GEOPHYSICS, VOL. 42, NO. 3 (APRIL 1977); P. 562–571, 7 FIGS., 2 TABLES

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GEOPHYSICAL METHODS FOR THE INVESTIGATION OF LANDSLIDES

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Landslides occur extensively in all countries of the world. A landslide is a complex geologic body composed of a combination of layers having contrasting and gradational physical properties. In assessing the danger of landslides, it is of prime importance to investigate the structure of the landslide slope and its water saturation as well as the properties and status of the soils comprising the slope. The investigation and full evaluation of all these problems by traditional methods of engineering geology are sometimes impossible.

Electrical and seismic methods are used to obtain the information needed to determine slope stability. Experience has been gained from long-term investigations carried out in various regions of the Soviet Union. Applications include evaluating geologic and hydrologic conditions related to the occurrence of landslides. Primary attention is devoted to the study of landslide slopes proper. The geologic structure of a landslide is considered in modeling it and determining the thickness of both the landslide body and the slip zone. The methods of self-potential, resistivity, and temperature measurement are analyzed for characterization of the seepage flow through the landslide body. Self-potential, resistivity, and temperature anomalies are associated with sites of increased landslide activity.

Useful engineering properties of soils may be obtained from field and laboratory geophysical measurements. Measurement of changes of geophysical parameters with time are significant in assessing changes in the states of landslide soils.

Observation of the direction and velocity of landslide movements is possible with magnetic and electrical methods.

Examples of geophysical investigations of landslides in the Crimea, on the Black Sea coast of the Caucasus, and in the Volga River Valley are presented.

INTRODUCTION

The term "landslide" implies a sudden or gradual rupture of rocks and their movement downslope by the force of gravity. Landslides may occur in many settings: on the banks of rivers, lakes, reservoirs, and seas as well as on mountain slopes. They often affect extremely valuable areas of economic development and endanger engineering structures. Where they occur on the edges of quarries and on the slopes of open pit mines, landslides menace the exploitation of mineral deposits.

Landslide control is enormously expensive and labor-consuming and is not always effective. Sometimes the intensity of deformation even increases after control procedures are initiated.

A valid assessment of landslide hazard requires the solution of specific problems concerning the structure and composition of the slope as well as the status and properties (e.g., thickness and water content) of individual layers of rocks. Data on the groundwater regime should also be developed. Estimates of slope stability must be based on the results of these investigations, supplemented by data on the climatic and hydrologic conditions of the region, the economic activity of man, and the history of local landslides.

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The application of geophysical methods provides new means of rapid investigation of vast areas, producing data with increased accuracy from a larger number of sample points than is possible by the use of geologic engineering techniques. As an additional advantage, the determination of the mechanical properties of the wet and dry soils is not made on single samples of limited volume, but is based on measurements of large volumes of rocks directly involved in the processes occurring in the slope under investigation. Thus, the parameters measured automatically reflect the combined geologic and hydrologic characteristics, which sometimes cannot be identified separately. Moreover, the potential value of regime[1] observations increases significantly because geophysical measurements can be repeated any number of times without disturbing the environment.

We shall delineate the major problems of the investigation of landslides by geophysical methods and deal with certain aspects of the data interpretation.

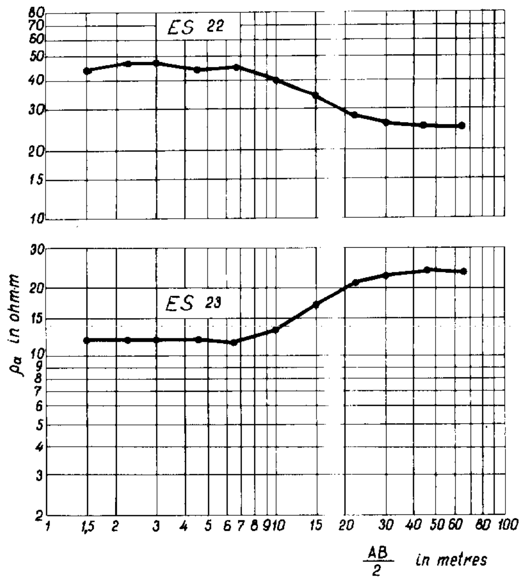

FIG. 1. Vertical electrical sounding curves measured at a landslide site on the southern coast of the Crimea.

INVESTIGATION OF THE GEOLOGIC CONFIGURATION OF A LANDSLIDE

Landslides are characterized by a combination of layers oriented in different directions and having varying degrees of physical property contrasts and gradients.

The complexity of the geologic configuration of landslides makes it necessary to investigate them in detail. The rapid variation with distance of geoelectrical conditions in landslide slopes is illustrated by the comparison of the two electrical sounding curves obtained at measurement stations 100 m apart at a site on the southern coast of the Crimea (Figure 1). It is most probable that the landslide deposits at electrical sounding station ES 23 are heavily saturated with water which causes the relatively low apparent resistivities (about 12 Ω-m) seen on this curve at values of AB/2 less than 15. Naturally, under such conditions, a single sounding cannot provide very representative data. It is not an exaggeration to say that a sparse network of measurement stations on a landslide is sure to lead to failure of the investigation.

When it is not economically and technically feasible to establish a uniform grid of observation points, the landslide investigation should be conducted by use of a system of profiles. In such cases, it is recommended that three profiles be located along the axis of the landslide, i.e., approximately along its direction of flow. Then a number of profiles should be oriented across the landslide body. Both the longitudinal and transverse profiles should extend beyond the landslide boundary to make it possible to compare the measurement values obtained within the displaced landslide mass and those associated with the stable slope.

In addition to the use of a sufficient density of measurement stations, one should use techniques designed to cope with the specific problems expected. Frequently, the electrical sounding curves and refraction traveltime graphs turn out to be difficult to interpret because the interfaces to be detected are discontinuous and closely spaced, and the layers are thin, often with gradual or small changes in the rock properties. For instance, a slip zone in homogeneous soil may be so thin that it does not affect the geophysical measurements at the ground surface despite a strong contrast of physical properties within the zone.

An important phase of the interpretation of electrical soundings consists of simultaneous consideration of entire groups of curves, with the

[1] The term regime is used to include the boundaries and parameters of the system.

rejection of those curves which are not typical of a given site. Apart from the resistivity values and general shapes of the curves, minor flexures should be noted if they reoccur systematically in a particular group of curves, and are not caused by roughness of the terrain.

When interpreting electrical soundings, it is important to consider a gradient in the conductivity of an intermediate layer which, in the majority of cases, is representative of the slide zone. According to recent investigations (Zhigalin, 1973), the three-layer curves calculated for sections with an intermediate layer of continuously changing conductivity differ significantly from those plotted for models with constant resistivities. For flowing landslides characterized by a three-layer section of H-type ($\rho_1 > \rho_2 < \rho_3$) where the intermediate layer conductivity changes exponentially with depth, a formula has been obtained to calculate the apparent resistivity curves

$$\rho_a = \rho_1 \left[1 + 2 r^2 \int_0^\infty R \, J_1(m r) \, m \, d m\right],$$

where $R = \{[(2T)/(P - S) - 1]e^{2mh} - 1\}^{-1}$, T, P, S are coefficients depending on the section parameters. The curves calculated from this formula make it possible to interpret the soundings more accurately than is possible with curves for simple beds. The divergence may amount to 20–100 percent, depending upon the value of the conductivity gradient and the intermediate layer thickness.

The interpretation of seismic recordings obtained in areas of considerable seismic wave attenuation should involve a thorough analysis of wave propagation and registration for both longitudinal and transverse waves. The spread-shotpoint layout used in making seismic observations must always provide for obtaining direct and reverse traveltime curves.

Statistical methods of distinguishing useful signals from background noise are also very significant in interpreting data from both electrical and seismic surveys. In each case, it is necessary to apply filtering techniques in order to enhance signals useful for solving specific problems.

For example, in mapping landslide bodies it is frequently difficult to detect ρ_a anomalies associated with the contact zone because of considerable noise associated with strong and nonuniform weathering of the slope rocks. Our experience indicates that in such cases it is most expedient to smooth the observed ρ_a values with a filter of the form (1 + cosine), which effectively reduces the high-frequency noises and makes it possible to distinguish weak anomalies (cf., Ilyina, 1973).

There are numerous examples of successful applications of electrical and seismic prospecting methods to the investigation of the geologic configuration of landslide bodies. Some of these are presented in the following paragraphs.

Examples

The investigation of a landslide slope in the Volga River Valley, where H-type curves prevail

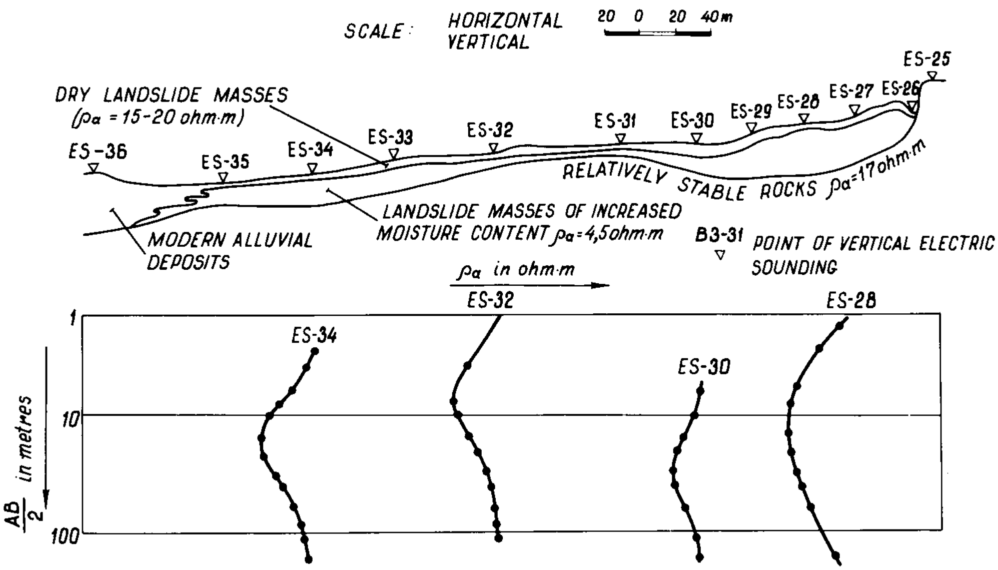

FIG. 2. Geoelectric section of a landslide slope in the Volga River Valley.

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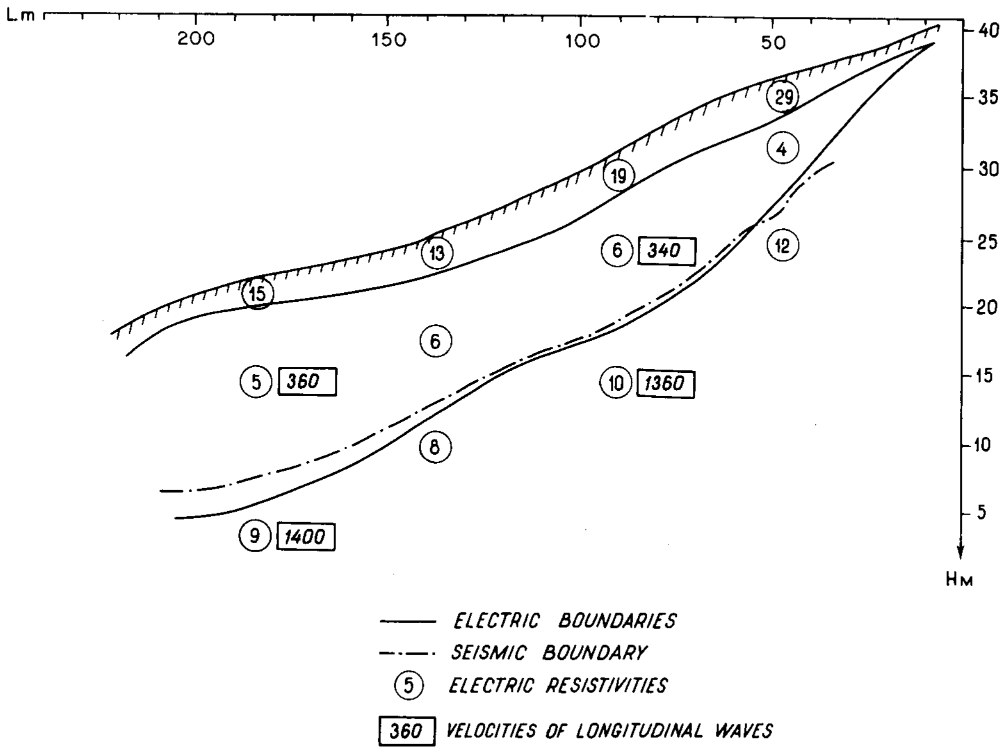

FIG. 3. The electric and seismic boundaries of a flowing landslide near the town of Sochi.

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($\rho_1 > \rho_2 < \rho_3$), produced the cross-section shown in Figure 2. The upper layer, composed of comparatively dry landslide deposits, has a resistivity ρ_1 of the order of 20 Ω-m. The second layer, the main part of the landslide mass, is characterized by an increased moisture content (34–37 percent) and, consequently, by a reduced resistivity ρ_2 of 4–5 Ω-m. The third layer, consisting of clayey rocks undisturbed by landslide processes, has a moisture content of 25–28 percent and displays resistivities of the same order as the first layer. The layering interpretation shown in this cross-section was later confirmed by drilling.

Figure 3 shows the results of geophysical investigations carried out on one of the flowing landslides on the Black Sea coast of the Caucasus near the town of Sochi. The body of this landslide is composed of loamy rocks underlain by a weathered crust of argillites. Electrical surveys have distinguished the following three layers in the slope: the upper layer (ρ_1 = 13–29 Ω-m) corresponding to the landslide body, the middle layer (ρ_2 = 4–6 Ω-m) corresponding to the slip zone and coinciding with the most weathered part of the argillites, and the lower layer (ρ_3 = 9–12 Ω-m) corresponding to undisturbed argillites comprising the base of the landslide.

Seismic measurements identified a single boundary that divides the landslide slope into two distinct masses of rock. The upper one (with V_1 = 340–360 m/sec) comprises the landslide body and the slip zone, and the lower one (with V_2 = 1360–1400 m/sec) corresponds to the upper surface of the argillites. There is good agreement between the seismic boundary and lower electrical boundary in the upper portion of the slope, whereas near the landslide toe the seismic boundary is higher than the electrical one by 1.0–1.5 m. This may be explained by the considerable fracturing in the upper part of the nonweathered argillites which allows an increase in their moisture content; the abrupt increase in the velocity of longitudinal waves from 360 to 1400 m/sec occurs along the top of the fractured zone, but the increase of resistivity occurs only at its base. Thus, the discrepancy between the seismic and electrical

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boundaries may indicate the thickness of the weakened zone which later may be affected by the landslide process.

If there is a need to study the geologic configuration of submarine extentions of landslides, this can be done by seismic methods. Some techniques which tentatively may be called "shore-to-sea" methods are also applicable. In this case, a sledge hammer is used to produce a seismic signal by striking a steel plate placed on the shore, and measurements are made by use of seismic receivers lowered to the sea bottom. This makes it possible to survey the offshore area out to a distance of several dozen meters, which is frequently sufficient for studying the landslide tongue protruding into the water; such tongues are rather characteristic of the landslides developed along sea shores. If these measurements are combined with the determination of electrical resistivities, then it is possible to get an impression of the composition and properties of the rocks in such protrusions. Electrical investigations carried out by us have shown that such measurements can be made most successfully by special arrays attached to a cable; these are analogous to logging probes used to investigate boreholes. Arrays of different dimensions are moved along the bottom when the cable is wound in by a winch. It should be borne in mind that geometric factor K_S (in the ρ_a formula) of an array placed on the bottom of the sea depends not only upon the array dimensions, but also upon its depth. For instance, the geometric factor of a three-electrode array AMN submerged to a depth h is determined from the following formula:

$$K_S = 4\,\pi r^2 \frac{r^2 + 4\,h^2}{2r^2 + 4\,h^2},$$

where r is the array spacing; it is equal to $A0$ where 0 is the middle of the MN interval. For $r/h \leq 7$ the factor for an array placed on the bottom is practically equal to that of the same array located on the water surface. For $r \ll h$, the resistivity value measured by the given array is $\rho_{a_S} \rightarrow \rho_0\rho_1/\rho_0 + \rho_1$, where ρ_0 is the resistivity of the water layer, and ρ_1 is the resistivity of the first layer of bottom deposits.

The location of submarine landslide protrusions can also be determined by conducting observations of submarine springs within the protrusion. These springs are detected by an increase in the electrical resistivity of sea water, anomalous water temperatures, and anomalous values of natural electric fields (Bogoslovsky and Ogilvy, 1974).

INVESTIGATION OF GROUNDWATER AS A FACTOR IN LANDSLIDE FORMATION

Slope stability and, consequently, the entire landslide process is significantly affected by the groundwater contained in the landslide body. The level of groundwater determines the weight of the landslide body as well as the supporting hydrostatic pressure which, together with the hydrodynamic pressure of seepage flow, are factors which affect the landslide body stability. Therefore, a geophysicist is always confronted with the task of determining the level of groundwater and its fluctuation with time.

The presence of clay layers in the geologic section of the majority of landslides hampers the application of electrical prospecting for determining the depth of groundwater. However, the level of groundwater often can be accurately established from the change in seismic velocity associated with a change in saturation of soil or rock. The ratio of the longitudinal wave velocities in water-saturated and nonsaturated rocks depends upon the lithology, density, porosity, and depth of the rocks. Experience has shown that this ratio usually exceeds 1.4, which means that refracted waves propagate well along the groundwater surface. However, it is not a good refractor of shear waves since the velocity of transverse waves is only slightly dependent upon the degree of water saturation.

It should be noted that there is no distinct groundwater table in those areas where a landslide body is fully or partially composed of heavy clays. In such areas it is possible to speak of different degrees of wetting of the landslide soils.

Of great interest are observations of the fluctuation of the boundaries and parameters of the groundwater table because it affects slope stability. Seismic surveys made for this purpose should be systematically repeated along the same profiles, with absolutely identical arrays and measuring techniques. It is most significant to observe the fluctuations between periods of maximum and minimum precipitation. Sometimes one may succeed in detecting the change in the depth of groundwater after heavy rains. Comparison of contour maps of the groundwater table compiled at different times makes possible an assessment of the dynamics of groundwater table fluctuation

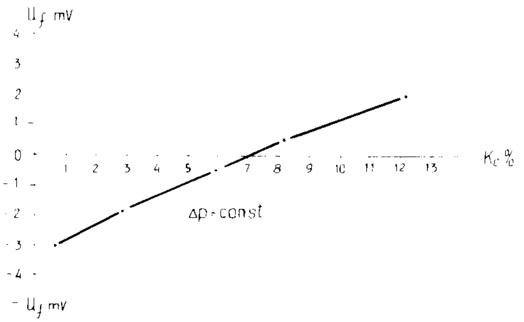

FIG. 4. Dependence of streaming potential U_f on the clay content K_c of a sandy medium. The data are from laboratory measurements by the authors. The pressure drop Δp was held constant.

which is a function of groundwater supply and the area of recharge.

A landslide frequently acts as a large drainage basin, collecting groundwater from a well-defined and sometimes very large area. On the other hand, some parts of a landslide serve as barriers preventing water flow and causing waterlogging of some portions of this landslide.

Use of self-potential and temperature measurements

The application of the SP method (method of natural electrical potential measurements) to groundwater seepage investigations is based on the measurement of potentials induced by water flow through rock. Under natural conditions, the magnitude of these potentials may reach dozens of millivolts.

Maps showing contours of equal values of streaming potentials compiled for homogeneous soils often reflect the pattern of water table contours. These maps contain data on the spatial configuration of the seepage flow, its direction, and its intensity.

The distribution patterns and polarities of electrical potentials are influenced not only by hydrologic factors, but also by the lithology of the soil. For example, zones having high clay content are indicated by positive anomalies similar to those observed over areas of flowing water. Figure 4 contains a graph demonstrating the dependence of streaming potential U_f on the clay content K_c of a sandy medium. The data are from laboratory measurements obtained by the authors. For clay contents $K_c \geq 7$ percent and constant pressure drop, the streaming potential values are positive. Therefore, reliable interpretation of SP contour maps requires comparison of those maps with maps of electrical resistivity, which indicate changes in soil lithology. This method of investigation was used extensively by the authors for studying landslides of the Black Sea coast of the Caucasus and the Crimea.

In certain cases, the locations of areas of groundwater discharge where landslide movement is imminent are indicated by a change in the intensity of the natural electric field. Under such conditions it is useful to measure the superficial potential density

$$\sigma_{uf} = \frac{\Delta U_f}{S_a}.$$

Here ΔU_f is the maximum increment of the potential within the detected positive anomaly; and S_a is the area of the anomaly.

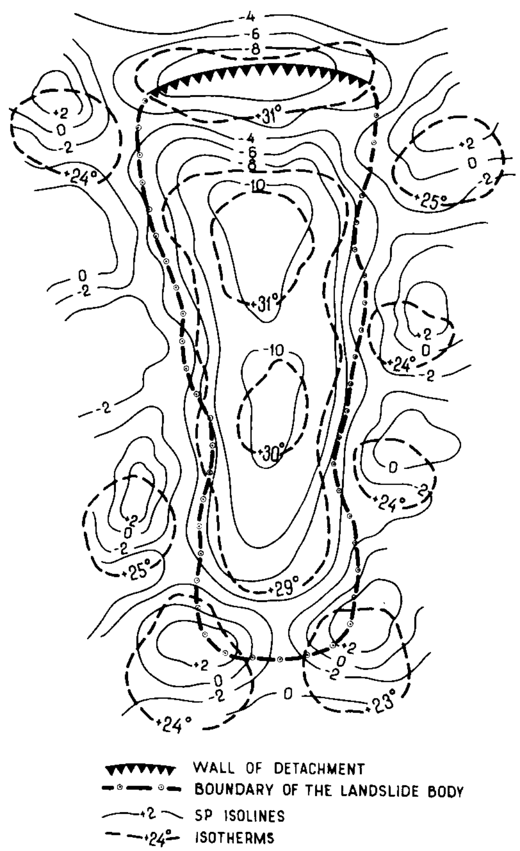

FIG. 5. The results of SP and temperature measurements made on a flowing landslide near the town of Adler. SP contours are marked in mV; temperature contours are labeled in °C.

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At a constant water content, σ_{ut} for a landslide is constant; σ_{ut} increases with an increase in the rate of water inflow per unit of area. The area S_a of the anomaly is indicative of the size of the region with excessive moisture content; therefore, the measurement of this parameter and its change with time may draw attention to sites on a slope where the rocks are becoming less consolidated. Thus, sets of detailed maps compiled at different times of the year reflect some concealed processes in the life of a landslide.

Data obtained from measurements of the thermal field effectively supplement data from SP measurements, since they also reflect the details of groundwater flow and the degree of water saturation of the landslide body. Temperature measurements are made by the use of an auger of special design with a thermistor on its tip. Temperatures are measured at a fixed depth below the zone of diurnal fluctuation. In the conditions of the Black Sea coast of the Caucasus, this zone extends down to a depth of 1.0–1.5 m.

Examples.—The effective use of both methods may be illustrated by the results of investigations carried out in 1972 on a small flowing landslide near the town of Adler (Figure 5). The position of the landslide body is indicated by distinct negative anomalies. The equipotential contours generally follow the landslide boundaries and the minimum gradients are in the direction of groundwater flow. The potential minima occur along the landslide axis and reflect the character of seepage flow which is controlled by the undulations of the underlying impermeable bed (or layer) and the change in water permeability of the landslide body. The negative anomaly at the head of the landslide is associated with water infiltration through the fractures located near the wall of detachment.

The landslide body is characterized also by increased temperatures reaching +31°C. These anomalies are associated with heating of the upper soil strata in those places where groundwater level is at a greater depth. At the sites of seepage outflow (in the peripheral parts of the landslide and near its toe) the temperature drops to +23°C.

Resistivity measurements

In addition to the use of the SP method, seepage flows in a landslide body can be investigated by the resistivity method. In homogeneous rocks, ρ_a maps may also indicate the degree of water saturation. Figure 6 shows a resistivity map compiled from soundings run on a shallow landslide near the town of Gagra. The decreased resistivity values in the central part of this landslide correspond to the area of greatest water saturation of soils. The narrow zone of low resistivity in the northwestern part of the site indicates an underground canal bringing water to the central part of this landslide where the new wall of detachment has been formed.

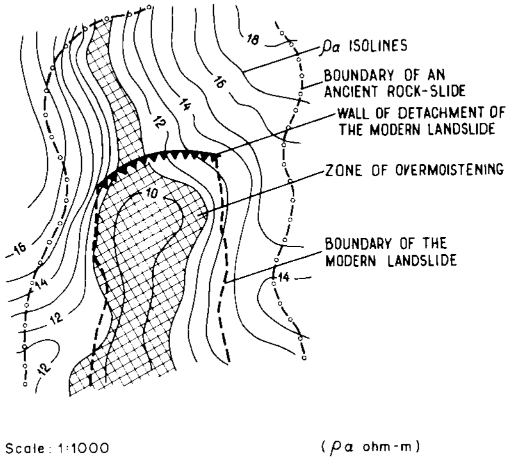

FIG 6. Resistivity contour map of a landslide near the town of Gagra.

STUDY OF THE PHYSICAL PROPERTIES AND STATUS OF LANDSLIDE DEPOSITS AND THEIR CHANGE WITH TIME

Even though the use of geophysical methods for studying the properties of landslide soils is relatively new, it is already possible to draw some general conclusions regarding the results obtained.

The natural structure of rocks undergoes change primarily in the slip zone where the rocks are actually broken, their mineralogical composi-

Table 1. Comparison of electrical resistivities of bedrocks and rocks in the landslide body. (Data from measurements made on the Black Sea coast of the Caucasus and the Crimea.)

	Electrical resistivity, Ω-m	
Rocks	Bedrock	Rock in landslide body
Argillites	60–100	30–45
Clayey sandstones	30– 80	20–30
Shales	30– 80	10–20
Clays	6– 10	4– 6

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tion is altered, and their moisture content and pore water salinity is increased. These changes result in a decrease in electrical resistivity. The resistivity of water samples taken in the slip zone may be 1.5 to 2 times lower than the average resistivity of groundwater in the site under investigation.

The most pronounced rise in electrical conductivity is exhibited by relatively high strength rock with rigid bonding such as argillite, shale, and clayey sandstone occurring in the slip zone. The rise in conductivity is considerably less in clay with high plasticity (Table 1). The properties of soils in the slip zone change more and more with every successive movement of the landslide, resulting in the development of a medium with gradients of physical properties within the slip zone, e.g., electrical and seismic parameters.

Sliding downslope also alters the mechanical properties of the rocks: the rocks are broken, their resistance to displacement decreases, and they become less stable. Various combinations of zones of compression and deformation develop, and these zones are characterized by corresponding variations in elastic properties.

Investigations near the town of Kafan (Armenia) carried out by Grigorian (personal communication) in 1970–1972 showed that surficial rocks of different lithologic types (ranging from light loam to clay) are characterized by a smaller range of variation of seismic parameters when they occur in landslides than when they occur in bedrock (Table 2). At the same time, a decrease in the velocities of both longitudinal and transverse waves is observed in the unstable part of the slope, and the V_s/V_p ratio for the rocks composing the landslide body is higher than for the same rock types in the stable slope.

The difference in the seismic properties of landslide rocks and bedrocks is also seen in measurements of the effective coefficient of attenuation of seismic waves. This coefficient α is found from the following relation:

$$A(x) = A(0)e^{-\alpha x},$$

where $A(0)$ is the wave amplitude (near the source) and $A(x)$ is the wave amplitude at a distance x from this source.

The effective coefficients of longitudinal α_p and transverse α_s wave attenuation in landslide rocks are higher than in similar bedrock. For the rocks in these measurements, the greatest changes of elastic characteristics are observed in loams.

Table 2. Seismic parameters of bedrock and rock in the landslide body using the hammer seismic method (after M. Grigorian). f = 50–80 cps.

Type of rock	V_p, m/sec		V_s, m/sec		$\overline{\alpha}_p\left(\frac{1}{m}\right)$		$\overline{\alpha}_s\left(\frac{1}{m}\right)$		V_s/V_p	
	Bedrock	Landslide rock	Bedrock	Landslide rock	Bedrock	Landslide rock	Bedrock	Landslide rock	Bedrock	Landslide rock
Light loam	370–400	200–300	200–210	150–190	0.09–0.12	0.45–0.48	0.08–0.12	0.39–0.43	0.52–0.54	0.63–0.68
Medium loam	490–580	240–390	230–250	180–220	0.06–0.1	0.43–0.44	0.05–0.11	0.38–0.40	0.43–0.49	0.56–0.75
Heavy loam	620–780	420–650	240–260	190–230	0.04–0.08	0.44–0.45	0.05–0.07	0.40–0.42	0.39–0.40	0.43–0.45
Loamy sand	310–370	250–270	190–210	150–190	0.11–0.15	0.55–0.58	0.14–0.17	0.50–0.52	0.60–0.62	0.60–0.70
Silty clay	340–880	530–690	250–280	200–230	0.3 –0.31	0.33–0.34	0.12–0.16	0.30–0.32	0.30–0.32	0.33–0.37
Clay with sand	890–950	600–740	280–300	210–250	0.09–0.11	0.32–0.34	0.10–0.12	0.29–0.33	0.30–0.31	0.35–0.35
Clay	1600–1750	830–980	310–380	270–290	0.03–0.06	0.28–0.31	0.02–0.05	0.24–0.27	0.20–0.22	0.28–0.32

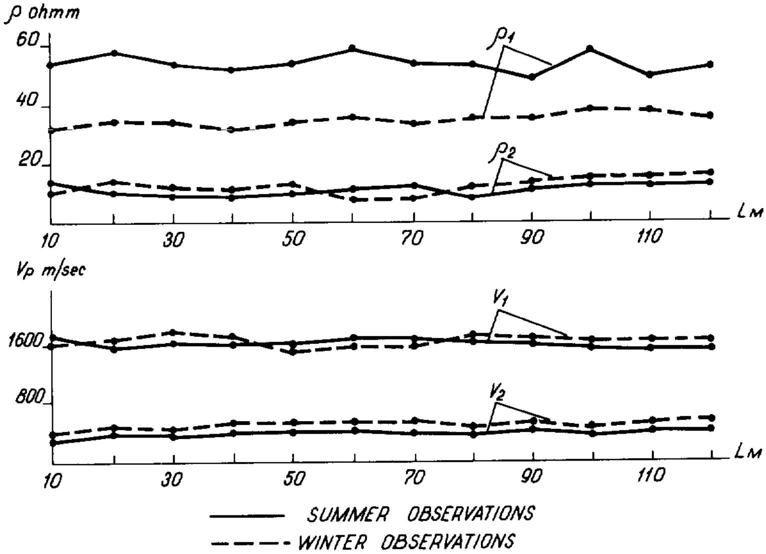

FIG. 7. Variation of ρ_a and V_p values obtained from regime observations made on a landslide near the town of Adler.

The variation of seismic properties within the landslide body and the conditions governing these variations are also of interest. Measurements of the velocities V_p and V_s give lower values at the head of a landslide, i.e., at higher elevations where the effects of linear deformation prevail, than in the landslide tongue. It is of interest to consider this finding in the light of the observation that the landslide toe occurs in the zone of compaction which accounts for the consolidation of soil in this area. (In addition, α_p and α_s decrease along the landslide axis in the downslope direction. At the lowest elevation of a landslide the values of these parameters may turn out to be even smaller than on the stable slopes.)

The variation of physical properties of soils with time is a phenomenon frequently encountered when geophysical methods are applied to landslide investigations. Time variability is most evident in the zone of aeration. Electrical resistivity, natural electric potential, elastic moduli, and other parameters are strongly affected by fluctuations of moisture content and temperature. This fact allows one to draw some conclusions concerning the causes of observed variations in the physical properties of soils in different seasons of the year.

To illustrate this point, the following example is presented with the data obtained from one of the landslides near the town of Adler. Winter and summer observations established that the resistivity values characterizing the landslide body (ρ_1) and the slip zone (ρ_2) do not change equally with time (Figure 7). The resistivity of the lower layer ρ_2 is practically the same in winter and summer, which indicates that the moisture content of rocks in the slip zone does not change. On the other hand, the resistivity ρ_1 of rocks in the upper stratum increases considerably in the summer because of the seasonal change in the moisture content of landslide soils. It is characteristic that the velocity of longitudinal waves in the landslide body (V_1) is practically the same in the winter and summer. Therefore, in this case, the resistivity method provides a more effective means of studying the moisture content variations of landslide deposits.

INVESTIGATION OF THE LANDSLIDE MASS DISPLACEMENT PROCESS

Reliable data on soil displacements can be obtained from measurements of both the deviation of wells lined with special flexible casing and the displacement of casing in the observation wells. But these methods are technically complicated and expensive and provide a means of investigating only small displacements. However, in many cases, especially those involving the investigation of flowing landslides, one has to deal with comparatively large soil movements. In such instances, it is recommended that position mark-

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ers be used to provide continuous information on displacement. Magnets lowered into uncased boreholes represent the simplest type of self-powered position marker.

Very strong magnets should be used. Otherwise, the anomaly produced on the surface will not exceed the background noise, even if the magnets are lowered to a depth of only 4–6 m. The authors' investigations have shown that it is most expedient to employ composite magnet dipoles consisting of 4–6 cylindrical magnets with a total length of no more than 0.5 m.

Position markers should be located far from iron structures, electric power transmission lines, and other sources of man-made magnetic fields. Magnetic observations should not be made in areas affected by electric railways and haulage systems.

Magnetic field observations are made in a radial or rectangular grid network with station spacings of 0.25–0.5 m. The observation points must be precisely located. The emplacement of magnetic markers should be preceded by a normal background magnetic field survey. In order to improve the accuracy of measurements, observations are made simultaneously with two magnetometers, one of which is located at a base station. As a result, an average measurement accuracy of 3–4γ can be achieved.

The results of every repeated magnetic survey are represented graphically in the form of a magnetic intensity contour map whose maximum corresponds with the position of the projection of the position marker on the ground surface. Displacement of the marker can be determined by triangulation from immovable points on the slope. The appropriate time interval between successive surveys depends upon the landslide activity of a certain slope and may vary from 0.5 months to 12 months. Using the results of such surveys, one compiles maps of differential displacement ΔZ from which can be determined the horizontal displacement of position markers. When interpreting observational results one should consider both the vector displacement L of the magnetic marker and the vector displacement l of the position of the orifice of the well into which the marker was lowered. The ratio of these vectors $\bar{L}$ $\bar{l}$ is an index of the landslide body mobility. For block landslides this ratio can be used to distinguish the sites of maximum landslide displacements.

Observations can also be made with electric markers consisting of a number of electrodes left in a well. Their displacement can be observed from the change of the maximum values of the electric potential measured at the earth's surface.

CONCLUSIONS

Application of geophysical methods to the investigation of landslide phenomena makes it possible to solve several problems, the most significant of which are: (1) determination of the geometry of landslides and their water saturation, (2) assessment of the physical properties and states of the rocks comprising the landslide, and (3) the study of the motion of the landslide mass.

The geophysical investigations which are carried out directly on landslides should include:

1) Combinations of self-potential, resistivity, seismic, temperature, and magnetometer surveys. Some special methods not mentioned in the text include borehole inclinometer measurements, and analysis of microseismic noises occurring in the soil strata of slopes.
2) Detailed measurements sufficient to reveal significant peculiarities of geometry, physical properties, and wetting of the slopes.
3) Systematic repetition (partial or complete) of regime observations at times of the year that are most meaningful in terms of water inflow and landslide activation.

It should be pointed out that the data of reconnaissance and detailed geophysical surveys can be employed directly in planning landslide control procedures. Geophysical measurements that are made to determine the effectiveness of artificial landslide control techniques constitute a specific and rather unique application of the methods of exploration geophysics. The authors plan to write a special paper on this subject.

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