Method of Investigating Groundwater-vein Streams by Measuring One-meter-depth Temperature in Landslide Areas

Part 1*

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Introduction

The occurrence of a landslide is very often correlated with topographical and geological characteristics of the landslide area as well as the existence of groundwater in the area. Therefore, overall information about surface and underground water in the landslide area is required in order to elucidate the mechanism of the slide, to predict its activity, and to design construction works for its prevention.

On the basis of various findings and observations hitherto accumulated on groundwater in and outside landslide areas, the water may be divided into two categories; the one flowing at a low filtration velocity through strata which are regarded hydrogeologically as aquifers, and the other flowing at considerably high filtration velocities through stratum portions, water veins which are distinguished in permeability from their surroundings. When the water veins postulated above are supplied with a large quantity of water at a stretch by a heavy rain or meltwater, or when abnormal effects are exercised on the veins by an earthquake, banking, or other causes, a possibility of landslide occurrence is developed. Therefore, in order to elucidate the above-mentioned mechanism etc., it is necessary to grasp the routes and scales of these water veins.

The conditions of existence of groundwater in and outside landslide areas used to be investigated mainly by seismic and/or electrical methods which utilize either elastic or electrical properties of soil mass including water, respectively. These methods are useful to detect places where water may exist in a relatively large quantity. However, the both methods have furnished little information with regard to water existing in a vein form.

Considering circumstances in summer that many landslide areas are rich in cold spring water and on the other hand the earth's surface is heated to a warmer temperature by solar radiation, the utilization of the temperature difference between them could offer useful information on the location and size of water vein. Reflecting upon the methods so far used, the author found out that methods utilizing thermal properties of water and soil are not included among them.

Prospecting methods applying underground temperature measurement at shallow depth have been studied and employed mainly in the field of hot-spring exploration. YUHARA (1955) presented a method by which the scale and existence depth of a hot-spring vein are estimated theoretically from a temperature-distance curve obtained by measuring 1-m-depth underground temperature. Except for the field of hot-springs, NOMURA and MAKINO (1958) carried out preliminary investigations for mining by measuring temperature of shallow depth up to 60 cm, and examined the accuracy of ther-

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nometer, the measuring method of temperature, and other details to be considered during measurement. In the field of shallow-groundwater exploration, KAPPELMEYER (1957) studied the measuring method of underground temperature at 1.5 m depth, and discussed the influence of diurnal and annual variation and the disturbance in the distribution of shallow-underground temperature caused by the groundwater rising from the deep parts. And CARTWRIGHT (1974) presented a method of deducing the routes of flowing groundwater by utilizing the disturbance of shallow-underground temperature at the place of recharging and discharging areas of groundwater.

TAKEUCHI (1972 b) intended for the first time to adopt this investigation method for obtaining useful information on the flowing groundwater in shallow layers in and around landslide areas, and examined the applicability of this method in the Kamiohgi landslide area with rather uniform topography, geology and ground conditions, and obtained positive results.

But various factors affecting the measured results of shallow depth underground temperature have not fully been examined so far in the investigation cited above. Furthermore, in the branch of shallow groundwater exploration, important problems such as the following have remained almost unsolved; the theoretical feasibility of the flowing groundwater being investigated having a high filtration velocity in shallow layer, and seasonal and spatial applicable limit as a function of the thermal condition between ground and water.

In this paper, the heat condition of a flowing groundwater is discussed first, theoretically considering the annual variation of underground temperature around the vein stream, and applicability of the method for investigating the vein stream by measuring underground temperature at shallow depth is examined. Second, on the basis of theoretical considerations a practical procedure for exploring a groundwater vein is presented, where the difference between the normal 1-m-depth underground temperature and the flowing groundwater temperature and the distance between measuring points required for deducing the scale and the existence depth of a vein stream, and the appropriate times for the investigation by this method are discussed, and further the reproducibility of the measured results is examined. Finally, various factors as ground condition, topography, geological condition, etc. affecting the temperature are discussed.

1. Theoretical consideration of the investigation method of groundwater-vein streams by underground temperature measurement at one meter depth

1-1 Principle of the method

When water temperature is measured at spring-water points and in test bore holes in landslide areas, we find that the annual variation of temperature is comparatively stable and its value is about $\pm 2^{\circ}\text{C}$ for groundwater flowing at a high filtration velocity. On the other hand, for the temperature of soil near ground surface it is about $\pm 15^{\circ}\text{C}$ at a depth of one meter. This is a considerably large value. Therefore, there occurs seasonally a relatively large difference between the temperature of soil near ground surface and that of groundwater flowing at a high filtration velocity. Then if the above-stated groundwater flows in the form of a vein (a water vein and the part of soil mass with the same temperature in the vicinity of the vein will be collectively called a groundwater vein), it is possible that an abnormal distribution of temperature as compared with areas without vein stream is generated within the ground (Fig. 1). If it is the case, it will be possible that the location of the vein can be deduced in three dimensions by measuring the temperature of soil near ground surface

Fig.1 Schematic diagram of a groundwater-vein stream and the shallow-layer temperature,
 1...normal 1-m-depth underground temperature (θ_u)
 2...1-m-depth underground temperature ($\theta_{z=1}$)
 distributed by the existence of a vein stream in summer and autumn,
 3...ground surface, 4...groundwater surface,
 5...geologically weak parts (a place where groundwater of high filtration velocity is flowing),
 6...scale of the groundwater vein estimated by calculation.

and by detecting the places where the distribution of underground temperature is abnormal. In what follows, a vein-stream model is made on the basis of the results of groundwater survey in the Matsunoyama landslide area, Niigata Pref., Japan, which is the typical Tertiary type landslide, and the equations of heat transfer are derived. Then, the influence on the temperature of surface-layer soil of the existence of a vein stream is numerically analyzed, and the results are compared with those obtained by the field survey.

1-2 A simplified model of a vein stream and its surroundings

In order to make a vein-stream model, the assumptions presented below are introduced on the basis of the results of the field survey :

(1) The vertical distribution of temperature in test bore holes shows that its temperature gradient is about $5 \times 10^{-4} \text{ }^\circ\text{C/cm}$, which is considerably small as compared with the critical temperature gradient, about $5 \text{ }^\circ\text{C/cm}$ (YUHARA and SENNO, 1969), for natural convection generation in porous materials. Therefore, we assume that in and around a vein stream there is no heat transfer due to natural convection.

(2) The diurnal and annual variations of the temperature of soil at depths of 0.3~6.5 m were measured at ten points in the investigated area, and the thermal diffusivities of soil mass were calculated from their amplitudes and phase angles. The diffusivities exhibited values of $3 \sim 8 \times 10^{-3} \text{ cm}^2/\text{sec}$ with the mean of about $5 \times 10^{-3} \text{ cm}^2/\text{sec}$. Similarly to usual landslide areas, the investigated area also consists of a soil layer weathered from bed rock or colluvium, which is 10~15 m in depth. From these facts, soil mass in and around a groundwater vein is regarded as thermally almost isotropic and homogeneous.

(3) In the temperature range 0 to $30 \text{ }^\circ\text{C}$, within which temperature variations will be considered, physical properties of substances in and outside a vein are assumed not to be affected by temperature variations.

From the above assumptions we can consider that in a vein heat is transferred only by forced

Fig. 2 Simulation model and coordinate system.

convection and conduction, and that in its surrounding soil mass heat is transferred only by conduction.

1-3 Simulation model of the underground temperature distribution

Based on the above assumptions, a model of a vein stream can be constructed as follow :

Figure 2 shows a simulation model of the underground temperature distribution and the coordinate system. In this model the cross section of a vein stream is approximated by a rectangle, and the stream is assumed to be horizontal. The coordinate system is a three-dimensional rectangular one with the x-axis along the stream of groundwater, the y-axis horizontally perpendicular to the vein stream, and the z-axis vertically downwards.

When groundwater of constant temperature flows through the vein, the equation of non-stationary heat transfer in the vein is given by

$$\begin{aligned} \frac{\partial \theta}{\partial t} = & - \frac{C_w \rho_w}{C_e \rho_e} v \cdot \frac{\partial \theta}{\partial x} + \frac{\partial}{\partial x} \left(m_x \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y} \left(m_y \frac{\partial \theta}{\partial y} \right) \\ & + \frac{\partial}{\partial z} \left(m_z \frac{\partial \theta}{\partial z} \right) \end{aligned} \quad \dots\dots(1)$$

For heat transfer in soil mass around the vein, since it is merely due to conduction, the equation of non-stationary heat transfer becomes

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(m'_x \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y} \left(m'_y \frac{\partial \theta}{\partial y} \right) + \frac{\partial}{\partial z} \left(m'_z \frac{\partial \theta}{\partial z} \right) \quad \dots\dots(2)$$

In Eqs. (1) and (2) θ is the temperature as a function of x, y, z and t, t the time, m_x , m_y , and m_z the thermal diffusivity of the vein in the x-, y-, and z-directions, respectively, m'_x , m'_y , and m'_z the thermal diffusivity of the soil mass around the vein in the x-, y-, and z-directions, respectively, v the filtration velocity, C_w and ρ_w the specific heat and density of water, and C_e and ρ_e the specific heat

Fig. 3 Initial (1) and boundary (2) conditions; in initial condition,

$$\begin{aligned}
 z < \text{isothermal layer, } \theta &= \bar{\theta}_a + \theta_s \exp \left(-z \sqrt{\frac{\pi}{m\tau}} \right) \sin \left(-z \sqrt{\frac{\pi}{m\tau}} - \epsilon \right) \\
 z \geq \text{isothermal layer} = z_i, \theta &= \bar{\theta}_a + \gamma (z - z_i).
 \end{aligned}$$

and density of a mixture of soil and water, respectively. From the assumption (2) in 1-2 we have $m_x = m_y = m_z = m'_x = m'_y = m'_z = m$.

In order to solve Eqs. (1) and (2) we take as the initial and boundary conditions (See Fig. 3) :

Initial conditions;

$$\left. \begin{aligned}
 t=0, \text{ the temperature in the vein stream is } \theta &= \theta_{wo}, \text{ and the temperature} \\
 \text{outside the vein stream is } \theta &= \bar{\theta}_a + \theta_s \exp \left(-z \sqrt{\frac{\pi}{m\tau}} \right) \sin \left(-z \sqrt{\frac{\pi}{m\tau}} - \epsilon \right) \\
 \text{at } z < \text{isothermal layer, } \theta &= \bar{\theta}_a + \gamma_z (z - z_i) \text{ at } z \geq \text{isothermal layer} = z_i
 \end{aligned} \right\} \dots\dots(3)$$

Boundary conditions;

$$\left. \begin{aligned}
 \partial \theta / \partial z &= \lambda (\theta - \theta_a) \text{ at } z = 0, \text{ with } \theta_a = \bar{\theta}_a + \theta_s \sin \left(\frac{2\pi}{\tau} t - \epsilon \right) \\
 \theta &= \bar{\theta}_a + \gamma (z - z_i) \text{ at } z \geq \text{isothermal layer,} \\
 \partial \theta / \partial y &= 0 \text{ at } y = 0 \text{ and } y \rightarrow \infty, \\
 \theta &= \theta_{wo} \text{ at } x = 0, 0 \leq y \leq w_1, \text{ and } D_1 \leq z \leq D_2, \\
 \text{and } \partial \theta / \partial x &= 0 \text{ at } x \rightarrow \infty,
 \end{aligned} \right\} \dots\dots(4)$$

where θ_a is the air temperature near the earth's surface, $\bar{\theta}_a$ the mean air temperature, θ_s and ϵ the amplitude of the air temperature and its phase difference, respectively, τ the period of variations in air temperature, m the thermal diffusivity, λ the factor h/k with h Newton's cooling constant and k the thermal conductivity of the soil layer, θ_{wo} the temperature of flowing groundwater of the entrance, γ the geo-thermal gradient, D_1 and D_2 the upper and lower depths of the stream, respectively, and W_1 the half width of the stream.

1-4 Solutions by finite difference method

Equations (1) and (2) can be solved approximately by finite difference method: As is shown in Fig.4, the space region to be calculated is divided into rectangular lattices with spatial differences Δx , Δy , and Δz . Denoting by Δt the time difference and by $t+1$ $\theta_{i,j,k}$ the temperature of a lattice point (i, j, k) at time $(t+1)$, we can write the difference form of Eq. (1) as follows:

Fig. 4 Region for difference calculation.

$$\left\{ t_{+1} \theta_{i,j,k}^{(n+1)} \right\} = \left[t \theta_{i,j,k} + \phi \Delta t \left\{ -a \frac{t_{+1} \theta_{i+1,j,k}^{(n)} - t_{+1} \theta_{i-1,j,k}^{(n+1)}}{2\Delta x} + m \frac{t_{+1} \theta_{i+1,j,k}^{(n)} + t_{+1} \theta_{i-1,j,k}^{(n+1)}}{\Delta x^2} \right. \right. \\ \left. \left. + m \frac{t_{+1} \theta_{i,j+1,k}^{(n)} + t_{+1} \theta_{i,j-1,k}^{(n+1)}}{\Delta y^2} + m \frac{t_{+1} \theta_{i,j,k+1}^{(n)} + t_{+1} \theta_{i,j,k-1}^{(n+1)}}{\Delta z^2} \right\} + (1-\phi) \Delta t \left\{ -a \cdot \right. \\ \left. \frac{t \theta_{i+1,j,k} - t \theta_{i-1,j,k}}{2\Delta x} + m \frac{t \theta_{i+1,j,k} + t \theta_{i-1,j,k} - 2t \theta_{i,j,k}}{\Delta x^2} + m \frac{t \theta_{i,j+1,k} + t \theta_{i,j-1,k}}{\Delta y^2} \right. \\ \left. \left. - 2t \theta_{i,j,k} + m \frac{t \theta_{i,j,k+1} + t \theta_{i,j,k-1} - 2t \theta_{i,j,k}}{\Delta z^2} \right\} \right] / \left(1 + \frac{2m\phi\Delta t}{\Delta x^2} + \frac{2m\phi\Delta t}{\Delta y^2} \right. \\ \left. + \frac{2m\phi\Delta t}{\Delta z^2} \right) \quad \dots\dots(5)$$

In order to quicken the calculation of Eq. (5), the accelerated Liebmann method (SMITH, 1971) was used (Eq. 6).

$$t_{+1} \theta_{i,j,k}^{(n+1)} = \omega \{ t_{+1} \theta_{i,j,k}^{(n+1)} \} + (1-\omega) \{ t_{+1} \theta_{i,j,k}^{(n)} \} \quad \dots\dots(6)$$

The difference form of Eq. (2) can be represented by

$$\left\{ t_{+1} \theta_{i,j,k}^{(n+1)} \right\} = \left[t \theta_{i,j,k} + \phi \Delta t \left\{ m \frac{t_{+1} \theta_{i+1,j,k}^{(n)} + t_{+1} \theta_{i-1,j,k}^{(n+1)}}{\Delta x^2} + m \frac{t_{+1} \theta_{i,j+1,k}^{(n)} + t_{+1} \theta_{i,j-1,k}^{(n+1)}}{\Delta y^2} \right. \right. \\ \left. \left. + m \frac{t_{+1} \theta_{i,j,k+1}^{(n)} + t_{+1} \theta_{i,j,k-1}^{(n+1)}}{\Delta z^2} \right\} + (1-\phi) \Delta t \left\{ m \frac{t \theta_{i+1,j,k} + t \theta_{i-1,j,k} - 2t \theta_{i,j,k}}{\Delta x^2} \right. \right. \\ \left. \left. + m \frac{t \theta_{i,j+1,k} + t \theta_{i,j-1,k} - 2t \theta_{i,j,k}}{\Delta y^2} + m \frac{t \theta_{i,j,k+1} + t \theta_{i,j,k-1} - 2t \theta_{i,j,k}}{\Delta z^2} \right\} \right] / \\ \left(1 + \frac{2m\phi\Delta t}{\Delta x^2} + \frac{2m\phi\Delta t}{\Delta y^2} + \frac{2m\phi\Delta t}{\Delta z^2} \right) \quad \dots\dots(7)$$

In order to quicken the calculation of Eq. (7), the accelerated Liebmann method was used (Eq. 8) ;

$$\theta_{i,j,k}^{(n+1)} = \omega \{ \theta_{i,j,k}^{(n+1)} \} + (1-\omega) \{ \theta_{i,j,k}^{(n)} \} \quad \dots\dots(8)$$

where n is the number of iteration, ω the relaxation coefficient, ϕ the constant, and $a = v \cdot C_w \rho_w / C_e \rho_e$. The stability of calculation of Eqs. (6) and (8) is held without reserve for $1/2 \leq \phi \leq 1$. The present calculation was carried out stably by taking $\Delta x = 10.0$ m, $\Delta y = 2.0$ m, $\Delta z = 1.0$ m, $\phi = 0.999$, and $\omega = 1.3$. Calculation was iterated till the variation in temperature at the iteration numbers n and $n+1$ become smaller than 10^{-3} °C at all the lattice points.

1-5 Parameters used in the present calculation

In the present calculation, data obtained in the Matsunoyama landslide area and parameters calculated using them were used (Table 1). The initial values adopted were observed values in April.

Table 1 Parameters used in calculations

$C_w = 1.0$ cal/gr °C	$\theta_{w0} = 9.0$ °C
$\rho_w = 1.0$ gr/cm ³	$\bar{\theta}_a = 16.5$ °C
$C_e = 0.4$ cal/gr °C	$\theta_s = 12.6$ °C
$\rho_e = 1.5$ gr/cm ³	$\epsilon = 1.05$ rad
$m = 5 \times 10^3$ cm ² /sec	$D_1 = 200, 300, \text{ and } 400$ cm
$v = 1 \times 10^{-5} \text{ -- } 1 \times 10^1$ cm/sec	$D_2 = 1200, 1300, \text{ and } 1400$ cm
$\tau = 3.15 \times 10^{-7}$ sec = one year	$W_1 = 400$ cm
$\lambda = 0.42$ m ⁻¹	

1-6 Numerical results and discussions

In this paragraph the results of calculation are compared with the measured ones obtained by the field survey to examine the simulation model and the equations of heat transfer, and finally the applicability of the method of investigating vein streams by measuring the underground temperature at 1-m-depth is described.

1-6-1 Effect of filtration velocity on temperature in a vein stream

We examine how the temperature in a vein stream varies with the filtration velocity of flowing groundwater. Figure 5 shows the relation between the filtration velocity and the mean temperature in a vein-stream cross section (y - z plane) at 600 m from the vein entrance along the x -axis, with the elapsed time as parameter. From the figure we see that the temperature in the vein stream rises sharply at filtration velocity lower than 2×10^{-2} to 8×10^{-3} cm/sec, asymptotically approaching the mean value of normal underground temperature in the vicinity of the vein stream at that moment, and that, conversely, when the filtration velocity exceeds the above value, it asymptotically keeps the temperature at the entrance. At Matsunoyama the filtration velocity of flowing groundwater is 4×10^{-2} cm/sec, and the spring-water temperature varies annually within the range 9.0 ± 1.0 °C. The fact that the flowing groundwater is of low temperature with a small annual variation may be interpreted by Fig. 5, if one assumes stable water temperature at the entrance due to certain unknown mechanisms.

Figure 6 shows variations of vein-stream temperature at the distance of 500 m (ordinary landslide-area length) and 1000 m (large-scale landslide-area length) from the entrance versus infiltration velo-

Fig. 5 Relation between the the filtration velocity (v) of a vein stream and the mean temperature($\bar{\theta}_w$) in the vein at $x = 600\text{m}$.

city with underground temperature $\bar{\theta}_a$ as a parameter, where $\Delta\theta$ implies the difference between the temperature at the entrance and those at the respective distances. If one uses this figure, it will be possible that the filtration velocity of flowing groundwater can be estimated provided that the temperature difference between two places in the x -direction can be measured.

1-6-2 Vertical distributions of temperature in and outside a vein stream

In order to investigate the difference in vertical temperature distributions in and outside a vein stream, the calculated results are compared with data obtained by field survey in Fig. 7. In the figure C-2 is a test bore hole in a place where groundwater at a filtration velocity of $4 \times 10^{-2} \text{ cm/sec}$ exists, and the solid line in the right half shows the temperature distribution in the hole, while the results of groundwater-flowing-strata logging are illustrated on the left. H-2 is located in a flat place at the same level as C-2 50 m apart. In H-2 there is groundwater having an extremely low filtration velocity; its temperature distribution is shown by a solid curve in the right. On the left the results of groundwater-flowing-strata logging are given in the same manner as in C-2. In the figure the dotted lines show the calculated results, for filtration velocities of 3×10^{-2} , 5×10^{-3} , and $1 \times 10^{-3} \text{ cm/sec}$, respectively. We see from the figure that the calculated results are in good agreement with the measured values. The vertical temperature gradient is not practically observed in a vein stream where the filtration velocity is large, but it is considerable in the case where the filtration velocity is small. This result shows that heat transfer by flowing water increases with increasing filtration

Fig. 6 Filtration velocity (v) of a vein stream and temperature variation ($\Delta\theta$) of flowing water after infiltration distance (L); dotted line... $\bar{\theta}_a=13.8$ °C. solid line... $\bar{\theta}_a=16.5$ °C.

velocity and that the temperature of flowing groundwater itself is little affected by the temperature of the surrounding soil. On the other hand, as the filtration velocity decreases, heat conduction from the surrounding soil mass has a great influence on the water temperature, and it is assimilated to that of the surrounding soil. This supports the calculated results described in 1-6-1.

1-6-3 Difference between the normal 1-m-depth underground temperature and the 1-m-depth temperature just above a vein stream

In order to examine the difference between the underground temperature ($\theta_{z=1, y=0}$) at 1-m-depth just above flowing groundwater and that in place unaffected by flowing groundwater (normal 1-m-depth underground temperature θ_a) as a function of time, the calculated results are compared with field data in Fig. 8. In the figure the solid lines show the variations of the difference ($\theta_a - \theta_{z=1, y=0}$) with time, which were obtained from the calculation model, and the dotted lines the results of field measurement. Every temperature difference shows positive and negative peaks in Aug.—Sep. and

Fig. 7 Comparison between the measured vertical temperature distribution in test bore holes and the calculated results (Matsunoyama, July, 20, 1975);

C-2...hole where a groundwater-vein stream is clearly observed ($v=4 \times 10^{-2}$ cm/sec),

H-2...hole about 50 m distant from C-2 and having nearly the same height as C-2, where the existence of the vein stream is not clear,

1-4...results of groundwater-flowing-strata logging,

C-2; 1...before NaCl injection, 2...just after injection, 3...10 min. after injection, 4...20 min after injection,

H-2; 1...before NaCl injection, 2...just after injection, 3...20 min. after injection,

4...50 min. after injection,

$k\Omega$ ...relative resistivity,

5...actual vertical temperature distribution,

6...calculated result for $v=3 \times 10^{-2}$ cm/sec,

6'... " " $v=5 \times 10^{-3}$ cm/sec,

7... " " $v=1 \times 10^{-3}$ cm/sec,

A...tuff, B...shale, C...tuffaceous shale, D...sand stone.

Jan.—Apr., respectively, and both the calculated and measured results are in good agreement.

1-6-4 Applicability of underground temperature measurement for investigating vein streams

From the preceding paragraphs it appears that the thermal states in the vicinity of a vein stream can be satisfactorily described by the simulation model and the equations of heat transfer. On the basis of these results we have examined the applicability of underground temperature measurement for investigating vein stream (Fig. 9).

In Fig. 9 numbers (1)~(5) show the distributions of calculated temperature in Jul.—Nov., respectively. Every curve shows a minimum at the center of a vein stream, approaching gradually the normal 1-m-depth underground temperature with distance from the center. The thermal effect of the vein stream is apparent. In this model the effect amounts to 0.2°C even at a distance of 15 m from

Fig. 8 Variation with time of the measured difference between the 1-m-depth underground temperature ($\theta_{z=1}$) just above the main groundwater-vein stream and normal 1-m-depth underground temperature (θ_u) in the Matsunoyama landslide area (dotted line), and calculated results (solid line);
 Sp-2,3,5...the vein-stream top is at depth of 1.5-2.0 m,
 Sp-3'.....the vein-stream top is at depth of 4-5 m,
 Cal.....the case of simulation models;
 a.....the vein-stream top is at depth of 2m,   b.....the vein-stream top is at depth of 4m,

Fig.9 Variations of 1-m-depth underground temperature near a vein stream,
 1...July, 2...August,
 3...September, 4...October,
 5...November.

the central axis. In addition, the difference between the 1-m-depth underground temperature ($\theta_{z=1, y=0}$) just above the vein-stream central axis and that at the normal 1-m-depth varies with the seasons; in the present calculation, it varies from -2.7 to -1.3 °C. Such a temperature difference and such an influenced area will be enough for the detection of places of abnormal temperature due to the existence of a vein stream, since the accuracy of a thermometer in use at present is 0.1 °C. Furthermore, it is possible that from the temperature-distance curve (referred to as the $\theta_{z=1}-y$ curve) obtained by field survey we can deduce the scale of a vein stream and its existence depth. Studies of the deduced method have been made by YUHARA (1955) in connection with the investigation of a hot-spring vein. A solution may be derived by applying his method.

2. Method of investigating 1-m-depth underground temperature, appropriate times for the investigation, and reproducibility of measured results

2-1 Method of measuring 1-m-depth underground temperature

The 1-m-depth underground temperature was measured by a thermistor-type precision thermometer (photo. 1) which is suitable for measuring underground temperature which is not subject to large fluctuation. The thermometric body was prepared by enclosing a thermistor element in the tip of a small pipe 2 mm in diameter and 5 mm long sticking out, like a needle, in the tip of a hollow stainless pipe 120 cm long, the small pipe being thermally isolated from the hollow pipe. The indicator has a total measuring width of 10.0 °C with an accuracy of 0.1 °C, and a measuring range of 0.0 to 35.0 °C by a four-stage selector.

The measuring method is as follows: With an iron rod 25 mm in diameter and 150 cm long, a hole 100 cm in depth is made at a measuring point, and the thermometric body is inserted into the hole. When the body reaches the hole bottom, the pipe is pushed into the ground, so as to secure the contact of the instrument with the ground.

Photo 1 Thermistor-type precision thermometer used for underground temperature measurements in landslide areas;
A...Indicator for the thermometer,
B...thermistor-type precision thermometer,
C...iron rod for boring.

2-2 Influence factors during measurement

When a hole is made with the iron rod, the temperature of soil in the vicinity of the hole wall will be disturbed by the friction heat produced between the rod and the hole wall and by the influx of air into the hole. This may bring an error on measured values. In order to examine this effect, many holes were made in a narrow area homogeneous in topography, ground conditions and soil nature, and the thermometric body was inserted into every hole at intervals of thirty-second lag after perforation. As a result any significant difference in temperature in these holes could not be found (Fig. 10a). Thus, it was shown that the above mentioned disturbance did not exert much influence on measured values. Therefore, the thermometric body thereafter was inserted into a hole immediately after its perforation.

Before the above test an assimilation time as for temperature of a thermometric body with ground was investigated. We measured for ten thermometric bodies with the same characteristics the time required from insertion to the stable reading of indicator. The result showed that at about five minutes after insertion all the thermometric bodies indicated stable values (Fig. 10b). In actual measurements, therefore, temperature reading was taken ten minutes after insertion of the thermometric body.

Fig.10a The relation between the underground temperature at one meter depth and the time of insertion of the thermometric body into the hole after perforation; (a) Aug., 28, 1971, (b) Nov., 17, 1971.

Fig.10b An assimilation time as for temperature of thermometric bodies with ground. The standard value for each thermometric body was defined by the value which was unchanged three times successively in every measurement.

It is possible that when a hole is made, the surrounding surface water flows into the hole, and the water may disturb measured values. However, in the cases so far examined, holes with standing water have been only about 1.8% of all the measuring points (about 12,000) and insignificant. If the influx of surface water into a hole should be prevented, it would be realized by throwing up a small earth-work around the hole.

2-3 Difference between the normal 1-m-depth underground temperature and the flowing groundwater temperature, and the distance between measuring points required for estimating the scale of a vein stream

In order to estimate the existence depth and scale of a vein stream using YUHARA's method (1955), it is necessary to draw the $\theta_{z=1}-y$ curve as possible for determining the y coordinate of inflection point of $\theta_{z=1}-y$ curve. For this purpose the difference between measured temperature and the normal 1-m-depth temperature must be detected theoretically at four points at least. We examine the distance between measuring points and the difference between the normal 1-m-depth temperature and flowing groundwater temperature required for investigating vein stream having various depths and scales under the condition that four data points were given (Figs. 11 and 12). As a result, for investigating vein stream of radii 5~10 m and the existence depth smaller than 10~20 m respectively in ordinary landslide areas, it is shown that the distance between measuring points should be 5~10 m

i.e. the values of y in Fig. 11, 26 to 35 m. And Fig. 12 shows some examples of the relation between the radius of a vein stream (r) and the existence depth of central axis of the vein (b) necessary for generating disturbance on the normal 1-m-depth underground temperature with the temperature difference between ground and water $|\theta_c|$ and the horizontal distance y as parameters. For example, $|\theta_c| = 5^\circ\text{C}$ and $y = 10\text{ m}$, in other word in case the difference between the normal 1-m-depth underground temperature (θ_u) and the flowing groundwater temperature (θ_w) is equal to 5°C , if the central axis of the vein stream of radius 10 m exists at 11 m depth, $(\theta_u - \theta_{z=1})$ is equal to 1.0°C at the distance 10 m from the central axis ($y = 10\text{ m}$), and 0.4°C at $y = 20\text{ m}$ (See the uppermost part of the figure). Under the same condition, if the central axis exists at 30 m depth, $(\theta_u - \theta_{z=1})$ is equal to

Fig. 11 Diagram for determining the required distance between measuring points in case of $\theta_c = 10.0^\circ\text{C}$, $\theta_{z=1} \geq 0.2^\circ\text{C}$, $\lambda = 0.42\text{m}^{-1}$;
 b .....existence depth of central axis of vein,
 r .....radius of a vein, y .....distance from x-axis.

Fig. 12 Relation between the radius of a vein stream and the existence depth of central axis of the vein necessary for generating disturbance on normal 1-m-depth underground temperature with the θ_c and y as parameter;
 b .....existence depth of central axis of the vein,
 r .....radius of the vein, y .....distance from x-axis, a-a'...line of $b - r = 0$, b-b'...line of the deepest depth of central axis of the vein necessary for disturbing the θ_u , o-o'...line of existence range of central axis of the vein necessary for disturbing the θ_u .

0.2 °C which is the smallest necessary value for detecting the disturbance of temperature by the thermometer. If the central axis of the vein stream exists deeper than the depth, the disturbance of temperature does not appear in the measured results ($\theta_{z=1}$). Accordingly, if the central axis of the vein exists between o-o' line, disturbance in the normal l-m-depth underground temperature (θ_u) due to the existence of the vein is detectable. The curve b-b' shows the deepest bound of the central axis of the vein which can disturb the normal l-m-depth underground temperature. In case of $|\theta_c| = 3^\circ\text{C}$ and $y=20\text{ m}$, the vein streams of radii 5~10 m can not disturb the normal l-m-depth underground temperature (See the middle part of the figure). And the range of depth of the central axis of the vein which can disturb θ_u is fairly narrow in case of $|\theta_c| = 2^\circ\text{C}$ and $y=10\text{ m}$, and it is practically difficult to survey the vein stream. Therefore, it is considered that the temperature difference $|\theta_c|$ necessary for this method is between 2°C and 3°C , and we take the value $|\theta_c|$ tentatively 2.5°C .

2-4 Procedure for determining the normal l-m-depth underground temperature and the flowing groundwater temperature

In order to estimate the scale of a vein stream, it is necessary to determine the normal l-m-depth underground temperature (θ_u) and the flowing groundwater temperature (θ_w). The temperature θ_w can be determined by measuring that of spring water in the investigated area or that of water at the flowing groundwater stratum in a test bore hole. On the other hand, it is necessary to determine θ_u from data obtained in the investigated area to estimate parameters of a vein stream. In Japan θ_u has been statistically determined by FUKUTOMI (1951) in connection with the investigation of hot-spring. Using FUKUTOMI's results, the author derived a formula for determining θ_u for an area having any latitude and any height and for any month (Table-2). In Table-3 θ_u determined by the formula is compared with that measured in some landslide areas. It seems from this table that θ_u can be determined without large errors by using the formula.

Table 2 The relation between $\theta_{z=1}$ and φ (L), h.
(obtained from the diagrams of FUKUTOMI (1951))

		(°) range of φ (L)	(m) range of h
January	$\theta_{z=1} = -1.27 \varphi (L) - 0.0020 h + 54.02$	31 — 38	0 — 1000
	$\theta_{z=1} = -0.29 \varphi (L) - 0.0020 h + 17.32$	38 — 45	0 — 1000
February	$\theta_{z=1} = -1.31 \varphi (L) - 0.0027 h + 54.18$	31 — 48	0 — 1000
	$\theta_{z=1} = -0.21 \varphi (L) - 0.0027 h + 17.33$	38 — 45	0 — 1000
March	$\theta_{z=1} = -1.23 \varphi (L) - 0.0040 h + 52.00$	31 — 38	0 — 1000
	$\theta_{z=1} = -0.44 \varphi (L) - 0.0040 h + 21.99$	38 — 45	0 — 1000
April	$\theta_{z=1} = -1.12 \varphi (L) - 0.0045 h + 51.00$	31 — 41	0 — 1000
	$\theta_{z=1} = -1.00 \varphi (L) - 0.0045 h + 46.29$	41 — 45	0 — 1000
May	$\theta_{z=1} = -1.13 \varphi (L) - 0.0047 h + 55.19$	31 — 41	0 — 1000
	$\theta_{z=1} = -1.74 \varphi (L) - 0.0047 h + 81.27$	41 — 45	0 — 1000

June	$\theta_{z=1} = -1.09 \varphi (L) - 0.0046 h + 57.06$	31 - 41	0 - 1000
	$\theta_{z=1} = -1.55 \varphi (L) - 0.0046 h + 76.72$	41 - 45	0 - 1000
July	$\theta_{z=1} = -1.11 \varphi (L) - 0.0043 h + 61.42$	31 - 41	0 - 1000
	$\theta_{z=1} = -1.66 \varphi (L) - 0.0043 h + 84.69$	41 - 45	0 - 1000
August	$\theta_{z=1} = -0.99 \varphi (L) - 0.0040 h + 59.37$	31 - 41	0 - 1000
	$\theta_{z=1} = -1.55 \varphi (L) - 0.0040 h + 82.60$	41 - 45	0 - 1000
September	$\theta_{z=1} = -0.86 \varphi (L) - 0.0037 h + 54.37$	31 - 41	0 - 1000
	$\theta_{z=1} = -1.39 \varphi (L) - 0.0037 h + 76.32$	41 - 45	0 - 1000
October	$\theta_{z=1} = -0.83 \varphi (L) - 0.0033 h + 49.87$	31 - 41	0 - 1000
	$\theta_{z=1} = -1.05 \varphi (L) - 0.0033 h + 59.24$	41 - 45	0 - 1000
November	$\theta_{z=1} = -0.97 \varphi (L) - 0.0028 h + 50.93$	31 - 41	0 - 1000
	$\theta_{z=1} = -0.55 \varphi (L) - 0.0028 h + 34.32$	41 - 45	0 - 1000
December	$\theta_{z=1} = -1.01 \varphi (L) - 0.0024 h + 48.67$	31 - 41	0 - 1000
	$\theta_{z=1} = -0.51 \varphi (L) - 0.0024 h + 28.72$	41 - 45	0 - 1000

$\theta_{z=1}$ .....underground temperature at one meter depth ($^{\circ}\text{C}$)

$\varphi (L)$ .....latitude of the landslide area ($^{\circ}$)

h .....altitude of the landslide area (m)

Table 3 Examples of comparison between calculated values
and observed values in a few landslide areas

	MATSUNOYAMA			MIYAGAMI			NAWAMATA		
$\varphi(L)$	37° 51'			35° 32'			37° 30'		
h	390 m			520 m			70 m		
	obs.	cal.	dif.	obs.	cal.	dif.	obs.	cal.	dif.
1	6.2	6.3	-0.1	6.5	7.9	-1.4	6.5	6.3	+0.2
2	4.8	4.7	+0.1	5.9	6.2	-0.3	4.8	4.9	-0.1
3	4.3	5.1	-0.8	5.7	6.2	-0.5	5.8	5.6	+0.2
4	5.1	7.4	-2.3	8.6	8.9	-0.3	8.6	8.7	-0.1
5	10.3	11.4	-1.1	12.3	12.6	-0.3	11.1	12.5	-1.4
6	14.5	14.7	-0.2	16.4	16.1	+0.3	15.9	15.9	0.0
7	18.1	18.0	+0.1	20.0	19.7	+0.3	19.5	19.5	0.0
8	20.9	21.0	-0.1	21.9	22.1	-0.2	21.8	22.0	-0.2
9	21.3	20.9	+0.4	21.5	21.9	-0.4	21.3	21.9	-0.6
10	18.2	17.9	+0.3	18.6	18.6	-0.1	18.7	18.5	+0.2
11	14.5	13.8	+0.7	13.7	15.0	-0.3	13.7	14.3	-0.6
12	9.4	9.6	-0.2	11.2	11.5	-0.3	10.4	10.6	-0.2
av.	12.3	12.6	-0.3	13.6	13.9	-0.3	13.2	13.4	-0.2

($^{\circ}\text{C}$)

2-5 Appropriate times for the investigation of underground temperature

Since this method utilizes the difference θ_c between θ_u and θ_w , it is difficult to apply this method at a time at which both temperatures become equal; moreover, even if there is a small difference θ_c , we would not detect much by measuring it when the difference is too small.

The optimum time for underground temperature measurement is the time at which $|\theta_c|$ becomes maximum. Since according to field surveys the flowing groundwater temperature is always nearly constant, the optimum time can be determined as the time when the highest and lowest temperatures on ground surface are propagated to 1-m-depth.

If the variation of temperature with in the ground is given by

$$\theta = \bar{\theta}_a + \theta_s \exp\left(-z\sqrt{\frac{\pi}{m\tau}}\right) \sin\left(\frac{2\pi}{\tau} \cdot t - z\sqrt{\frac{\pi}{m\tau}}\right) \quad \dots\dots(9)$$

then the amplitude of temperature at depth z is

$$2\theta_s \exp\left(-z\sqrt{\frac{\pi}{m\tau}}\right) \quad \dots\dots(10)$$

Fig.13a Difference (θ_c) between the 1-m-depth underground temperature($\theta_{z=1}$) and the flowing groundwater temperature (θ_w) (Nawamata landslide area, Ishikawa Pref.) ; shaded parts are inappropriate times.

Fig.13b Difference (θ_c) between the 1-m-depth underground temperature($\theta_{z=1}$) and the flowing groundwater temperature (θ_w) (Matsunoyama landslide area, Niigata Pref.) ; shaded parts are inappropriate times.

Fig.13c Difference (θ_c) between the 1-m-depth underground temperature ($\theta_{z=1}$) and the flowing groundwater temperature (θ_w) (Miyagami landslide area, Hyogo pref.); shaded parts are inappropriate times.

Fig.14a Variation with time of $\theta_{z=1}$ -y curve on a fixed measuring line (Nawamata landslide area).

and the time required for the propagation of this variation up to depth z is

$$t = \frac{z}{2} \sqrt{\frac{\tau}{m\pi}} \quad \dots\dots(11)$$

Substitution $z=100$ cm, $m=3-8 \times 10^{-3}$ cm²/sec, and $\tau=3.15 \times 10^7$ sec=one year in Eq. (11) yields a value of about 30 days for the time. Therefore, if the variation of temperature on ground surface is known, the optimum time for 1-m-depth underground temperature measurement can be estimated as the times 30 days after appearance of the highest and lowest temperature on ground surface. Fig. 13 a, b, and c show the monthly variations of θ_c obtained in some landslide areas. We see from the figures that the amplitude $|\theta_c|$ roughly amounts to 10 °C, and that $|\theta_c|$ approaches to zero twice a year. In the figures, the upper and lower horizontal lines show the temperature difference ± 2.5 °C required to apply the method, which was determined in 2-3, and the vertical lines the intersections of those lines and the θ_c curve. The shaded parts will be called the inappropriate times for investigation. The optimum times for investigation are March and September in the case of Niigata pref., Ishikawa pref., and north part of Hyogo pref., and this agrees with those supposed from simulated results in

1-6-3.

2-6 Reproducibility of the measured results

If the distribution of 1-m-depth underground temperature measured by this method varies from measurement to measurement, it is inappropriate as an investigation method. In order to examine the adequacy of the present method in this respect, fixed measuring lines were prepared in landslide areas, Matsunoyama, Miyagami, and Nawamata, to carry out periodic measurements (Fig. 14). We see from the figures that in these landslide areas some anomalies on $\theta_{z=1}$ are sustained through the observed period. Therefore, the results of this investigation method by underground temperature measurement may be regarded as reproducible. The fact that measured values at different times give similar distributions suggests that the pattern is not accidental one, but may be attributable to physically meaningful phenomena having some influence on the underground temperature over a long period of time. The reproducibility of two dimensional distribution was also confirmed in the landslide areas of Matsunoyama (TAKEUCHI & SHIMA, 1976 a), Gotenyama (TAKEUCHI, 1972 a), and Ushigatani.

Fig.14b Variation with time of $\theta_{z=1}$ -y curve near springwater points (Matsunoyama landslide area).

Fig.14c Variation with time of $\theta_{z=1}$ -y curve near springwater points (Miyagami landslide area).

3. Various factors affecting the 1-m-depth underground temperature

The 1-m-depth underground temperature will be affected by various factors, such as topography,

geology and ground conditions. In this paragraph, examination is made of the influence of these factors on the underground temperature, and a method of correction is proposed for factors having significant influences.

3-1 Influence of diurnal and annual variations

When there is a diurnal variation in measured underground temperature, it is necessary to correct every measured value at every measuring time. Moreover, annual variations must be taken into account, since a part of them becomes innegligible when investigation is made over a long period. The thermal diffusivities calculated with the aid of the amplitude and phase difference of diurnal and annual variations range from 3 to $8 \times 10^{-3} \text{ cm}^2/\text{sec}$ in landslide areas. Fig. 15 shows the relation between the amplitude of diurnal underground temperature variation and the depth with the thermal diffusivity as parameter, the amplitude of underground temperature variation at ground surface being assumed as 20°C . From the figure we see that the diurnal variations can be neglected if underground temperature is measured at a depth of one meter. Accordingly, we made it a rule to measure at one meter depth in principle by a reason of abovementioned. If annual variations of the 1-m-depth underground temperature become innegligible in a long-term investigation (Fig. 16), fixed-point observations must be made at a spot, and corrections must be made as occasion demands.

Fig. 15 Relation between the amplitude (θ_s) of diurnal underground temperature variation and the depth with the thermal diffusivity (m) as parameter;
 ← the range of the thermal diffusivity in landslide areas.

Fig. 16 Examples of variation of 1-m-depth underground temperature in a long-term investigation;
 1...Matsunoyama (Nov., 8-17, 1971),
 2...Matsunoyama (Aug., 21-29, 1971),
 3...Miyagami (Sep., 1-4 1973),
 4...Nawamata (July, 14-29, 1976).

3-2 Influence of geology

The influence of geological factor on the underground temperature is expected to be great, and this has been utilized in prospecting. Variations in underground temperature due to geology result from the difference between the thermal conductivities of geological formations. Let us now suppose that, as is shown in Fig. 17, strata A and B are adjacent to each other with a thickness of ℓ over a uniform substratum C. The temperature difference between strata A and B at the level Δz from the surface of substratum is given by

Fig. 17 Schematic diagram of temperature variation due to geological variation.

$$\frac{k_A (\theta_C - \theta_A)}{\ell} = \frac{k_B (\theta_C - \theta_B)}{\ell} = q \quad \dots\dots(12)$$

$$\theta_C - \theta_A = \frac{\ell}{k_A} q \quad \theta_C - \theta_B = \frac{\ell}{k_B} q \quad \dots\dots(13)$$

$$\theta_A - \theta_B = \ell \cdot q \left(\frac{1}{k_B} - \frac{1}{k_A} \right) = \frac{q \cdot \ell}{k_A k_B} (k_A - k_B) \quad \dots\dots(14)$$

$$\Delta\theta = (\theta_A - \theta_B) \frac{\Delta z}{\ell} = \Delta z \cdot q \frac{k_A - k_B}{k_A k_B} \quad \dots\dots(15)$$

where $\Delta\theta$ is the temperature difference between strata A and B at Δz , ℓ the layer thickness, k_A and k_B the thermal conductivities of strata A and B, respectively, θ_A , θ_B , and θ_C the surface temperature of each strata A, B, and C, respectively, and q the quantity of heat flux from the mean crust depths.

As an example where adjacent strata differ remarkably in thermal conductivity, we take for k_A that of shale ($3.6 \times 10^{-3} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ deg}^{-1}$) and for k_B that of granite ($5.6 \times 10^{-3} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ deg}^{-1}$); furthermore, we take a values of $1.4 \times 10^{-6} \text{ cal cm}^{-2} \text{ sec}^{-1}$ for the mean terrestrial heat flux (DAMBARA & TOMODA, 1969), and $\Delta z = 1.9 \times 10^3 \text{ cm}$. Substitution of these values into Eg. (15) gives for $\Delta\theta$ a value of 0.2°C .

Although the above example is a case where rocks different remarkably in thermal conductivity are adjacent to each other at a large thickness, geology in many landslide areas consist actually of a mixture of rocks and/or soil whose thermal conductivities are of nearly the equal order of magnitude. Estimated temperature differences for some landslide areas were always insignificant. Therefore, it

will be justifiable to neglect the influence of geology on the 1-m-depth underground temperature.

3-3 Influence of microtopography of the ground

The fact that topographical factors, such as the inclination direction of a slope and the height difference of measuring points, affect underground temperature was pointed by UEHARA (1961), HIRATA (1931), YAMASHITA, et al (1978), etc..

Since in a landslide area individual landslide zones face in nearly the same direction, the influence of slope-inclination direction on the underground temperature is supposed to be uniform over the whole area. The relation between the height difference of measuring points in longitudinal as well as transverse directions and the 1-m-depth underground temperature was investigated using data for some landslide areas. The result showed that any significant correlation could not be observed for height differences up to 350 m in longitudinal direction and those up to about 10 m in transverse direction. We therefore concluded that the influence of microtopography could be tentatively neglected for usual landslide areas. However, at a place where the topography changes suddenly, the influence of solar radiation from the side cannot be ignored and the effect must be taken into consideration in deciding the location of a measuring point (UWAI, 1932, KODAIRA, 1932).

3-4 Influence of ground condition

In the field of agricultural meteorology, the relation between the ground conditions (ground surface condition within a radius of 3 m from a measuring point) and the underground temperature in general up to a depth of about 50 cm at which the roots of plants can arrive has been studied (TAMADE, 1925, YAKUWA, 1943, MACKINNEY, 1929, WOLLY, 1881, YAKUWA, 1932). However, as far as the author is aware, the relation between the 1-m-depth underground temperature and the ground conditions has not been studied in either of the field of agriculture, hot-spring prospecting or mine prospecting. Moreover, KAPPELMEYER (1957) and CARTWRIGHT (1974), who utilized the underground temperature for groundwater investigation, did not touch upon this subject.

Using about twelve thousand data obtained up to now, the author has classified the ground conditions as follows for investigating the correlation with the underground temperature:

- A-A...Open lands (grounds without grasses, such as waste lands and school grounds),
- B-B...Roads with a great deal of car traffic,
- B'..Roads without car traffic, paths, foot-paths between rice-field, etc.,
- C-C...Ridges between rice-fields, rice fields, etc.,
- C'..Wet lands (ponds, swamps, the neighborhood of a spring-water points, etc.),
- C''..Former rice fields (grounds used as rice fields until two or three years ago),
- D-D...Farm-lands (lands tilled once a year at least),
- E-E...Grasslands (lands without being tilled),
- F-F...Forest lands (no matter what kinds of trees and the existence of underbrush),
- F'..Plant fields, tea-plantation, shrubs, brush, etc..

Data accumulated up to date were summed up according to this classification in order to examine the temperature difference at various ground conditions. The result showed that in summer and autumn the mean temperature was lower (deviation from the average of all the measured values was -2.0°C at the lowest and -1.3°C on the average) in forest lands(F) and higher (the deviation was $+2.0^{\circ}\text{C}$ at the highest and $+1.0^{\circ}\text{C}$, on the average) in roads(B) and ridges(C) (Fig. 18). This is

Fig. 18 Relation between coded ground conditions and underground temperature (only for summer and autumn);

A...open lands, B...roads, B'...paths, C...ridges, C'...wet lands, D...farm lands, E...grass lands, F...forest, F'...bushes, and G.C...coded ground conditions.

Fig. 19 An example of relation between ground conditions and solar radiation(%) in the Matsunoyama landslide area (Aug., 20, 1974);

A...open land, C...ridges, E...grass lands, F...forest,

QT...heat flux of solar radiation,

QR...reflected heat flux on the ground surface,

QE...lossed heat flux by evaporation,

QS...residual heat flux in the invariable layer,

$Q_T - Q_G - Q_R$ ...flowing heat flux into the ground.

Q_G ...reflected heat flux on the ground condition,

QA...lossed heat flux by Austausch phenomena,

QL...lossed heat flux by long wave radiation,

Table 4 Diurnal variation of underground temperature and heat flux in invariable layer in the Matsunoyama landslide area.

1974. 8. 20.	A			C ¹			E			F		
time	Ta	Ua	dUa	Tc'	Uc'	dUc'	Te	Ue	dUe	Tf	Uf	dUf
0	25.40	647.7		24.93	673.1		23.57	445.5		20.62	266.0	
2	24.95	636.2	-11.5	24.57	663.4	-9.7	23.33	440.9	-4.6	20.48	264.2	-1.8
4	24.88	634.4	-1.8	24.43	659.6	-3.8	23.25	439.4	-1.5	20.47	264.1	-0.1
5	24.73	630.6	-3.8	24.30	656.1	-3.5	23.21	438.7	-0.7	20.38	262.9	-1.2
6.5	25.05	638.8	+8.2	24.22	653.9	-2.2	23.18	438.1	-0.6	20.40	263.2	+0.3
8	26.53	676.5	+37.7	24.33	656.9	+3.0	23.27	439.8	+1.7	20.65	266.4	+3.2
9	27.78	708.4	+31.9	24.65	665.6	+8.7	23.57	445.5	+5.7	20.80	268.3	+1.9
10	28.47	726.2	+17.8	25.02	675.5	+9.9	23.65	447.0	+1.5	20.93	270.0	+1.7
11	29.75	758.6	+32.4	26.42	713.3	+37.8	24.38	460.8	+13.8	21.68	279.7	+9.7
12	31.02	791.0	+32.4	27.45	741.2	+27.9	25.08	474.0	+13.2	21.93	282.9	+3.2
13	31.07	792.3	+1.3	28.30	764.1	+22.9	25.17	475.7	+1.7	21.78	281.0	-1.9
14	31.00	790.5	-1.8	28.12	759.2	-4.9	24.80	468.7	-7.0	21.70	279.9	-1.1
15	29.67	756.6	-33.9	27.75	749.3	-9.9	24.80	468.7	0.0	21.57	278.3	-1.6
16	29.38	749.2	-7.4	27.47	741.7	-7.6	24.75	467.8	-0.9	21.55	278.0	-0.3
17	28.70	731.9	-17.3	26.92	726.8	-14.9	24.60	464.9	-2.9	21.47	277.0	-1.0
18	27.89	711.2	-20.7	26.52	716.0	-10.8	24.40	461.2	-3.7	21.28	274.5	-2.5
19	27.25	694.9	-16.3	26.02	702.5	-13.5	24.17	456.8	-4.4	21.07	271.8	-2.7
20	26.95	687.2	-7.7	25.75	695.3	-7.2	24.20	454.0	-2.8	20.91	269.7	-2.1
22	26.74	681.9	-5.3	25.49	688.2	-7.1	23.90	451.7	-2.3	20.87	269.2	-0.5
24	26.42	673.7	-8.2	25.20	680.4	-7.8	23.84	450.6	-1.1	20.81	268.4	-0.8
ave.	27.68	705.8		25.89	699.0		24.05	454.5		21.07	271.8	
total		+26.0			+7.3			+5.1			+2.4	

Ta, Tc', Te, Tf.....average earth temperature in invariable layer (deg),

Ua, Uc', Ue, Uf.....heat flux in invariable layer (cal cm⁻²),

dUa, dUc', dUe, dUf.....heat flux at each time (cal cm⁻²),

attributable to the fact that the overall effect of solar radiation, degree of shielding, and reflecting in various ground conditions have great influence; the difference between the thermal properties of soil arising from the different ground conditions was revealed to have only a small effect (TAKEUCHI & SHIMA, 1976 b). Figure 19 shows schematically the heat transfer at the ground surface for each of the ground conditions, the total solar radiation being taken as 100. Table-4 shows part of the results of investigation in Matsunoyama. On the day at which this investigation was carried out, a heat of 26.0 cal cm⁻² day⁻¹ was accumulated in open lands, while only a heat of 2.4 cal cm⁻² day⁻¹ was accumulated in forest lands.

The variation of the 1-m-depth underground temperature with the ground conditions can be explained by variation in thermal diffusivity. If the variation of underground temperature is given by Eq. (9), then the amplitude of the temperature θ'_s at depth z in given ground conditions is given by

$$\theta'_s = \theta_s \exp \left(-z \sqrt{\frac{\pi}{m_n \tau}} \right) \quad \dots\dots(16)$$

where m_n is the thermal diffusivity in the given ground conditions, θ_s the amplitude of the ground-surface temperature, τ the period, and z the depth.

Table-5 shows the highest values of the amplitude of the temperature wave at a depth of one meter for each of the ground conditions, which were obtained from Eq. (16) with $z=100$ cm and $\tau=3.15 \times 10^7$ sec=one year, the amplitude of the ground-surface temperature and the thermal diffusivity found in each landslide area being used for θ_s and m_n . In Matsunoyama there is a temperature difference of 1.9°C between C and F; in Miyagami 2.3°C between A and F; and in Nawamata 2.6°C between A and F. Therefore, the difference of 1-m-depth underground temperature between the various ground conditions does not exceed the order of $\pm 1.0^\circ\text{C}$. This agrees with the observed results obtained up to date.

Since the influence of ground conditions on the 1-m-depth underground temperature amounts to $\pm 2^\circ\text{C}$ at the highest, it can not be neglected in estimating the scale of a vein stream using the $\theta_{z=1}-y$

Table 5 Amplitude of the 1—m—depth underground temperature for each of ground conditions (case taking 20°C for the amplitude on the ground surface).

Name of landslide area	Ground condition	Thermal diffusivity (m) $\times 10^{-3} \text{ cm}^2 \text{ sec}^{-1}$	θ_s $^\circ\text{C}$	θ'_s $^\circ\text{C}$
Matsunoyama	open land	4.6	20	12.6
	rice field	5.5	20	13.1
	grass land	3.3	20	11.5
	forest	2.9	20	11.2
Miyagami	open land	4.5	20	12.5
	farm	3.6	20	11.8
	grass land	3.2	20	11.4
	forest	2.2	20	10.2
Nawamata	open land	3.2	20	11.5
	rice field	3.0	20	11.2
	farm	2.7	20	10.9
	grass land	2.2	20	10.2
	forest	1.5	20	8.9

curve. Therefore, a method of correction for the influence of ground conditions was formulated:

Find the mean value ($\theta_{T.A.}$) of all the data obtained in an investigated area, and then find the mean values ($\theta_{E.A.}$) for each of the ground conditions. Take the difference between both mean values. This difference ($\Delta\theta$) will be regarded as the amount of variation generated by the influence of ground conditions. Deduct $\Delta\theta$ from the measured value (θ_M) obtained in each of the ground conditions. This value will be regarded as the corrected 1-m-depth underground temperature. In order to compare data different in the season and place of investigation, the value ($\Delta\theta_d$) obtained by subtracting the total mean value from the corrected value is calculated:

$$\Delta\theta_d = \theta_M - \Delta\theta - \theta_{T.A.} \quad \dots\dots(17)$$

$$= \theta_M - \theta_{E.A.} \quad \dots\dots(18)$$

Conclusions

The applicability of the method of investigating groundwater vein by measuring shallow-layer temperature is investigated. Practical methods for exploring groundwater vein are proposed. And various factors as ground condition, topography, geology, etc. affecting the temperature are examined; main results are as follow:

- 1) Theoretical examination is made of the possibility of utilizing the thermal relation between the annual variation of 1-m-depth underground temperature and that of flowing groundwater temperature to detect a groundwater vein by measuring 1-m-depth underground temperature. As a result, the applicability of this investigation method is shown.
- 2) It has been shown that in the present model the variation of temperature in the stream direction is less than $0.3^\circ\text{C}/\text{km}$, provided that filtration velocity of vein-stream-like groundwater is above $1 \times 10^{-1} \text{ cm/sec}$. Therefore, in the usual landslide areas the variation of temperature in the stream direction may be neglected.
- 3) In order to estimate the depth and scale of a vein stream of radii 5~10 m using the $\theta_{z=1}-y$ curve, the difference between the normal 1-m-depth underground temperature and the flowing groundwater temperature is required to be above $\pm 2.5^\circ\text{C}$.
- 4) In order to detect vein streams of radii 5~10 m, it is enough to take the distance between measuring points smaller than 5~10 m at $|\theta_e| = 10^\circ\text{C}$. In case of small $|\theta_e|$ and/or large radius of the vein stream, it is necessary to determine the distance between measuring points taking these view points into consideration.
- 5) The optimum time for 1-m-depth underground temperature investigation is March and September in Niigata Pref., Ishikawa Pref., and north part of Hyogo Pref..
- 6) The distribution of 1-m-depth underground temperature influenced by groundwater vein is not an accidental one, but it is reproducible.
- 7) Since various factors affect the 1-m-depth underground temperature, examination is made of influences of those factors, and the following conclusions are obtained:
  - a) The diurnal variation of 1-m-depth underground temperature is not observed. However, there are annual variations. Therefore, corrections must be made for the latter.

- b) Geological factors can be neglected in a place composed of rocks nearly the same kind as in an ordinary landslide area.
- c) Topographical factors do not exert significant influence for places facing in nearly the same direction as in a landslide area and for height difference up to 350 m in longitudinal and relative heights up to 10 m in transverse direction. However, in measuring temperature, a place where the topography changes suddenly should be avoided.
- d) Ground conditions exert a great influence on the 1-m-depth underground temperature: In summer and fall they yield a temperature variation of $+2^{\circ}\text{C}$ in rice fields and open lands, and -2°C in forest land. Therefore, a method of correction for them is proposed.

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References

- CARTWRIGHT, Keros (1974): Tracing Shallow Ground Water Systems by Soil Temperature, *Water Resource Research*, Vol. 10, No. 4, pp. 847-855.
- DAMBARA, Takeshi and Y. TOMODA (1969): *Geodesy and Geophysics*, the Kyoritsu Shuppan, Co., Lt., p. 255.
- FUKUTOMI, Takaharu (1951): On the Possibility of the Prospection of Hot-Spring by the Geographical Distribution of Underground Temperature in 1 m depth (The 1st Report), *Journ. Fac. Sci., Hokkaido Univ., (Geophysics)*, No. 1, pp. 21-34.
- HIRATA, Tokutaro (1931): Relative Observation Results at South and North Slopes, *Journal of the Forest Hydrological Experiments*, No. 13, pp. 206-240.
- KAPPELMEYER, O. (1957): The Use of Near Surface Temperature Measurements for Discovering Anomalies due to Cause of Depth, *Geophysical Prospecting*, Vol. 5, No. 3, pp. 239-258.
- KODAIRA, Yoshio (1932): Underground Temperature on a Hill Top, *Geophysical Magazine*, Vol. 5, pp. 89-98.
- MACKINNEY, A.L. (1929): Effects of Forest Litter on Soil Temperature and Soil Freezing in Autumn and

- Winter, Ecology, Vol. x, No. 3, pp. 312-321.
- NOMURA, Shiichi and N. MAKINO (1958): Preliminary Experiments of Geothermal Prospecting Method, Journal of Mining Metallogical Institute of Japan, Vol. 74, pp. 271-276.
- SMITH, Gordon D. (1971): Numerical Solution of Partial Differential Equations, the Saiensusha & Co., Ltd., pp. 29-33.
- TAKEUCHI, Atsuo (1972a): Underground Temperature Survey in and around the Landslide Area (2), Jisuberi, Vol. 8, No. 4, pp. 29-37.
- TAKEUCHI, Atsuo (1972b): Underground Temperature Survey in and around the Landslide Area (1), Bulletin of the Disaster Prevention Research Institute, Kyoto University, Vol. 21, Part 3, pp. 201-216.
- TAKEUCHI, Atsuo and M. SHIMA (1976a): Reproducibility of the Distribution of the Underground Temperature at One Meter Depth and One Varified Example of the Availability of Underground Temperature Survey, Geophysical Exploration, Vol. 29, No. 6 pp. 11-18.
- TAKEUCHI, Atsuo and M. SHIMA (1976b): On the Effect of Ground Condition on the Underground Temperature and Solar Radiation Reaching to the Ground Surface, Annuals, Disaster Prevention Research Institute, Kyoto University, No. 19B-1, pp. 351-370.
- TAMADE, Mikitoshi (1925): Relation between in and outside of Underground Temperature in the Forest, Jour., of the Forest Hydrological Experiments, No. 7, pp. 120-146.
- UEHARA, Masaki (1961): Physical and Meteorological Studies on the Cultivation and Utilization of Slope Land, Technical Bull. of the Faculty of Agriculture, Kagawa University, No. 7, pp. 1-113.
- UWAI, Kanefumi (1932): Some Problems on Underground Temperature, Journal of the Meteorological Society of Japan, Sec. 2, Vol. 10, No. 12, pp. 703-713.
- WOLLY, E. (1881): Über den Einfluss des Wassers auf die Bodentemperature, Forschungen auf dem Gebiete der Agrikultumphysik, Vol. 4, pp. 147-188.
- YAKUWA, Risuke (1932): Über die Bodentemperature in der verschiden Bodennarten, Geophysical Magazine, Vol. 6, pp. 179-187.
- YAKUWA, Risuke (1943): Untersuchungen über die Bodentemperature, Memoris of the Sapporo Meteor ological Observatory, Vol. 2, No. 3, pp. 42-106.
- YAMASHITA, Kohji, M. KOYANAGI, F. NAITO and K. ASAKURA (1978): On the Diurnal Variation of Soil Temperature at the Mountain Slope, Geographical Review of Japan, Vol. 51 No. 3, pp. 245-255.
- YUHARA, Kozo (1955): Geothermal Prospection of Underground Heat Source, Society of Exploration Geophysicsts of Japan, Vol. 8, No. 1, pp. 27-33.
- YUHARA, Koyo and K. SENO (1969): Geology, Geophysics and Geochemistry of Hot and Mineral Springs, the Chijinshokan & Co., Ltd., p. 132.

地すべり地における 1 m 深地温測定による 地下水流脈調査法について——第 1 部

竹 内 篤 雄

要 旨

地すべり活動に直接大きな影響を与える脈状地下水の存在位置と規模を推定する一方法として、流動地下水温と平常浅層地温との差を利用した浅層地温測定による地下水流脈探査法の可能性について検討した。

第 1 章では現地観測結果に基づいて水脈のモデルを構築し、非定常三次元熱伝達式を建て、それを差分法により数値解折した。ついでその結果を現地観測結果と対比し、そのモデルと熱伝達式の妥当性を示した。さらに浅層地温測定によって地下水流脈存在による平常浅層地温の乱れは十分に握えられることを示した。

第 2 章では浅層地温測定方法と同調査法の適用時期および調査結果の再現性を中心にのべてある。測定方法は温度差の小さい地温を測定するに適した測定器を用い、測定は測温体埋設後 10 分経てから行なうことにした。次に流脈規模を推定するに必要な測点間隔と流動地下水と平常 1 m 深地温との最低必要温度差について検討し、半径 5 ～ 10 m の流脈を探査するには 5 ～ 10 m の測点間隔と $\pm 2.5^{\circ}\text{C}$ 以上の温度差が必要であることを示した。三番目に同調査法は流動地下水と平常 1 m 深地温との温度差を利用したものであるため、その適用期間を求める必要がある。現地調査、理論計算によるとそれは 9 月と 3 月を中心とした期間であることが示された。最後に同調査結果の再現性は十分にあることを現地調査によって示した。

第三章では測定値に關与する諸種の因子が検討された。日変化は 1 m 深で地温を測定する限り、測定値への影響は無視できるが、年変化は長期調査を行なう場合はその影響があるので、必要に応じてそれを補正する。地質の相違による影響は殆んどない。地形の影響は標高差 350 m 程度までは測定値に影響をおよぼさない。さらに地況は $\pm 2^{\circ}\text{C}$ もの影響をおよぼす場合があるので、その補正方法を提案した。

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