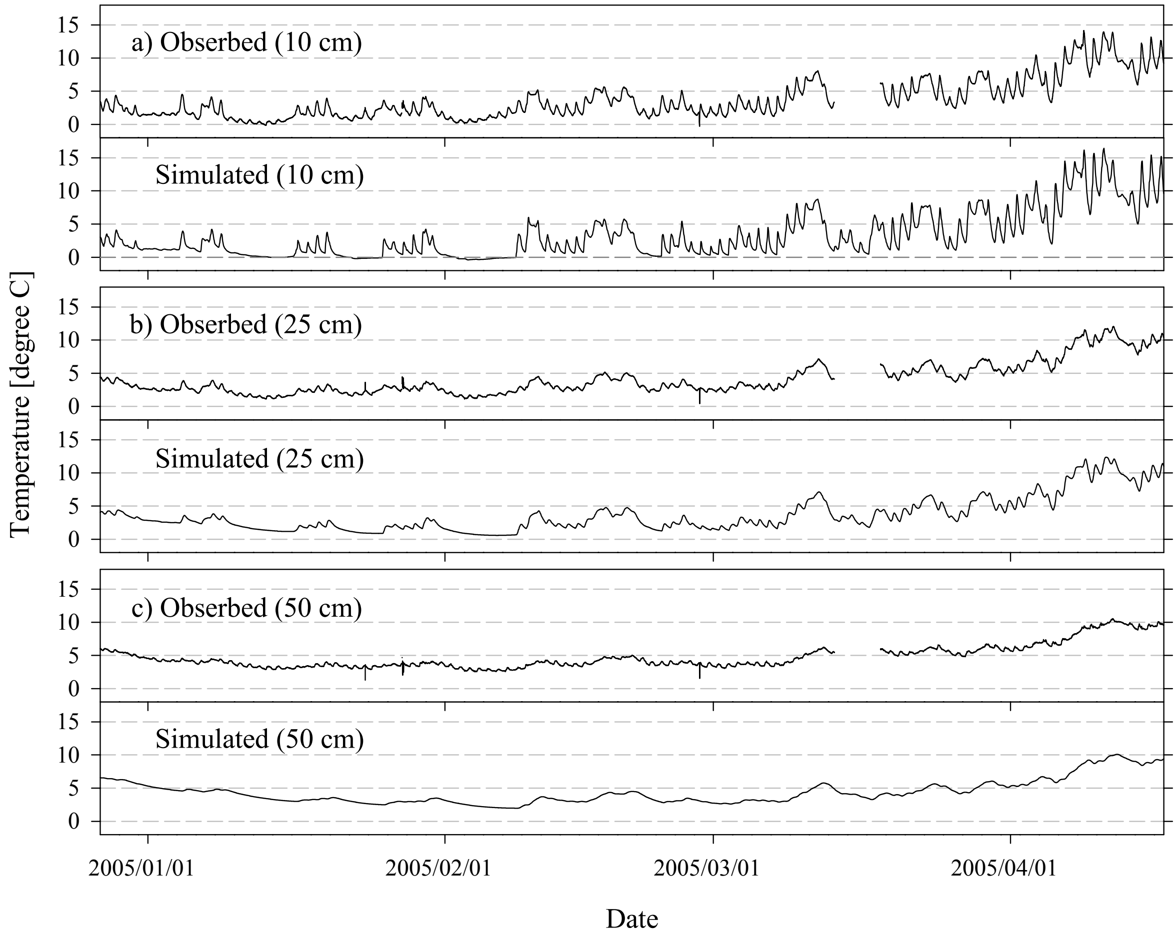

Fig. 9 Comparison between the observed and simulated subsurface temperatures

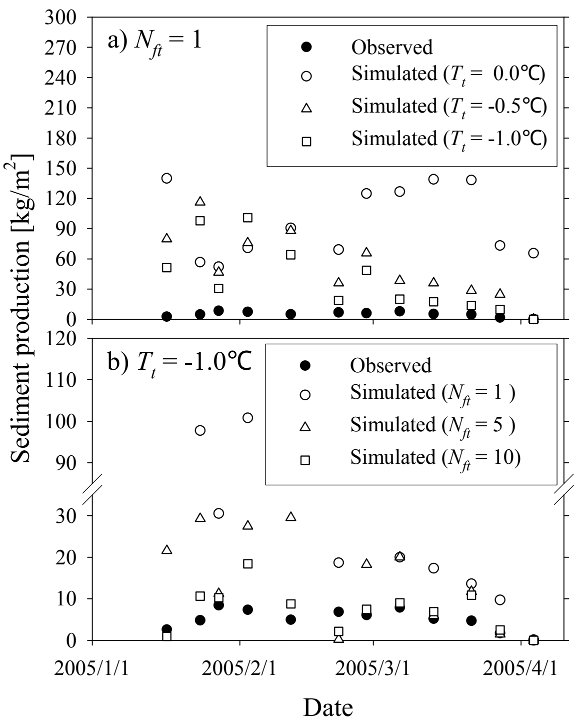

Fig. 10 Simulated sediment production: a) Necessary number of freeze and thaw cycle, N_{ft}, was fixed to be 1, b) Threshold temperature for freezing, T_t, was fixed to be -1.0 degree C

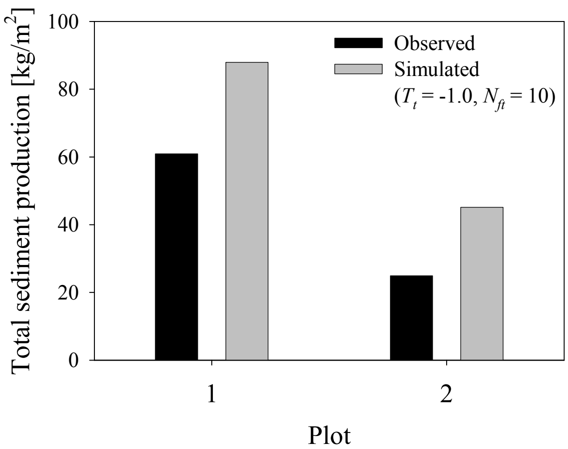

Fig. 11 Comparison between the observed and simulated total sediment produciton (T_t = -1.0°C and N_{ft} = 10 were applied for the simulation)

overestimation of the simulated sediment production were not improved at all, as long as N_{tf} was fixed to be 1 (the results is not shown). However, the simulated sediment production decreased as N_{ft} increased, and the observed change of sediment production was well simulated with N_{ft} = 10 (Fig. 10b). The total sediment production simulated with T_t = -1.0 degree C and N_{ft} = 10 shows little difference with the observed result in both plot 1 and 2. However, the quantitative relation between plot 1 and 2 are well simulated (Fig. 11). These simulated results indicate that the multiple experience of freeze and thaw cycle is necessary for the weathered bedrock to be granulated into sediment. However, the value N_{ft} = 10 which is employed in the last simulation may not be optimum for all type of bedrocks. It must depend on the geology and intensity of the effect of weathering.

4. CONCLUSIONS

According to the observation conducted on a bare slope in Tanakami Mountains and model simulation for the observed results revealed several important findings, as follows

(1) The freeze and thaw action in winter season practically causes active sediment production granulating the weathered granite bedrock in the observed bare slope in Tanakami Mountains.
(2) The surface cover on the bedrock controls the effect of freeze and thaw. Therefore, the amount of sediment production reduced in case the bedrock was covered by the sediment.
(3) It seemed to be necessary for the bedrock to experience the multiple freeze - thaw cycles to granulate and become sediment. For the case of the observed slope, around 10 cycles was necessary, however, it depends on each bedrock geology and level of weathering.
(4) It is possible to simulate the thermal conductance within the bedrock and resulting sediment production by the simple mathematical model presented in this paper.

Because the observed results presented here are limited for the site, it is necessary to extent the observation site to other geology climatic zone to elucidate the general mechanism of the sediment production due to freeze and thaw action. In this research, several simplifications have done in the model simulation, such as the ignorance of water flow within the weathered bedrock or thermal conductance through atmosphere. Therefore, several improvements which must be done for the simulation model still remain.

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