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GEOLOGICAL REGULARITIES OF THE DEVELOPMENT OF LANDSLIDES AND ROCKFALLS AS THE BASIS FOR THE THEORY OF THEIR STUDY AND PROGNOSIS

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ABSTRACT

The problem of the study and prognosis of rockfalls and landslides with the goal of evaluating the stability of high slopes with a complex geological structure became more versatile and important than 10-15 years ago. It is due to a more extensive construction in mountain areas characterized by complicated geological conditions, increase in the class of structures, etc. Despite the progress in the elaboration of the theory of landslide and other gravitational processes and geological regularities of their development and improvement of research methods, new problems and requirements in structural design and engineering practice present themselves too quick for particular scientific-methodical efforts. A high natural slope is a complex geological unit with a long history of formation altering under the influence of natural and artificial factors. Because of this, traditional methods of rock mechanics are not applicable either to the study, or to the evaluation of the contemporary stability of high slopes of a complex structure. Methods of field and experimental investigations in regions affected by landslides and/or rockfalls should be those of engineering geology and proceed from the structure and history of formation of a slope as a whole, rather than of a particular landslide.

Evaluation of general and local, long-term and contemporary slope activity as well as prognosing of landslides and rockfalls in critical cases and at detailed stages of investigations call for combination of various methods: comparative-geological ones, those of modelling and of calculation (primarily those of final elements) which mutually check one another. For rough estimates of stability and prognoses it is admissible to use a single method, but the comparative-geological analysis is always indispensable. A successful application of methods of modelling and calculations of the state of stress in rocks and stability of slopes of a complex geological structure with the use of computers is possible only if engineering-geological study of high natural slopes is comprehensive and takes account of all main factors and elements.

It is impossible to work out substantiated engineering-geological and geotechnical models for carrying out experimental work and calculations of the state of stress and stability of high slopes with a complex structure by new methods without previous elucidation of the main geological regularities and factors of the initiation of landslides and rockfalls of various types, volumes and mechanisms of their development. If this fundamental thesis is neglected and simplified schemes are used for calculations and modelling due to the lack of data or deep insight into the main geological regularities of the structure and development of landslides and

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a slope as a whole, then the application of new experimental devices and computers will result in great mistakes rather than advantages with a seeming use of present-day methods of investigation.

The main geological regularities of the development of landslides and processes related to them are also of importance for grounding combined measures and the sequence of their carrying out with the aim of controlling landslides and rockfalls and general strengthening of slopes.

The progress in science and technology has had a considerable influence on engineering geology, including the problem of the study of landslides, rockfalls and high natural slope stability. This is due to both the new tasks and requirements to the engineering-geological grounding of construction of unique structures in platform and fold-mountain regions and the possibilities of using new technique, including electronic computers with large memory, in field investigations as well as in experimental and analytic ones. The use of computers makes it possible to find new approach in analyzing the state of stress of high slope rocks and landslides and rockfalls which are likely to develop on them to estimate stability of slopes of complex geological structure by considerably more precise methods of calculation. The last decade has been characterized by a successful introduction of methods of modelling on stands on a large scale using equivalent and photoelastic materials to study stability of slopes of complex geological structure, analyze development of sliding movements on them and their state of stress. These experimental methods enable one to elucidate new aspects of the mechanism of a landslide which is effected by a great number of factors and to obtain an approximate quantitative estimates of stability of slopes and stress distribution in heterogeneous rock masses forming them.

Of many environmental elements and factors controlling both the most important geological regularities of development and types of landslides, rockfalls, ossovs and other gravitational phenomena on slopes and the technique of their study and prediction as well as principles of control, the following ones will be considered.

1. STRATIGRAPHIC-LITHOLOGICAL COMPLEXES OF SLOPE ROCKS AND THEIR MECHANICAL PROPERTIES

The notion "regional types of landslides" suggested by I. V. Popov and now commonly used implies specific landslide features occurring in different formations of rocks which developed in regions of different geological history and climatic zoning. Of the three features mentioned the first one is the most important, determining the possibility of development and types of landslides, rockfalls, ossovs and other slope related phenomena. Landslides are known to happen in almost all existing rocks, but their lithological constitution, facial variability both in cross-section and by strike, presence of "weak" streaks and contacts, bedding and jointing are of crucial importance. The nature of rocks and masses they form, any of which is characterized by a specific lithological-facial and structural-jointing non-homogeneity, controll to a substantial degree their regime of moistening, weathering and erosion resistance, and therefore their mechanical properties.

The role of rocks as the chief element of the environment, where landslides and other gravitational phenomena develop is well known and to confirm it we shall quote the next few examples. High landslide-affected slopes along the river Dniester in the region of the Moguilyov-Podolskaya Hydro Electric Power Station are formed by stratified, lithologically different rocks: carbonate and sandy thicknesses of Miocene and Senonian in the upper part and siltstones, sandstones and argillites of the Paleozoic and Proterozoic age in the lower one (Zolotarev, G. S. *et al.*, 1973). Among Proterozoic deposits there were found with the aid of numerous wells and in outcrops 21 streak of greenish-gray and violet-brown clays ranging in thickness from 1 to 26 cm and with the total thickness up to 1,6 m and characterized by less strength and different mineralogical composition as compared to the inclosing siltstones. It was the presence of streaks of clay in highly lithified terrigene rocks of Paleozoic and Proterozoic ages and the alternation of series of more hard layers of sands with silts that created weakened contacts and zones where block glides are usually widespread. Similar conditions for block-glide occurrence can be found in the regions along the rivers Volga and Kama where there are deposits of interstratified red clays, marls, sandstones and limestones of the Upper Perm (fig. 1).

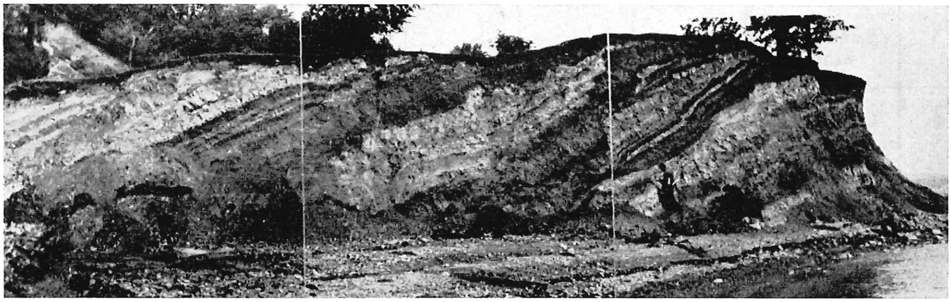


FIG. 1. — *Landslides of blocky structure in stratified heterogeneous rocks of the Upper Perm in the Middle Volga region.*

Of no less significance for the development of large landslides in the littoral zone near Odessa are clayey lignified varieties in Miocene clay strate and streaks of fine-grained saturated sands of quick nature. The stratigraphic-lithological rock complexes mentioned above as well as most other ones are characterized by facial variability of their texture and composition and their features are to be correlated with areas of developing landslides. The difference between strength values of rocks of "weak" streaks or contacts and the principal part of a stratified thickness can be judged by the data shown in the table 1.

TABLE 1. — *Strength values and other characteristics of rocks and their variations with weathering and tectonic disturbances*

No	Rocks	Natural water content W %	Bulk density with water content m/M³	Angle of internal friction φ°	Cohesion C kg/sm²	Uniaxial compressive strength R kg/sm²	Longit. wave velocity V_p m/sec.
1	Siltstones and silts stratified, lithified, dense, Proterozoic age; the r. Dniester	6-8	2.35-2.40	24-26°		190-200	1 100
2	Same rocks weathered	14-16	1.96	20-22°	0.65-0.90	–	350
3	Same rocks with tectonic fissures	12	2.10-2.24	12-15°	0.22-0.75	–	–
4	Clays greenish-grey hydrolaminar, thin-layered; Proterozoic; r. Dniester	20-23	2.10-2.20	17°	0.3-0.6	–	–
5	Same but slightly weathered	16-19	2.16	12-18°	0.2-0.6	–	–
6	Clays violet-brown hydromicaceous with pyrite; Proterozoic; r. Dniester	15-25	1.90-2.20	14-17°	0.40-0.70		
7	Same but with slightly reduced compaction and weathered	18	2.15	12°	0.20-0.30		
8	Chalkstones, stratified, fissured: the Black Sea coast of the Caucasus		2.56-2.62	40°	4.0	530-900	4 000-5 000
9	Same but a) within a tectonic fracture		2.48-2.54	26-30°	0.5-1.0	–	2 000
	b) badly weathered		2.35-2.40			50-100	500-1 000

TABLE 1 *(continued)*

No	Rocks	Natur. water cont. W %	Bulk density with water content m/M³	Angle of internal friction φ °	Cohesion C′ kg/sm²	Uniaxial compressive strength R kg/sm²	Longit. wave velocity V_p m/sec.
11	Clays black, dense, stratified; Oligocene; the Black Sea coast of the Caucasus	15-18	2.04-2.23	10-13°	1.7-1.8	10-12	1 600-2 000
12	Same but intensively weathered; horizon "B"	26-22	1.80-1.90	13-15°	0.4-0.45	3-5	200-300
13	Clays dark-grey, indistinctly layered, plastic; Miocene; the littoral near Odessa	18-25	1.91-2.0	11-16°	0.4-1.0	8-9	–
14	Same but with lignitic lices	30	1.85-1.90	8°	0.01	–	Ed = 6 500 kg/cm²

2. TECTONIC STRUCTURE AND JOINTING

Tectonic fractures of different orders, jointing in the area of fractures, and folding in rock masses of mountain slopes as well as systems of vertical and inclined tectonic and lithogeneous joints in sediments and intrusive bodies of platforms form an important factor of the development of large block-slides and rockfalls. All types of disturbances of fractured or folded nature in rock masses represent zones of weakened strength considerably aggravated by superimposed processes of weathering and sometimes those of karst or suffusion. It is the presence of such zones which determines the possibility of separating both lumps and packets of relatively small volume and enormous blocks from the parent massifs.

Large landslides and rockfalls are most likely to occur in such circumstances when high slopes extend in parallel or at low angles to the strike of divergences and zones of main tectonic fissures as well as to their intersections. Joint and fracture dipping in the direction of a slope, especially when their angles of inclination are less than the average steepness of a slope, considerably contributes to a landslide development. The similar confinement of landslides and rockfalls which seems to be one of the most salient features was observed in all mountain-fold areas including that of the Toctogule Hydro Electric Power Station on the Naryn river (fig. 2). If the river intersects with the fracture normally, as is the case with the Naryn-regional Tallasso-Fergansky fault having several hundreds of meters in width within the gorge part of the Toctogule reservoir, frequent small rockfalls and crumblings rather than large landslides prevail on the mountain slopes of the valley.

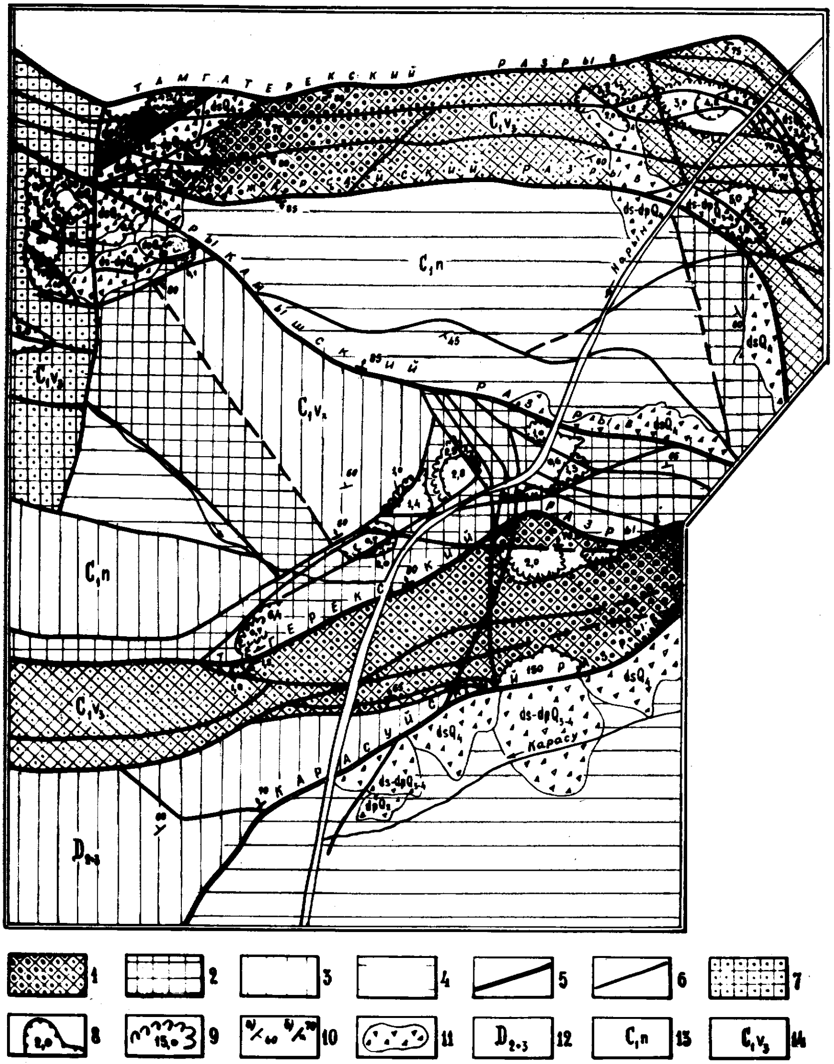


FIG. 2. — *Confinement of landslides and rockfalls in metamorphosed Paleozoic deposits to tectonic structures (from the archives of Geological Department of the MSU and Ghyidro-proyekt, 1967). Structural blocks with different heights of uplift during the recent period: 1, maximum; 2, mean; 3, relatively low; 4, lowest. Fractures with the widths of the zones of fragmentation: 5, hundreds of metres; 6, tens of metres; 7, block bendings (uplifted parts); 8, surfaces of parting (niches) of landslides and rockfalls; 9, potentially unstable rock masses; 10, bedding of: a) rocks, b) tectonic fractures (fissures); 11, rockfall trains (dr) and tali (ds); numbers show supposed volumes (in cubic metres) of rockfalls (dr) and landslides (dp) as well as those of potentially unstable rock masses; 12, Devonian limestones and dolomites. Lower Carboniferous: 13, shales and tufaceous sandstones; 14, limestones.*

As it has recently been found out by drilling, the frontal mountain ranges in the area of the towns N. Aphone, Mussery, and Gagry (possibly in other areas, too) on the Black Sea littoral of the Caucasus represent huge masses of limestone of Chalk and Upper Jurassic period thrusted over Paleogene and Miocene thicknesses of clays. The frontal parts of these tectonic structures whose carbonate rocks were considerably disturbed during folding, fracturing and overthrusting turned into the regions of development of large landslides and ossovs, which may be seen as a band on high slopes facing the sea. The bedding of Oligocene and Miocene clays under the overthrusted limestones contributes as well to the development of large landslides of extrusion, since high gravitational and tectonic stresses are seated in the thicknesses of clays. One of such landslides is shown in figure 3.

FIG. 3. — *Large Upper Pleistocene landslides in limestones of the frontal thrust zone (Gagry region of the Black Sea coast of the Caucasus).*

A great number of similar landslides have been registered in the basins of such rivers as Zeravshan in Tadjikistan, Shakhimardan in Kirghizia, Cheremosh in the Carpathians, and in other areas.

Similar confinement of niches and landslide parting surfaces to the main systems of tectonic fissures may be observed in the Upper Chalk marls, limestones and Tertiary chalks of the Lower Volga Region where landslides have very large for platforms volumes—up to 1.5-1.8 km along the river and extending 600 to 700 m deep into the banks (fig. 4). In many regions, primarily in mountain-fold areas, widespread Pliocene and Quarternary landslides, rockfalls and ossovs may give an indication of the presence of tectonic disturbance zones and large joints which are frequently buried. And vice versa, if fractures, overthrust zones, etc. are found, landslides or their residues are to be looked for.

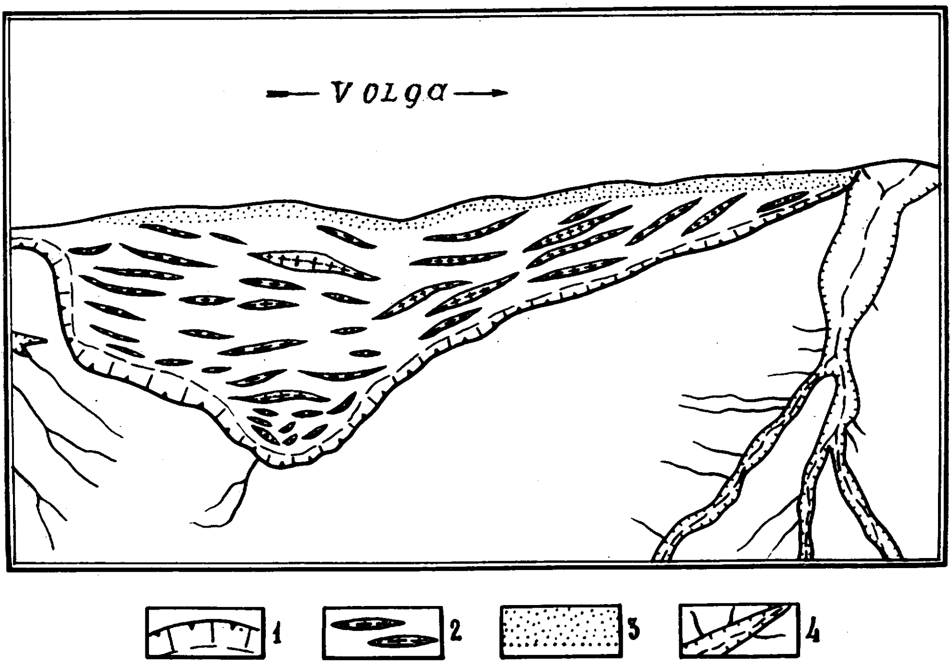


FIG. 4. — *Landslides-blocks in carboniferous and gaize rocks of the Lower Volga region. 1, the edge and upper part the scarp of the landslide; 2, displaced blocks of carboniferous rocks in the form of hills; 3, the towing-path of the Volga; 4, gullies and ravines.*

Neotectonic Movements and Geological History of Slope Formation

Fold and fracture neotectonic structures inheriting and changing more ancient ones creat the present-day tectonic plan, result in more fragmentation and weakening of rock masses, complication of small folding and fracturing, thus affecting to a significant extent underground water movement.

Neotectonic movements, their intensity, orientation and differentiation determine the general degree of erosional dissection of territory, the nature and development of sea and lake coasts. If the height of a river bank or sea coastal slope depends on the degree of an uplift, its steepness is primarily controlled by the rock nature, the rate and differentiation of uplifting as well as by climatic-hydrological factors. The contemporary tectonic movements influence to a substantial part the magnitudes and distribution of natural stress fields, particularly in fold-mountain regions. One can presume the presence of residual tectonic stresses in isolated "closed" structures. Irregularity of tectonic movements is typical of not only fold-block structures in mountain areas but also of platforms, in particular, of the Lower Volga and Kama regions, where it has been proved by the observations of Moskvitin, A. J. (1954), Kozhevnikov, A. V. (1959) *et al.* (fig. 5). The uneven growth of many structures in the east of the Russian Platform caused an alternation of narrowings and widenings of the Middle and Lower Volga valley, elevations

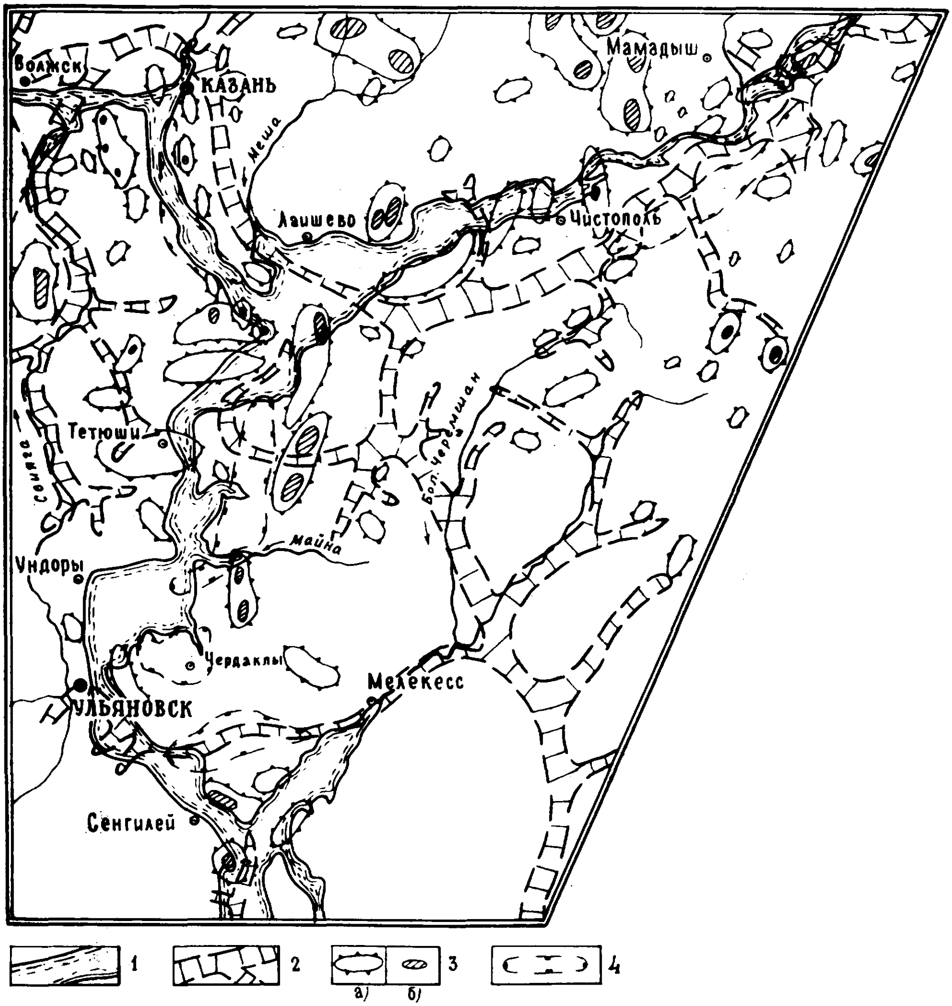


FIG. 5. — *The scheme of tectonic structures and buried Pliocene valleys of the Middle Volga and Kama regions (after A. V. Kozhevnikov abridged): 1, the contour of a reservoir; 2, the borders of buried Pleistocene valleys; 3, brachy-anticlines (a) and their arches (b); 4, brachy-synclines.*

and sinks in the relief of the Middle Quaternary (the fourth) terrace, which can be clearly seen, for example, near the city of Ulianovsk. In the Lower Kama region the growing brachystructures gave rise to the existing features of the hydraulic regime of the river, caused undermining row of the left bank, now of the right one, and, hence, alternation of steep and gentle slopes or steep slopes and terraces which are situated above the flood level. Different plan position of Neogene and Quaternary river valleys affected in different ways the structure and formation of contemporary landslide-affected slopes of the Volga, Kama and their influxes as well as some other rivers of the Russian Platform.

Even greater influence exert neotectonic structures and regime of movement on the formation of slopes in fold-mountain areas where river-bed erosion prevails. Slopes of convex profile have formed within the limits of intensively-rising blocks of hard rocks, for example, in metamorphosed limestones of the Naryn valley, while gentle concave slope profiles are characteristic of the regions of relatively slow uplifts (intermontane areas) in the same rocks. Differentiation of movements of fold-block structures, development of buckles, etc.—all this affects the intensity of undermining of the right and left banks of a river and, in the final analysis, the morphology of their slopes.

Uplift rate changes during Pleistocene and Holocene determine different steepness and height of slope parts of different age. In the case of relatively slow uplifts the processes of weathering and ablation (washdown, crumbling, landslides, etc.) of broken rocks form more gentle slopes, whereas faster tectonic movements result in slope processes in equally hard rocks "lagging behind" erosion downcutting.

In the Naryn valley Sheshenia, N. G. (1968) observed the confinement of landslides and rockfalls in Lower Carboniferous limestones to slope parts of different age as well as to the structures with different movement intensity. Thus, for example, about 50 % of landslides and rockfalls fall on the most uplifted structural blocks and only 8 to 10 % on the least uplifted ones (fig. 2).

In the valley of any mountain river crossing different lithological complexes one can find examples showing how neotectonic regime affects different types of slopes being also related to formation of zones of weathering and stress unloading in rock masses. Therefore the history of slope formation, their genetic and morphological types, occurrence of various landslides, rockfalls, tali, etc. should be considered against the general background of recent and contemporary tectonic movements with elucidation of correlating relationships. One and the same stratigraphic-lithological rock complex may give rise to rockfall-talus, landslide, erosion (washdown) and talus slopes. Rockfall and landslide slopes as they are formed can be in different states: potentially unstable, unstable and practically stable. The problems of the stages of forming of landslides and slopes, the importance of the geological history of their development for the appraisal of their stability have been repeatedly considered in the works of soviet (I. V. Popov, 1946, 1964; G. S. Zolotarev, 1949, 1961, and so on) and foreign scientists (Terzaghi, 1962, and so on).

The analysis of the geological history of formation of the slopes is of great importance in evaluating their stability and predicting landslides and rockfalls. The littoral area of South Crimea is one of the regions where such prediction is needed; engineering-geological mapping has been carried out in its western part using methods of stereophotogrammetry (O. N. Bolagayeva, V. S. Fedorenko, and

B. M. Famintsyn under the guidance of G. S. Zolotarev). The littoral slopes in the region under consideration are characterized by greater steepness, intensive development and a complex combination of rockfalls and landslides of various types superimposing one another. Against the general background of irregular uplifts of the Yaila and the littoral slope combined with eustatic fluctuations of the sea level an intensive abrasion and gully development has been taking place in the areas where sandstones and argillites of Middle Jurassic and Taurian series and rubbly-clay slide deposits.

Several stages may be singled out in the history of formation of the littoral slope and the Yaila step during which landslides and rockfalls occurred in different regions. The crests—western, central and eastern—stand out sharply enough in the relief of the contemporary slope, and beyond them there can be found numerous Upper Pleistocene and Holocene landslides of complex structure, gullies and blocky rockfalls accumulations (scheme in fig. 6 and cross-section in fig. 7). Landslides, rockfalls and talus—proluvial trains of Middle Pleistocene origin—have left residues on crests, more frequent on the middle part of the slope. In the slope base there occurred landslides of several generations with the displacement bed up to several tens of metres below the contemporary sea level which were caused by intensive abrasion in the epoch of Neoeuxin transgression. Later on the frontal parts (tongues) of these landslides were eroded as evidenced by large limestone blocks on the sandbank. The Upper Pleistocene landslides are usually thrusted over the ancient (beach) deposits.

The Middle Pleistocene landslide masses are partially capped by talus deposits and proluvium and form the most gentle and stable slope parts. In the base of the Yaila step a train formed of younger movable rockfall-talus accumulations is located on the crest. The adjacent elevated parts suffered an intensive destruction at the end of the Middle and the beginning of the Upper Pleistocene; new erosion coombs developed on these parts and turned to landslide ones with distinctive clumpy-rubble clay flow-slides of complex structure. The recent movability and temporary stability of these flow-slides is attested by heaps of large limestone clumps near the edge of water, while clayey-rubble flow-slide masses have been washed out.

In the Upper Pleistocene and in Holocene the heads of growing gullies reached the base of the contemporary Yaila step which resulted in the increase of its steepness. Here, according to the relief features, seats of natural stress concentrations and stress drops are to be expected in argillites and sandstones overlain by limestones. Stress unloading, possible phenomena of slow extrusion in the sandstone-clayey thickness, processes of compactness reducing and weathering along the joints in the limestone mass resulted in repeated occurrence of rockfalls having volumes of 10-20 to 150-160 thousand cubic metres on the high Yaila step. One of such falls occurred above the landslide coomb between the central and eastern crests and loaded the middle part of the slope by its weight which increased the potential instability of the latter; some of large clumps rolled down almost to the water line.

The presence of layered limestones which are more susceptible to erosion in the Yaila step, to the east of the central crest, their syncline-like bedding and tectonic fractures contribute to more abundant inundation and caused a considerable development of young rockfalls whose accumulations cover to a great extent the littoral slope.

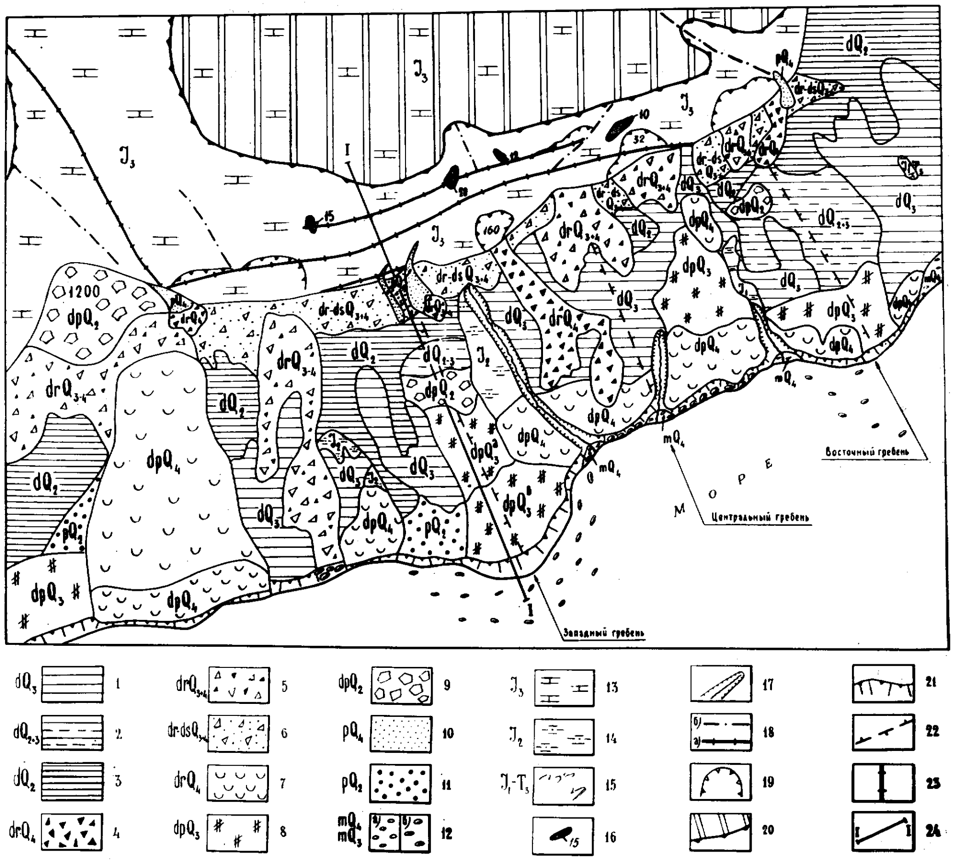


FIG. 6. — *The scheme of the development of slopes in the western part of the South Crimea coast (after V. S. Fedorenko, O. W. Bolagayeva and G. S. Zolotarev). Slopes of talus deposits, relatively gentle: 1, Upper Pleistocene; 2, not dissected; 3, Middle Pleistocene. Rockfalls—limestone blocks: 4, Holocene; 5, Upper Pleistocene and Holocene, not dissected; 6, tali and small rockfalls, Upper Pleistocene and Holocene, detailed, limestone, with blocks, very often travelling. Landslides of several generations and slopes formed by them, with a complicated stepped microrelief, blocky-detrital-clayey; 7, Holocene, checked and periodically active; 8, mostly Upper Pleistocene of complexe structure, practically stable; 9, mostly Middle Pleistocene, limestone-blocky, with breaks. Debris cones formed by debris limestones and gravel-sandy material with carbonate-clayey filling: 10, Holocene; 11, ancient, practically stable; 12, contemporary beach: a) gravel and sand changing its condition after storms, b) lumps washed out from landslides; 13, Upper Jurassic limestones (J_3), massive (reef) and stratified, forming the step of Yaila; siltstones, argillites and sandstones, jointy, forming the slopes of washdown or the slopes of gullies; 14, of Middle Jurassic, monoclinal bedding (J_2) and 15, Taurian series, strongly dislocated (T_3+J_1); 16, rockfall hazardous limestone blocks and lumps and their volumes in thousands of cubic metres; 17, ravines, mostly growing; 18, tectonic fractures: a) main and b) feathering; 19, niches of rockfalls and their volumes in thousands of cubic metres; 20, Pliocene karst—erosional surface and the edge of the Yaila step; 21, contemporary abrasion step; 22, watershed ridges; 23, tectonic fractures (in the cross-section); 24, cross-section line (see fig. 7).*

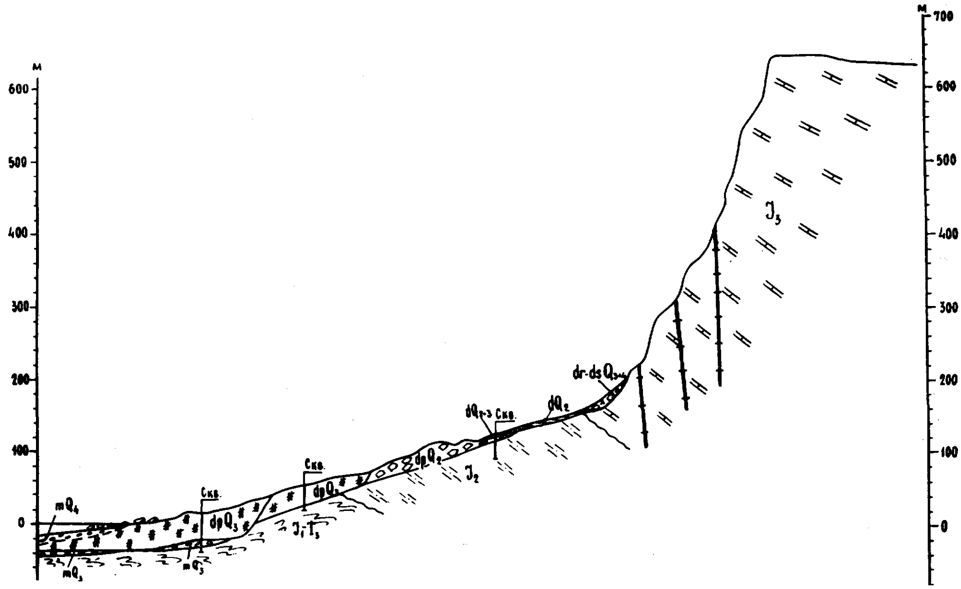


FIG. 7. — *A geological cross-section of the South Crimea littoral slope affected by landslides and rockfalls along the line I-I.*

Another interesting example of the analysis of the history of landslide and rockfall development is the valley of Zeravshan river near the village of Iny in Tadjikistan where on April 24, 1964 a landslide occurred having the volume of about 20 to 22 million cubic metres, which damed the river (fig. 8). The development of landslides in this area may be visualized as follows (fig. 9). In the Upper Pleistocene, at the period of formation of the downcutting from the terrace IX to the terrace VIII above the flood level of the rivers Matcha and Fandaria which form the Zeravshan river, a landslide developed in dislocated shales of the Silurian period weathered down to a substantial depth; it created a dam of the volume of more than 100 million cubic metres. This landslide exhibited a tremendous displacement energy and its frontal part in the form of shale and clay blocks moved upward the stream not less than 1.5 km. The lake formed at this place eroded the dam and there remained isolated hills formed by shale benches with the total volume of about 5 to 6 million cubic metres stretched in the form of a narrow strip at the base of a high step of the undissected terrace IX-X on the right bank.

Another large landslide with an approximate volume of more than 20 million cubic metres occurred in the same area as a result of deepening of the bed of the river and, which is most important, of the basal undermining of the landslide slope existing at that period. This landslide, which also created a dam and a lake, may be placed into the epoch of formation of the terrace VII or VI above the flood level, i.e. into the very end of the Upper Pleistocene. The frontal part of the landslide advanced 500-600 m over the surface of the terrace VIII on to the right bank and ran into the hills of the previous landslide, what can be registered from wells and in outcrops. In Holocene, because of intensive uplifts a down-cutting of

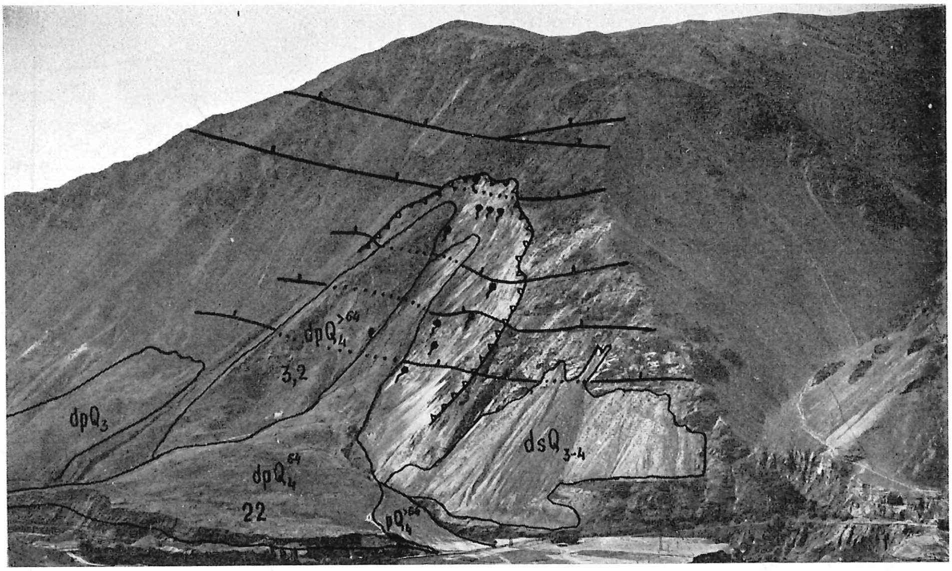
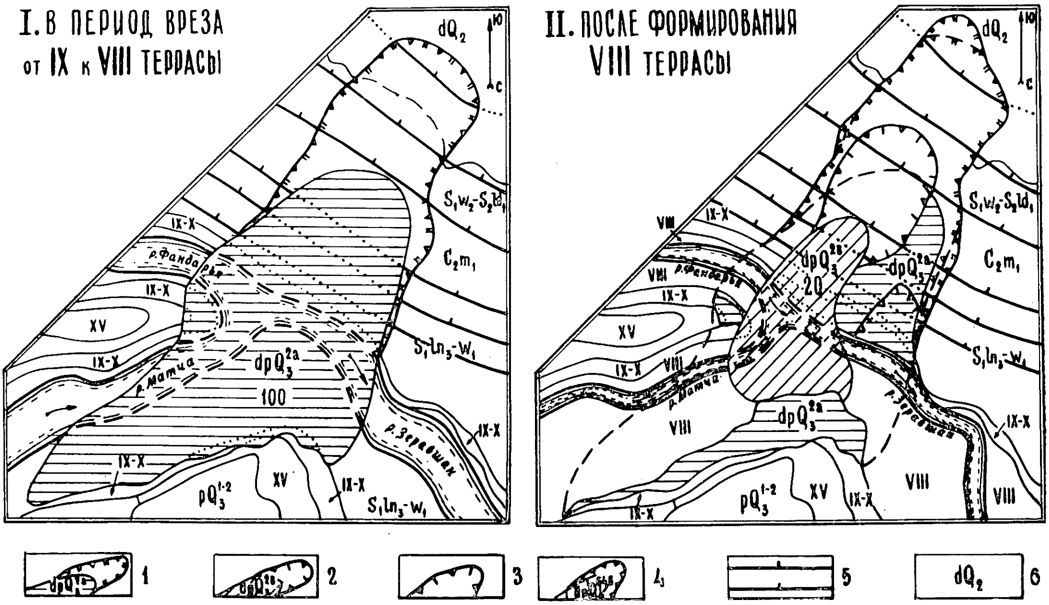


FIG. 8. — *The landslide of April 21, 1964 of the volume of about 22 million cubic metres in weathered Silurian clayey shales on the left bank of the Zeravshan near the village Iny, in Tadjikistan.*

the Zeravshan developed, and a river canyon up to 50 m deep formed in Silurian shales with residues of the Upper Pleistocene alluvium of the terrace VIII on both river banks which later on prevented direct undermining of the landslide slope. At the same time and after these landslides, small rockfalls, intensive crumblings, slipouts and washdown, sometimes in the form of small mudflows, occurred originating on the steep slopes of their niches of parting. Lateral undermining being absent, these processes resulted in a more smooth concave profile of the slope with partially clobbed surface which is the reason for its relative stability. The above-mentioned landslide of May 24, 1964, which entrained with it ancient landslide slump-clayey masses, occurred in the adjacent part, where according to an aerial photo of 1953 there had been slope of a convex profile, at the height of about 300 to 600 m above the river, in shales. The landslide tongue advanced 150 to 200 m over the pebbles of the right bank terrace of 50 m high and reached the accumulations of the Upper Pleistocene landslides.

The formation of similar grand landslides with catastrophic development in time (during several dozens of minutes) is due to the presence of jointed shales, the increase of their thickness and degree of weathering as well as building up in time of the inundation of the eluvium and ancient landslide masses in the lower part of the slope. This results in such considerable decrease of their strength that even in the absence of undermining any small external factor, a weak shock for instance is sufficient to make slump-pebble-clay masses displace, which begin to move downwards on a steep slope (30-35°) increasing their energy and entraining benches of weathered shales and accumulations of older landslides and tali.



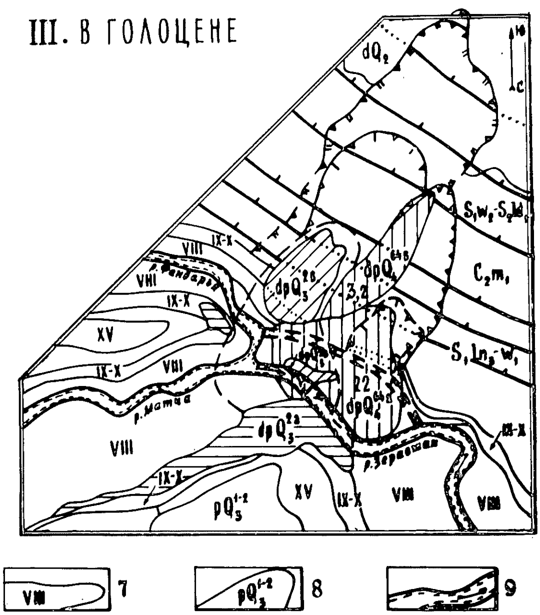


FIG. 9. — *Schemes of the development of the landslides in the Upper Pleistocene and Holocene on a slope of the Zeravshan near the village of Iny, in Tadjikistan (made by G. S. Zolotarev, O. N. Bolagoyeva, A. L. Rogozin, and V. S. Fedorenko). The landslides and edges of their niches of parting: 1, formed at the period of the downcutting from terrace IX to terrace VIII of the Zeravshan valley (dp Q_3^{2a}), later on scoured; 2, Upper Pleistocene, after the formation of the alluvium of terrace VIII (dp Q_3^{2b}), later on partially scoured; 3, Holocene (dp Q_4), reworked by the landslide of 1964; 4, occurred on April 24, 1964 (dp Q_4^{64}). Note: supposed landslide volumes are given in millions of cubic metres. 5, breaks separating benches of Paleozoic clayey shales and sandstones, the age of which is shown by an index; Middle Pleistocene talus slopes; 7, erosion-accumulative terraces of the Zeravshan and Matchi and their heights: XV-alluvium (a Q_3^1), $H = 170$ m; X and IX-alluvium (a Q_3^2), $H = 80$ m and 70 m; VIII-alluvium (a Q_3^2), $H = 60$ m; 8, Upper Pleistocene proluvium (p Q_3^{1-2}); 9, the beds of the rivers Fandaria, Matchi, and Zeravshan.*

Seismicity is a form of manifestation of contemporary tectonic processes and as applied to the slope stability problem it should be visualized as a factor contributing to rock mass fragmentation which results in changing of their mechanical and other properties and as a "power" factor almost instantly redistributing stresses in slope rocks and creating seats of stress concentration endangering the slope stability. Quantitative evaluation of seismicity influence on the occurrence of rockfalls, landslides, ossovs and kurums on high slopes is little developed. Field observations show that displacements occur most frequently and are of the greatest volumes in upper parts of mountain slopes within the limits of which the degree and the thickness of zones of exogene failure are considerable.

The calculations of seismologists show that the horizontal component of seismic waves increases not less than 1.5 to 2 times and perhaps more in the upper part of slopes of mountain river valleys as compared to their toe (Lamzina, G. A. *et al.*, 1973). This is a significant factor of slope stability disturbance, especially if one bears in mind that it shows up where rocks are weathered and weakened to the most extent.

Distribution and Magnitudes of Natural Stresses

The study of natural stress fields has begun comparatively recently in the U.S.S.R. and abroad in connection with underground mining, construction of hydroelectric power stations and tunnels and it is being given now a great deal of attention. Geological Department of the Moscow State University carried out *in situ* stress measurements in jointed solid rocks of mountain slopes in the regions of Sayanskaya and Toktogulskaya Hydro Electric Power Stations in 1963-1966 and, later on, in the Tertiary clays of landslide slopes near Odessa and in Abkhazia. For further development of theoretical tectonics the knowledge of stresses in the Earth crust were essential and attempts were made to evaluate them by calculation on the basis of seismicity data (M. V. Gzovsky, 1971). The results of the *in situ* measurements made by N. Hast, T. Nilson, I. A. Turchaninov *et al.* as well as by V. M. Kutiepov and many other investigators, whose works have been published in the collection "The State of Stress of the Earth Crust" (Publishing House "Nauka," 1973) conclusively indicate that effective stresses, including horizontal ones, exceed the weight of the overburden rocks by many times and that in the vicinity of movable tectonic fractures they attain 700 to 1 000 kg/cm^2 at the depths of first hundreds of metres. Experiments on models showed the great importance of joints, fracture zones, low strength streaks and other features of the geological structure of high slopes as well as the influence of their morphology on stress distribution (works by G. S. Zolotarev, Y. A. Kamennova, A. A. Shariy *et al.* in the collection "The Problems of Engineering Geology and Soil Engineering," 1968, 1973).

Stress magnitudes and distribution, seats of their concentration and drops assume a particular importance while evaluating the stability of high slopes at the base of which there are clay thicknesses overlain by hard rocks (effusive, intrusive ones, limestones, etc.). Similar structure is typical on the landslide slopes of the South Crimea littoral, the Black Sea coast of the Caucasus, the seacoast of Chernogoria, the region near the town of Gandlov in Czecho-Slovakia, as well as the valleys of the rivers Angara, Volga, Inguri and many other areas. In clay thicknesses underlying hard rock masses zones of high natural stresses arise due to gravitational and tectonic forces which considerably increase with great height and steepness of a slope. Stress drops with substantial gradients are usually confined to zones of tectonic disturbances and to streaks of rocks of lower strength which brings about seats of so called strength deficiency and surfaces of probable landslide displacements.

The complex nature of natural stress distribution in rock masses of high slopes of heterogeneous structure and multiplicity of geological factors determining their values are responsible for the fact that this problem which is extremely important for engineering geology, tectonophysics, geomechanics and civil engineering is rather difficult to study. It is clear that we cannot reliably estimate the stability of a high slope of complex structure without data on the distribution of real stresses and their values, the more so in areas with active contemporary tectonic movements; the values of mechanical properties of rocks alone are not sufficient. At the same time, the real stress field in rock masses is a combination of particular fields: gravitational, tectonic, including temporary seismic, temperature field, hydrodynamic and sometimes crystalline. Stress distribution is considerably influenced by such factors as lithologic-facial variability of rock constitution and textures by dip and strike; fold and fracture disturbances, tectonic and other kinds of jointing; degree and regime of moistening of rock masses, presence of zones of exogene failure and some other features of geological environment. Investigation of the state of stress of high slope rocks in connection with their stability is therefore a task of engineering geology which should be accomplished by using methods of geomechanics. Considering the stability of slopes of the South Crimea coast and other areas from the point of view of correlation of stress magnitudes with rock strength at the base of a slope, the formation of enormous landslides of different age in displaced sandstone masses so widely distributed can be readily explained.

Zones of Exogene Failure of Slope Rocks

The processes of unloading of natural stresses and those of weathering and sometimes leaching (the initial stage of formation of karstic conditions) and suffusion form zones of exogene failure of rocks, frequently rather great, confined to slopes and adjacent surfaces if erosion, dissection, undermining or engineering entrenchment are present. The structure of zones of weathering and stress unloading, the rate of their formation and engineering-geological characteristics depend on initial rocks, climatic factors and geomorphologic conditions, microrelief and period of formation included. The variation of rock strength in different zones of weathering is not equal, but it is rather significant. Some data showing how values of mechanical properties of rocks vary are given in the table 1.

Occurrence of landslides, rockfalls, ossovs and kurums, development of erosion and abrasion are directly related to the processes of rock weathering. The structure of zones of weathering is rather a complicated one and physico-mechanical properties of rocks are characterized by a considerable variability, which makes it necessary to adopt a unified scheme of their subdivision proposed by G. S. Zolotarev (1971) in development of the existing ones. According to this scheme, the zone of weathering should be divided into 3 zones: dispersional (I), fragmental (II) and jointy one (III) (fig. 10) which, in their turn, should be subdivided into horizons (for instance, the dispersional one into A, B, C and D) with different engineering-geological properties.

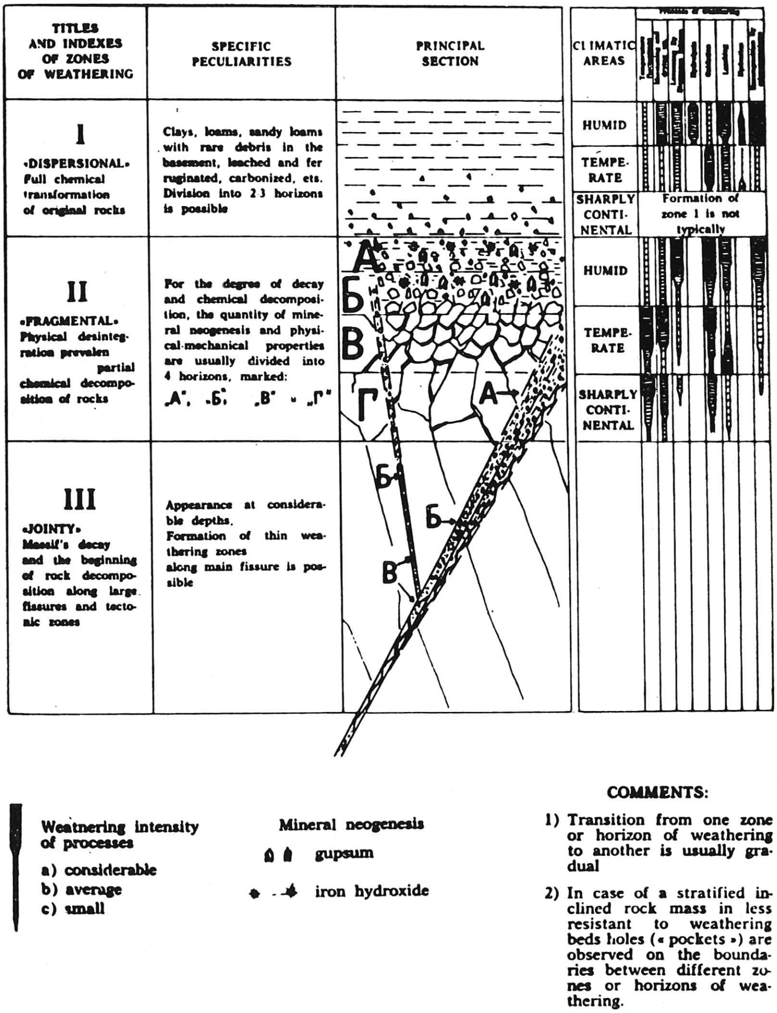


FIG. 10. — *General scheme for an engineering-geological division of the weathering crust.*

The greatest thicknesses of zones of weathering and the greatest degree of rock failure are confined to ancient parts of slopes and surfaces which are characterized by potential instability despite the fact that usually their steepness is less than that of the slopes which are being undermined within the limits of younger downcuttings. The presence of a formed dispersional zone of weathering on a slope attests that either processes of wash-out and sliding are inactive or virtually absent, or that processes of weathering rather than those of denudation prevail or they indicate that the eluvium accumulations are very old. Eluvium of the dispersional zone as well as rocks of the horizon "A" of the fragmental zone are usually absent on high steep slopes in areas with active neotectonic movements.

The development of small and large flow- and landslides typical of all fold-mountain and platform regions affected by landslides is related to a considerable moistening of both eluvium of sandy, marly and clayey rocks and weathered material washed out or crumbled from higher parts of a slope. A flow-slide forms in an erosion zone when rubble-clayey accumulations attain a critical degree of moistening; as this takes place, their strength decreases so much that for a given slope steepness sliding begins in the form of viscous-elastic masses (Zolotarev, G. S., 1961).

Landslides and rockfall-landslides in intrusive rocks of Baikal region and Georgia—granites of Dziruly and Khrami rocks massifs (Areshidze, G. M., 1964; Djavakhishvili, E. L., 1964)—are well known; their formation was possible only as a result of intensive weathering, both along tectonic joints and on a slope surface.

According to the findings of Scientific Research Institut of Structures and Hydroenergetics of Tbilissi, on hillside of the Khrami river jointy granites up to 50 m in depth were involved in block-sliding movements. The landslide caused fractures of the lining of a diversion tunnel and seriously damaged an open pipe-line—the rate of displacement of the supports of the latter amounted to 3 to 12 cm per year.

Groundwater Distribution and Regime

The role of groundwater in landslide development and disturbance of slope stability should be evaluated in two qualitatively different aspects, the main of which being the factor of rock mass strength decrease, especially in tectonic zones and joints of weathering and along the contacts where there are accumulations of clayey material. Hydrodynamic or hydrostatic pressure, as a rule, are of little significance in a general shear force balance, excluding the cases when a pressure water head in the toe of a landslide-affected slope is observed or when the permeability of jointy rocks in hillsides substantially differs vertically and laterally.

It should be kept in mind that the velocity of seismic waves in watered rock masses exceeds that in "dry" ones by 30 to 50 % which may result in a disturbance of stability of high slopes with rock masses prepared to displacement. Therefore not only distribution and heads of underground water, but also their regime, irregular and particular seasonal watering of rocks and territory are important factors in development of different types of landslides as well as any other gravitational phenomena on high slopes. Thus, underground water in different cases should be considered as an active factor and as an element of the environment where landslides, ossovs, etc. develop.

Underground water, which is formed in the thick zone of weathering of Silurian clayey shales and sandstones and in ancient slope accumulations plays an important role in the development of grand landslides like that which took place in the Zeravshan valley, near the village of Iny (fig. 8), in 1964 and of many similar ones. Water content in rocks of the zone of weathering increases irregularly in time because of both of snow-melt and rainfall water infiltration and water moving along near-fracture zones of enhanced jointing. The hydrodynamic scheme of the landslide slope of the Zeravshan near the village of Iny is shown in figure 11. An abundant water moistening of shale eluvium and slope accumulations is attested

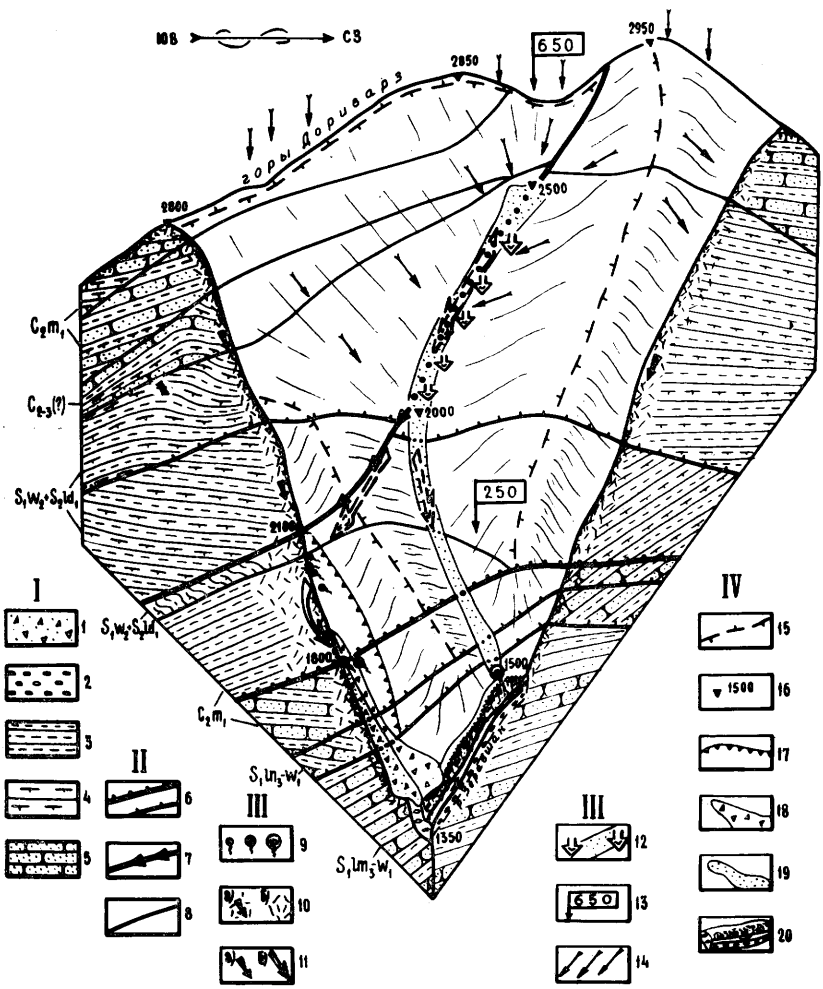


FIG. 11. — *A hydrodynamic scheme of the landslide slope of the Zeravshan near the village of Iny (after R. M. Nikitin). I. Lithological constitution of the deposits: 1, those of the landslides—lumps, debris, sandy loam; 2, alluvial ones—pebble, debris; 3, clayey and coaly-clayey shales; 4, siliceous schists; 5, sandstones. — II. Fractural tectonic disturbances: 6, thrusts Alpine, waterproof; 7, Alpine faults, in some places water-bearing; 8, Hercynian faults. Note: fractures buried under Quaternary deposits are shown by a dashed line. — III. Underwater release, movement, and feed: 9, springs and groups of springs; 10, a near-slope zone of weathering and unloading of rocks: a) moistened, and b) drained; 11, the main directions of underwater flow movements (by a dashed line in plan): a) dispersed and b) concentrated; 12, the place of a supposed absorption of the underbed flow of a mountain stream by a permeable zone of fault; 13, precipitation mm/year; 14, a slope run-off. — IV. Geomorphological elements: 15, lines of local watersheds; 16, heights of distinctive points of relief (m); 17, the niche of parting of the landslide of 1964; 18, the body of the landslide of 1964; 19, the flood plain of a mountain stream, accumulative; 20, the terrace of the Zeravshan—erosional accumulative.*

by the data of hydrogeological observations. There had been "mochezhenes" (1) and springs on the slope with an overall discharge of several litres/sec before the landslide of 1964. Immediately after the landslide occurred on April 24, 1964 the number of springs increased and their total discharge amounted to about 40 litres/sec as a result of more favourable conditions of water release at the scarps of the niche of parting, and 2 to 3 months later it dropped down to 10 litres/sec. This is a significant fact indicative of a presumably considerable water moistening of eluvium and slope accumulations in mountain arid regions.

In the connection with the abovesaid, tasks and methods can be outlined of investigating and prognosing both small and large landslides in rubble-clay alluvium and ancient slope accumulations. It is necessary to elucidate the interactive regularities of the eluvium formation through the use of various geomorphological elements [with the aid of degree of weathering (B_c) and zone thickness values], increase in time of general moistening (W_o) of eluvium and ancient slope accumulations and variation of their strength depending on the degree of weathering and moistening. These regularities may be shown diagrammatically in outline as follows (fig. 12). The processes of weathering and moistening of slope rocks take place at the same time superimposing one another. A general increase in moistening of eluvium and slope accumulations up to a critical value results in the fact that their strength decreases to such an extent that sliding becomes inevitable and in the case of high slopes and given large rock masses a grand catastrophic landslide develops which has a tremendous energy. Moistening of slope rocks takes place irregularly: during years with poor precipitation general moistening may well decline and, on the contrary, it may considerably increase during years with abundant precipitation, which can be seen from the diagram (fig. 12). The evaluation of the increase in general moistening of eluvium and ancient slope accumulations must be based on water balance for which the data of regime hydrometeorological and hydrogeological observations for several years are needed. The data of engineering-geological study of cross-sections of eluvium of different age as well as those of stationary observations of the rate of formation of its different horizons on base areas are also required. The regularities of variation of weathering and moistening of slope rocks and, therefore, values and probable time of the decrease of their strength being established, a prognosis of landslides occurrence in time and measures directed at preventing hazardous consequences may be well grounded.

Interconditionality of the Development of Landslides and other Phenomena; their Prognosis and Problems of Slope Stability Evaluation

The study of landslides, rockfalls, ossovs and kurums in platform and fold-mountain regions with the aim of their prognosis and slope stability evaluation has shown that there are intimate relationships between each of them and the processes of abrasion, erosion weathering and other ones changing mechanical properties and the state of stress rocks. All these processes take place against the general background of differentiated neotectonic and contemporary movements,

(1) Permanently wet land due to the outflow of underground water.

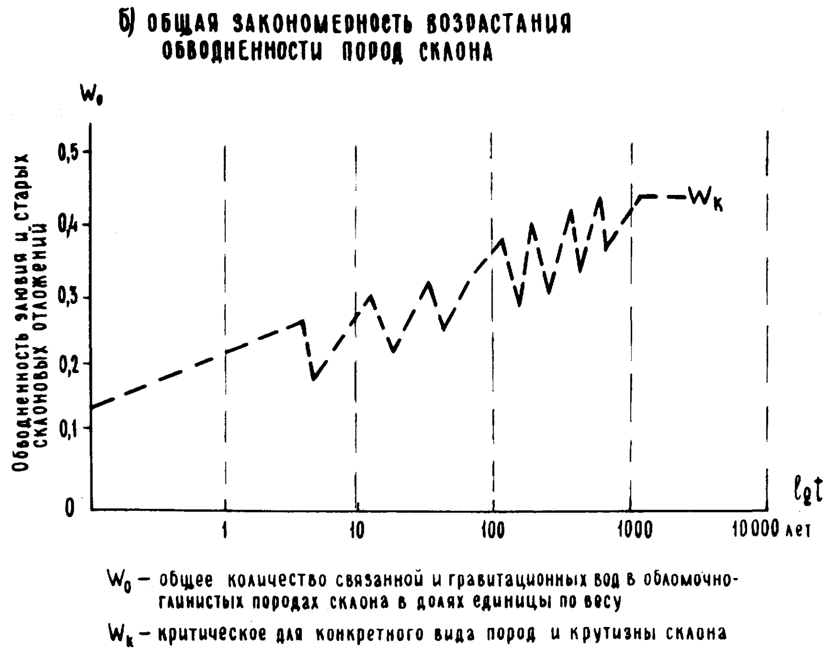


FIG. 12. — *General regularities of strength variation of eluvial and ancient slope accumulations versus the degree of their weathering and moistening.*

including seismicity and under the influence of climatic-hydrological factors varying in time. Differences in types, volumes, recurrence and other features of landslides and other phenomena stem from the geological structure, history of formation and morphology of a slope, features and state of stress of rocks, distribution and regime of underground water. The rockfall-landslide slopes of the Southern coast of the Crimea, the valleys of the Zeravshan, Volga, Dniester and many other regions may serve as striking examples of interconditionality of development of geological processes. Determination of geological regularities, role of individual environmental elements and factors in the development of landslides and rockfalls of various kinds should be considered as the tasks and theory of their study which allows to realize prognoses in a well-founded way and evaluate slope stability. Extensive use have been made in engineering practice of various approximate methods which become traditional for evaluation of the stability of excavation slopes and natural ones being based on the assumption that stresses in a zone of displacement created in this or that way are caused by the weight of overburden rocks. The practice of their use for the evaluation of landslide slope stability has shown that results of calculations in most cases don't comply with the real state of a slope. This explains why N. N. Maslov (1955), I. V. Popov (1964), G. S. Zolotarev (1948, 1961) and other authors point out that engineering geological analysis is of decisive importance, as compared to methods of calculation, while evaluating stability of slopes with a complex structure. This reasonable conclusion is accounted for by the fact that assumptions in selecting rock characteristics and generalisation of an engineering geological cross-section which allows to make a calculation of stability by traditional methods are such that real conditions are inevitably and considerably distorted and existing stresses, influence of the history of slope formation and a possible type and mechanism of landslide development cannot be taken into consideration.

Experiments on models from photoelastic and equivalent materials can approximately characterize zones of stress concentrations and probable slipping surfaces in slope rocks as well as the mechanism of a landslide process. Such experiments were carried out time and again, but the success of their application depends on how well the schematization of the real engineering-geological record is grounded and is determined to some extent by difficulties in selecting rock characteristics and by adherence to similarity criteria.

The method of finite elements provides better possibilities for performing calculations of the state of stress in rocks, stability of slopes with complex structure, and the history of formation. Analytic and experimental investigations carried out with the aim of evaluating the stability of landslide-affected slopes of the Dniester valley, the results of which are presented in the collection of works (B. S. Ukhov, V. V. Semionov, P. E. Root, *et al.*) edited by G. S. Zolotarev (1973), have led the authors to the following conclusions:

Generalisation of an engineering-geological cross-section is the most critical factor influencing largely reliability of the results of a study of the state of stress in rocks and stability of slopes with a complex geological structure both by methods of finite elements and by experiments on models; this generalisation must differ depending on methods of modelling or calculation;

Stability modelling and calculation by the method of finite elements requires a more comprehensive study of lithologic-facial variability of a slope, strength and deformation properties of heterogeneous rock masses and its typical elements—"weak" streaks and contacts along tectonic, lithogeneous and exogenous joints, different horizons of weathering, etc., as well as data on regime and distribution of underground water and natural stresses;

Stresses and displacements of individual elements within a real rock mass of a high slope are conditioned not only by its geometry and characteristics (as it is customary to assume), but also by the history of slope formation, depending on the intensity of erosion downcuttings and undermining (or during working of a trench or a quarry), reduction of rock compression and kinematics of sliding block displacement and, hence, results of stability calculation may substantially differ from the "final unaltered" slope profile;

The method of finite elements and at a less extent but in a more obvious way, experiments on models with the use of computers offer strong possibilities of performing radically new calculations of the state of stress in rocks, stability of high slopes with a complex structure, and solving other problems, including evaluation of the efficiency of preventive measures;

The analysis of the results of the investigations performed leads to an important conclusion that reliability of slope stability evaluations, prognoses of landslide development, volumes, and nature by methods of calculations and modelling depends to a considerably more extent on initial data, i.e. the generalized engineering-geological scheme, the validity of assumptions of the slope development, probable types of landslide, and selected values of mechanical characteristics of rocks for each individual element of the record rather than on the accuracy and potentialities of a specific method limited to a certain degree. As it is known, the comparative geological method of prognosing landslides and rockfalls and slope stability evaluation is an approximate one; it is based on observations in nature of geological regularities of initiation and development of these phenomena in time and interrelation with due regard for main geological, climatic-hydrological and some other factors. Considering landslides and rockfalls as complex geological phenomena influenced by many factors the establishment of distinguishing features of the environment and regularities of initiation, development and types of these phenomena is a theoretical foundation for their study on the basis of which approximate-quantitative methods of slope stability prognosis and evaluation may be used. Analysis of geological factors and regularities of the development of landslides, rockfalls, ossovs and other gravitational phenomena will make it possible to ground the efficiency of various engineering measures directed at strengthening of slopes by the same methods of calculation and modelling.

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