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Study on Groundwater Flow System Using Underground Temperature Survey Method

Takehiko OKUYAMA*[1] and Masayuki IMAIZUMI*[2]

*[1] Department of Structural Engineering, National Research Institute of Agricultural Engineering
(Tsukuba, Ibaraki, 305 Japan)
*[2] Environmental Resources Division, Japan International Research Center for Agricultural Sciences (Tsukuba, Ibaraki, 305 Japan)

Abstract

Groundwater flows which contribute significantly to slope failure are concentrated in highly permeable layers or continuous fracture zones and are referred to as groundwater vein streams. The underground temperature survey method is a simple technique for measuring the temperature at a depth of 1 m from the ground surface. The method not only enables to locate the groundwater vein streams, but also to determine the radius and the depth down to their center assuming they have a cylindrical section. A distance of about 6 m or less between the measurement points is essential for the accurate estimation of the radius and depth of groundwater vein streams. On the other hand, measurement conducted at 20 m intervals is sufficient for approximate location, and the difference between the temperature at a measurement point and the average temperature of neighboring measurement points provides a useful clue for the detection of a temperature change associated with ground water vein streams without considering influences of the topography and land cover. An underground temperature survey was conducted in a landslide area in Niigata prefecture for the study of the groundwater flow system. The depth of the groundwater vein stream estimated by this method agreed well with that determined by conductivity logging, permeability test and temperature logging conducted in a boring hole.

Discipline: Irrigation, drainage and reclamation
Additional key words: boring, land conservation, landslide

Introduction

Groundwater provides us with drinking water of good quality, but it sometimes causes problems such as slope failure and/or flood damage to field crops. It also transports chemical materials such as fertilizer or waste water that has infiltrated from the ground surface. Shallow ground is generally composed of various strata which have been piled up in a complex manner throughout the formation process, and thereafter, were modified by mass movement associated with debris avalanche and sedimentation. The water filtration rate through the soil layers is mostly dependent on the magnitude of the permeability of the soil layers and hydraulic gradient. Gravel and/or sand-rich layers display a higher permeability than clayey soil layers. Continuous fractures are often present in a bedrock, mainly due to faults or joints. Hence, groundwater most likely flows through such areas which are designated as groundwater vein streams[5]. We need to have more information about the actual movement of groundwater to prevent disasters caused by the flow rate. It is essential to develop a reliable and convenient technique to detect the location of groundwater vein streams and to estimate the rate of groundwater flowing through them.

The survey methods of groundwater flow system usually adopted consist of measurement of the groundwater level, pumping test, tracer test and several logging techniques depending on the physical properties of aquifer or groundwater. These methods are generally applied using wells or boring holes. Hence the results of the survey are influenced by the location of the wells or holes.

The underground temperature survey in terms of measurement of shallow underground temperature change associated with groundwater vein streams is a simple technique to predict the location of groundwater vein streams and their size.

Principles and procedures of underground temperature survey

The principle of the underground temperature survey is based on the difference in the temperature between the groundwater flowing in vein streams and in other parts of the ground. The difference causes changes in temperature at a depth of 1 m ($T(1m)$). The temperature fluctuations of groundwater flowing out of a mountain and through vein streams at a high velocity are less appreciable than those of groundwater flowing at a low velocity through layers with a low permeability. The temperature of groundwater vein streams is lower in summer and higher in winter than the temperature in other parts of the ground away from groundwater vein streams. The $T(1m)$ decreases in the vicinity of the groundwater vein streams in summer and conversely increases in winter compared to $T(1m)$ far from the stream (Fig. 1). The reason for measuring the temperature at a depth of 1 m is that it scarcely changes diurnally at that depth. Underground temperature distribution under a steady state is calculated using coordinates, assuming that a cylindrical vein stream is a heat source in the ground which is parallel to the land surface. The following assumptions are made to simplify the calculation of the changes of $T(1m)$.

1) Heat is transferred only by conduction in the profile.
2) The land surface is an infinite plane and the length of a groundwater vein stream is infinite.
3) Soil layers are homogeneous with respect to thermal transfer.

The equation of the steady-state thermal conductance for two dimensions and boundary conditions is as follows:

$$\partial^2 T/\partial x^2 + \partial^2 T/\partial z^2 = 0 \quad \text{.......................... (1)}$$
$$T = T_w;\ x^2 + (z-b)^2 = r^2$$
$$\partial T/\partial z - hT = 0;\ \ z = 0$$

where T_w is the groundwater temperature in vein streams, b the depth to the vein center, r the radius of the vein, h the cooling coefficient, based on Newton's law of cooling.

The approximate value of the temperature at 1 m depth at a distance x from the center of a vein stream is obtained by the following equation[6]:

$$T(1m) = \frac{T_w - T_u}{\log\dfrac{b+a}{b-a}} \left\{ \log \frac{(1+a)^2 + x^2}{(1-a)^2 + x^2} + \frac{4(1+a)}{h(1+a)^2 + x^2)} \right\} + T_u \quad \text{....... (2)}$$

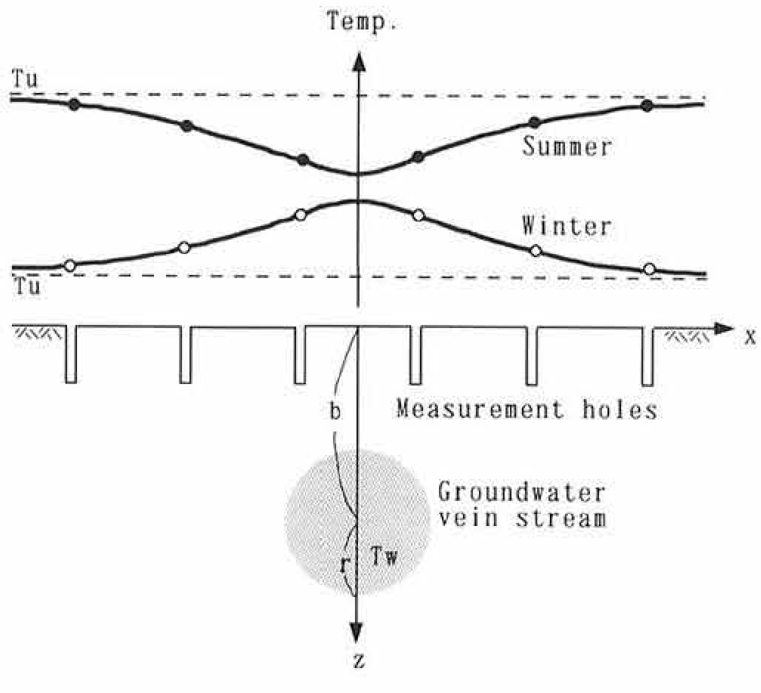

Fig. 1. Temperature change at a depth of 1 m due to a groundwater vein stream

where, T_u: normal temperature at 1 m depth,
a: $(b^2 - r^2)^{0.5}$.

T_u corresponds to the maximum temperature in summer or the minimum one in winter when the measurement is performed on the survey line. T_w is measured by using a well or spring. The depth down to the center and the radius of the veins are determined using a trial and error method by systematically changing constants to minimize any difference between the calculated and measured values. A portable computer is very useful for calculating these values in the field.

At present, the study has shown that the values most frequently recorded for the depth and radius of groundwater vein streams are 9 and 6 m, respectively. When the temperature difference between the groundwater vein stream with the above dimensions and $T(1m)$ far from its center is higher than 6°C, the change of $T(1m)$ can be detected at a level of more than 0.5°C over a range of 25 m on a transverse line of the groundwater vein stream. Therefore, $T(1m)$ measurement at 20 m-intervals along the transverse line is sufficient to detect the zone of temperature changes[4]. The magnitude of the temperature difference of $T(1m)$ at a certain measuring station compared with the mean value of the $T(1m)$s at its neighboring stations on either sides is represented by ΔT. ΔT is a useful index as it enables to detect the localized changes of underground temperature due only to groundwater vein streams. As a result, the effect of the difference in land cover and/or topography on $T(1m)$ is minimized by using ΔT values, instead of using $T(1m)$ values alone (Fig. 2).

$$\Delta T_{i,j} = T_{i,j} - (T_{i,j-1} + T_{i,j+1})/2 \quad \text{.......... (3)}$$

where, $T_{i,j}$: $T(1m)$ at the measuring station (i,j), i and j indicate the position number in the inclined and transverse directions, respectively.

When the survey is planned for an area of more than several hectares, it is highly recommended to measure $T(1m)$ at 20 m-intervals at first, for estimating the rough locations of groundwater vein streams.

More detailed surveys at 6 m intervals or less should be conducted to calculate the depth and radius of the groundwater vein streams for the zone with limited temperature changes.

Observation holes with a diameter of 2 cm and a depth of 1 m are drilled using a motor-driven auger (Plate 1). Temperature is measured at the bottom of the holes using platinum RTDs (resistance temperature devices) and a thermometer especially designed for this purpose and accurate to within 0.01°C[2,3].

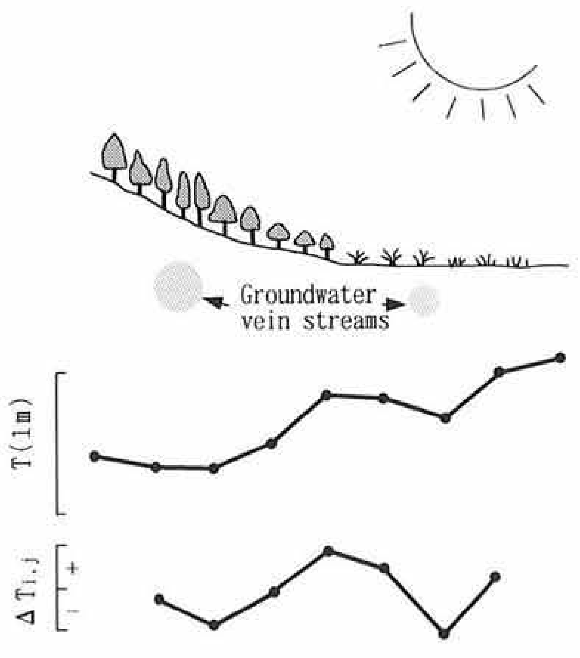

Fig. 2. Temperature difference compared with the mean value of neighboring points on both sides

Survey of groundwater flow system in a landslide area

1) Site and methods

There are many landslide areas in Niigata

Plate 1. Motor-driven auger used for the drilling of a measurement hole

Prefecture in Japan. Underground temperature survey and other investigations were carried out to study the groundwater flow system in the tertiary mudstone landslide slope in the town of Itakura in the southern part of Niigata Prefecture. The study area was located on hilly slopes covered with fresh and/or weathered mudstone and colluvium. Fig. 3 shows an outline of the study area and survey line arrangement in the 24 ha area, and the estimated locations of the groundwater vein streams are also indicated. There is a reservoir for irrigation in the upper part of the area and the gentle slope beneath the reservoir is used for paddy fields.

The $T(1m)$ value was measured every 20 m on survey lines D to O, every 4 m or 5 m on survey lines A to C and R to W in September 1993 or August 1994. During this time, the $T(1m)$ value decreased due to the groundwater vein streams in the surrounding area.

Several boring holes at a depth of 40 m were dug by the Hokuriku Regional Agricultural Administration Office. Standard penetration tests (SPT), conductivity logging and permeability tests were carried out in addition to core samplings. Conductivity

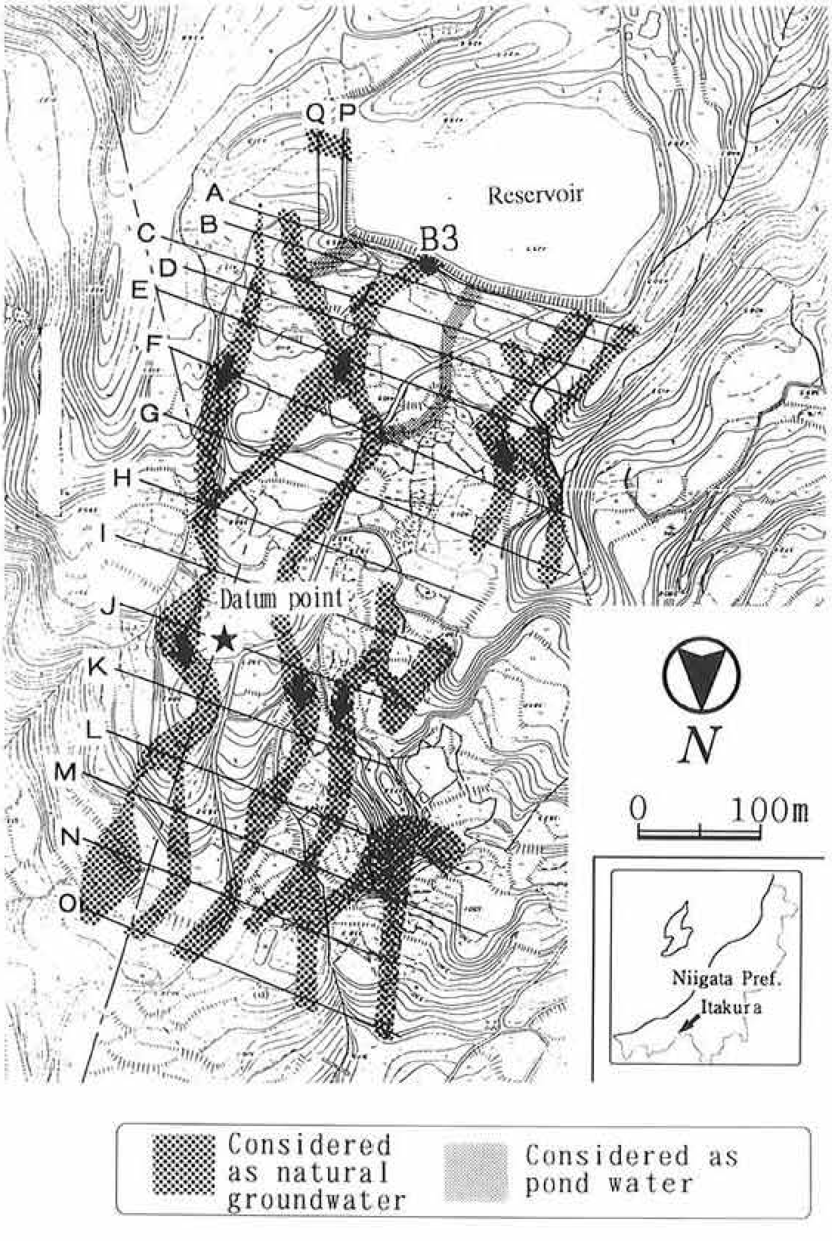

Fig. 3. Outline of the survey area and estimated location of the groundwater vein streams

logging is a conventional method used to determine the depth of the groundwater vein streams based on the increase in electric resistivity of water in the hole which has been previously lowered, due to the inflow of groundwater. In this study, a new method to determine the depth of the groundwater vein streams based on the change in the temperature of the water in the hole referred to as temperature logging method was tested. With this method, the water temperature in the hole was measured at various depths after heating the water by a couple of degrees using an electric heater. At the depth of the groundwater vein streams, the resistivity increased and the temperature decreased faster than in other layers by conductivity logging and temperature logging, respectively. The hydrogeological profiles obtained by these investigations were compared with the location of the groundwater vein streams estimated by the underground temperature survey.

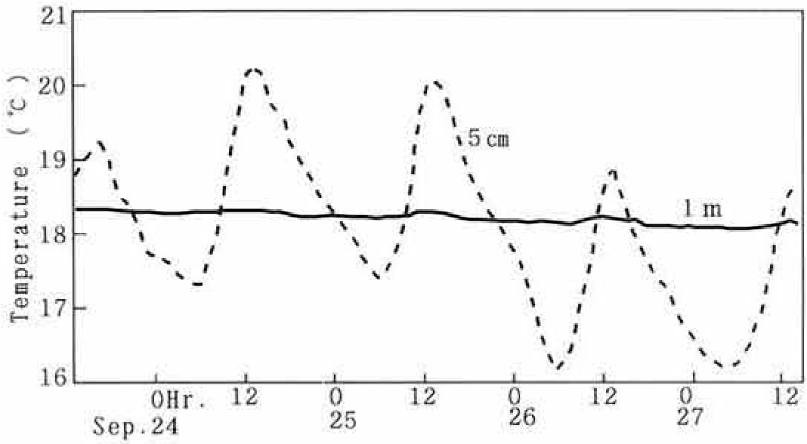

Fig. 4. Underground temperature variation in depth at the datum point

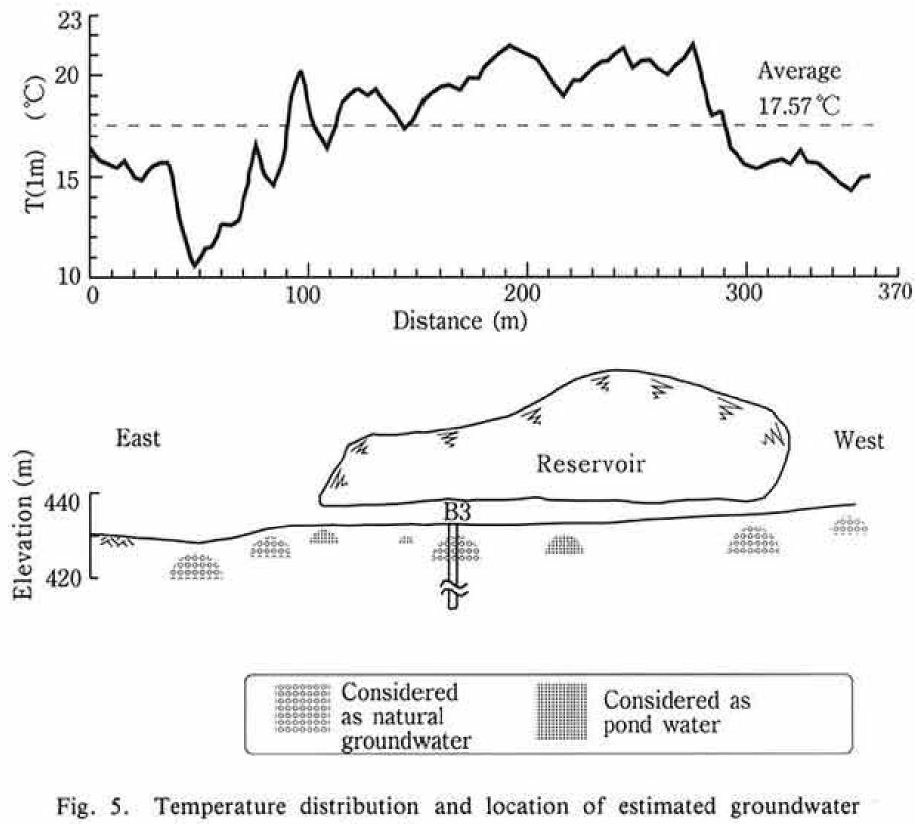

Fig. 5. Temperature distribution and location of estimated groundwater vein streams on Line A

2) Results and discussion

The variations in temperature at a depth of 5 cm and 1 m measured continuously at the datum point (★ locations in Fig. 3) during the survey period are depicted in Fig. 4. The diurnal variation of temperature was more than 2°C at a depth of 5 cm, but less than 0.1°C at a depth of 1 m. The range of temperatures at a depth of 1 m in the daytime, during the test period, was only 0.2°C. This fact shows that since the change in the ground surface temperature scarcely affected the temperature at a depth of 1 m, the underground temperature survey was carried out under very stable conditions.

The low temperature zones were detected based on Eq. (3) in a rough survey and are shown in Fig. 3 as the assumed locations of the groundwater vein streams. The temperature distribution at a depth of 1 m and profile along the measuring line A, determined on the bank of the reservoir, are shown in Fig. 5. The depth and the radius of the groundwater vein streams were determined based on Eq. (2). The origin of groundwater flowing through the vein streams was divided into natural groundwater from the mountain and water leaking from the reservoir, in terms of T_w substituted into Eq. (2). Temperature of the natural groundwater was around 11°C, which was lower than that of the pond water ranging from 17 to 20°C.

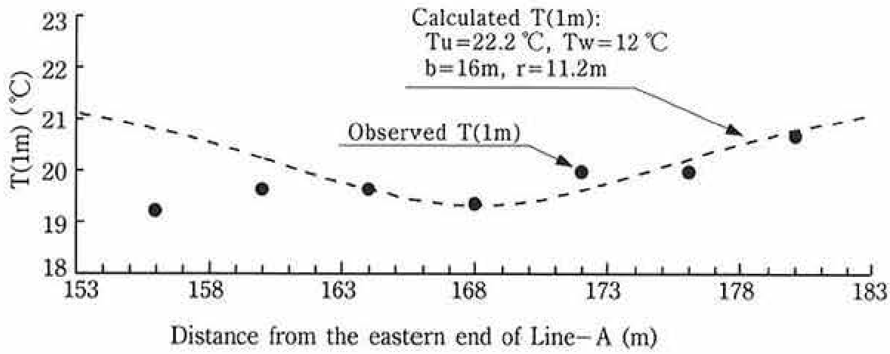

Fig. 6. Comparison of measured and calculated $T(1m)$ on Line-A

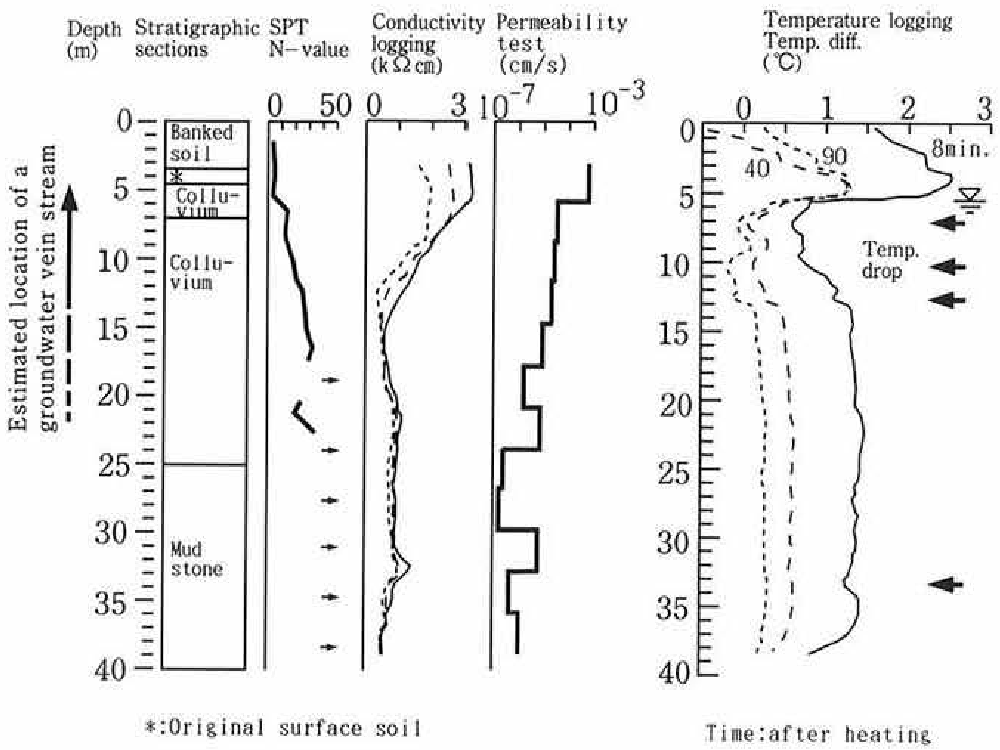

Fig. 7. Profile and results of tests from boring hole B3

Fig. 6 shows the $T(1m)$ values actually measured and the temperature changes calculated near the measuring station, 168 m from the eastern end of line A. The depth down to the center and the radius of the groundwater vein stream were estimated at 16 and 11.2 m, respectively, by using the curve fitting method. Therefore, the depth down to the top and bottom of the vein stream was 4.8 and 27.2 m from the land surface, assuming that the section was cylindrical.

A boring hole (B3) at the depth of 40 m penetrated into the eastern part of the groundwater vein stream on line A. The profile and test results of B3 are shown in Fig. 7. The profile was characterized by the N values obtained from the standard penetration test representing the weathered mudstone and colluvium strata occurring in this area[1]. In some cases the N values of colluvium were less than 50 below the 5 m thick strata of banked soil and old surface layer. It was assumed that there was a groundwater flowing zone at a depth of 3 to 15 m, where fast recovery of electric resistivity was revealed at the point where the conductivity logging test was performed and a permeability greater than 10^{-5} cm/s was measured in the permeability tests. The results of the temperature logging test indicated that there were 3 water flowing zones in the same depth range. The test also indicated that a groundwater vein stream was present at a depth of 33 m in the fresh mudstone stratum.

The depth of the upper half of the vein stream which was considered to be a circular section based on the underground temperature survey coincided well with that of the highly permeable zone determined from tests conducted in the boring hole as shown in Fig. 7. It is reasonable to assume that the cross section of the groundwater vein stream corresponded to a semicircular or horizontal layer rather than to a circular one, due to the decrease of the permeability associated with the consolidation and the lower degree of weathering in the deeper ground.

In the survey area, a large amount of groundwater showed a low temperature even in summer, because the large amount of snow which falls in winter reaches the groundwater all the year round. This condition causes large temperature changes in the shallow ground which is advantageous for an underground temperature survey. Oozing water from the reservoir into the groundwater vein streams was identified based on the difference in temperature in the lower area of the embankment.

Conclusions

The underground temperature survey proved to be a very useful method for detecting the location of the groundwater vein streams. The presence of groundwater vein streams in colluvium strata on a landslide slope was confirmed by several kinds of tests carried out in boring holes.

The underground temperature survey is also a labor-saving method that is suitable for both a rough survey of a large area and a precise investigation of a small groundwater vein stream. It is recommended to apply the method in combination with other physical prospecting methods such as electrical or radioactive prospecting and test boring in order to obtain information on the groundwater flow as well as the hydrogeologic structure.

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