LANDSLIDE IN LOESS ALONG THE BANK OF THE DANUBE

GLISSEMENT DANS UN LOESS AU BORD DU DANUBE

A. KEZDI, Prof. Dr. techn.
Technical University, Budapest.

SYNOPSIS Paper describes and analyses the sudden spreading of a loess plateau caused by the rise of the ground water table beneath a newly constructed industrial plant. After the outline of the geological conditions, physical characteristics of the soil and the results of stability analysis are given.

1. INTRODUCTION

On the Hungarian section of the Danube, southward of Budapest, the riverside is very steep, with rifts and pits, in a length of 5o-7o km. The Danube forms here a dividing line between the Great Hungarian Plain in the middle of the country, and the western part of it, the undulating country of the so-called Transdanubia. The steep riverside rises to 5o-6o m above the water-level; it consists of loess, as loess covers a great part of Transdanubia. The Danube itself flows along a fault, a geological trench.

Beginning in the fifties of the century, a new steel plant and a new town have been built on this territory, about 7o km south of Budapest. Subsequently, several other industrial plants have been added to the original project; all these on the top of a plateau formed by the loess layers, at a distance of 3oo-6oo m from the crest of the same. Later, in the course of the extension of the colony, dwelling houses were built much nearer to the crest. Two pumping stations, built on the shore, elevate drinking and industrial water to the plant and the town.

About ten years after the construction of the main establishments, on February 29, 1964, a tremendous slide occurred, in a few hours, like a sudden spreading, on the section just above the first pumping station. An earth mass, with a length of approx. 13oo m, and a width of 15-2o m, came suddenly into a downward and outward motion; the bottom of the Danube was lifted, and the narrow, flat strip along the shore was horizontally displaced. The above mentioned pumping station also moved horizontally 35 m, and it was rotated around its vertical axis by 12°, without any change in its vertical position or any damage to the machinery. Fortunately, there were no casualties. The main part of the movement was over in a few hours; later, only secondary movements were observed.

The repairing of the damages, the re-establishment of the facilities, the remedial measures and proctective works, required the sum of approx. 25 million dollars. In view of the high construction volume, the determination of the Hungarian authorities to reveal the causes and conditions of the disaster was fully justified. To this effect, investigations and explorations, measurements and laboratory tests have been made. These investigations made the design of economical protective measures and dewatering system possible. The preliminary investigations included geological, hydrogeological, soil physical and mechanical explorations and testing. In the following I would like to point out the salient features of the findings. The volume of the work done prohibits the presentation of the details; after the final conclusions have been drawn, an official publication will give account of the whole complex.

The writer, after September 1964, acted as a scientific consultant to the Bureau, which was responsible for the investment of the protective works and measures. The Bureau was headed by Director GÁBOR, S.

The view of the slide is given in Fig. 1. and 2.; the latter displays the wrecked water pipes coming from the pumping station.

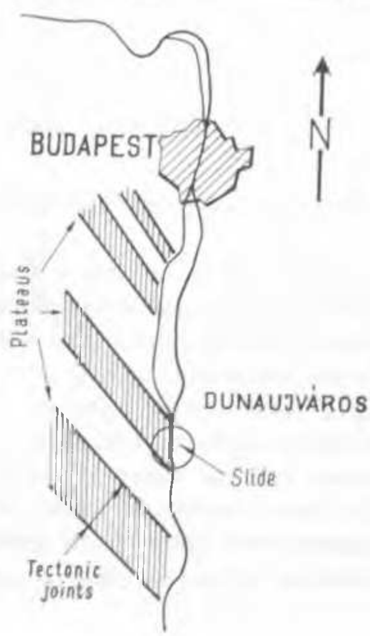
Fig. 1 View of the slide from the West

2. GEOGRAPHICAL AND GEOLOGICAL DATA

The loess plateaus on the right bank on the Danube are dissected by NW-SE cracks, according to the regional tectonic structure of the country. (Fig. 3.) The joints are, in the opinion of Schmidt-Eligius (1966), dislocated and therefore open and waterbearing. The loess layers which cover the surface of the right-bank plateaus are of pleistocene origine, they are aeolian, wind-laid sediments with a well pronounced aelotropy and macroporous structure. (Kézdi, 1968.) Beneath the loess, there are Pannonian sediments, alternating clay and fine sand layers. The dividing line between the two formations is more or less clearly verifiable. A geological section through the place affected by the slide is given in Fig. 4. It should be mentioned that the Danube itself forms here an island, the western branch of the rriver having been closed by a dike several

Fig. 2 The broken pipes of the displaced pumping station

Fig. 3 Sketch of the plateaus along the western bank of the Danube after Schmidt-Eligius



decades ago. So, for a certain length, there is no direct flow at the foot of the plateau. This fact does not mean, however, that the presence of the river will not affect the stability of the high bank.

There are two water levels beneath the surface. The first, a free one in the loess layer, is fed by the precipitation on the area, while the second one, in the Pannonian layers, has a rather high piezometric level. (Fig. 4.)

In the past, several slides and spreadings occurred in this territory. Based on archeological findings, revealing the existence of a Roman "castrum" here, and on the study of historical maps, Domján (1952) demonstrated that the edge of the plateau moves gradually westward; every now and then there were slides on different parts of the bank, the Danube washed away the debris and the former dangerous situation was created again and again. According to Domján, in historical times, an average of 3-5 m movement in every hundred years was likely to occur. Even during the years of construction, several slides had to be registered and, therefore, the erecting of buildings in a strip of 2-300 m width along the edge was forbidden.

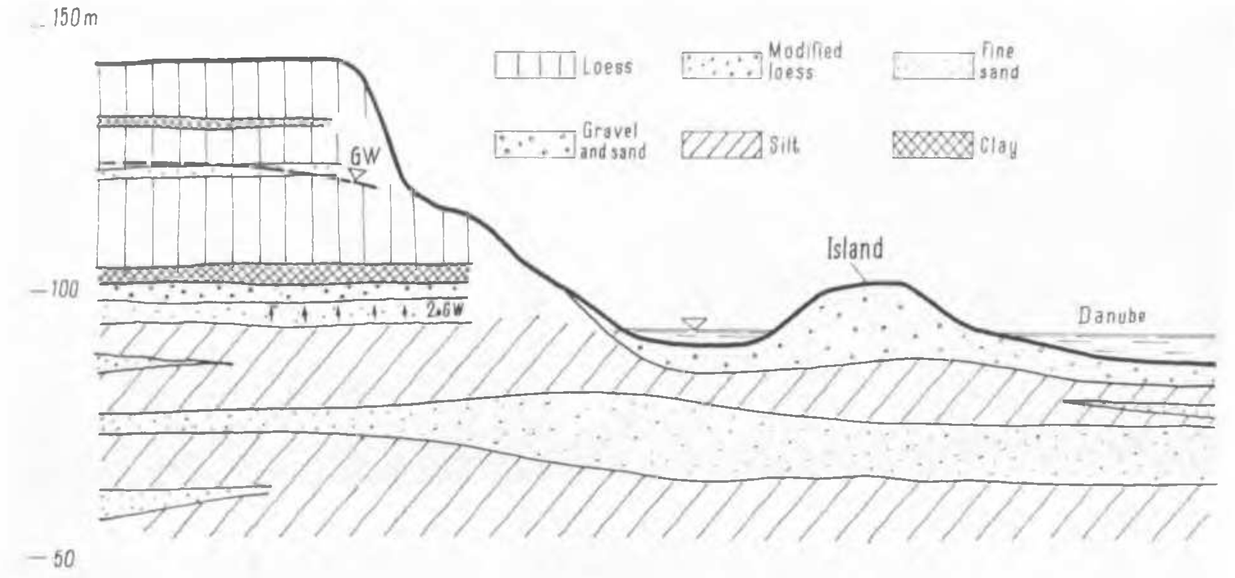


Fig. 4 Geological section of the affected area

3. CONDITIONS PREVAILING BEFORE THE SLIDE

The situation outlined above has been rather drastically changed through the construction activity. A formerly agricultural land was transformed into an industrial and city territory; rainfall could enter into the soil in a concentrated manner, and what makes things worse, leaking water pipes and sewers supplied a great amount of water which caused a very significant rise of the ground water table. Fig. 5. gives an idea about the degree of this rise, presenting the contour-lines of equal rising heights, in meters. A very important factor in the development of these water-cupolas was the aelotropy of the loess: the coefficient of permeability being much greater in the vertical direction, due to the more or less vertical network of root holes. (Terzaghi-Peck, 1967.) The original water table had a slight slope toward the river, so the reservoir was drained through the foot of the steep loess-wall. After the rise of the water level, the gradient became greater, thus increasing the seepage forces acting on the earth masses immediately beneath the surface.

Of course, the piezometric level of the second groundwater-table did not remain unaffected by the rise of the upper level; there must have been somewhere interconnections between the waters. Rainfalls in remote areas could also contribute to the increase of the pore water pressure in the sand layers sandwiched between impermeable clay strata.

While the construction of the plant and the city was going on, some signs showed a certain extent of movement right in the vicinity of the plant, where later the slide occurred. Just on, the rim of the loess wall, there was an old, abandoned house which showed cracks and fissures. So we decided to take measurements from time to time, and so, we could foretell the slide, because the reference points showed a movement of an increasing rate. However, the extent of the slide was many times greater than anticipated. The movement of an observed point up to the occurrence of the slide is given as an example on Fig. 6.

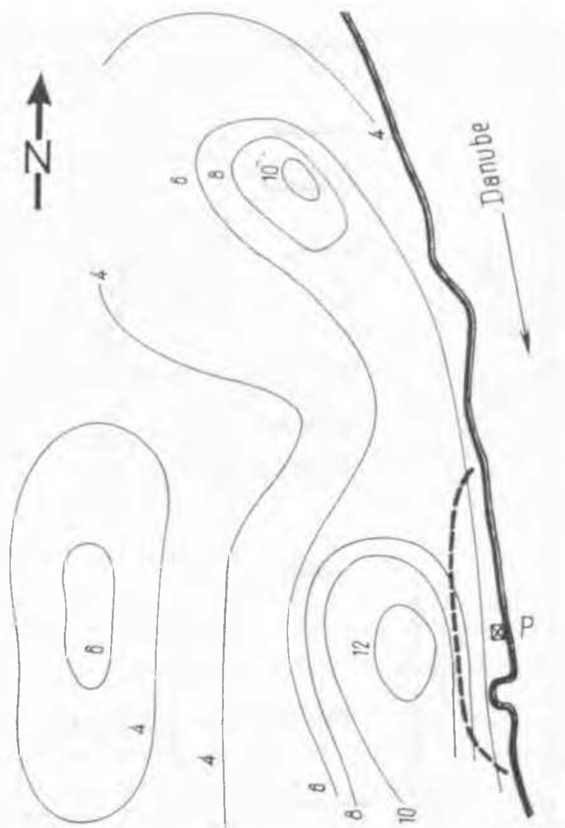


Fig. 5 Rise of the upper water table; formation of water-cupolas
P - pumping station

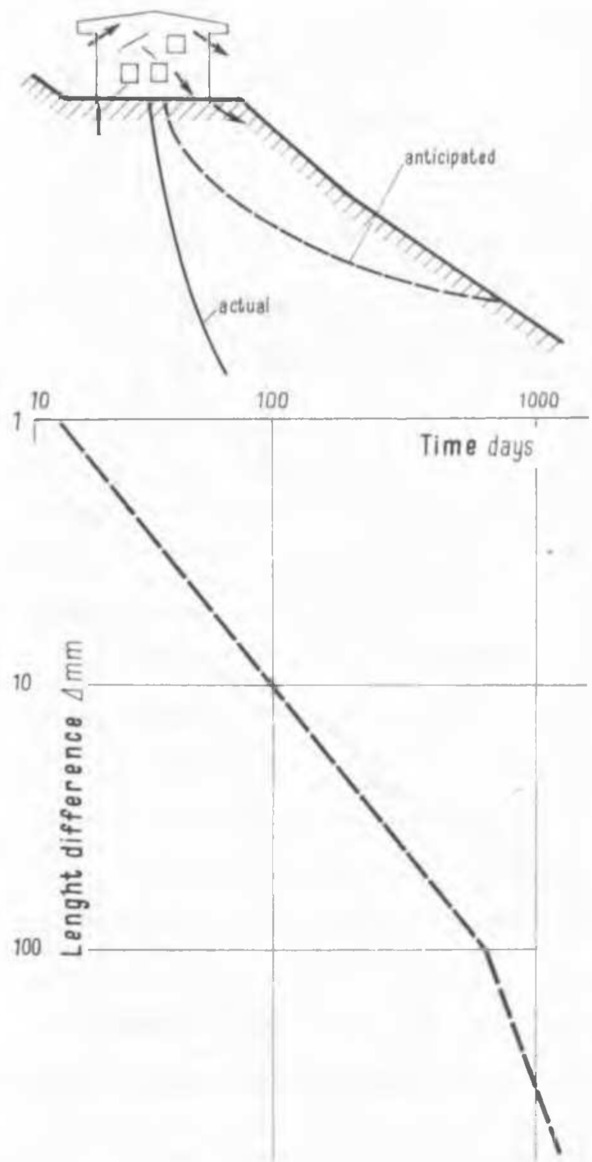


Fig. 6 Movement of a house on the rim of the loess plateau

After the slide, in 1965, several further reference points were installed. The measured movements showed very interesting regularity and correlations. In Fig. 7., I plotted the change in the distance between two reference points installed at the top and at the foot of the plateau, further the velocity of the movement, the level of the Danube, the summation of the rainfall and the variations of the temperature as well: it can be seen, that there is a marked correlation e.g. between the velocity and the water level. This fact gives right to the assumption that a rising water level reduces the shearing strength on a certain critical plane. However, this fact cannot be considered as the only agent which produced the slide.

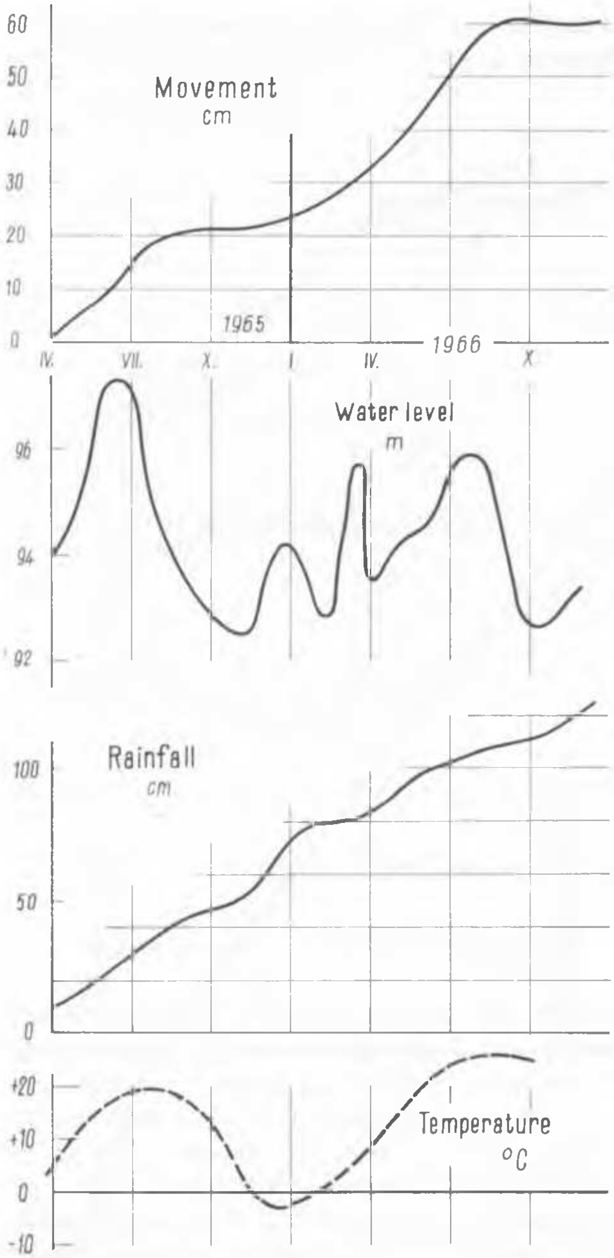


Fig. 7 Analysis of the measured movements of the loess wall

4. SOIL CONDITIONS; PHYSICAL PROPERTIES

A representative sample of the bore hole profiles obtained in the area is given on Fig. 8.; it does not need any further explanation. The collapse of structure, which is

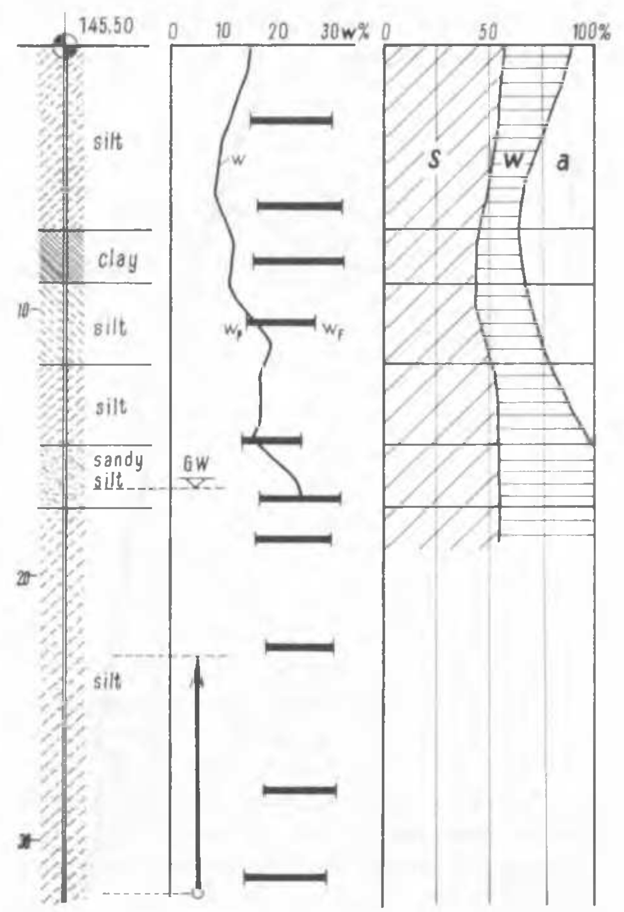


Fig.8 Index properties of soils from a drill hole in the area of the slide

characteristic for macroporous soils, could be experienced in all samples with three phases subjected to compression and inundation. However, saturated samples from beneath the water table, do not exhibit this property. As we shall see later, the "seat of the slide" was situated in the lower, saturated layers, so, the collapsing structure was not a decisive factor in the problem. On the other hand, strength characteristics play a very important part. Based on a great number of tests, the interesting diagram in Fig. 9. could be obtained. Triaxial tests furnished the important data in Fig. lo., showing the Coulomb-lines for different testing conditions. For the stability investigations, the "consolidated-undrained" strength parameters are competent; the consolidation pressure corresponded to the weight of the layer above the assumed sliding surface. No drainage was allowed, because the movement occurred very rapidly.

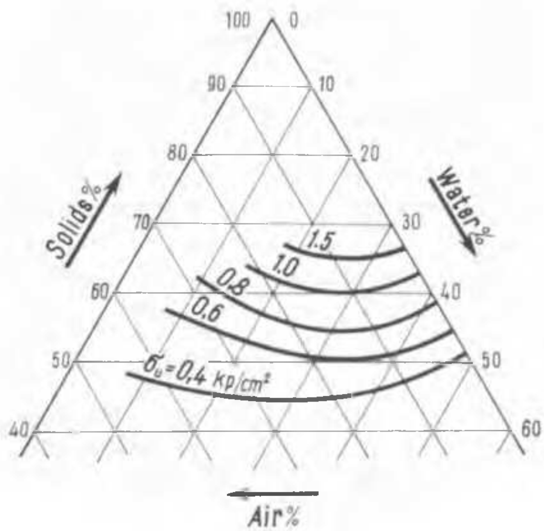


Fig. 9 Unconfined compression strength as a function of phase composition

Permeability tests revealed the above mentioned aelotropy of the loess: the k-value in the vertical direction was more than hundred times greater than that in the horizontal direction. This fact was responsible for the rather steep phreatic line of the first groundwater level, which caused high seepage pressures.

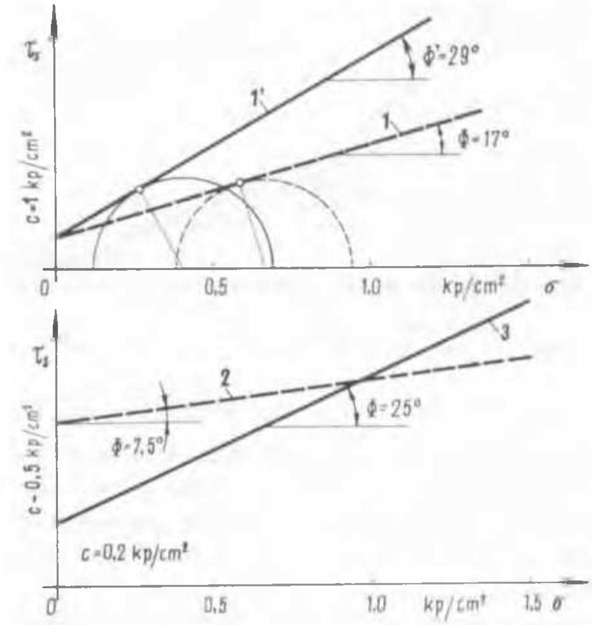


Fig. lo Shear strength parameters. 1 - saturated; no volume change; 2 - saturated, unconsolidated; no volume change; 3 - saturated, consolidated

5. STABILITY ANALYSES

In the course of the investigations several types of stability analysis were applied. It was clear, right at the beginning, that the usual circular sliding surface must not be assumed here, the mechanism of the slide being completely different. First, we plotted several cross sections of the bank, in one single drawing, and selected the most dangerous one, accepting it for the purpose of stability analysis. It was, then, combined with the representative soil profile and physical - particularly strength - characteristics. The exploration of the hydrogeological conditions furnished the momentaneous height and the probable variations of the piezometric level of the second ground water level, so the basic data could be put together. These are given in Fig. 11. The upper ground water level which formed a depression line, was replaced, for simplicity, by two broken lines, one being horizontal, the other one making an angle α with the horizontal.

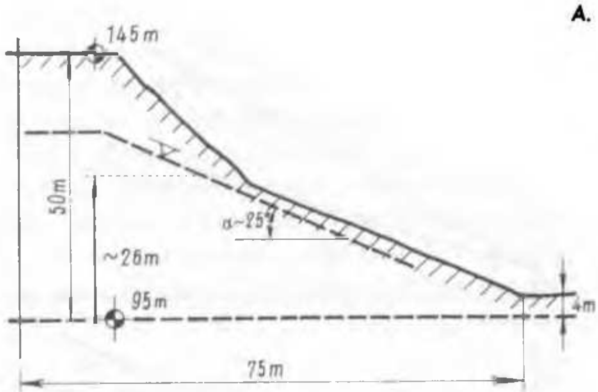


Fig. 11 Basic data for stability analysis

Before entering into the numerical calculations, we have to form an idea on the mechanism of the slide. Previous experiences and observations during and after the slide, showed that the seat of the slide lay in a certain depth, where the shearing resistance was substantially weakened so that the pushing forces, the shearing stresses along the same plane, could overcome the total resistance. The latter was furnished by the shear strength and the passive earth pressure as wel well. When failure along the critical plane occurs, the shear strength drops Fig. 12 and the movement spreads out. The incipient failure will be caused by the increase of the active forces: this was actually the main effect, since the rise of the water level increased both the active earth pressure and the seepage forces. An additional effect came into being due to the increase of the piezometric pressures (this was due to high Danube water, see the correlation in Fig. 7) which reduced the shearing strength:

$$[\tau_s = (\sigma - u)\tan\Phi' + c]$$

So, the progression of the slide can be traced, in the writer's opinion, as given in Fig. 13. Herein, the increase of the seepage force a , of the piezometric stress b and the variations of the shearing and resisting forces c are plotted. The factor of safety drops to unity, when the sum of the driving forces becomes equal to the resisting forces. The factor of safety is therefore given by (see Fig. 14)

$$\nu = \frac{T + E_p}{S + E_a}$$

T, the resisting tangential force can be calculated as

$$T = N'\tan\Phi + sc,$$

where N' denotes the effective normal force on the critical plane, due to the dead weight of the sliding block.

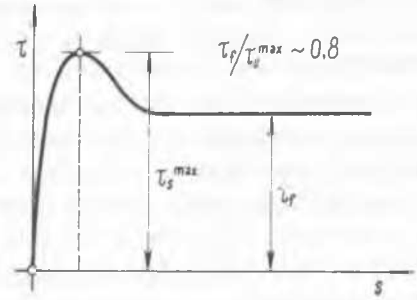


Fig.12 Difference between maximum and final shear strength

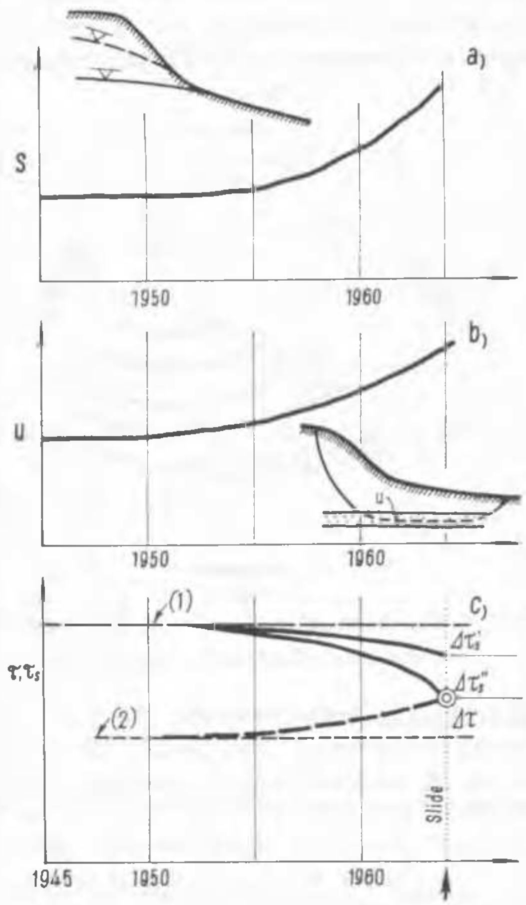


Fig. 13 Mechanism of slide

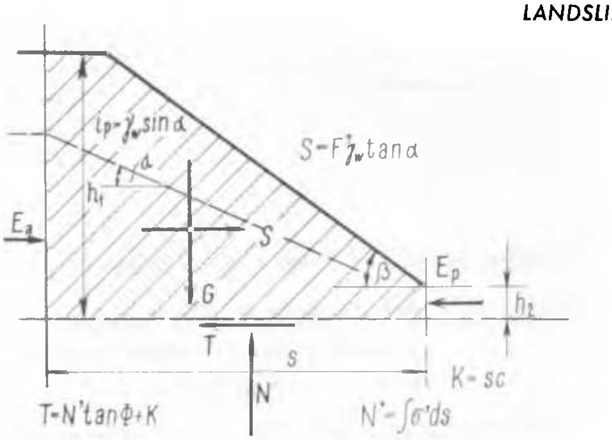


Fig. 14 Equilibrium of forces

The height of the critical plane could be determined with a sufficient accuracy; also the extension and dimensions of the displaced block were known, so, the value of the piezometric stresses was the only uncertain quantity. Therefore, we calculated the safety factor assuming different values for the neutral stress acting in the critical plane; Fig. 15 presents the result of these calculations. We obtained ν = unity for a piezometric head 122 m above sea level. This value agrees very well with the observations before the slide, so it proved that the assumed mechanism of the slide cannot be far from reality. Since the original water levels - first and second ground water - were

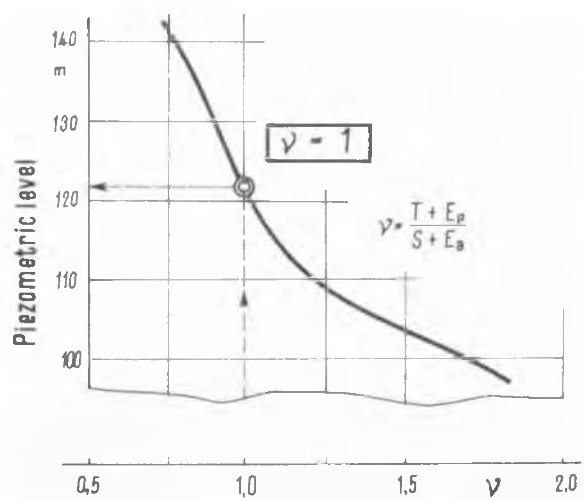


Fig. 15 Factor of safety as a function of the piezometric head on the critical plane

known, it was possible to calculate the factor of safety for the state before constructions started; it was

$$\nu = 1{,}24$$

It dropped to $\nu = 1$, due to the rise of the water level. After the movements stopped, its value was somewhat greater than 1, but the question arose, how to increase the stability of the plateau and to protect the constructions against further movements.

6. RECONSTRUCTIONS

In possession of the relevant features of the slide and having recognized the real causes, remedial measures could be proposed. Of course, any procedure employs one of the following methods: either we reduce the active forces, or we increase the resisting forces. Both methods were applied here. First, at the proposal of the writer, wells were installed at a certain distance back from the crest in order to lower the upper ground water table and, at the same time, to reverse the direction of seepage in the upper part, further, to reduce the piezometric level of the second water table. Then, shafts and galleries were built at the foot of the plateau, for drainage purposes and in order to increase the shearing strength of the afflicted masses. A fill in and by the Danube was made to protect the riverside from being washed away. As an additional measure, the shaping of the sides was provided, in order to take good care of the precipitation and to prevent gullying; also the appearence of the hillside particularly from a Danube ship should fulfill aesthetical requirements. It should go too far to discuss these constructions in detail; I give here only a table displaying the new factors of safety, due to these remedial measures. The new landscape is shown in Fig. 16. –

Table 1.

Safety factors

Condition	ν	$\Delta\nu$
Before the rise of ground water	1,22	-
At spreading	1	-
Lowering of the upper ground water level	-	o,24
Dewatering at the foot	-	o,12
Other effects	-	~o,15
After reconstruction	~1,5	-

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Fig. 16 Condition of the river bank after the remedial measures