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Underground temperature survey for the study of shallow groundwater flow system

Takehiko Okuyama, Seiichiro Kuroda, Hiroomi Nakazato, Isamu Natsuka
National Institute for Rural Engineering, Tsukuba, Japan

Abstract: Groundwater preferentially flows through sediment layers with high permeability such as colluvium. Its flow paths are called groundwater vein streams. An underground temperature survey is a method to locate vein streams by underground temperature anomalies associated with flowing groundwater. A groundwater flow system near an irrigation reservoir located in the upper part of a landslide block was surveyed with this method. After a geomembrane lining was installed in the reservoir, the total cross-sectional area of the vein streams in the aquifer decreased to as little as 0.35 times that before installation of the liner. A change in groundwater quality also indicated that the mixing of groundwater with leaked water from the reservoir stopped after installation of the lining.

1. Introduction

Test borings and geophysical prospecting methods such as seismic or electrical prospecting are commonly used to study geological structures and groundwater flow systems. Shallow sediments are generally composed of a complex mixture of various strata. Groundwater preferentially flows through gravel- or sand-rich layers of high permeability or through continuous fractures. Flow paths through such areas are called groundwater vein streams. It is difficult to locate and estimate the depth and size of groundwater vein streams from only a small number of borings or from geophysical prospecting.

An underground temperature survey is a simple technique for estimating the location, depth, and size of groundwater vein streams by changes in underground temperature associated with groundwater flow. Underground temperature is measured at the depth of 1 m below the ground surface. Such a survey requires few people and is easy to conduct as part of landslide prevention works in mountainous areas.

2. Principle of the Underground Temperature Survey

Underground temperature depends on air temperature, solar radiation, and heat flow from deeper strata. Heat is transferred mainly by conduction and water movement. Diurnal temperature changes can be neglected at depths of 1 m or more from the ground surface owing to the large specific heat and small thermal conductivity of soil. Seasonal changes in underground temperature occur with a time delay that is larger at greater depths (Fig. 1). The difference between the temperature at the depth of 1 m, *T(1m)*, and that of groundwater is largest in February and March and in August and September. Therefore, the value of *T(1m)* relative to the natural temperature is increased in February and March and decreased in August and September in the vicinity of a groundwater vein stream be-

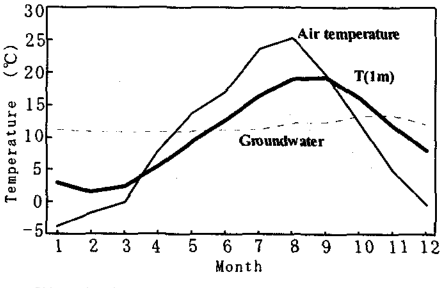


Fig. 1. Seasonal variations in the temperatur of air, the temperature at 1 m dept [*T(1m)*], and groundwater temperature.

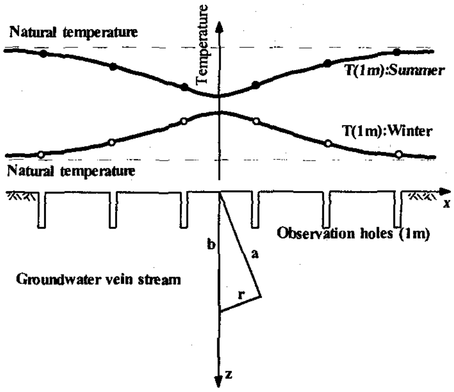


Fig. 2. Diagram of water temperature changes at a depth of 1 m in the vicinity of a groundwater vein.

cause of the groundwater flowing through the sediments (Fig. 2).

The underground temperature distribution under a steady state is calculated by using a co-ordinate system (Fig. 2), assuming that a vein stream is an underground cylindrical heat source parallel to the land surface. The following assumptions are made to simplify the calculation of the changes in $T(1m)$.

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

The equations for steady-state thermal conductance in two dimensions and boundary conditions are as follows:

$$\partial^2 T/\partial x^2 + \partial^2 T/\partial z^2 = 0 \qquad (1)$$

$$T = Tw;\ x^2 + (z - b)^2 = r^2$$

$$\partial T/\partial z - hT = 0;\ z = 0 \qquad (2)$$

where Tw is the groundwater temperature in vein streams, b is the depth to the vein centre, r is the radius of the vein, and h is 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 centre of a vein stream is obtained by the following equation (Yuhara, 1955):

$$T(1m,x) = \frac{Tw - Tu}{\log\left[(b+a)/(b-a)\right]}\left[\log\frac{(1+a)^2 + x^2}{(1-a)^2 + x^2} + \frac{4(1+a)}{h\left[(1+a)^2 + x^2\right]}\right] + Tu \qquad (3)$$

where Tu is the temperature at 1 m depth away from any groundwater vein streams and a is $(b^2 - r^2)^{0.5}$

Tu corresponds to the highest measured temperature in summer or the lowest one in winter along the survey line. Tw is the groundwater temperature measured in a well or spring. The depth down to the centre and the radius of the vein are determined by changing the values of the variables to minimise any difference between the calculated and measured temperature distributions.

Measurement of temperature

Fig. 3. Drilling of an observation hole.

Fig. 4. Location of the field study site.

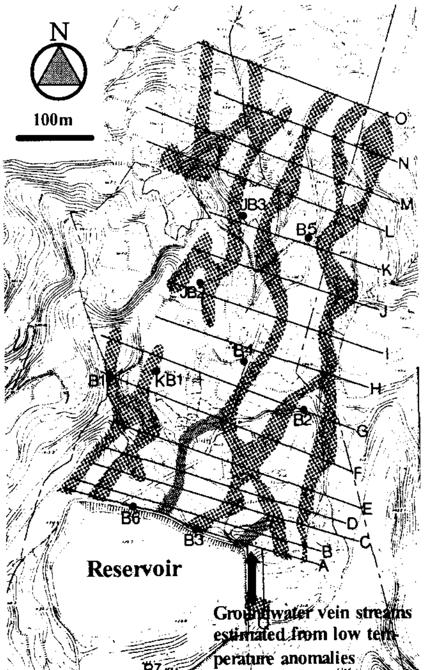


Fig. 5. Map of the study area, locations of survey lines and boreholes, and locations of groundwater vein streams estimated by temperature anomalies in 1993.

T(1m) is usually measured at horizontal intervals of 4 m or less, and equation (3) is applied to determine the depth and radius of the vein stream along a survey line perpendicular to the estimated groundwater vein stream. Observation holes with a diameter of 2 cm and a depth of 1 m are drilled using a motor-driven auger as shown in Fig. 3. Platinum RTDs (resistance temperature devices) and a specially designed thermometer with a measurement error of 0.01 °C are used.

3. Changes in Groundwater Flow Systems by Landslide Prevention Works

An increase in pore-water pressure acting on the slip surface of a landslide block causes a reduction in shear strength and is the most important cause of landslides. Infiltration of rainfall and leakage from ponds in the upper part of a landslide block should be reduced to lower groundwater pressure in the block. For this reason, underground drainage works are the most popular countermeasures against landslides. Analysis of the groundwater flow system, especially the detection of groundwater vein streams, is essential for the design of effective underground drainage works.

Field study in a landslide area

Figure 4 shows the location of the study site in Itakura town, Niigata Prefecture, Japan. There are many landslide blocks covered with fresh or weathered mudstone and colluvium in the area. A very old irrigation reservoir named Oike with a pondage of 100 000 m^3 is located in the upper part of a landslide block (Fig. 5). Water leakage from the reservoir was estimated to be 230 m^3 a day by hydrologic observation. The site was chosen because consolidation of the reservoir was planned by the Ministry of Agriculture, Forestry and Fisheries. An underground temperature survey and temperature logging in boreholes were carried out to locate groundwater vein streams and to study changes in the groundwater flow system in the vicinity of the reservoir before and after consolidation. The reservoir was consolidated between 1998 and 1999 by covering the reservoir floor and dam with a geomembrane liner to control water leakage. A cross-section of the lined dam is shown in Fig. 6. The geomembrane liner is a suitable measure for leakage control in landslide areas because of its large deformation coefficient, the small quantities of earthworks, the short period required for its installation, and its lower cost compared with other possible measures such as an earth blanket.

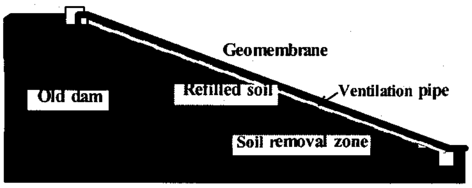


Fig. 6. Cross-section of the consolidated dam with geomembrane liner.

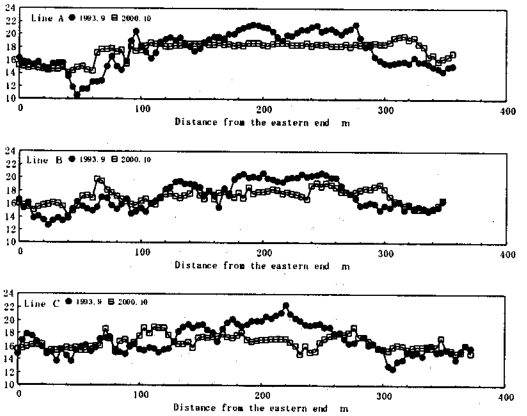


Fig. 7. Distribution of T(1m) along survey lines A, B, and C in 1993 and 2000.

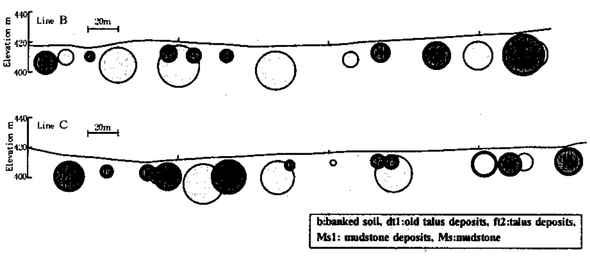


Fig. 8. Estimated locations of groundwater vein streams along survey lines A, B, and C in 1993 and 2000.

The first underground temperature survey was carried out in September 1993 (Okuyama and Imaizumi, 1997). Fifteen survey lines were established on the northern slope below the reservoir dam, and two lines on the eastern side of the reservoir (Fig. 5). The underground temperature was measured at the depth of 1 m, every 4 m along survey lines A, B, C, and every 20 m along the other survey lines. The temperature of the water flowing from the reservoir was 17.82 °C and that of the groundwater was 11.6 °C. The depth and radius of the groundwater vein streams crossing survey lines A, B, and C were calculated by using equation (3).

The second survey was carried out in October 2000, after consolidation of the reservoir was finished. The survey lines were the same as those used in 1993.

T(1m) and the results of the analysis along survey lines A, B, and C for the two periods are shown in Figs. 7 and 8. In 1993, groundwater vein streams were estimated to be located mostly in the colluvium down to a depth of 10 m In 2000, only a few vein streams were found, and their size was reduced, especially along survey line A, which was the survey line nearest to the reservoir. This result means leaked water from the reservoir flowed into vein streams before consolidation of the reservoir, but only groundwater from natural sources flowed after the geomembrane lining controlled leakage from the floor of the reservoir and the bottom of the dam. Figure 9 shows the change in the total area of the cross-sections of those vein streams along lines A, B, and C (Fig. 7) between 1993 and 2000. The ratio of the total cross-sectional area of the vein streams in 2000 to that in 1993 was 0.35 along line A, 0.56 along line B, and 0.91 along survey line C (Okuyama et al., 2003).

Change of groundwater quality

The chemical components of the groundwater in boreholes and of surface water around the reservoir were analysed before and after consolidation as well. Figure 10 shows hexadiagrams of water components in water from three boreholes and ponded water. Borehole B7 is located upstream from the reservoir. B3 was drilled on the dam in 1992, but was removed when the dam was improved, so water was collected from KB2, located 30 m downstream along the same vein stream, in 2002. B4 is located below the reservoir dam, 170 m from KB2. Water was sampled at the depth of 6 m in the

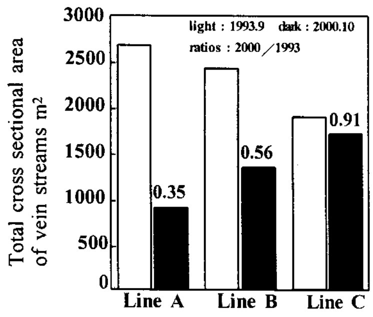
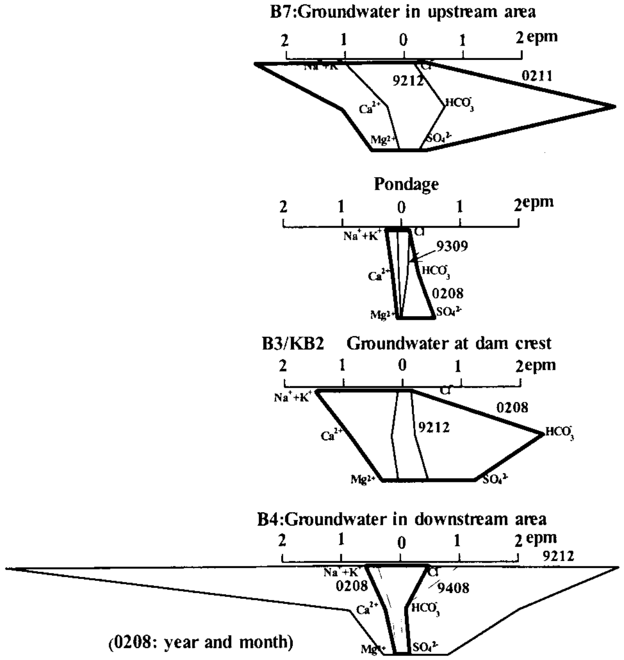


Fig. 9. Total cross-sectional areas of groundwater vein streams along survey lines A, B, and C in.



(0208: year and month)

Fig. 10. Hexadiagrams showing the chemical composition of water samples.

boreholes, which was approximately the depth of the groundwater vein streams.

The groundwater in B7 was assumed to be from natural sources, not mixed with leakage water. Concentrations of ions in KB2 increased in 2002 compared with those in B3 in 1992, and the patterns of the hexadiagram, indicating overall chemical composition, were similar in KB2 and B7 in 2002. This change in B3/KB2 suggests that water leakage from the reservoir diminished in 2002 owing to the consolidation of the reservoir. High ion concentrations in B4 in 1992 reflected mixing with deep salt water just after drilling, but there was a little change between 1994 and 2002, because the change of water quality beneath the reservoir did not reach distant B4.

4. Conclusions

An underground temperature survey was conducted to detect groundwater vein streams supplying groundwater to a landslide block. The groundwater vein streams were estimated to be located mainly in the colluvium layer. The cross-sectional area of these vein streams decreased after consolidation of the irrigation reservoir with a geomembrane liner. Changes in groundwater quality suggested that the mixing of the ponded water with groundwater stopped. An underground temperature survey is a useful method of field survey to study shallow groundwater flow systems for purposes such as the design of landslide prevention measures and environmental studies.

Acknowledgement

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