The Seismic Refraction Survey in Landslide Areas

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Abstract

Some topics of seismic refraction survey in landslides such as an interpretation procedure for a Mirage layer; fan shooting for detecting faults in the bed rock by a short spread of transducers; a wave-front method for interpreting well-to-surface data are herein described referring to case histories of surveys in landslides in Shikoku and Niigata. Some results by the seismic method are compared with those by other ones such as electrical-resistivity method, γ-ray measurement, boring-log evaluation, water-table observation by means of boreholes, etc. A synthetic application of a series of geophysical methods is recommended in view of experience in these landslides.

1. Introduction

A seismic refraction method is often employed for investigating the underground structure in landslide areas. Among various geophysical methods the seismic one is believed to be completely established and technically fully developed. In reality, however, this is not the case, for there are special difficulties in applying this method to landslides because of complicated topographies, underground structures, etc. For instance, if a gentle inclination of layering may not be assumed as very often is the case in landslides, there arises a problem that the solution satisfiyng measured data becomes non-unique, and moreover that a rather tedious work is required only to find one of the innumerable possible solutions.

A careless interpretation, therefore, may sometimes lead to an inaccurate result, and there are many problems yet to be solved in data acquisition as well as in interpretation. The author and his colleagues have performed seismic and other geophysical surveys at several landslides in Tokushima Prefecture, Shikoku, and Niigata Prefecture, Central District Japan, during the past few years, and it may be of some significance to discuss those cases for finding a sound application of this classic technique to such complicated environments as can occur in landslides.

In the present paper some topics such as an interpretation procedure for a Mirage layer, fan shooting for detecting faults in the bed rock by a short spread of transducers, a wave-front method for interpreting well-to-surface data are described. Then some results of seismic surveys are compared with those by other methods. Finally, a synthetic application of a series of geophysical methods is recommended in view of experience in exploration in these landslides.

2. Some Topics of Seismic Refraction Survey in Landslides

2.1 A Mirage Layer in a Crystalline-Schist-Type Landslide

A refraction survey was carried out in the Kamisaga landslide in Tokushima, which is situated in the Mikabu-Greenrock belt consisting of Paleozoic ultra-basic metamorphic rocks. This landslide is characterized by a bed rock of high velocity reaching 2.7 or 5.9 km/s and a conspicuous Mirage phenomenon, or curved time-distance curves, in the over-lying colluvium.

A gradual increase of velocity with increasing depth is often expressed by a linear function of depth, in which case a ray path becomes a circle passing through a shot point and an observation point[1]. Although this assumption is simple and convenient, the velocity increase is not always linear but of a more complicated nature, and Hollister[2] discusses such cases as given by the following expression:

$$V = C(z+A)^{1/n}$$

where C, A, n are constants at each site.

For the case of a Mirage layer underlain by a halfspace with a uniform high velocity a conventional multilayer-analysis method cannot be applied but an alternative one is required. If the velocity in a layer of great depth followed the above expression, a ray path would be a curve similar to a circle, but in the present case the Mirage layer is bounded by a bed rock of uniform velocity, and a refraction at the critical angle would occur when a ray impinges upon the bed rock of either 2.7 or 5.0 km/s. In other words, the circle-like ray, which would have its deepest point at a depth z_{max} corresponding to $V(z_{max}) = V_1$ in the Mirage ground extending suf-

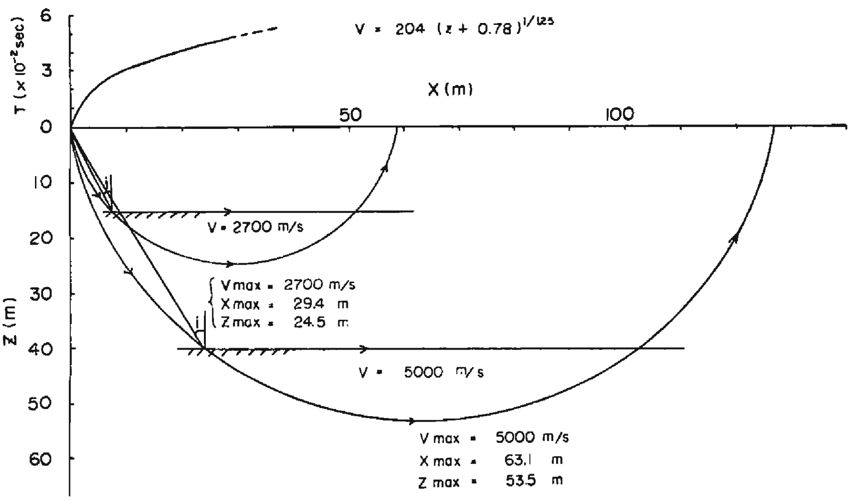

Fig. 1 A traveltime-distance curve (upper half) and ray paths (lower half) in a Mirage layer. The ray, which would reach the maximum depth z_{max} corresponding to V_{max} in a Mirage layer, suffers a critical-angle refraction, if it impinges on the bed rock of $V = V_{max}$.

ficiently deep without bed rock, suffers critical-angle refraction at the surface of the bed rock of velocity V_1, at whatever depth it may be encountered, since for that ray the value of $\sin i(z)/V(z)$ at any depth z must be equal to $1/V_1$, i.e. $\sin(90°)/V_1$ throughout the path, i being the angle of incidence (**Fig.1**).

In analysing the depth of the bed rock one must note that the apparent critical angle and the mean velocity in the Mirage layer vary greatly according to the depth of the bed rock D. The mean velocity in the Mirage layer is given by

$$\bar{V}=(D/\cos i_D)/\int_0^{S_D}[1/V(z)]ds=(D/\cos i_D)/\int_0^D[1/V(z)\cos i]dz$$

where $\cos i=\sqrt{1-\sin^2 i}=\sqrt{1-[V(z)/V_1]^2}$

$$\cos i_D=\sqrt{1-\sin^2 i_D}=\sqrt{1-(\bar{V}/V_1)^2}$$

and i_D is the apparent incident angle. Therefore,

$$D/[\bar{V}\sqrt{1-(\bar{V}/V_1)^2}]=\int_0^D[1/\{V(z)\sqrt{1-(V(z)/V_1)^2}\}]dz$$

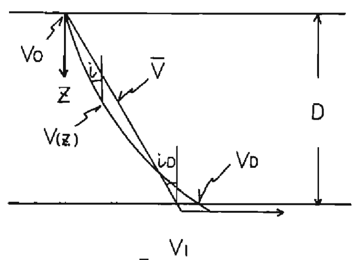

Fig. 2 The mean velocity $\bar{V}$ and the apparent critical angle i_D corresponding to a curved ray in a Mirage layer $V(z)$. $\bar{V}$ and i_D depend on the thickness of the Mirage layer D.

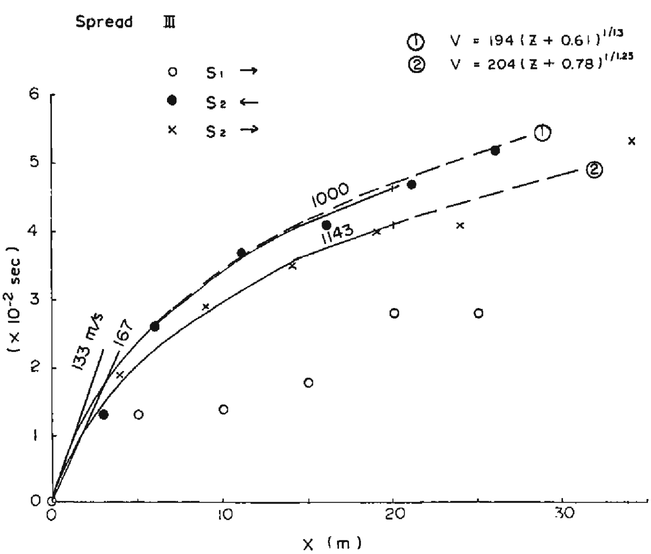

Fig. 3 Curved traveltime-distance plots in the Kamisaga landslide and their expressions after Hollister.

The right-hand side in the above relation can easily be calculated, if one assumes the value of D on trial, and $\bar{V}$ can be determined in turn. $\bar{V}$ must be within the range from V_0 to V_D, i.e. from the velocity at the surface to that at the bottom of the layer, and if this condition is not satisfied, one must reassume D and iterate the same procedure until the prescribed condition would be satisfied (**Fig.2**).

In the present study the traveltime-distance curves are compared with those based on the expression after Hollister as shown in **Fig.3**, and as a representative expression for the middle part of the area the following relation has been derived.

$$V=204(z+0.78)^{1/1.25}$$

where z must be smaller than 15 meters. The characteristics of colluviums can be expressed quantitatively by the constants C, A, n, if relevant data would be systematically collected.

2.2 Fan Shooting for Detecting Longitudinal Faults in a Bed Rock by a Short Spread of Transducers

In the Shobu landslide in Tokushima Prefecture a fan-shooting procedure was carried out for detecting longitudinal faults in bed rock, which should be difficult to be detected by ordinary profile shooting along a line of limited length. This scheme was first tried by Kanda[3] in 1966 in a survey for a dam foundation. The landslide

$$D_R=\frac{1}{2}\left\{T_{QR}+T_{SR}-\left(\frac{L_{QR}+L_{SR}}{V_2}+D_Q+D_S\right)\right\}$$

where $D_Q+D_S=T_{QS}-\dfrac{L_{QS}}{V_2}$

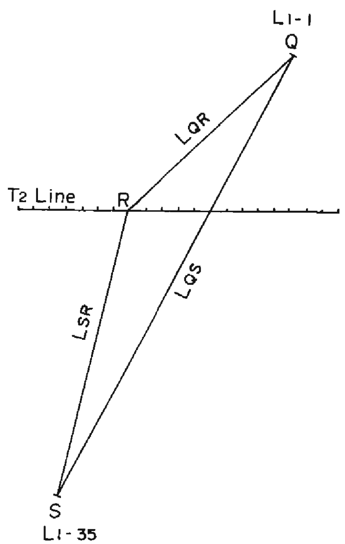

Fig. 4 The layout of measuring line T_2 for a fan shooting at Q and S. T is travel time, D_R, D_Q and D_S are the delay times at R, Q and S, respectively, and V_2 is the bed-rock velocity.

is situated in the Sanbagawa metamorphic belt, and the area consists of alternating argillaceous schist and green schist.

A series of profile shootings in this area revealed an overall layering consisting of a surface layer of 0.5 to 0.7 km/s, a second layer of 2.0 to 2.5 km/s and bed rock of 3.0 to 3.5 km/s. The fan shooting was planned on two transverse measuring lines of 130 to 190 meters long, T_2 and T_3 lines, from which only the analysis of T_2 line will be described below. Transducers were set at 10-meter intervals along the measuring line, and shot points were selected at the uppermost and the lowermost points of the slope, more specifically at L1-1 and L1-35, about 100 and 200 meters offset from the measuring line T_2, respectively (**Fig.4 and 6**).

In the case of offset shooting a delay time is given by

$$D_R = 1/2[T_{QR} + T_{SR} - ((L_{QR} + L_{SR})/V + D_Q + D_S)]$$

where V is the velocity in the bed rock, T travel time, L distance, and suffixes denote the points given in **Fig.4**. The sum of delay times at Q and S, $D_{sum} = D_Q + D_S$, can be estimated by subtracting L_{QS}/V from the total traveltime T_{QS} in the profile shooting along L_1 line, as 25.1 ms, where the velocity 3.5 km/s is assumed for the bed rock. T' curve or $T_{meas} - D_R$ are plotted by small solid circles in **Fig.5**. In the next step we construct a theoretical T' curve $D_Q + L_{QR}/V$ or $D_S + L_{SR}/V$ for the two shots selected above. For this purpose we must know the value of D_Q and D_S separately instead of their sum, D_{sum}. We assume that the measured T' and the theoretical ones coincide at the two closest observation points from every shot point, i.e. No.4 for the shot point Q and No.18 for the shot point S, respectively. In other words, we assume that the total traveltime from Q or S is composed of the sum of $D_Q + L_{QR}/V + D_R$ or $D_S + L_{SR}/V + D_R$, where D_R is the delay time at the closest point R. It will be demonstrated later that this assumption is valid. Thus, the delay times at the both shot points are determined as $D_Q = 18.1$ ms and $D_S = 2.0$ ms (milli-seconds) yielding $D_Q + D_S =$

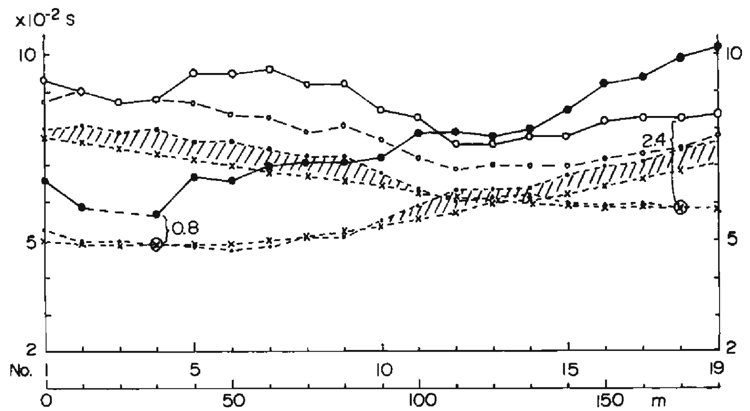

Fig. 5 The time-distance curve for T_2 line. The measured and calculated T' curves for shots at Q and S are given by small solid circles and crosses, respectively. The diffferences between measured and calculated values are shown by hatches. The delay times due to the first layer only are given by small open circles.

20.1 ms, which is not equal to 25.1 ms employed in calculating the measured T' curve. This discrepancy is caused by the errors included in T_{QR} and T_{SR} for certain measuring points, but for the moment we continue to calculate D_Q+L_{QR}/V and D_S+L_{SR}/V for all observation points and plot the values by $\times$ in **Fig.5**.

The theoretical T' curve and the measured T' curve do not at all points coincide with each other, and the differences are shown by hatches between these curves. It is noted in the figure that the difference is significant only in the farther halves of the spread for each shot point, i.e. from No.11 to 19 for shot S and from No.1 to 10 for shot Q. The amount of the difference is from 5 to 7 milli-seconds at all points assigned above.

The fact that the measured T's are greater than the theoretical ones only in the farther halves of the spread for every shot suggests that the measured values only in the farther halves contain extra delays caused by a certain low-velocity zone, and that the zone must exist between No.10 and 11 (**Fig.6**). The position of this low

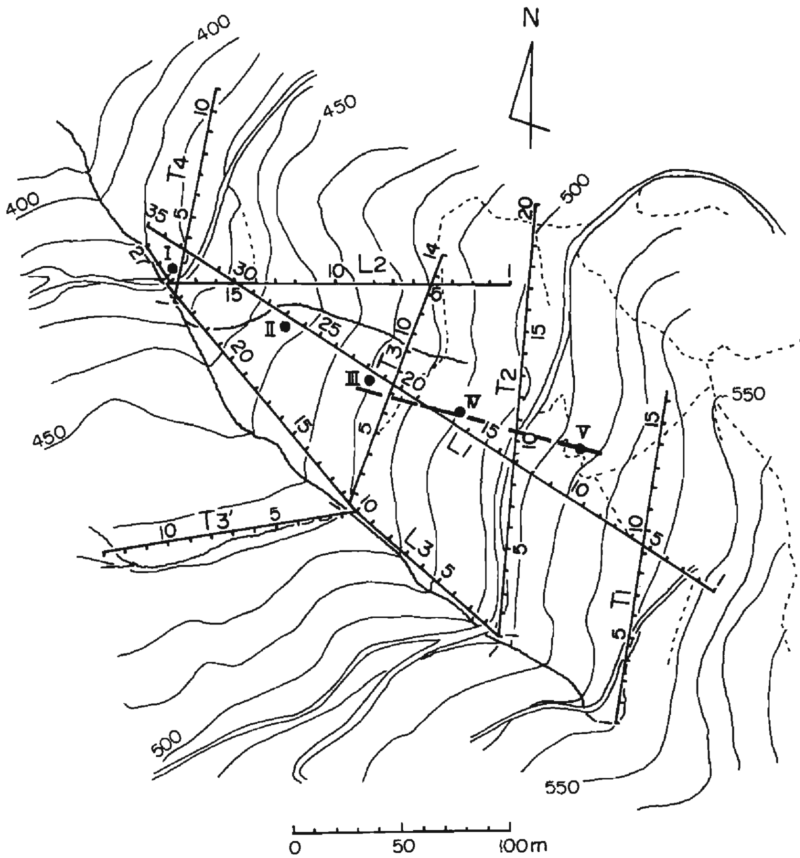

Fig. 6 The low-velocity zone inferred by the fan shooting and profile shooting is shown by a thick broken line, which is correlated with a depressed topography and a lineament discernible in an air photograph.

-velocity zone is correlated with a depressed topography and a lineament discernible in an air-photograph.

If this presumption is valid and the delay due to the zone is 5 milli-seconds, this delay must be included in the measured values of either T_{QR} or T_{SR} in the farther halves for each shot point. Therefore, $D_{sum}=D_Q+D_S=25.1$ ms also includes the error by 5 milli-seconds, while D_R calculated using this value of D_Q+D_S does not contain any error from the same source, because an equal amount of error is included both in the measured value T_{QR} or T_{SR} and $D_{sum}=D_Q+D_S$ and cancels in the derivation of D_R. The difference between D_{sum} and the sum of separate D_Q and D_S by 5 milli-seconds, thus, may be attributed to a low-velocity zone between No. 10 and 11, and the validity of the assumption that the measured and the theoretical T' coincide at the closest measuring points from each shot, for which points the rays have not yet passed through the low-velocity zone, is demonstrated.

The delay times calculated in the above are the sum of those due to the first layer and those due to the second layer. If one subtracts the value due to the first layer, which can easily be determined by a profile shooting on a short spread, from the total delay time, the difference T should be due to the second layer, which is given by $h=T\cdot V_2/\cos\theta_{23}$, where V_2 is the velocity in the second layer, and θ_{23} is the critical incident angle between the second layer and the bed rock. The result is shown in **Fig.7**.

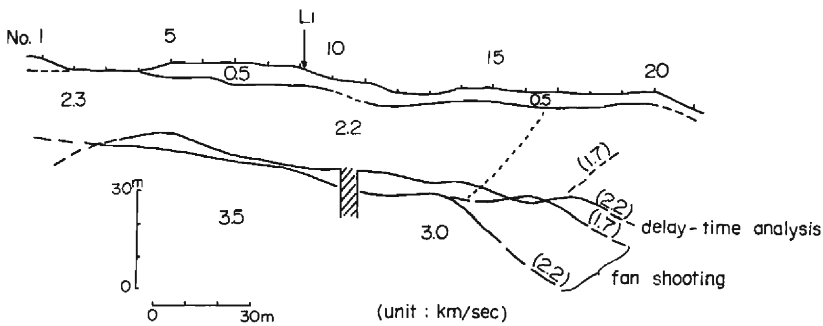

Fig. 7 The profile along T_2 line. A low-velocity zone in the bed rock in the middle of the spread is given by hatches.

2.3 A Wave-Front Method[4] for Interpreting Well-to-Surface Data

In the Matsunoyama landslide in Niigata Prefecture a well shooting was performed in order to investigate an underground-velocity distribution, in which a borehole-type three-component transducer was pressed against a borehole wall by an inflated rubber tube for measurement, released and displaced to another depth within the hole of 27 meters depth for measurement in the next stage.

The geology of this region is tertiary and the rocks are predominantly mudstones. Shots were delivered by hitting the end of a wooden plate about 2 meters long and 30 cm wide and with a weight of about 150 kg upon it. Shot points were located

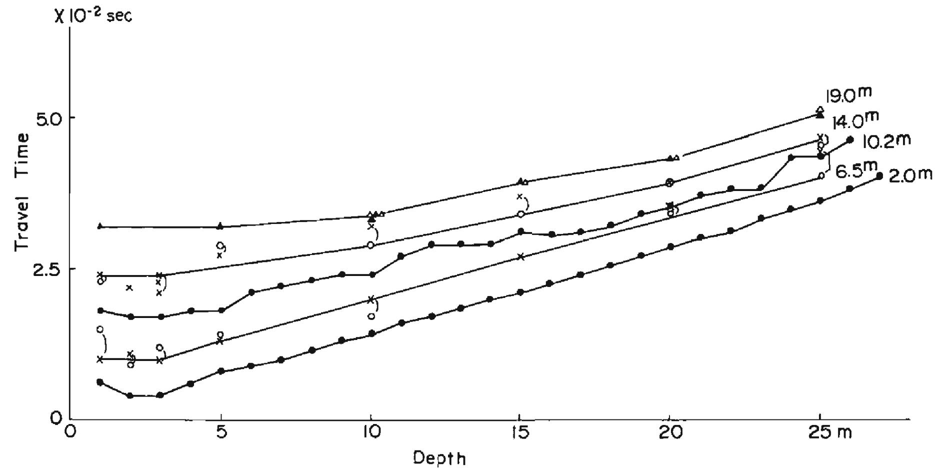

Fig. 8a The time-depth curves for *P*-wave arrivals observed in a borehole in the Matsunoyama landslide. The parameters are horizontal distances of shot points from the borehole mouth.

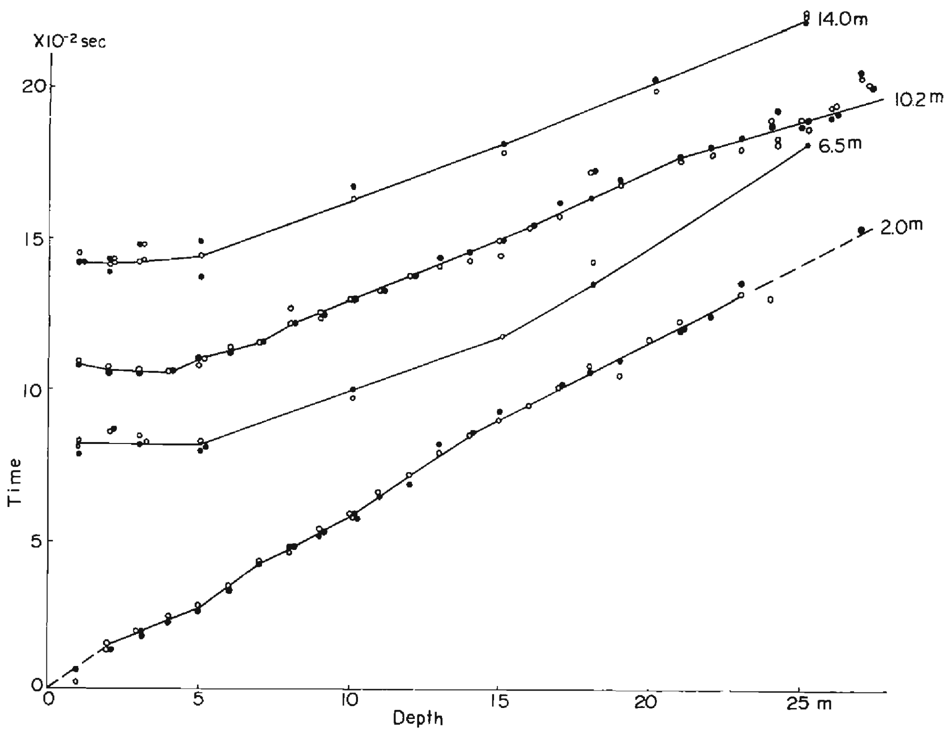

Fig. 8b The time-depth curves for *S*-wave arrivals observed in a borehole in the Matsunoyama landslide. The parameters are horizontal distances of shot points from the borehole mouth.

not only at the mouth of the borehole as usual but at distances of 5, 10, 15, 20 and 25 meters from the borehole on the ground surface.

Travel times of P and S waves versus depth are given in **Fig.8 a,b**. The velocity at any depth along the hole may be seen from the results for the shot at 2.0 m, while velocities in shallower layers may be determined from data for shot points at every horizontal distance received by a transducer at 1.0 meter depth, which yields data corresponding to an ordinary surface refraction work.

As for a P-wave structure, a preliminary interpretation of an ordinary surface survey reveals a two-layered structure with a first layer of 300 m/s and a subgrade of 700 m/s. Analysis of data for $d=10, 15, 20, 25$ m by wave-front method assuming two regions of 300 m/s and 700 m/s yields almost the same results as the above as shown in **Fig.9.**

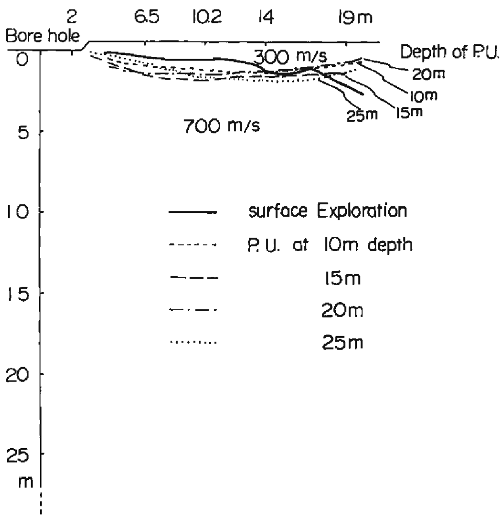

Fig. 9 The P-wave-velocity profiles determined by wave-front method for data at various transducer depths.

From uphole shooting, S-wave velocities along the hole are estimated to be 160 m/s for depth 0 to 14 m, 200 m/s for depths greater than 14 m, while from surface survey it reveals that a surface layer of 35 to 50 m/s with thickness of 0.3 to 0.5 m, which is lacking at the borehole mouth, is underlain by a layer of 100 m/s. Therefore, the discontinuities dividing regions of 35 to 50 m/s, 100 m/s, 160 m/s and 200 m/s must be determined.

First, $t=(0.3\text{–}0.6)$ m/(35–50) m/s$=0.01$ sec. is subtracted from the measured values except at $d=2.0$ m, which is equivalent to displace the shot points except that at 2.0 m to the bottom of the surface layer. A wave-front method is applied to the revised data for a transducer at 10.15 m depth for determining the boundary between 100 m/s and 160 m/s regions. An example of the graphical approach of the wave-front method is shown in **Fig.10.** In the next stage the boundary between

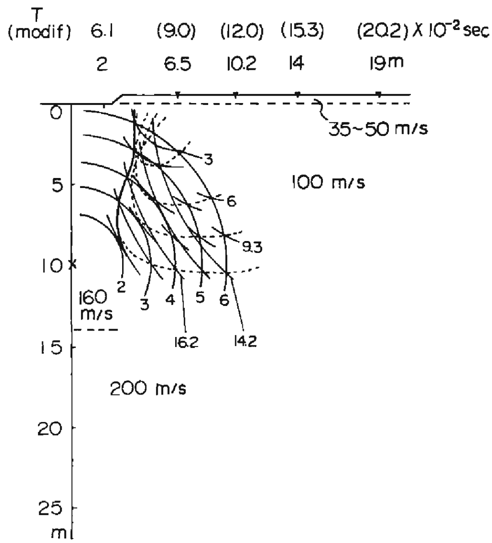

Fig. 10 An example of wave-front method for S-wave arrivals measured at the depth 10 m and for shot points at distances of 6.5, 10.2, 14 and 19 m.

160 m/s and 200 m/s regions is determined from the data for a transducer depth z=20 m. Discrepancies among cases for different shot points or transducer depths are tolerable, and the results may be seen on the whole as reliable.

Fig.11 is a synthetic representation for both structures for P and S-wave velocities. This example shows that the well-to-surface method enables a survey of a rather deep structure with a reasonable effort, if the method is properly applied.

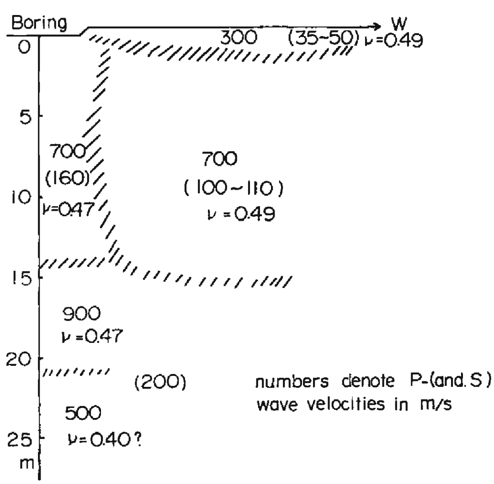

Fig. 11 A synthetic representation of P and S-wave-velocity structures.

3. Comparisons of Structures Estimated by a Seismic-Refraction Method with Those by Other Methods

In this section some examples of comparison of structures estimated by a seismic-refraction method and those by other methods such as electrical-resistivity method, γ-ray measurement, etc. will be presented.

In the Shobu landslide in Tokushima, not only a seismic survey but an electric-resistivity survey by three-pole method with inter-pole distances from 0.5 to 30 meters were performed at 30 measuring points. The layout of the measuring lines is shown in **Fig.12**.

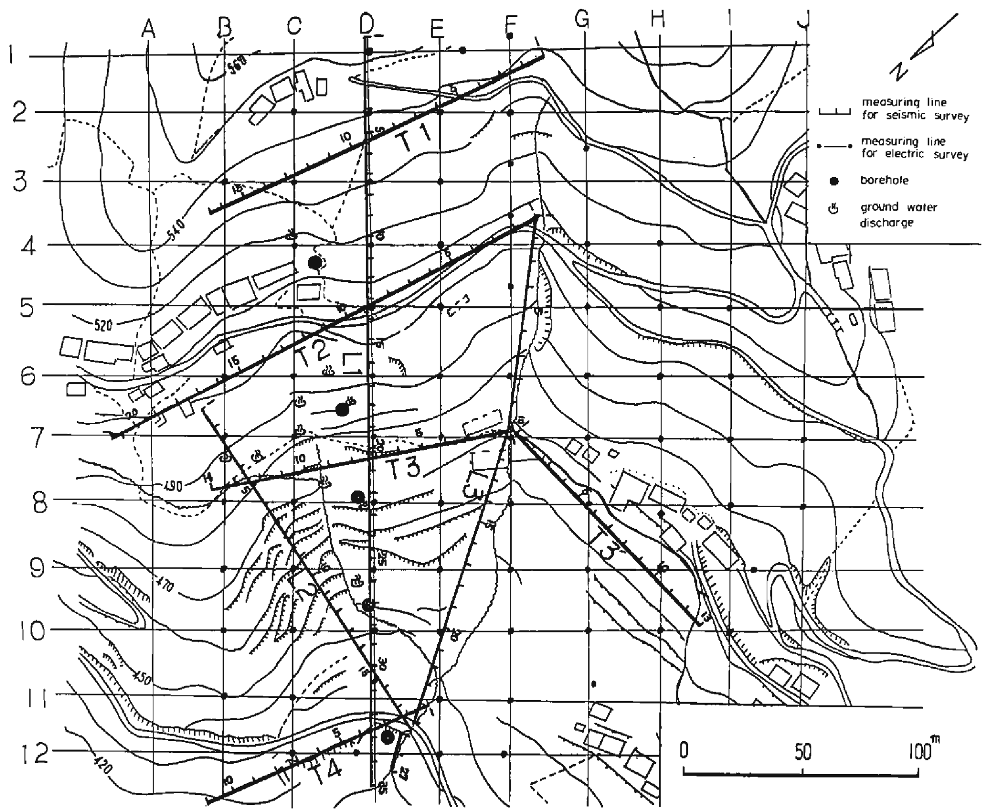

Fig. 12 The layout of measuring lines for seismic and electric surveys in the Shobu landslide.

The results of surveys along a longitudinal section is shown in **Fig.13**. While the seismic profile consists of a first layer of 0.5 to 0.7 km/s with thickness of 5 to 10m, a second layer of 2.0 to 2.5 km/s with the thickness of 20 to 30 m and a bed rock of 3.5 km/s, the electric survey gives a two-layered structure disregarding a surface soil of about 1 m thickness. The resistivity of the first layer is 20 to 90 KΩ-cm and that of the second layer 2 to 24 KΩ-cm, respectively.

The second layer determined by the electric method is very similar in configu-

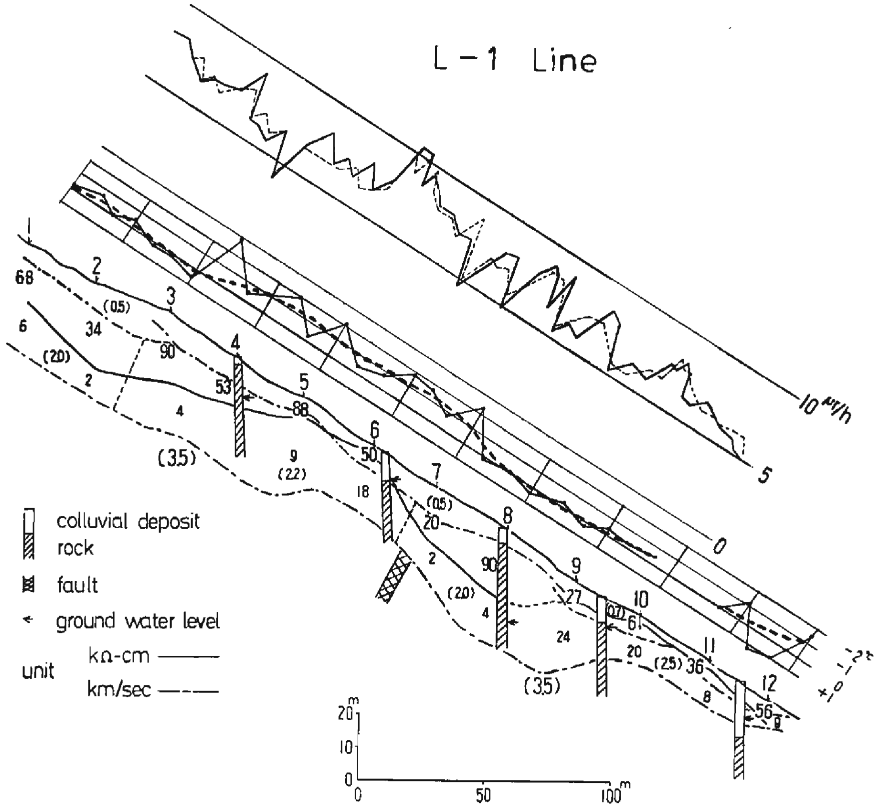

Fig. 13 A comparison of results along a longitudinal line L_1 in the Shobu landslide, concerning seismic-wave velocity, electric resistivity, groundwater levels, γ-ray intensity and 1 meter-depth ground temperature.

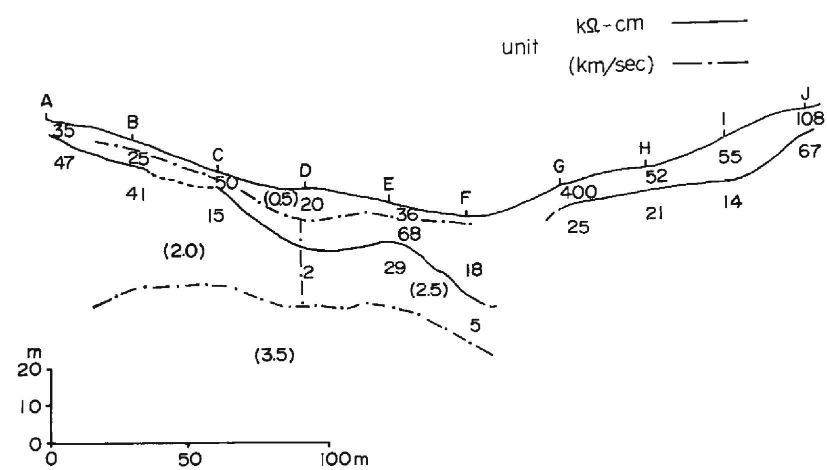

Fig. 14 Another comparison of results of seismic and electric resistivity surveys along a transverse line T_2 in the Shobu landslide.

ration to the bed rock seismically determined, however the depth of the former is smaller than the latter by more than 10 meters.

Fig.14 shows another profile along a transverse line, where the seismic method gives a first layer of 5 to 10 m thickness, a second one of 20 to 30 m and a bed rock, while the electric method reveals a first layer of 18 to 400 KΩ-cm with 10 to 20 m thickness and a second one of 2 to 67 KΩ-cm, which also implies the situation that the bed rock determined by seismic method and the second layer electrically determined are very similar in configuration but differ in depth by 10 to 20 meters.

From the above examples it seems that the results by seismic as well as electric methods often are similar in configuration but unequal in depth. The situation will be understandable, if one compares the both estimated structures with boring logs and the water-table measured in boreholes in **Fig.13**. The upper boundary of the bed rock or the bottom of the colluvium determined seismically are in good agreement with that of the boring logs, while the top of the second layer electrically estimated agrees well with the ground-water levels indicated by arrows in **Fig.13.** Bearing this in mind one would correlate the parts of low resistivity at D and F in **Fig.14** with a lower topography or a brook where the water content of soil should be higher (See also **Fig.12**). The bed rock of 3.5 km/s is considered to correspond to an impermeable layer referring to boring cores with few fissures, while the second layer of 2.0 to 2.5 km/s to a weathered part of it or to a stiff colluvium, either one a permeable layer. Thus, the upper surface of the electrically-determined second layer corresponds probably to a water-table within the permeable layer composed of weathered bed rock or colluvium.

In **Fig.13** the results of γ-ray measurement and 1 m-depth ground temperature are also shown. It is interesting to note that the peak of γ-ray intensity seems to correspond to the seismically inferred fault and a lower temperature to a higher water-table.

5. Discussion

In the preceding sections some topics of seismic-refraction survey in landslides have been presented and a few examples of parallel employment of various exploring methods at a site are described. In the present section the manner of application of seismic method to landslides will be discussed.

There are engineers who consider the seismic method as not suitable for landslide investigation. It is sometimes true, if the method is applied incorrectly, or if they demand too much from seismic surveys. However, it is in general a prejudice against the method, since it can afford useful data when properly applied. Such people may consider geophysical surveys to be un-necessary, if they had some boring logs, and look at the geophysical methods and boring in a competitive position.

Although seismic data can be analysed without boring logs, the interpretation would be improved and the reliability would be increased significantly, if some boring data would be supplied to back up interpretation.

It is evident that the all aspects of a landslide cannot be elucidated only by seismic method, because it usually includes information only on the boundary between the colluvium and the bed rock or that between the weathered and fresh rocks, and very rarely on the water-table also. From the above information the position of a sliding surface cannot be determined but only suggested. The case at Shobu gives such an example.

If one performs a little more collaborative investigation than usual, a boundary with a poorer contrast also can be detected as shown by the case in Matsunoyama. In such an investigation, the use of wells as shot or observation holes is very desirable. In a ground with layers of high-contrast velocities on the other hand, it is rather difficult to determine thicknesses and velocities of every layer, because seismic rays are apt to be propagated through a particular layer exclusively, thus carrying little information on the other layers. Such a tendency is easily found by ray tracing[5]. The use of wells eliminates such defects by forcing the rays to be propagated dispersively through every part of underground space. Therefore, a well-to-surface or well-to-well shooting is recommended, if a high reliability is demanded.

A combination of various exploring methods is always desirable, since the data from electric resistivity, γ-ray, geotherm or other procedures including boring will substantially elucidate the state of underground in landslides, through which the results of seismic survey also may become more useful than when independently evaluated. Such examples are shown by the case of the Shobu landslide. The electrical resistivity strongly reflects the state of under-ground water and its application is especially useful in landslide investigation, and it is recommended that at least the seismic and electric methods be combined when investigating landslides.

Lastly, the timing of seismic survey in the course of landslide investigation will be discussed briefly. Preceding the discussion an ordinary procedure of landslide investigation in Japan must be described as a background; When a landslide hazard occurs, it is usual to execute investigations including boring, seismic survey, electric survey, on-surface as well as in-ground strain measurements, etc. first, then on the basis of the data thus obtained a stability analysis is performed, and/or countermeasures such as earth removing, drainage, retaining walls, etc. are designed. During the process the seismic method is often applied in order to help select the position and the depth of borings or for supplying data on the under-ground structure for a stability analysis.

The seismic method is useful for investigating over a wide area or for determining an overall situation within the ground, for example bed rock, faults, etc. The above purposes correspond to a preliminary survey. This method is also applicable as a means for determining the depth of bed rock with a high accuracy, if information from some boring logs is available and a collaborative survey is practicable. It is desirable that boreholes be used for shooting or receiving signals in order to secure a high reliability of interpretation of the results. This type of seismic survey, which is first applicable after some borings have been executed, is not uneconomical, yet it is useful for reasonable planning of drainage or construction work. The seismic method, thus, may be applied two-fold both as a preliminary survey and as a precise one as well.

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References

1) Tazime, K.: Seismic Exploration Method for Civil Engineers, Maki Book Company, 1977 (in Japanese).
2) Hollister, J. C.: A Curved Path Refraction Method, Seismic Refraction Prospecting ed. by A. W. Musgrave, Soc. Exploration Geophysicists, 1967, pp.213-230.
3) Kanda, Y.: Fan Shooting Applied to Investigate the Deep Bed Rock in the Valley, Geotechnics, IV, 1966, pp.104-109 (in Japanese).
4) Rockwell, D. R.: A General Wave Front Method, Seismic Refraction Prospecting ed. by A. W. Musgrave, Soc. Exploration Geophysicists, 1967, pp.363-415.
5) Bois, P., M. La Porte, M. Lavergne and G. Thomas: Well-to-Well Seismic Measurements, Geophysics, Vol.37, No.3, 1972, pp.471-480.