Investigation of Groundwater Flows Inducing Fluidized Landslides at Source Areas of Debris Flows in Metamorphic Mountains, Japan

Gen Furuya,[1)] Akira Suemine,[2)] Takeshi Komatsubara,[3)] Naoki Watanabe[4)] and Hideaki Marui[5)]
1) Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan (furuya@landslide.dpri.kyoto-u.ac.jp)
2) Tokushima Landslide Observatory, D.P.R.I., Kyoto University, Ikeda-cho shuzu, Miyoshi, Tokushima 778-0020, Japan (suemine @mail.netwave.or.jp)
3) Environmental Science Research Niigata, 8-13 Yoshida-higashisakae-cho, Tsubame, Niigata 959-0291, Japan
4) Research Center for Natural Hazards and Disaster Recovery, Niigata University, 8050 Ikarashi-ninicho, Niigata 950-2181, Japan (jibanken@cc.niigata-u.ac.jp)
5) Research Center for Natural Hazards and Disaster Recovery, Niigata University, 8050 Ikarashi-ninicho, Niigata 950-2181, Japan (maruihi@cc.niigata-u.ac.jp)

Abstract

We conducted a 1-m-depth ground temperature survey and water-chemistry analysis at source area of debris flow in metamorphic mountains, Shikoku Island, southwestern Japan, to clarify the relationship between distributions of focused on the vein-like groundwater flows that increase pore-water pressure, and clarified the relationship between distributions of fluidized landslides (slope failures inducing debris flows) and groundwater veins. Results of this study lead to the following conclusions: The slope failures appear to concentrate around shallow groundwater veins and groundwater veins rising from deep layers. This means that slope failures caused by these groundwater veins in addition to rainfall. Two types of groundwater originate in the deep layers: one has short storage time as indicated by the fact that dissolved substances are low; the other is stored for a lengthy period as noted by a high concentration of dissolved substances.

Keywords: slope failure, groundwater flow, soil temperature, water-chemistry

Introduction

Most of shallow slope failures in humid areas are caused by heavy rainfall. Some of the slope failures turned into fluidized landslides causing serious damage to social infrastructure and human life. Debris flows occurred in the Tobinosu Torrent, Nishi-iyayama-mura Zentoku, Miyoshi city, Tokushima, Shikoku Island, during heavy rainfall (maximum accumulated rainfall is 476mm/day and intensity of rainfall is 65mm/hour) on 29 June 1999. These debris flows were generated by slope failures at source area of this torrent, which caused damage to houses and road (Photo 1).

It is well known that the main factor associated with slope failure during heavy rainfall is increase in pore-water pressure. Generally, the groundwater regime is assumed uniform and constant when the landslide mechanism is examined. However, the importance of bedrock or substrate topography and fracturing as a control of subsurface flow gradually being recognized in hillslope hydrology (Selby, 1993; Montgomery et al., 1997; Sidle et al., 2000). Takeuchi (1981) noted that groundwater in natural slopes flows in a vein-like manner, i.e., in subsurface streams. This indicates that the location of such groundwater flow corresponds to higher permeability zones. From these back ground, Furuya et al. (2004) pointed out the location of slope failures were subjected to groundwater veins at the mountainside in metamorphic area by means of geophysical exploration and field investigation. In contrast, planar distribution of groundwater flow was not clarified at the source area of debris flow because all most research point of debris flow was its mobilization in a pass (torrent).

In this study, we conducted a ground-temperature survey at 1-m depth combined with slope-stability analyses to clarify the relationship between the distribution of slope failures and groundwater veins at a landslide in crystalline schist area. In addition, water-chemistry was investigated at springs and boreholes in and around the study area to elucidate the depths of the groundwater sources related to slope failures.

Study area

Fig. 1 shows the location of the Zentoku area in the Sambagawa metamorphic belt in the center of Shikoku Island, southwestern Japan. The investigation was conducted at the B and C tributaries of the

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Photo. 1. Debris flow at Tobinosu Torrent (Photo by Shikoku Mountains Region Sabo Office, M.L.I.T.)

Tobinosu Torrent, located at mid-slope in the Zentoku area. Bedrock of the Tobinosu Torrent consists mainly of pelitic schist and green schist, which is same as the middle and lower parts of the bedrock slope in Zentoku landslide (Fig. 2). Shallow part of the Tobinosu Torrent is different from the Zentoku landslide, which consists weathered material and colluvium at depth of 1–3m and bedrock and large boulders are locally exposed (Furuya et al., 2006).

Fig. 3 shows the topography of the source areas of the debris flow at the B and C tributaries of the Tobinosu Torrent. The average slope gradient in this area is 35°. In this area, three colluvial slope failures have resulted in debris flows triggered by the 1999 heavy rainfall. By observation of the scarps, materials of these slope failures were determined to be colluvium. Slope failure at the B tributary was located in the torrent bed; the volume of this failure was 2500 m^3. At tributary C, there occurred one large (called "large slope failure at the C tributary") and one small slide (called "small slope failure at the C tributary"), with combined volume of 3500 m^3 (Hiramatsu et al., 1999). The depth of these slides was 2–3 m. In addition, there was an old slide with a volume of several hundred cubic meters located between the slope failure at the B tributary and the large slope failure at the C tributary. Some small recent and older slope failures are shown in the northeast part of this figure. These small failures have not been considered in this study because their volumes were very small and the soil surface layer (colluvium) was thin. There are four springs in this area, located along the C tributary. One is on the scarp of the large slope failure at the C tributary. The others are located on the scarp and the upper part of the small slope failure. The groundwater discharge from these springs flowed on the surface for 5–10 m and then infiltrated into the slope (called "return flow").

Methodology of the investigation

1-m-depth ground temperature survey

Takeuchi (1980, 1981) developed the concept of ground-temperature surveys at 1-m depth to detect subsurface groundwater flow (called "1-m-depth ground temperature survey") in natural slopes and leakage of embankments at river. Principle of this method is that differences in relative ground temperatures disturbed by veins of groundwater are measured at a depth of 1 m. The ground temperature in the vicinity of the groundwater vein tends to be lower than the average ground temperature from summer to autumn because flowing groundwater temperature is lower than normal ground temperature at a depth of 1 m. In contrast, the ground temperature in the vicinity of the groundwater tends to be higher in winter to spring as compared to the temperature of the surrounding ground because flowing groundwater temperature is higher than normal ground temperature at a depth of 1 m. Takeuchi (1980, 1981) has noted that 1-m-depth ground-temperature surveys can be conducted when the ground temperature difference between the normal ground temperature at a depth of 1 m and the flowing groundwater temperature exceeds 2.5°C. Our survey at the B and C tributaries of the Tobinosu Torrent was conducted from on 17 to 19 September 2001. This term of the difference between

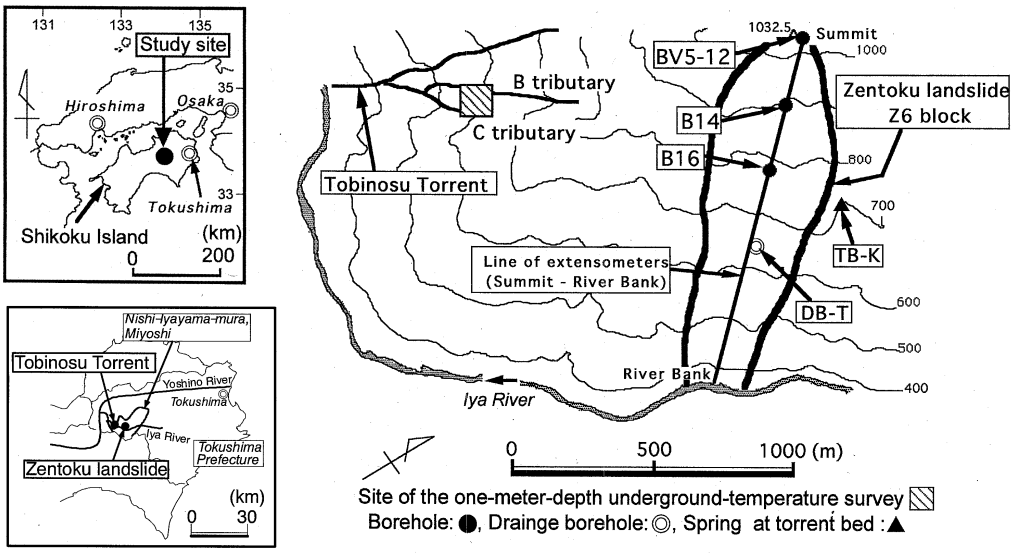

Fig. 1. Map of the study area

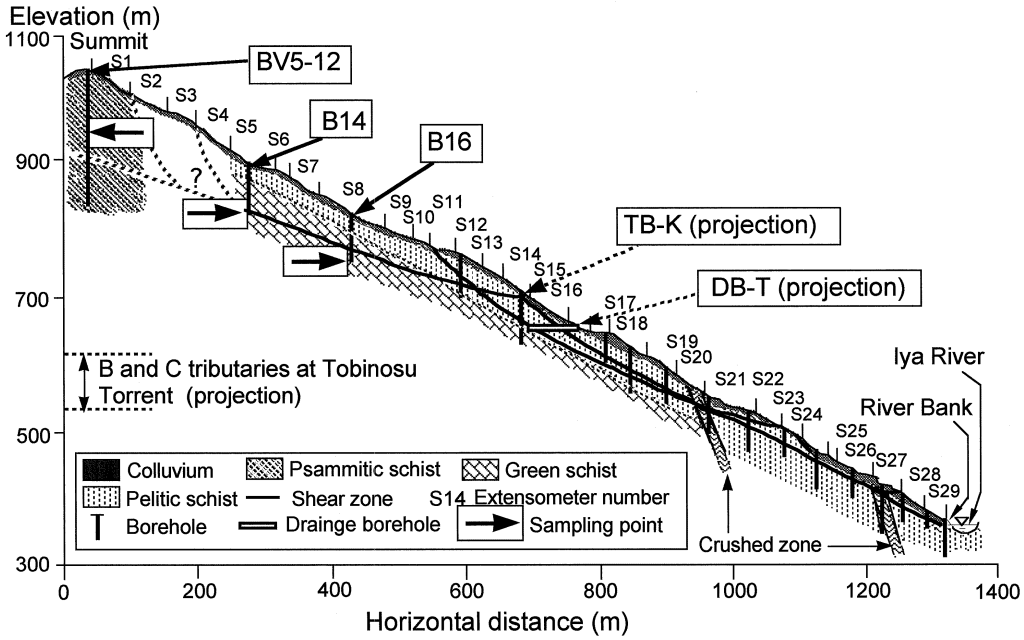

Fig. 2. Geologic cross section through the Zentoku landslide Z6 block along the line of extensometers, and location of measurement points for groundwater temperature

the normal ground temperature at a depth of 1 m and the flowing groundwater temperature were greater than 2.5°C.

The survey proceeded in the following four steps:

(1) A 10-m (15-m measurement grids established to survey temperatures (Fig. 1). There were 139 nodes in tributaries B and C (Fig. 3). No measurement grids were located in the northeast and southwest parts of Fig. 3 because the colluvium was less than 1 m thick in those areas (bedrock is partly exposed), thus a one-meter-depth ground-temperature survey was not possible.

(2) A 1 m deep hole was made at each point by penetrating a steel pick marked 100 cm (diameter = 2.5 cm; length = 150cm).

(3) Precise thermometers (readable precision 0.01°C) were inserted into the bottom.

(4) Temperature was measured for 10 minutes.

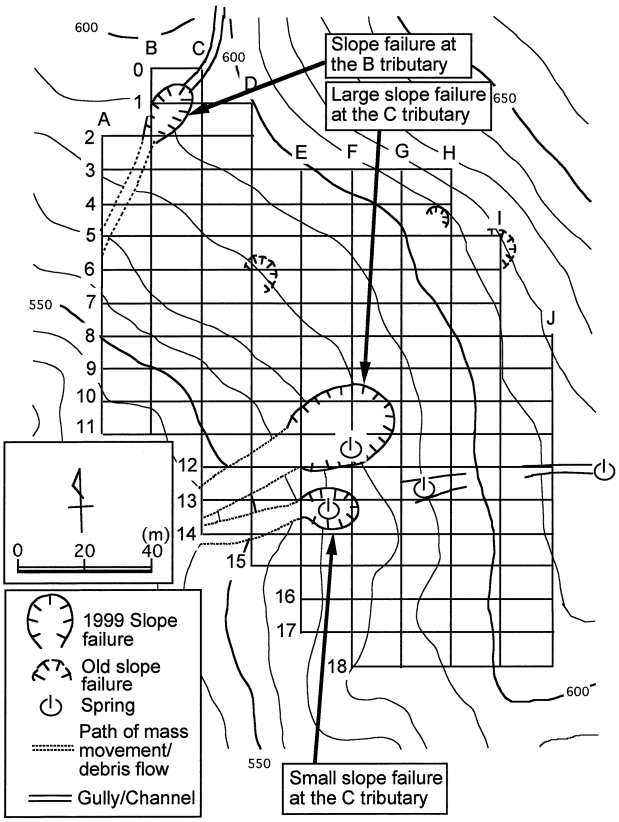

Fig. 3. Location of measurement grids for the B and C tributaries of Tobinosu Torrent

Measurement and analysis of water-chemistry

Differences in water-chemistry provide a useful index for classifying flowing groundwater. We measured water-chemistry of springs in and around the one-meter-depth ground-temperature survey sites. Temperatures of springs were measured at four points tributaries B and C (Fig. 3). If water-chemistry information for the flowing groundwater could be obtained, this would help estimate the depth of the origin of the groundwater because deeper groundwater is generally stored for longer periods and contains larger amounts of dissolved constituents than the groundwater at shallow depth. However, no deep boreholes were present in the Tobinosu Torrent catchment. The Z6 block of the Zentoku landslide, located approximately 1 km east of the Tobinosu Torrent, contains many boreholes for water-level monitoring and drainage, and the area has similar lithology. Thus, groundwater information (water-chemistry data) in the Z6 block was used to ascertain the depth of origin of the groundwater in the area of the B and C tributaries of the Tobinosu Torrent. Water-chemistry was measured in groundwater from boreholes and a spring entering the torrent bed of the Z6 block (Figs. 1 and 2). Borehole sampling locations BV5-12, B14, and B16 in the Z6 block were screened at their bottoms, which were located near the slip surface. Sampling points were at depths of 90, 70, and 49 m, respectively. DB-T is a drainage borehole that reaches bedrock. TB-K is a spring at the torrent bed. Water-chemistry measurements were conducted during the one-meter-depth ground-temperature surveys. Analyzed items were Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^-.

Results

Distribution of ground temperatures at 1 m depth

Fig. 4 shows an isothermal diagram of temperature ay 1-m depth from 15.5 to 20.5 by 1°C increments in the B and C tributaries of the Tobinosu Torrent. Maximum ground temperature was 20.6°C (node A3), minimum ground temperature was 15.1°C (node E13), and average ground temperature was 18.9°C in this area. The groundwater temperatures at springs at the B and C tributaries of the Tobinosu Torrent were lower than the minimum measured value for the adjacent ground. The temperature at the upper slope of node J12 was 12.7 °C; at node F12 (the large slope failure at the C tributary) temperature was 13.9°C; at nodes G12–13

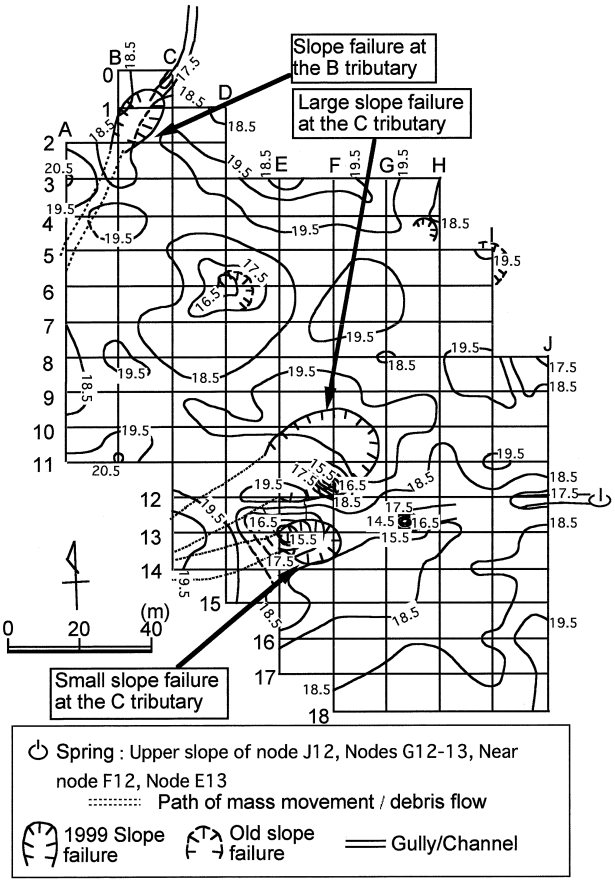

Fig. 4. Distribution of maximum slope angle at the B and C tributaries of the Tobinosu Torrent

temperature was 14.1°C, and at node E13 (the small slope failure at the C tributary) temperature was 13.5°C. The groundwater temperature of a spring near node F12 (spring of the large slope failure at the C tributary; Fig. 3) was remarkably lower than that at node E13. However, node F12 did not have the lowest temperature at the B and C tributaries of the Tobinosu Torrent, probably because the spring near node F12 was very small and the measurement interval was too large to detect the temperature effect of this spring.

Water temperature and chemistry for springs and boreholes

Fig. 5 shows groundwater temperatures, electrical conductivities, and hexa diagrams of ion concentrations for some springs at the C tributary, in boreholes and return flow at torrent bed in the Z6 block in September 2001. As for groundwater temperature values in this figure, the springs of at the C tributary are approximately the same as at all points of the Z6 block (i.e., 12 to 14°C). However, electrical conductivities are different between the waters from the C tributary and from the Z6 block. Electrical conductivity of the water at the node F12 (Large slope failure at the C tributary) is the same as that from boreholes in the Z6 block. In contrast, springs of the upper slope of node J12 and nodes G12–13 are the same as the return flow at torrent bed in the Z6 block. The difference in electrical conductivities is consistent with the differences in ion concentrations shown in Fig. 5. Upper slope of node J12 and nodes G12–13 do not show a definite water-chemistry pattern because this groundwater is extremely diluted. This water-chemistry pattern is similar to the results of the analysis at TB-K in the Z6 block. In general, waters in the soil and saprolite layers of the shallow zone have low ion concentrations because weathered materials such as soil and saprolite are residual materials depleted in soluble chemicals. In contrast, the area near node F12 a definite Ca-HCO_3 water-chemistry type appears similar to B16 and point DB-T of the Z6 block. Since the crystalline schist in the deep portion of the slope in the Zentoku area (Fig. 2) includes calcium rich minerals such as anorthite, actinolite and epidote, the formation of Ca-HCO_3 type water-chemistry can be represented as:

$$\text{Ca-mineral (e.g. anorthite)} + H_2O + CO_2 \rightarrow Ca^2 + +HCO_3^- + SiO_2 + \text{Clay-mineral}$$

Similar water-chemistry among the areas near nodes F12, B16 and DB-T suggests that all groundwaters

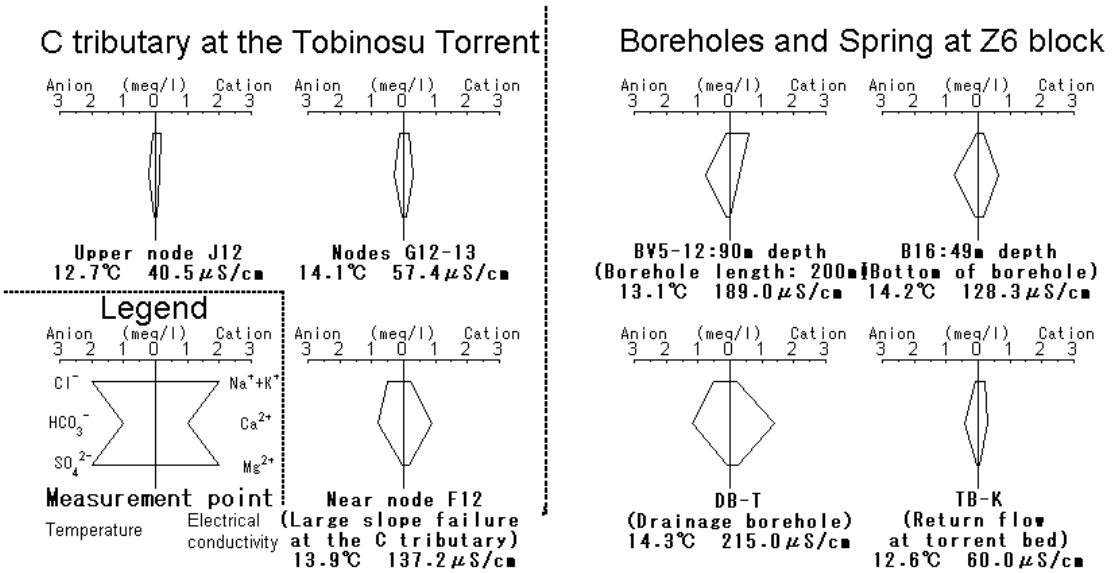

Fig. 5. Temperature measurements and chemical-analysis results at the Tobinosu Torrent and the Z6 block

were formed under similar hydrochemical and hydrogeological conditions. Thus, the water-chemistry near node F12 at the C tributary of the Tobinosu Torrent indicates that the groundwater is discharging from the deep part of the slope, such as in the landslide mass, compared with other nearby springs (upper slope of node J12 and nodes G12–13) at this tributary of the Tobinosu Torrent. The water-chemistry at BV5-12 is characterized by Na and K-HCO_3, which was different from the water-chemistry in the other boreholes of the Z6 block. The reason for this difference may have been that the deep part of upper slope is including natrium rich mineral such as albite. From difference of water-chemistry in boreholes in the Z6 block, the groundwater of BV5-12 is not flowing into the surveying area (the source areas of the debris flow at the B and C tributaries).

Relationship between slope-failure locations and groundwater veins

Distribution of slope-failures and groundwater veins

Fig. 6 shows the coupled distributions of the low ground-temperature zones, veins of groundwater, and the actual slope failures at the B and C tributaries, Tobinosu Torrent. This figure shows the lower-than-average ground temperature zones (18.5°C) and zones with temperature lower by 2.5°C than the average ground temperature. The veins of groundwater are as follows: zone 1 is along the B tributary (nodes C0 to B3); zone 2 is at the large slope failure at the C tributary; zone 3 extends from the upper slope of node J12 to the small failure at the C tributary with a branch vein at nodes I11 to F17, and zone 4 is within an area of approximately 40 m (40 m surrounding node D6 (Furuya et al., 2001 and Furuya et al., 2006). The vein of groundwater in zone 3 consisted of return flow because the springs in this zone were formed when surface water repeated infiltration and discharge at shallow layer of the upper part of the C tributary. These springs showed a concentration of dissolved ions (electric conductivity) similar to that at TB-K in the Z6 block (Fig. 5). The branch stream of this vein of groundwater starting from I12 may also have been fed by the return flow because discharge groundwater from the upper slope of node J12 was infiltrating in the gully.

No springs existed at the B tributary. However, the vein of groundwater along tributary B likely flowed beneath the bed of this tributary as indicated by the low ground temperatures along the torrent bed. Hence, it can be concluded that the type of return flow was similar to that in the TB-K of block Z6. The low-temperature distribution disappeared in the vicinity of node B3, suggesting that the vein of groundwater infiltrated into the deep zone of the torrent bed. The large slope failure at the C tributary had a very small spring near node F12. The water-chemistry of this spring differed from that of the vein of groundwater in zone 3, which flowed near the large slope failure (Fig. 5). In the Zentoku area, many cracks in bedrock outcrops were found during field investigations as well as in the rock mass during the construction of drainage wells. Hence, the vein of groundwater in zone 2 appeared promoted to by fissures. The water-chemistry of this vein

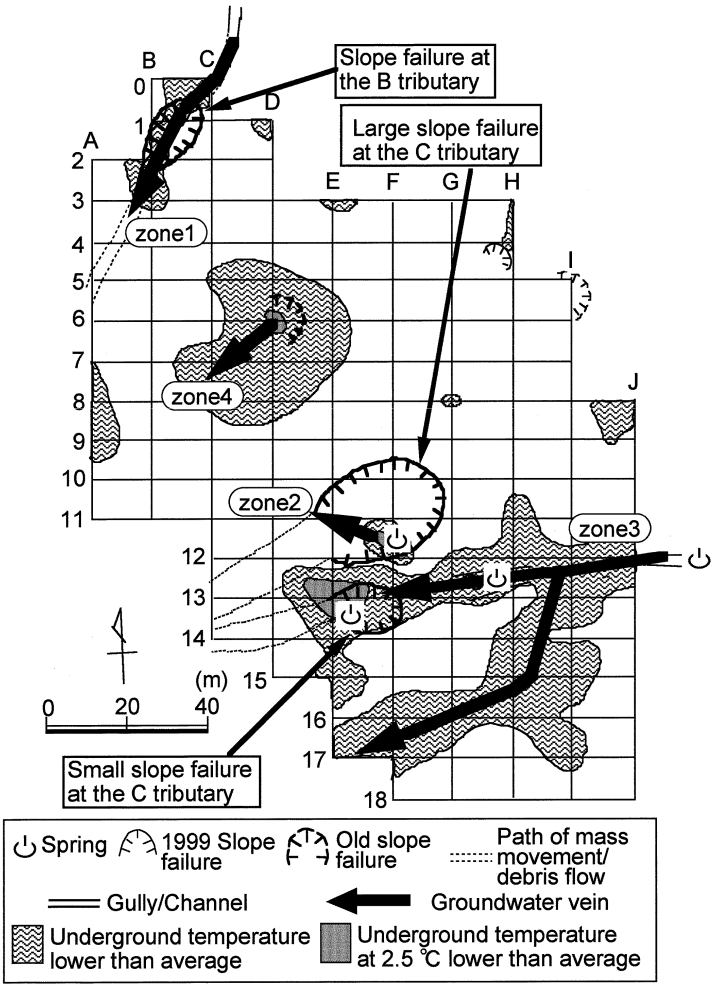

Fig. 6. Distribution of groundwater veins and slope failures at the B and C tributaries of the Tobinosu Torrent

and the dissolved ion concentrations were similar at locations B14 and DB-T in the Z6 block. Therefore, the vein of groundwater in zone 2 discharged from the deeper layers near the slip surface of the Z6 block. No springs occurred near node D6; however, it is believed that the deep layer of groundwater rose near the surface because the zone of ground temperatures was lower (by 2.5°C) than the average for node D6.

Three slope failures that generated debris flows were located in the measurement grids. A common feature of these slope failures is that they occurred in zones of low ground temperature. Among these, the slope failure at the B tributary and the small slope failure at the C tributary were related to return flow of groundwater vein in addition to the concentration of rainfall-induced groundwater in the veins of zoons 1 and 3. In contrast, the large slope failure at the C tributary was related to a fissure-type vein in addition to heavy rainfall. However, it is presumed that this slope failure did not occur at once but developed retrogressively toward the upper slope. The old slope failure at node D6 could have been caused by water rising from fissures.

Groundwater flow into slope failures at source area of debris flow

It was clearly shown that slope failures (fluidized landslides) inducing debris flow were located on and around the groundwater veins in the metamorphic area (Fig. 6). Although these slope failures were triggered, these veins can be divided into three types flows that in shallow layers and two types flow originating from deep layers. Fig. 7 indicates schematic diagram of groundwater vein into slope failure at source area of debris flow in the metamorphic area. The groundwater veins in the shallow layers were very low in dissolved substances because they flowed through weathered layers depleted in soluble minerals and rapidly discharged to the surface (Fig. 7(a)). Furuya et al. (2006) pointed out that one of fluidized landslides (slope failures) in the Z6 block located on a groundwater vein was flowing at extremely shallow layers. In the surveying area, the slope failure

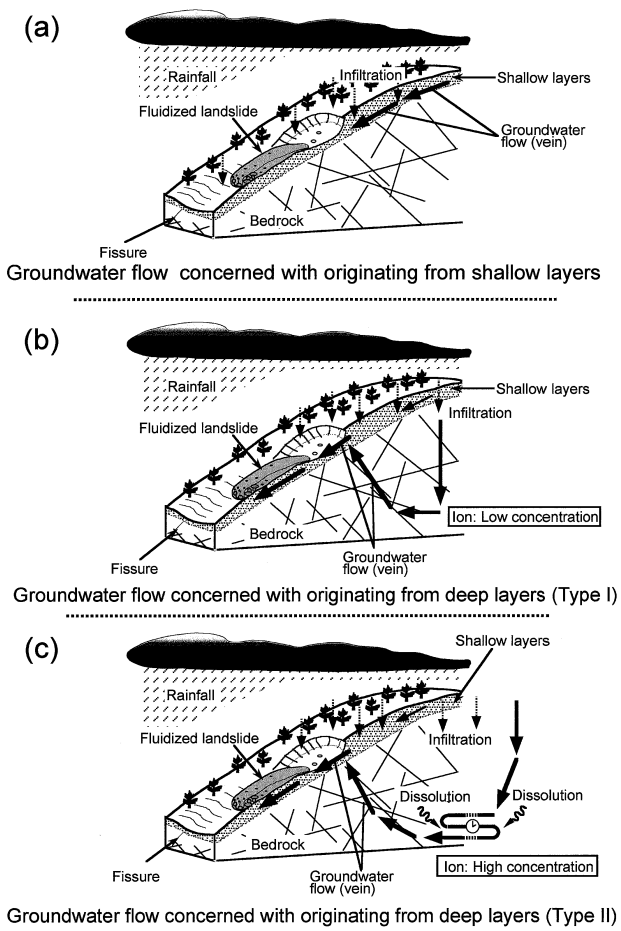

Fig. 7. Schematic diagram of groundwater flow into slope failure at source area of debris flow

at the B tributary may relate to the shallow layers type because the vein of zone 1 is flowing as return flow around the torrent bed of B tributary. The groundwater veins originating in deep layers were comprised of at least two types based on water-chemistry analysis.

The first type (Type (I)) corresponds to the infiltration of rainfall into deep layers of the slope; in this case, the groundwater temperature became approximately the same as the temperature of the surrounding material, and the groundwater vein rapidly discharged to the surface (Fig. 7(b)). Although the chemical reaction rate is unknown, this type of groundwater vein might not have sufficient time to react with the slope material. The small slope failure at the C tributary corresponds with the first type, but groundwater is flowing (zone 3) in several dozen meters of upper slope at the scarp (nodes F13 to J12 shown in Fig. 6) as the return flow. The second type (Type (II)) represents groundwater that was flown in long path, which was formed by the dissolution of soluble minerals around veins in the deep part of the slope during long time groundwater migration (Fig. 7(c)). The relatively high concentrations of dissolved substances, particularly Ca^{2+} and HCO_3^- in the vein of zone 2 (Figs. 5 and 6), might be due to reaction between the groundwater and rocks or colluvium, including anorthite, actinolite and epidote. It thinks that the groundwater is flowing some complicated and long path including from out side of topographic catchment area. The large slope failure at the C tributary relates to this type. In this study, we cannot exactly categorize the vein of zone 4 around D6 (Fig. 6). However, the vein of zone 4 may be categorized the first type or second type of originating from deep layers because the distribution of this veins is locally.

Conclusions

A one-meter-depth ground-temperature survey was conducted and combined with water-chemistry analysis to clarify the relationship between the distribution of slope failures inducing debris flows and the veins of groundwater in source area of debris flow, in metamorphic (crystalline schist) mountains area. The

conclusions of this investigation can be summarized as follows:

(1) The slope failures inducing debris flow were located in the vicinity of shallow groundwater veins with slightly lower than average ground temperatures (1-m depth) or in zones considered as veins of groundwater rising from deep layers which had remarkably lower than average temperatures or almost the same temperature as in deep portion of boreholes. Groundwater veins in addition to heavy rainfall caused these slope failures.

(2) At least two types of groundwater veins originate from deep layers. The first type (Type (I)) is associated with the groundwater infiltrating from rainfall, which has approximately the same temperature as the surrounding geologic material and quickly discharges to the surface. The second type (Type (II)) is infiltrated groundwater stored for longer period (flowing some complicated and long path), followed by subsequent discharge to the surface; this water includes dissolved substances from the rock or colluvium.

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