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Geoelectrical laboratory and field studies of groundwater occurrence in a landslide area: a case study from Japan

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Key Words: landslide investigations, electrical resistivity, water table, snowmelt

ABSTRACT

We present the results of electrical resistivity surveys carried out to estimate the seasonal variation of the water table level in a large-scale landslide area of Tertiary geology in Japan. One long profile, trending NE-SW, was established perpendicular to the main regional geology of the region. Three boreholes are located very close to the profile. The profile was surveyed twice, once before snowfall and once after snow had melted.

The relationship between resistivity and water saturation of pyroclastic materials was clarified through laboratory tests. We did this in order to estimate the water content of the pyroclastic layer from the observed resistivity distribution in the landslide area. The resistivity of the saturated pyroclastic deposit calculated using an empirical formula was found to be 570 Ω.m. Based on this computed resistivity, the groundwater level was deduced by assuming that the pyroclastic deposits were fully saturated beneath the water table. We show that the estimated water table before snowfall is lower than that inferred after snow has melted, by about 1.1 to 4.7 m. This suggests that the water table in the upper part of the pyroclastic layer in the landslide area fluctuates greatly, compared to the lower part. This seasonal groundwater fluctuation is possibly caused by the infiltration of water into the subsurface after snowmelt.

INTRODUCTION

Most current landslides are recurrences of previous landslides. The main factors in triggering these landslides are rainfall and snowmelt, which bring about an increase in pore water pressure at the slip surface, erosion at the landslide toe, and so on. Several other factors relating to the landslide generation mechanism must be studied in order to predict the type of disaster that may arise because of a slide, and to formulate measures for preventing slides. In order to obtain necessary data for landslide mechanism analysis, such as the shape and position of the slip surface, subsurface conditions, and groundwater distribution in the landslide area, most landslide experts make use only of borehole information. However, there are many cases in which such data are insufficient, so there is a need to design appropriate technology for predicting landslides (Matsuura et al., 1998). To overcome some of these problems, electrical resistivity surveys have increasingly been used as a survey technique for landslide studies. The resistivity method helps by revealing the resistivity characteristics of the subsurface, thereby providing valuable information on groundwater distribution and on the geological structure of the subsurface (Konishi, 1998).

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In this study, we have investigated the shape of the water table and its seasonal variations in a known landslide area in Japan, by conducting an electrical resistivity survey in this area in two phases, firstly before the onset of winter snowfall and secondly after the snow had melted. Using the well-established relationship between resistivity and water saturation, the water-table level in a pyroclastic deposit layer was estimated. In addition, the efficacy of the resistivity technique for groundwater investigations was examined by comparing the water-table level obtained using this method with observations from different boreholes in the survey area.

DESCRIPTION OF THE STUDY AREA

The Dozan River landslide region is located in the Mogami District of Okuramura, Yamagata Prefecture (Figure 1), where a large landslide occurred in May 1996 immediately after snowmelt. Cracking, and collapse of subsurface structures, occurred along the road that passed through the area. The end of the road slipped towards the Dozan River. In addition, the formation of a head scarp and collapse benches were observed in the upper part of the slide. The landslide affected area covering 1100 × 1200 m. The average gradient of the landslide slope is about 11°. Small corrugations were discovered in the landslide area and we inferred that these were probably relics of previous landslides.

The geology of the study area consists of Tertiary mudstone and tuffaceous sandstone, overlain by a pyroclastic layer. A distinct unconformity separates the tuffaceous sandstone from the pyroclastic layer (Figure 2). The pyroclastic layer was ejected by the Hijiori volcano, and is composed almost entirely of unconsolidated sand. Asano et al. (2000) showed that the pyroclastic deposit layer has not been disturbed by any landslide activity since deposition. Well-log data indicate that the entire pyroclastic deposit layer is an aquifer. There are also highly permeable tuffaceous sandstone and mudstone beds in some parts of the aquifer. A slip surface is also

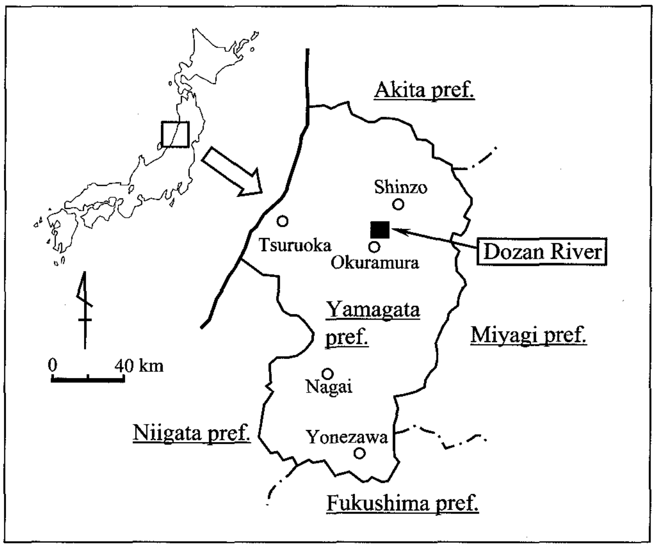

Fig. 1. Location of the Dozan River landslide area.

found within the mudstone bed. Therefore, the hydrogeological characteristics of the pyroclastic layer are clearly different from those of the tuffaceous sandstone and mudstone beds.

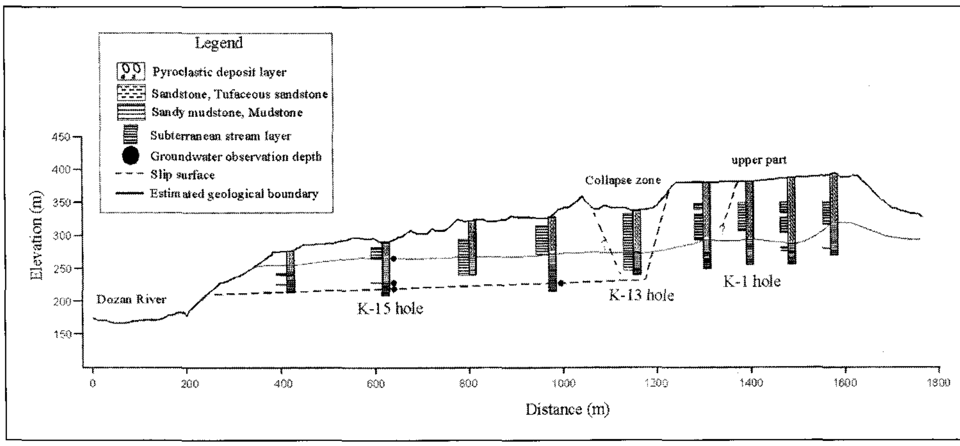

Fig. 2. Well-log information, geological stratigraphy, and the observed groundwater levels.

ELECTRICAL RESISTIVITY SURVEY

Using the electrical resistivity method, the true resistivity distribution in the subsurface can be estimated from the apparent resistivity distribution measured at the ground surface. The resistivity distribution directly beneath the measurement area being investigated are usually illustrated as multi-dimensional cross-sections, representing either the 2D or 3D structure of the subsurface. This method is widely used in geotechnical engineering for subsurface exploration of tunnel and dam sites, and in landslide areas (Matsui et al., 1997 and 1999).

As shown in Figure 3, we established a survey line perpendicular to the regional geology of the study area, for data acquisition purposes. Some boreholes exist close to this line, and we intended to correlate the inverted resistivity image of the subsurface with the borehole logs. The electrical survey was carried out along the same survey line on two different occasions, first after snow had melted (June 1–5, 1999) and secondly before the next snowfalls (October 24–30, 1999). The survey line was 1480 m long. The electrode layout used was the dipole-dipole configuration with electrode interval of 10 m. The depth of investigation with this method was 50 m.

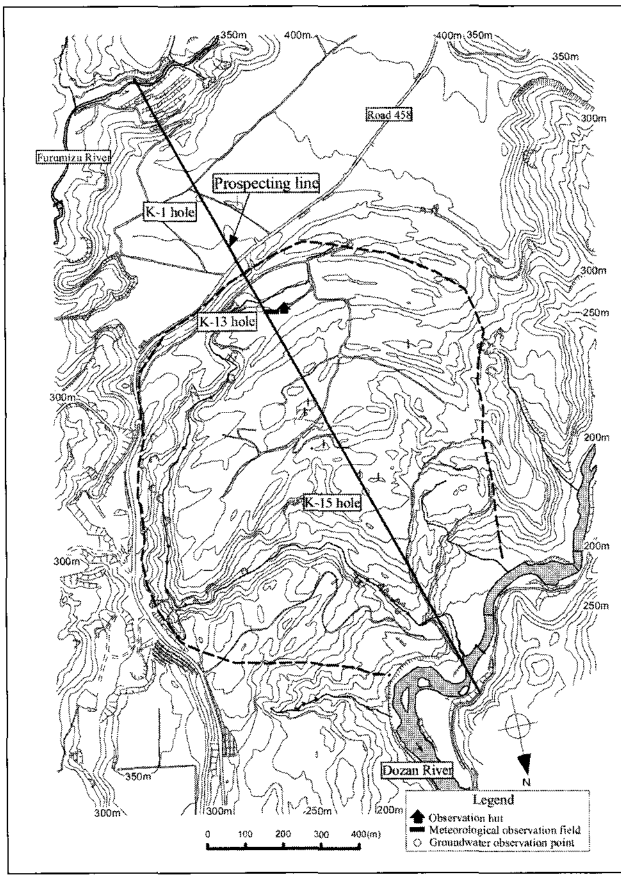

Fig. 3. Survey line and groundwater observation points in the research landslide area.

RESISTIVITY SURVEY RESULTS

The resistivity distributions in the subsurface beneath the survey area, obtained by inversion of field data, are shown as Figures 4 and 5. In these figures, the resistivity of the pyroclastic layer near the surface is greater than 1000 Ω.m, and tends to decrease with depth. This decrease in resistivity seems to be related to water saturation in the pyroclastic layer. In addition, a low-resistivity zone, with values of 100 Ω.m or less, is observed around the Dozan River, at the margin of the landslide area. In this area, there is a thin pyroclastic layer, overlying weathered tuffaceous sandstone and mudstone beds.

In general, we observe that the resistivity distributions in the subsurface of the landslide area were the same after the snow had melted as before the next snowfall, except for small differences in the upper part of the cross-section. These differences are apparently the result of seasonal groundwater fluctuation in the pyroclastic layer. According to water table information obtained from the boreholes mentioned earlier, the pyroclastic layer is saturated with groundwater. Therefore, it is necessary to clarify the relationship between resistivity and water saturation in pyroclastic deposits, so that we can estimate the degree of groundwater saturation in the pyroclastic layer from the resistivity distribution in the affected area.

Relationship between resistivity and water saturation of pyroclastic deposits

In the laboratory, the resistivities of pyroclastic samples were measured at different saturations, using groundwater collected from boreholes close to the survey line. This was done in order to examine the effect of saturation on the resistivity of the pyroclastic layer. First, the physical properties of the pyroclastic materials were obtained, using block samples collected from various locations in the survey area (Table 1). The samples were prepared by air-drying before adjusting the saturation. The same samples were used repeatedly and only the amount of water present was changed. The samples were compacted, using a rammer, to the wet density shown in Table 1 before the resistivity tests were carried out. The compaction method used is the 1990 standard number A1210: (Japan Industrial Standard).

The resistivity measurement system is shown in Figure 6 (Park and Matsui, 1998). It consists of a function generator for controlling transmission current, a signal conditioner for adjusting the signals and measured the potentials of the specimen, a data

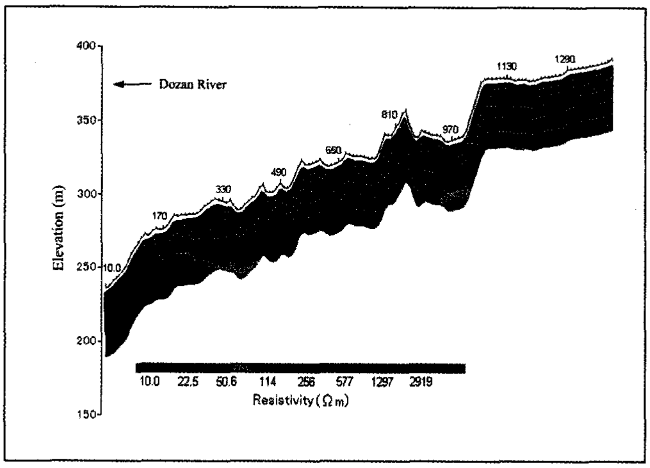

Fig. 4. Resistivity distribution after snowmelt (June 1-5, 1999).

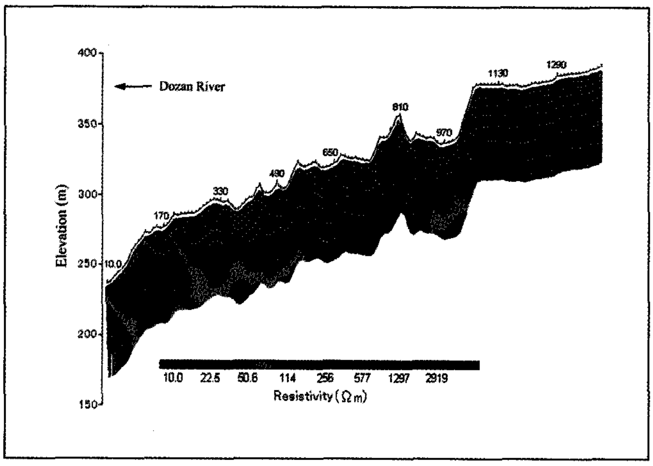

Fig. 5. Resistivity distribution before snowfall (October 24-30, 1999).

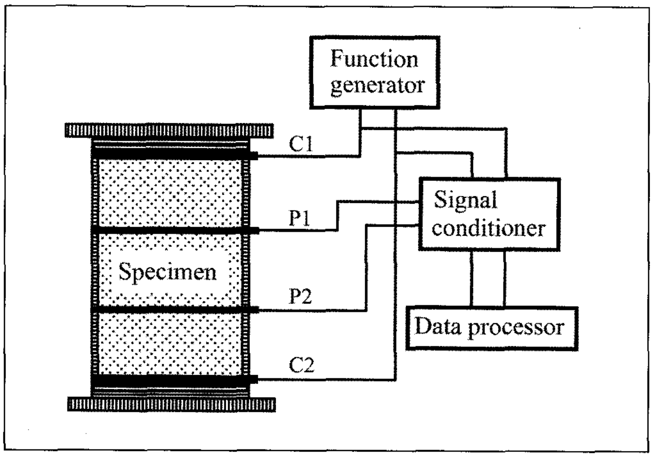

Fig. 6. Sample resistivity measurement system.

processor for calculating the resistivity of the specimen from input signals from a data logger, and an acrylic cylindrical sample holder. The function generator provided alternating current at an electrical potential of 3 V and a constant frequency of 0.03 Hz. In the sample holder, current was injected from 80-mesh copper electrodes (C1, C2) attached to each end of the sample, and the potential difference was measured from potential electrodes (P1, P2), which were 1 mm diameter copper wires inside the cylinder.

By measuring the potential difference in the axial direction when current flows through the cross section of the sample, the resistivity of a sample is given by equation 1:

$$R = \frac{S}{L}\frac{\Delta V}{I}, \qquad (1)$$

where R is the resistivity, S is the section area, L is the length of the specimen, I is the current and ΔV is the potential of the measured section.

The relationship between resistivity and amount of water present in the pyroclastic samples tested is shown in Figure 7. The saturation ranges from 4% to 20%. The resistivity of the pyroclastic material decreases with increasing amount of water present. These results show that resistivity of the pyroclastic material above the water table is largely determined by saturation. Saturation of the pyroclastic samples was calculated from the amount of water present, using equation 2:

$$S_r = \frac{w\rho_s}{e\rho_w}, \qquad (2)$$

where S_r is the saturation (%), w is the amount of water present in the sample (%), ρ_s is the density of soil particles (t/m^3), e is the void ratio, and ρ_w is the density of water (t/m^3).

Figure 8 shows the relationship between the resistivity and saturation in the pyroclastic samples, calculated from the amount of water present. The resistivity decreases with increasing water-saturation, as in Figure 7. Extrapolating the resistivity observations suggests that saturated pyroclastic samples would have a resistivity of 570 Ω.m. Based on this resistivity value we deduced that the 570 Ω.m resistivity isogram in the resistivity cross-sections represents the resistivity of the fully-saturated pyroclastic layer. This isogram therefore represents the water table in the pyroclastic layer.

Estimation of the water table

The water table estimated from the resistivity distribution after snowmelt is shown in Figure 9. The resistivity isogram of 570 Ω.m is considered to be the water table, as discussed above. This groundwater level is shown as a dotted line in the figure. We then compared the accuracy of the estimated water table by comparing the estimates with levels observed in boreholes. The average values of the water table observed during the survey period for the K-1, K-13, and K-15 holes were used. A strainer

Density of soil particles (t/m^3)	Water content (%)	Wet density (t/m^3)	Dry density (t/m^3)
2.69	11.85	1.74	1.56
Particle size distribution: Gravel, 25.25%; Sand, 73.28%; Silt, 1.48%			

Table 1. Average physical properties of pyroclastic materials.

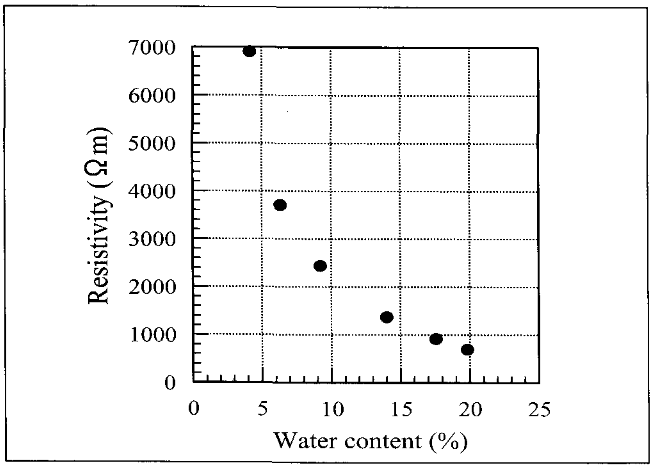

Fig. 7. Relationship between resistivity and water content of pyroclastic samples.

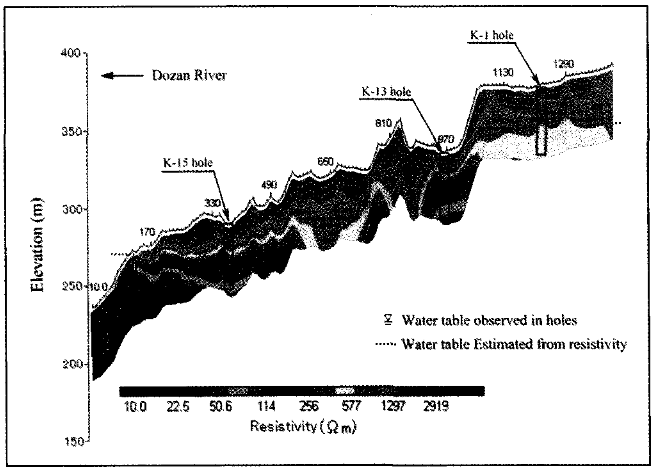

Fig. 9. Water table after snow melt, estimated from resistivity distribution.

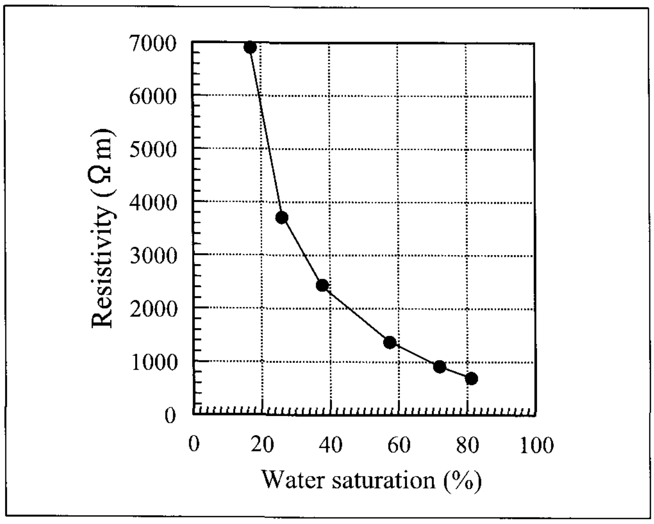

Fig. 8. Relationship between resistivity and water saturation of pyroclastic samples.

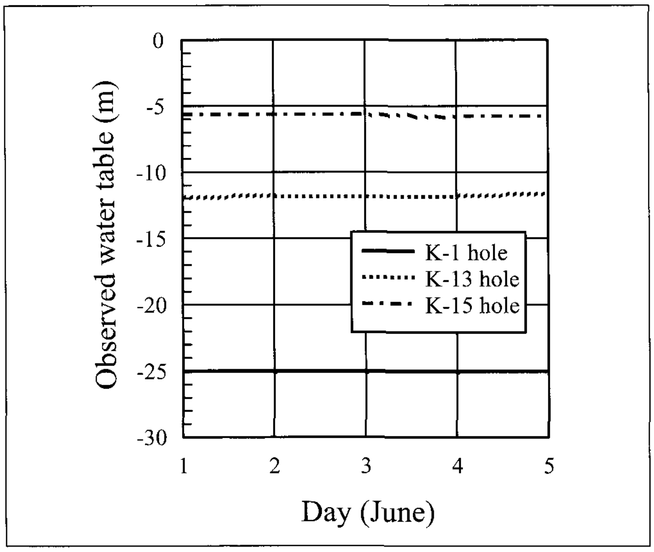

Fig. 10. Borehole observations of water table after snow melt.

Description	K-1 hole	K-13 hole	K-15 hole
After snowmelt (m)	-25	-11.8	-5.7
Before snowfall (m)	-29.7	-14.5	-6.8
Difference in water table (m)	4.7	2.7	1.1

Table 2. Comparison of the observed water tables after snowmelt and before next snowfall.

Influencing factors		Degree of influence Low resistivity ------ High resistivity	Geological conditions of rock mass
Porosity	Saturated condition	Large ---------------- Small	Weathered and fault/ fractured zones
	Unsaturated condition	Small ---------------- Large	
Pore fluid resistivity (Resistivity of groundwater)		Low ----------------- High	Components of groundwater
Water saturation		Large ---------------- Small	Water table
Water content by volume (Porosity and water saturation)		Large ---------------- Small	Weathered and fault/ fractured zones
Clay content		Much ---------------- Little	Weathered and altered zones

Table 3. Effect of various factors on rock material resistivity.

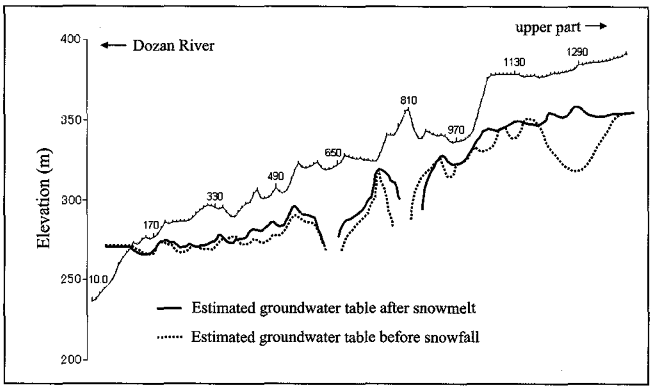

Fig. 11. Seasonal fluctuations of the estimated water table.

instrument was used to measure the water table in boreholes K-1 and K-13, and a piezometer installed at 23 m depth within the pyroclastic layer was used in borehole K-15 (see Figure 2).

Figure 10 shows the water-table level in the three boreholes observed during the survey period (after the snow had melted). The average water tables in K-1, K-13, and K-15 are 25 m, 11.8 m, and 5.7 m respectively. The water-table levels in holes measured using strainer agree quite well with those estimated from the resistivity distribution of the ground, but in the case of the K-15, the observed water table is slightly higher than the estimated one. A possible reason for this difference is that the water table in borehole K-15 is a little higher than the natural water-table level for the region. In addition, near the 810 m point, the estimated water table is very low, but the topography of this section is very rugged. It is possible that topographic effects were not properly accounted for in the resistivity inversion.

Seasonal variation in groundwater

The fluctuation of the water table estimated from the resistivity profiles after snow had melted and before next snowfalls is shown in Figure 11. The estimated water table before snowfall is generally slightly lower than that observed after snowmelt. In addition, the estimated water table in the upper part fluctuates greatly compared to that in the lower part of the landslide area. The observed water table levels in the boreholes are shown in Table 2. These are mean values observed during each survey period; after the snow had melted, and before next snowfall. The water-table observed before snowfall had dropped by from 1.1 to 4.7 m since snowmelt. The observed water table in borehole K-1, in the upper part, is also much deeper than that in K-15, in the lower part of the landslide area. These values show the same trend as that estimated from the resistivity inversions.

Observed water-table data during previous years has shown that the water table tends to rise a little from the end of May through June, when snow melts, giving a consistent long-term fluctuation of the water table observed in the K-1, K-13, and K-15 boreholes (Asano et al., 2000). This region receives a heavy snowfall, and infiltration of melt-water occurs when the snow melts. In addition, the aquifer in the topmost part of the landslide area serves as groundwater storage. Before snow falls, and without infiltration of melt-water from the surface, the water table in the upper part seems to fall much more than that in the lower part, because much groundwater flows from the upper part towards the Dozan River at the margin of the landslide area.

DISCUSSION

The resistivity below the water table depends mainly on porosity, resistivity of groundwater, and clay content. Of these factors, groundwater resistivity is observed to be almost constant for the same type of material. Therefore, the resistivity of the subsurface will be strongly influenced by porosity, which is related to cracks and fractures, and by clay content, which is related to weathering and other geological phenomena. This means that fault, fracture, and alteration zones show relatively low resistivity caused by increasing porosity and clay contents.

In addition, in the upper part of the rock mass, the resistivity of the material is strongly influenced by water saturation, and so can be predicted from the groundwater distribution. The factors influencing the resistivity of rock materials in this context are summarised in Table 3 (Matsui et al., 2000).

The research area is a large-scale landslide area where there is a thick pyroclastic layer on top of a Tertiary mudstone bed, and a slip surface exists within the mudstone. Observations of the water table in the existing boreholes confirmed that the water table lies in the pyroclastic deposit layer. The sand content of the pyroclastic layer is about 73%, and the permeability is also high, because the particle size distribution in all layers is almost homogeneous. For this reason, the water-table depths can be estimated from resistivity data obtained in an electrical resistivity survey, because the resistivity of the pyroclastic layer depends strongly on the amount of water present.

CONCLUSION

In this study we examined the application of the electrical resistivity method to groundwater investigation in a Tertiary large-scale landslide area. In this area, a thick pyroclastic layer lies on a Tertiary mudstone bed in which there is a slip surface, and the water table lies within the pyroclastic layer. Therefore, we established a survey line along the main longitudinal line, where boring had already been carried out, and an electrical resistivity survey was carried in two phases along this profile: the first before snowfall, and the second after snow had melted. The resistivity distribution in the subsurface was obtained by inversion analysis. To estimate the water table in the pyroclastic layer from the subsurface resistivity distribution, the relationship between the resistivity of pyroclastic deposits and water saturation was clarified through laboratory tests. As a result, we have shown that the resistivity of the saturated pyroclastic material is 570 Ω.m. Based on this resistivity value, the water table was estimated from the resistivity distribution of the ground by assuming that the 570 Ω.m isogram represented the water table in the pyroclastic layer. A comparison of the estimated water table and observed water table in boreholes found along the survey line showed good agreement. Furthermore, seasonal groundwater fluctuations were examined by estimating the water table from the resistivity distribution both before snow fell and after the snow had melted. The results confirmed that the estimated water table found before snowfall is, in general, lower than after the snowmelt by distances of between about 1.1 to 4.7 m. Also, the estimated water table in the upper part of the landslide area fluctuated greatly compared with that of the lower part. The seasonal variation was possibly caused by the infiltration of water during snowmelt. The estimated water table in the upper part greatly fluctuated compared to the lower part because the groundwater stored in the platform aquifer in the upper part flowed towards the Dozan River.

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전기비저항탐사에 의한 산사태 지역의 지하수조사

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요 약: 일본의 제 3 기 퇴적암이 분포하고 있는 대규모 산사태 지역에 있어서 계절에 따른 지하수위 변동을 파악하기 위하여 전기비저항탐사를 적용하였다. 기존의 시추조사가 수행된 NE-SW 방향으로 탐사측선을 설치하고, 동일 탐사측선에 대해서 눈이 녹은 6월과 눈이 오기전의 10월에 각각 전기비저항탐사를 실시하였다. 또한 산사태 지역에 두껍게 분포하고 있는 화산쇄설성 퇴적물 시료를 재취하여 실내에서 함수비를 인위적으로 조절하면서 전기비저항을 측정하고, 이 결과로부터 포화상태의 화산쇄성설 퇴적물의 전기비저항이 573 ohm-m 임을 밝혔다. 이 값을 이용하여 2 회에 걸쳐 실시한 산사태 지역의 전기비저항분포로부터 화산쇄설성 퇴적층 내에 분포하고 있는 지하수위를 추정할 수 있었다. 그 결과 눈이 오기 전보다 눈이 녹은 후의 융설기에 지하수위가 1.1~4.7m 정도 높은 것으로 평가되었으며, 화산쇄설성 퇴적층이 두껍게 쌓여 있는 산사태 지역의 상부에서 지하수위 변동이 큰 것으로 나타났다. 이러한 이유는 눈이 녹은 시기에 다량의 융설수가 지표로 침투되어 지하수위가 상승하고 있으며, 산사태 지역의 지하수 공급이 상부의 두꺼운 화산쇄설성 퇴적층에서 일어나고 있기 때문임을 알았다.

電気比抵抗探査による地すべり地の地下水調査

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要 旨: 本研究では、電気比抵抗探査による第三紀の大規模の岩盤地すべり地における季節変化による地下水変動を調べた。このため、地すべり地の既存のボーリング調査が行われた主測線に探査測線を設置し、融雪後と積雪前2回に渡って電気比抵抗探査を行い、地盤の2次元比抵抗分布を求めた。また、地盤の比抵抗分布からシラス層の中に存在する地下水面を推定するためにシラスの比抵抗と飽和度との関係を室内試験から明らかにした結果、飽和状態でのシラスの比抵抗は573Ωm であった。この比抵抗値に基づいてシラス層の地下水面以下は飽和状態であると見なし、融雪後と積雪前に行った探査結果より地下水面を推定した。その結果、融雪後に比べて積雪前の地下水位が全体に1.1～4.7m 程度低くなっており、地すべり地の末端部より冠頭部の地下水位が大きく変動していることが分かった。このように季節変化による地下水変動は、融雪時期における融雪水の浸透による影響であり、地すべり地の末端部より冠頭部の地下水位が大きく変動する理由は、冠頭部の台地は地下水涵養域であり、その多くの地下水は銅山川方向に流下しているためであることか分かった。

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