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Slope Response to Reservoir Water Level Fluctuations

Réponse d'une Pente à l'Oscillation du Réservoir

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SYNOPSIS A slope movement occurring in the bank of an artificial reservoir is described on the basis of data collected during 8 years of observations. Soils and rocks consist of originally jointed, intensely weathered marly limestones, which have reached different stages of alteration and deformation in various parts of the large mass involved in the slide. Stress increments are induced by water level oscillations at the toe. An analysis of observations shows that basic response of slope to external water level variations is fully drained and of viscous type. The overall apparent viscosity of the mass decreases with rate of water level rise.

1 - INTRODUCTION

Significant stability problems in reservoirs may arise under various conditions of operation, among which rapid drawdown has received in the past years much more emphasis than others.
There are however a number of examples of rising pool level as the critical factor producing instability of reservoir banks. The fact was pointed out by Lane (1966) by examining results of stability studies for partial pool as well as for instant drawdown cases. He recognized in fact, that while drawdown condition appears to be most critical, being labelled with a lower safety factor, this is principally due to the severe assumptions introduced in the analysis.
The mentioned line of thought was increasingly attracting attention and led some authors to the explicit aknowledgement of "critical pool level" in explaining most of the largest landslides in reservoirs. Kenney (1967) e.g. focused once again the responsibility of the rise of external water level in causing the enormous Vajont rockslide in Italy.
The phenomenon is evident in those reservoir slopes which are in condition of incipient motion, depicted by a safety factor close to unity. Starting from this condition, in fact, even a small reduction of mobilized resistance leads to a decrement of rate of displacements; on the other hand, an increase of the same resistance leads to an accelerated motion, which might no further be held under control.
This conceptual framework holds frequently in the case of banks of artificial reservoirs, because the pool oscillation induces stress variations, which can alter significantly the monotony of the effect of gravity field.
Notwithstanding such a simplified scheme of acting forces, the degree of geotechnical complexity is often so high that even a detailed investigation is not sufficient to identify the truly representative physico-mechanical model of the slope. One must recognize, then, to be feasible only a broad approach to the problem. This consists on a prolonged in situ observation of the phenomenon, with the aim of understanding the physical processes, upon which the instability of the slope depends (Bjerrum, Jørstad, 1963) and to establish some sort of trial and error correlation between the subsoil features appearing predominant and the set of data collected during a sufficiently long time.
The case reported in the paper refers to a slope, belonging to the basin of a reservoir in Sicily, where the set of described conditions is operative (Jappelli et al., 1977).
The reservoir has been obtained in 1962 by closing the course of Dirillo River, near the site of Ragoleto.
The slide under control, located on the right side of reservoir, has roughly a triangular shape delimited by two steep gullies. The length of slope is about 600 m; its width at shoreline is approximately 450 m. The mean slope of ground surface is of the order of 10° ÷ 15°.
The volume of the sliding mass is about 6×10^6 m^3.
The first signs of instability appeared at the time of first filling of reservoir (1963) and became more and more evident with time. They consisted in deep cracks of variable width, generally oriented parallely to the shoreline.
As soon as possible the site was put under observation and a plan of controls developed.

2 - INVESTIGATIONS AND GEOTECHNICAL CONTROLS

The plan includes surface observations, explo-

rative borings, displacements measurements of deep and ground surface points, in situ pore pressure measurements and laboratory tests on physico-mechanical properties of materials involved in the slide.
Control of movements have been carried out in 64 points of the topographic surface and with 9 deep seated inclinometers.
Inclinometers readings accompanied by accurate topographical controls have been taken at intervals of 1 m of depth between October 1977 and October 1978.
The surface measurements were started in 1972 and prosecuted with semestral frequency. The precision of displacements readings is of the order of ± 1 cm (horizontal) ± 1 mm (vertical).
A second set of measurements on surface points has been performed through five targets (A, C, fig. 1) located on a West-East optical alignment at the toe of slope near shore line.
Here the horizontal components of displacements in the direction normal to the alignment, i.e. North-South, have been recorded.
The observations were started in August 1972 and are still being carried nearly on alternate days, that is with a frequency much higher than the former.

3 - PHYSICO-MECHANICAL FEATURES OF THE SLIDE

The sliding mass is supported by a bedrock of cretaceous limestones, the structural layout of which has been observed in the Barone gully (fig. 1). The bedrock is overlaid by a thick mantle composed by limestone and marl in sharp fragments (S2) accompanied by a green or brown clay with a chaotic structural pattern. Somewhere the original structure formed by rather

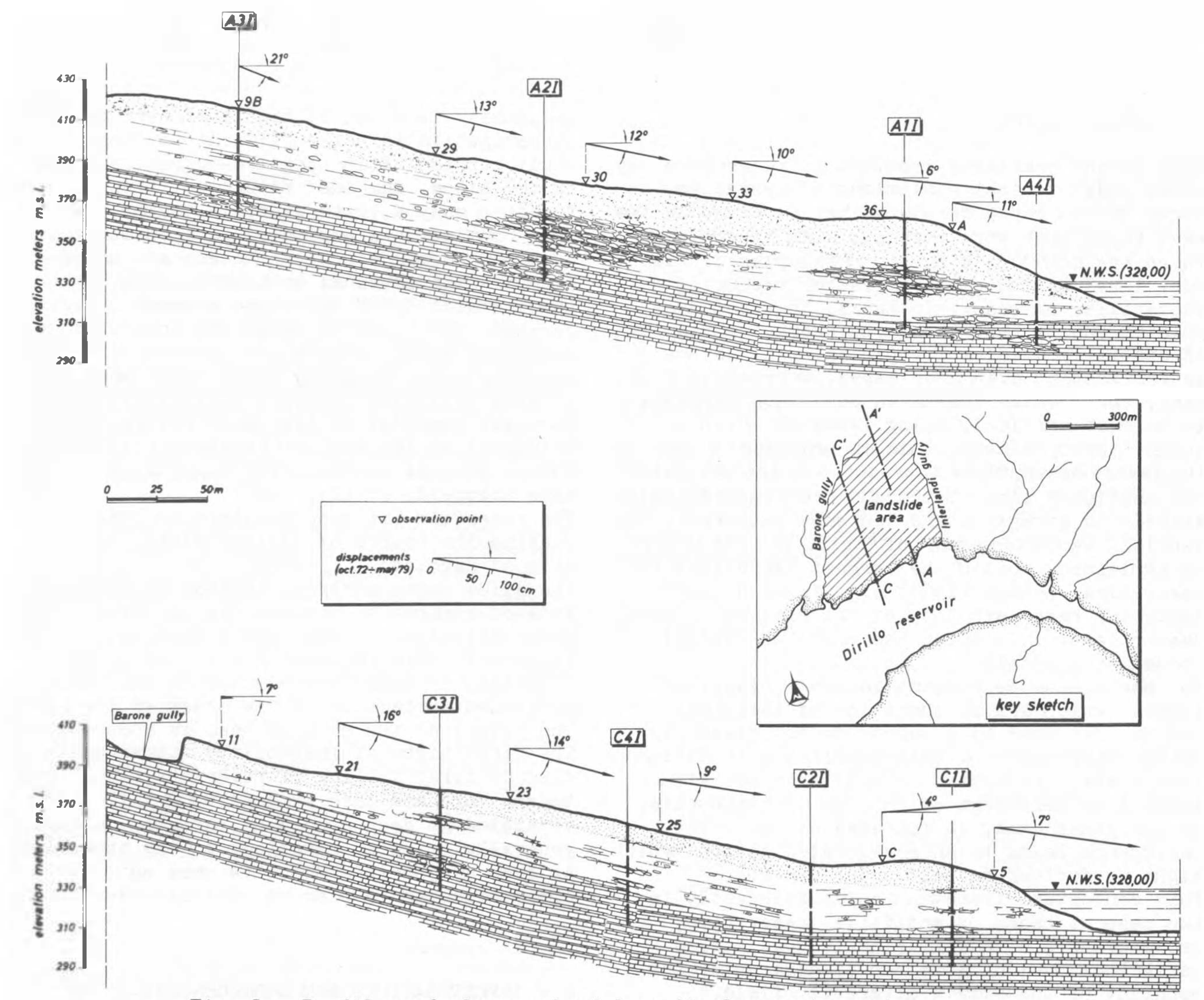


Fig. 1 - Profiles of slope and surface displacements vectors. Note different stages of rock disintegration within moving mass.

regular blocks (S4) with thin clay layers is preserved.
These materials might be the output of processes of alteration and deformation, which have reached different stages in various parts of the deposit. It is therefore possible that relatively intact, connected to firm bedrock, beside completely disintegrated zones, exist in the subsoil (fig. 1). The mentioned S2 and S4 soils are covered by a brown clayey gravelly silt (S1) rich of organic matter. Near the contact of debris with bedrock a very hard, overconsolidated marly clay (S3), a few dm thick, has been found occasionally in some of the borings. While these various types of soils appear to be distributed chaotically, some general features on the dislocation of the less disintegrated S4 can be easily put forward.
In fact the latter are found more frequently in section A-A' than in section C-C'. Moreover in A-A' it was not possible to distinguish the calcareous jointed marl S4 from bedrock.
The two opposite physical situation are also confirmed by the different behaviour of inclinometers in sections A-A' and C-C'.
In section C-C', where the transition from the mantle to the bedrock is relatively evident, the inclinometric tubes are strongly deformed in the vicinity of depth, where firm rock has been encountered. Moreover the movement seems to be concentrated at the base of detrital mass.
At section A-A' on the contrary, it was not possible to locate definitely the boundaries of the slide, as the inclinometer readings show that the soil-rock mass is in movement over the entire depth of observation.
Nevertheless, even if the inclinometers readings as indicators of absolute movements are to be considered with caution, they still maintain some reliability in a relative sense.
Therefore the records have been digested to obtain an indication of shear strain values and of their course with time in zones where the highest relative displacements have been measured (fig. 2). For section C-C' such a zone is confined at the base of sliding mass, while in A-A' it can be located between the true detrital mass and some relatively structured masses of calcareous marl of still uncertain extent.
One observes that in section C-C' (fig. 2a) the shear strain rate is higher and relatively more uniform than in A-A' (fig. 2b). Such different behaviour, which could be related to the quite different extent of marl S4 in the two sections, confirms that in the part of slope which is more distant from the Barone gully (fig. 1) the process has undergone a slower evolution and it is therefore in a less advanced stage.
Although extremely difficult to obtain meaningful in-situ or laboratory test results in such heterogeneous mass, a laboratory geotechnical identification of materials S1, S2, S3 has been performed. On one remoulded sample of the marly clay S3, the liquid limit of which was indeed exceptionally high (1.97), a shear test has been

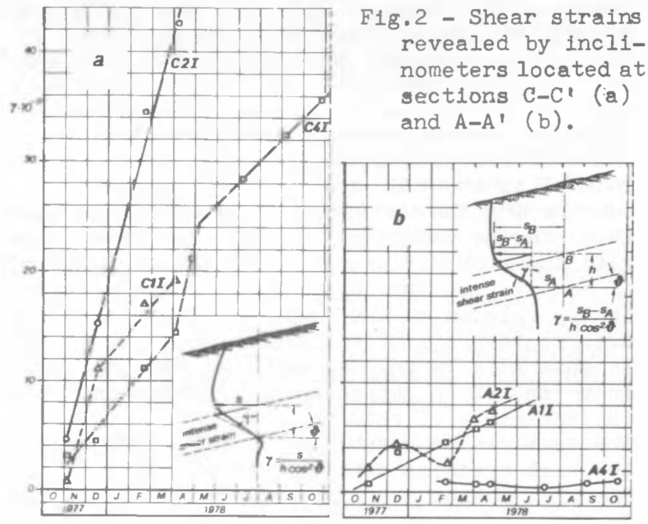


Fig.2 - Shear strains revealed by inclinometers located at sections C-C' (a) and A-A' (b).

performed, obtaining for the residual strength

$$c'_r = 0, \quad \varphi' = 13°$$

It is not sure, however, if these properties are the governing factors along the zone of sliding. Piezometers show that reservoir water constitutes in the slope a nearly horizontal table, which follows readily the pool oscillations.

4 - KINEMATICS

A detailed discussion of the trend of movements of the slope has been published elsewhere (Jappelli et al., 1977).
It must be remembered that the direction of the movement is more or less the same in nearly all points under control; such direction is toward the lake (South) with small components toward West in the highest and Eastward in the lowest part of the slope. Maximum displacement rate is about 10 cm/month.
From the whole set of horizontal displacements it can be recognized that the mass movement takes place around a center of instantaneous rotation located South-East of the Interlandi gully (fig. 1).
The displacements vectors relative to points of control falling on the sections show that the movement is congruent with dip of bedrock surface (fig. 1).
Because of their frequency, the readings taken at the targets at slope toe, appear even more interesting than the former.
One can observe a certain analogy of trend during three significant periods, in which, after a more or less rapid rise, the reservoir level has been kept appreciably constant for a relatively long time; in such periods the velocity peaks have been reached some time after the level attained the final elevations.
The data collected during such periods (E1, E2, E3), in which the slope was subjected to

particularly simple stress increments (fig. 3), are synthetically reported in Table I.
It can be recognized that during the most important filling events (E1, E3) of the reservoir, the velocity of movements has attained rather different maxima with diverse time lags.
The difference between the deviatoric stress induced in the two cases is not relevant considering the corresponding slight difference (4 m) in the excursion of reservoir level. Neglecting such difference, the diverse behaviour of mass in the two situations may be conveniently related to the rate of water level rise, i.e. to the rate of stress change.
It must also be pointed out that data do not show any clear dependency of slope response on the intensity of rainfall.
The fact can be assumed as a confirmation of the high draining capacity of the subsoil.
For that reason the excess pore pressures, due to the variations of total stresses, may be practically neglected.

TABLE I - Basic response of slope to main filling events

event	1 m/month	2 m m.s.l.	3 months	4 cm/month	5 months
E 1	12	315÷327	6.0	10	0.5
E 2	3.2	308÷324	4.0	2	1.5
E 3	8	320÷328	7.0	5	2.5

1) rate of water level rise
2) from elevation to elevation
3) permanency of maximum water level
4) maximum rate of horizontal dispacements
5) time lag

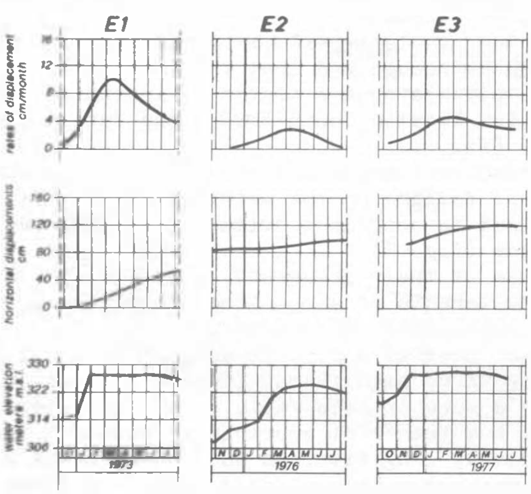
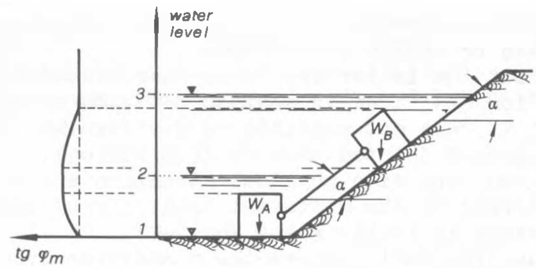


Fig. 3 - Basic response of the slope to rises of water level.

5 - TENTATIVE INTERPRETATION

In order to illustrate the mechanism of acting and resisting forces on a slope subjected to buoyancy, one may refer to fig. 4. Following usual suggestions on the matter, the sliding body is here schematically represented by two blocks resting on a horizontal and on an inclined plane, respectively (Kenney, 1967); the blocks are connected by a rigid beam freely pivoting about hinges. If only weight forces are active, and in absence of cohesion, the friction angle mobilized for the equilibrium assumes the expression indicated in the figure.



water level	$\overline{W_A}$	$\overline{W_B}$	
			$tg\,\varphi_m \simeq \dfrac{tg\,\alpha}{\frac{1}{\cos^2\alpha}\frac{\overline{W_A}}{\overline{W_B}}+1}$
1	W_A	W_B	$tg\,\varphi_{m1} \simeq \dfrac{tg\,\alpha}{\frac{1}{\cos^2\alpha}\frac{W_A}{W_B}+1}$
2	$\simeq 0,5\,W_A$	W_B	$tg\,\varphi_{m2} \simeq \dfrac{tg\,\alpha}{\frac{0,5}{\cos^2\alpha}\frac{W_A}{W_B}+1} > tg\,\varphi_{m1}$
3	$\simeq 0,5\,W_A$	$\simeq 0,5\,W_B$	$tg\,\varphi_{m3} \simeq \dfrac{tg\,\alpha}{\frac{1}{\cos^2\alpha}\frac{W_A}{W_B}+1} = tg\,\varphi_{m1} < tg\,\varphi_{m2}$

Fig. 4 - Simplified model describing the effect of water level rise on a discrete system of masses

As the water level rises the mobilized resistance increases until block A is fully submerged (critical pool level); whereupon it starts decreasing as soon as block B in turn is being submerged.

With reference to section C-C', assuming that the sliding surface coincides with the bedrock, a stability analysis conducted with $\varphi' = 10°$, $c' = 0$, shows that the safety factor is equal to unity, when the lake is empty; the same factor drops to about 0,92 at normal water storage, following to a variation of water level of about 20 m; correspondingly the increment of mobilized friction angle sufficient to keep the safety factor near unity is as small as approximately 1°.

From these results two factors emerge with evidence: firstly, in whatever condition the mobilized friction angle is very low; secondly, the increase of resistance that would be necessary for equilibrium from an empty lake condition to maximum level, is also very modest, even taking into account the slight differences between the different sections of slope.
Note that such a modest mobilized resistance is close to estimated residual values for clay S3. Although a continous clay layer bearing the sliding surface has not been found, it is possible therefore that the clay fillings govern substantially the mechanical behaviour of the structured mass.
The modest variations of mobilized resistance induced by changes of reservoir level are sufficient to activate a movement with the observed velocities and confirm that the resistance has reached the residual value on a large part of the slip surface.
In such conditions even a small reduction of resisting forces is likely to change the equilibrium of the body; consequently a condition of dynamic equilibrium holds, in which the influence of inertia and the rate of application of external forces might not be negligible.
Prior to the construction of a mathematical model of the phenomenon it is useful to attempt an indirect approach to the problem, with the aim of defining some parameters, that might be particularly significant.
The displacements and rates of displacements recorded at the targets during the three main filling events are interpolated by means of equations reported in fig. 5, being u_o an initial value of displacement, and A and B two parameters with dimensions of a length and of inverse of time, respectively.
It is possible therefore to find out the numerical values of A and B, for which the expression of v fits the corresponding experimental curves in the periods, in which the reservoir level has been kept at a certain elevation for a sufficiently long time (constant stress). The average results obtained for the three events reported in table I can be related to an empirical filling parameter representing the rate of water level rise (fig. 5).
The curve of parameter A seems to intersect the axis of the abscissas at a value of 2.5 of the filling parameter; correspondingly the parameter B seems to diverge. Note that in this case, the displacement is approaching zero. With some caution, due to the limited number of analyzable events, this can also be assumed as a confirmation of the empirical observations on the delay, with which movements are produced.
As for the physical meaning of parameter A, it is evident that it represents the final value of displacement consequent to a filling event in the hypothesis that successively the water level remains indefinetely in a steady position. How the rate of level rising actually influences the slope response is not quite clear. It seems plausible, however, to ascribe the phenomenon to three different factors, involving time effects :

a) the considerable reduction of viscosity of the material following to a rapid application of shearing stress and the subsequent increment of the same viscosity at successive constant stress level;
b) the presence of uphill directed seepage forces, the intensity of which, related to the difference of piezometric heads between the reservoir and the ground water table, is decreasing with time during each filling event;
c) the occurrence of inertia at the beginning of the first movements.

In favor of the first factor a limited experimental evidence exists; reference is made to a slide in a large morainic deposit wich forms the bank of Gepatsch reservoir in Austrian Western Tyrol (Breth, 1967).

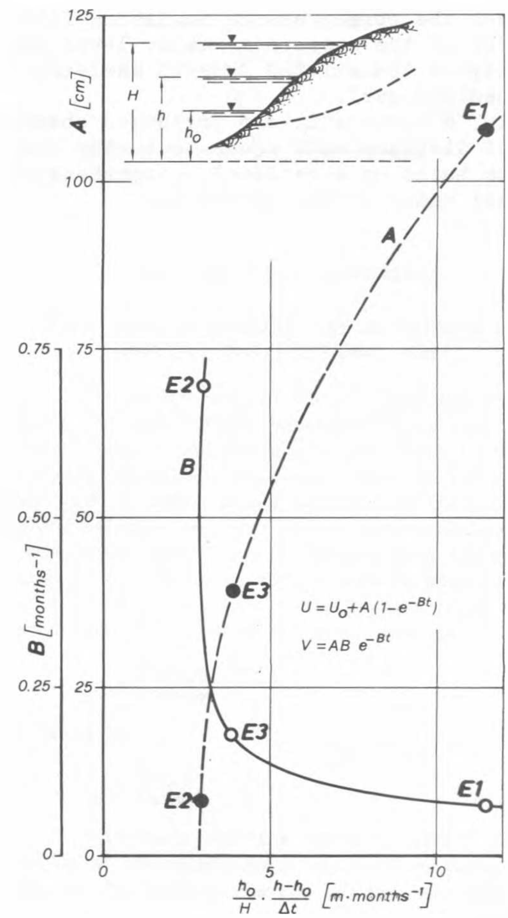


Fig. 5 - Parameters A and B describing the average progress of displacements and rate of displacements with time are related to water level rise.

The other factors could in principle be taken into account in a mathematical model; nevertheless the very intricated distribution of permeability tensor within the deposit precludes the possibility of a correct account of the effect of variable seepage forces.

6 - CONCLUDING REMARKS

With reference to a slope under control, some remarks on the behaviour of artificial reservoir banks subjected to oscillation of water level have been presented. Particularly, the influence of the rate of water level rise has been pointed out.
It is believed that the exposed concepts may apply to all the cases where the slope is in condition of incipient motion, being the governing resistance at residual value or the stress-strain curve being characterized by a brittleness index equal to zero.
This latter condition excludes that progressive failure be further operative.
Moreover the pore pressure variation following the rise of the reservoir water level should promptly be transmitted to soil skeleton (drained process).
Finally, a systematic and prolonged observation of displacements seems to be the only way to build up a rational, comprehensive, physical model of the phenomena.

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