ACTION OF RAINFALL AND MOISTURE INCREASE TO DEVELOP LANDSLIDES

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Abstract

Correlation of landslides and precipitation has long been observed. A lot of landslides ensue in springs following long, wet winters.

Cyclic variations of weathering and yearly rainfall are reflected by the yearly frequency of landslides.

Shear strength decreases exponentially with increasing water content.

Shear strength values of clays are seen to have decreased after drying — wetting cyles.

From the aspect of clay behaviour in shear, the most sensitive and most important parameter is the water content; namely, the presence and motion of water affect the development of most subsurface soil motions and landslides. Correlation of landslides and precipitation has long been observed [7]; among landslide causes rainfall is mostly — directly or indirectly — comprised [5]. This is especially true for stratum slides [8].

Most slope slides occur directly after a long or intensive rainfall period or important snowmelt. It will be endeavoured to support introductory statements on hand of examples, case studies at home and abroad, to point out the correlation between water content and shear strength, shear paremater, to warn slope designers of water content increase.

Examples, observations in this country

Precipitation is decisive for the development of seepage flow. A lot of landslides ensue in springs following long, wet winters (in particular, if protracted snowmelts forward water seepage into the soil, in winter, also evaporation is reduced).

Slope slides after development of a cut for the Godisa-Abaliget railway line vs. monthly precipitations over 90 mm have been plotted in Fig. 1. The correlation is unambiguous.

The effect of rainfall on the development of landslides is manifest from another example illustrated in Fig. 2 where precipitation in each ten days has been plotted, together with 60-year averages. The year 1976 is seen to be

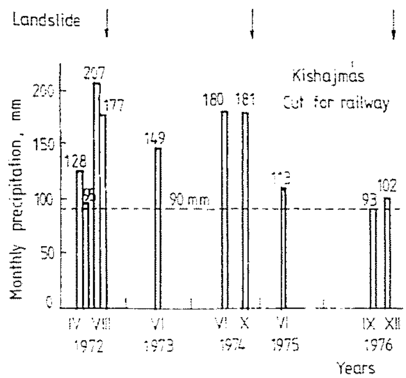

Fig. 1. Correlation between slope landslides and monthly precipitation

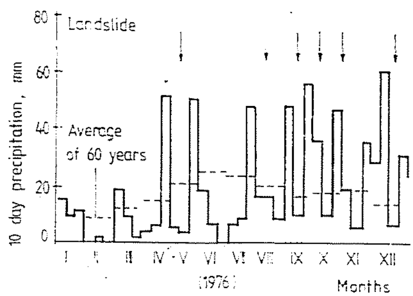

Fig. 2. Correlation of landslides and 10-day precipitation

much different. Partly, the yearly total rainfall was 703 mm, exceeding the 60-year average by 106 mm; and partly, also the yearly distribution much deviated. A glance at landslide times in the figure points out that they always followed a rather rainy period. The first landslide followed the rainy period by the end of April, then after August, landslides have become regular in conformity with consecutive rainy periods.

Cyclic variations of weathering and yearly rainfall are reflected by the yearly frequency of landslides. Yearly frequency of Hungarian landslides in the period from 1912 to 1980 have been plotted in Fig. 3, based on the investigations by the Author.

In the recent thirty years, even more landslides have been investigated and documented, a fact partly responsible for the increased number of filed ones. On the other hand, the increased yearly number of landslides is also due to the multiplication of civil engineering works and projects. There is an increase of urban development involving areas earlier avoided because of the risk of landslides (e.g. in Miskolc, Salgótarján, Komló). In addition to the yearly frequency of landslides, also the variation of total rainfall in the given period (1912 to 1980) has been investigated. Figure 4 shows the yearly rainfall

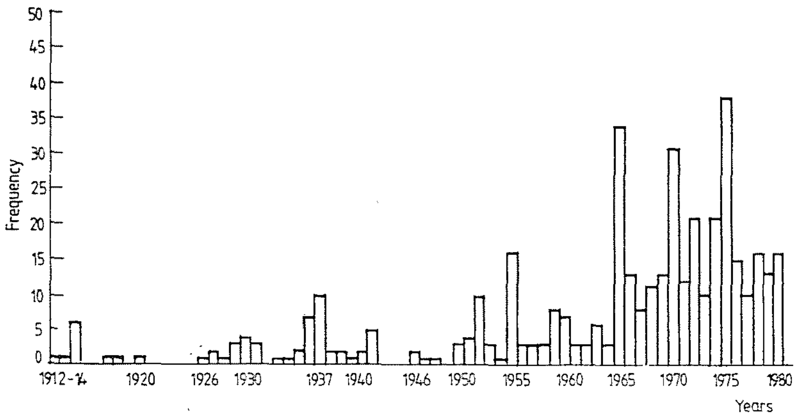

Fig. 3. Yearly frequency of landslides

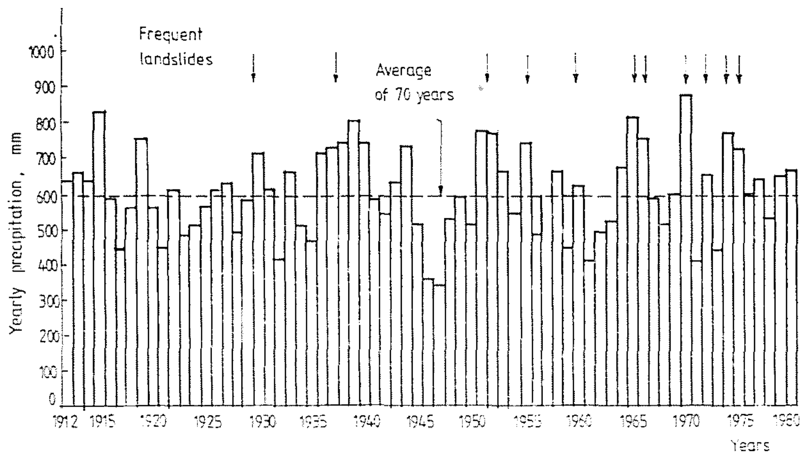

Fig. 4. Yearly precipitations from 1912 to 1980 (Eger)

in Eger. Years of frequent landslides have been indicated by arrows. In all these years, precipitation much exceeded the average of 70 years. In the quoted example of Eger, precipitation cycles of 4 to 7 years appear; but also here, cycles of 12 to 14, or 25 to 26 years, typical of Hungary, are manifest. Nationally, — in conformity with actual records — spring 1914, winters 1930/31, 1935/36 and 1936/37 were extremely wet. For instance, during the winter 1935/36 in Budapest there was a rainfall of 398 mm as against the average 124 mm (months December, January, February, March); in 1942, 1955, 1960 and 1965 there were again important precipitations in this country, with an increased number of landslides as concomitant (see Fig. 3).

Several landslides in Hungary may be attributed to preceeding deforestation. During the summer, part of the moisture evaporates from the forest subsoil hence little moisture gets into deeper layers. Deforestation may increase water seepage by 60 to 150 times [6].

Also microclimate may affect subsoil moisture to a degree (e.g. drying winds, sunshine), differentiating between south and north slopes.

North slopes keep snow longer, are frozen deeper; hence are slower to dry out, grow more of vegetation hampering erosion, so they are steeper sloping than are south slopes. In addition to evaporation referred to in connection with forests also roots are of importance for increasing the shear strength.

Experience abroad

Recent publications abroad enhance the role of precipitation in landslides [1, 10, 13, 9, 4]. Special importance to this problem has been attributed mainly in Japan, Hong Kong, Brazil, Italy and France. Since 1953, comparisons have been made between precipitation data and landslide frequency in Southern France [12], leading to the following conclusions:

— two months of dry period perfectly offset the effect of former excessive rainfall;
— rainfall milder than 5 mm/day are irrelevant to stability, groundwater conditions of the sloping area (low seepage);
— short-time rainfall — even if stronger than 20 mm/day — do not raise the water table because of fast runoff;
— rainfall over 300 mm may give rise to surface motions [14].

These conditions have been plotted in Fig. 5, relating precipitation and the expected time to pass until landslides.

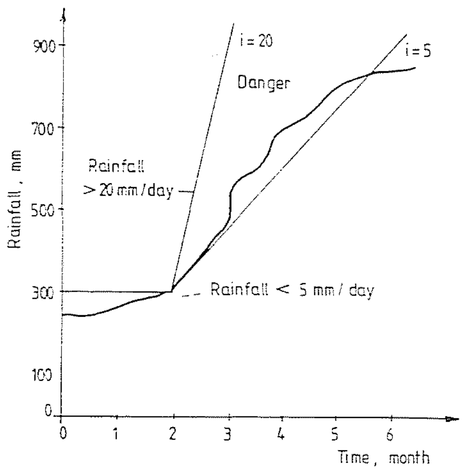

Fig. 5. Prognostication of landslides from precipitation values (Menneroud, 1983)

A similar correlation has been established in Brasil between precipitation and landslides [10].

In Japan, the Tsukuba Research Institute defined criteria of landslide risk due to rainfall. A system was constructed, emitting alarming signals in case of "hazardeous conditions", comprising:

— a rain gauge vessel and rainfall spectrum analyzer;

— a computer transmitting rainfall data to a local alarming center;

— alarming unit.

About similar systems for signalling landslides and alarming have been established in the USA [16].

1980 to 1982, weather was droughty in Italy. In this period, little surface motion occurred [2].

Hong Kong, with a yearly precipitation about four times that in Hungary, and with a territory consisting of about 60% of hillsides sloping more than 15°, may be considered as a site of field study of the correlation between rainfall and landslides. Over 90% of the great, frequent landslides may be directly attributed to driving rain and rainstorms [3].

Excessive rainfall in e.g. May and August 1982 caused — according to aerial photos — over 1500 landslides in the 1050 sq.km area of Hong Kong (causing, in addition to economic losses, 27 casualties).

Relationship between the mentioned daily rainfall volume in late May and early June 1982, and the number of landslides in these days has been plotted in Fig. 6 as an example. Most of the landslides occurred on May 29, the day of most rainfall. There were some landslides after these very rainy days, probably because of the delayed raise of water table.

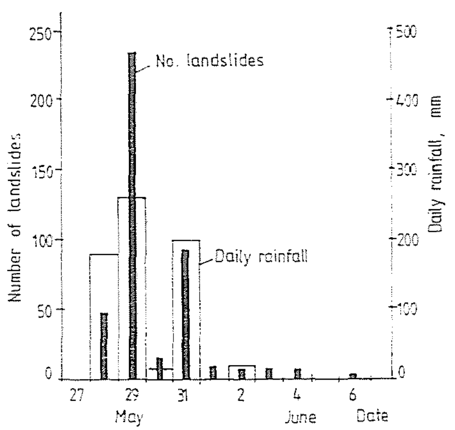

Fig. 6. Relationship between precipitation and number of landslides

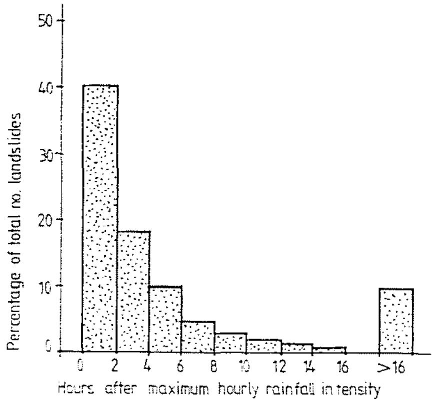

Fig. 7. Delay between rainfall and landslide

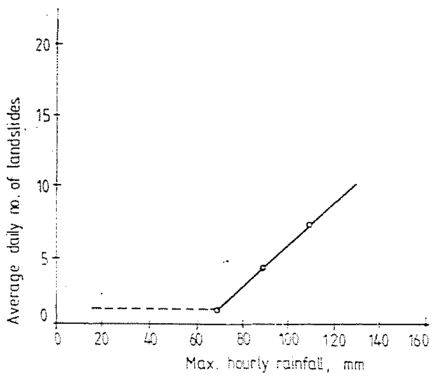

Fig. 8. Correlation between hourly precipitation and number of landslides (Brand, 1984)

Surface motions in the twenty-year period from 1963 to 1982 have been analyzed. An outcome illustrated in Fig. 7 suggests that most of the landslides occurred within four hours after the high-intensity rain, and that only about 10% of motions happened later than 16 hours after the rain in good agreement with conclusions drawn from Fig. 6.

Relationship between the hourly rainfall and the resulting number of surface motions has been plotted in Fig. 8 based on twenty years of observations. Below a rainfall intensity of 70 mm/h, there was a minimum number of landslides. Beyond this threshold, the number of landslides, and of course, the damages grew with the increase of rain intensity.

According to experience, rainfall below 100 mm a day does not cause serious surface motions.

Although these observations relate to circumstances in Hong Kong, they may be conclusive for Hungarian and other geotechnicians.

According to Skempton and Hutchinson [17], 7-year cycles may be observed in the frequency of landslides. Schuster and Krizek [15] point to long-time — 11 and 22-year — cycles of rainy years.

Team of the Institute of Geochemistry and Geophysics of the Belorussian Academy of Sciences, relying on many years of meteorologic observations and computer processing, stated that anomalous weather zones "travel" about 11 years around the globe. These cycles are due to the Sun, again with 11-ear, cycles of "activity".

Effect of moisture content increase on shear strength

Water content is known to strongly influence clay shear strength. With increasing water content, clay particles adsorb an increasingly thick water film, weakening or partly destroying bonds between particles.

With the thickening of water film between particles, cohesion decreases, soil at the layer boundary becomes so to say pulpy. Water primarily affects clay minerals and properties of some clay types of noncrystalline components.

Clay minerals are "softened" by water (e.g. montmorillonite swells), the texture of clay loosens. When at last shear stress exceeds "surface active stresses", particles glide on each another.

For 84 percent of Hungarian landslides, the effect of seasonal, seeping waters, layer waters can be demonstrated [8]. When cuts are made, the soil under the slope plane gets unloaded, it expands; part of the elastic "energy" accumulated in the earth mass is released, absorbed by the subsequent displacement. Expansion entrains increase of water content. The rate of expansion depends on the "hidden" deformation energy value of clay, from the preload.

Water absorptivity of some clay samples from cuts risking to slide have been investigated. Tests were made by placing dry soil clods on constantly humidified filter paper in the bottom of a vessel with a cover. Periodically weighing samples permitted to calculate water content variation. Of course, this is not an exact test; certainly, sample shape, size etc. affect the result. It is doubtless, however that clays can absorb rapidly much water causing texture change and strength loss [11]. Water absorption curves are shown in Fig. 9. By the way, the outlined test method obviously resulted in water absorption exceeding that possible under the surface of a cut slope.

Relationship between unconfined compression strength and water content of a greenish-grey rich clay ($w = 59$ to 63%, $I_p = 33$ to 36%) has been plotted in Figs 10. a and b. It is seen to follow the exponential law known from the literature:

$$\sigma_{ny} = 30\,000\ e^{-0.2w}\ (\text{kPa}),$$

where water content is given in percentages.

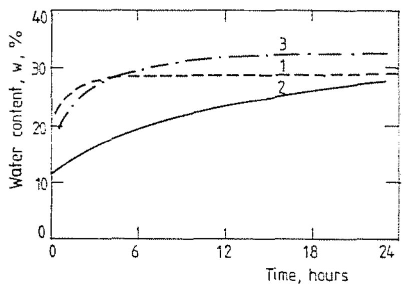

Fig. 9. Water absorption curves for clays of sliding risk

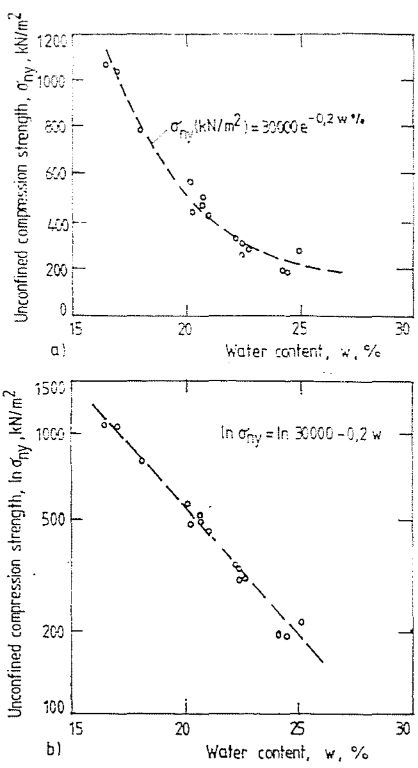

Fig. 10. Unconfined compression strength of greenish-grey rich clay vs. water content
a) plot to natural scale
b) semilogarithmic plot

Results of the Author's investigations into the reddish brown clay above the slip surface of the slid railway cut at Kishajmás are seen in Fig. 11. Beyond water content, also mean saturation values have been plotted on the abscissa. The unconfined compression strength is seen to be minimized even for a water content of 25% (at a saturation value $S \approx 1$).

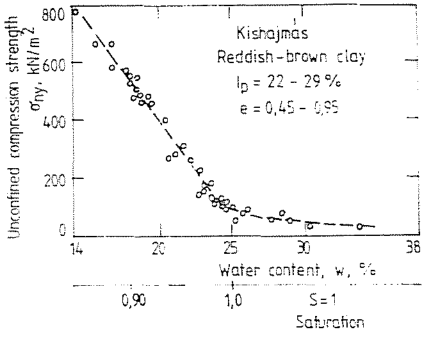

Fig. 11. Unconfined compression strength vs. water content or saturation

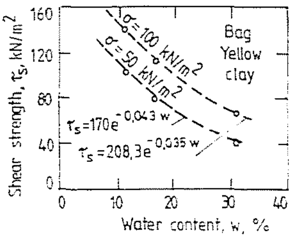

Fig. 12. Correlation between water content and shear strength from direct shear test

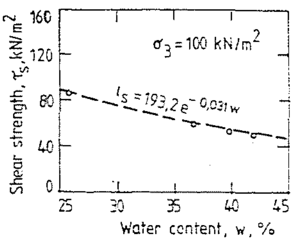

Fig. 13. Correlation between water content and shear strength from triaxial compression test

Similar relationships have been obtained in direct shear tests and triaxial compression test. Figure 12 shows the relationship between shear strength of yellow clay above the critical layer boundary of landslide in the cut of the motorway M-3 at Bag obtained in consolidated rapid direct shear test (at normal stresses $\sigma = 50$, and 100 kN/sq.m) and water contant $w > 5\%$. While relationship between shear strength at the layer boundary (slip surface) of a landslide in Hungary, determined by consolidated rapid triaxial test (lateral pressure $\sigma_3 = 100$ kN/sq.m) and water content ($w > 25\%$) has been plotted in Fig. 13. In these cases, the obtained relationships follow the law

$$\tau_s = ae^{-bw}$$

in the examined domains, where τ_s is in kN/sq.m units, and w in percentages.

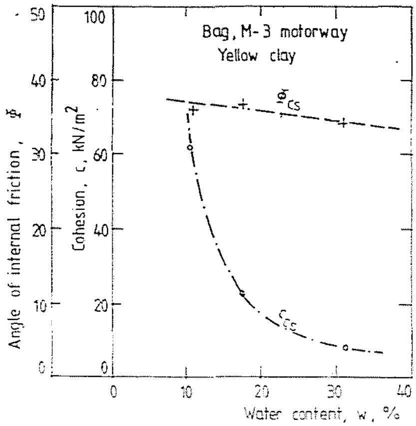

Fig. 14. Shear strength parameters vs. water content (form direct shear tests)

Shear strength decrease vs. moisture increase of the yellow clay above the slip surface of the cut of motorway M-3 at Bag has been plotted in Fig. 12.

Variation of shear strength parameters obtained in direct shear test vs. water content for the same clay is seen in Fig. 14. Peak value of the angle of friction is seen to have little changed (somewhat decreased) with increasing water content; while cohesion, the other shear strength parameter decreased exponentially with increasing water content. Another landslide was a convenient opportunity to examine water content-dependence of shear strength. Here landslide took place in the trough-like recession in the surface of a grey bentonitic clay, exhibiting water seepage. Water content of clay in the surroundings of the slip surface peaked at the trough bottom, from that both sides outwards, w gradually decreased.

Moisture-dependent variation of shear strength parameters at the interface, determined in consolidated rapid direct shear tests, is seen in Figs 15a and b. Residual value of the angle of internal friction is hardly less than the peak value for a water content $w > 30\%$; residual cohesion value is about half the peak value. Regression equations are:

$$\Phi_{cs} = 55.4 \ e^{-0.045 w},$$

$$\Phi_r = 47.4 \ e^{-0.042 w},$$

$$C_{cs} = 95.3 \ e^{-0.017 w},$$

$$C_r = 42.8 \ e^{-0.014 w}.$$

Plotting coherent shear strength parameters of a soil in a given condition in coordinate system $\Phi - c$ yields a point P. Shear strength of soils in different conditions may be compared by confronting distances $\overline{OP}$ of points P from

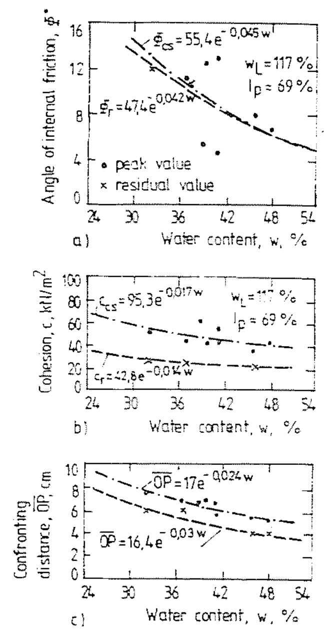

Fig. 15. Effect of water content on shear strength

the origin, as seen in Fig. 15c, exhibiting combined effect of friction and cohesion, at a rather perspicuous sensitivity to moisture.

The curve of moisture dependence of distances $\overline{OP}$ taken from the coordinate system to arbitrary scale is obtained from regression equations

$$\overline{OP} = 17.0 \ e^{-0.024w} \ (\text{cm})$$

for the peak value of shear strength, and

$$\overline{OP} = 16.4 \ e^{-0.03w} \ (\text{cm})$$

for the residual strength.

Regression equations are only valid at $w > 24\%$. Some clays exposed to periodical water seepages may suffer wetting and drying cycles, likely to affect shear strength. Effect of wetting-drying cycles on unconfined compression strength of four different "slippery" grey clays has been tested under laboratory conditions. Test samples 4 cm dia. and 6 cm high of each clay type have been taken side by side. The test procedure was the following:

After being bored, samples were wetted for 72 hours, then one to three specimens tested to failure. The others were dried for five hours at 50 °C, then another 72 hours of wetting followed, taking care to let the water content

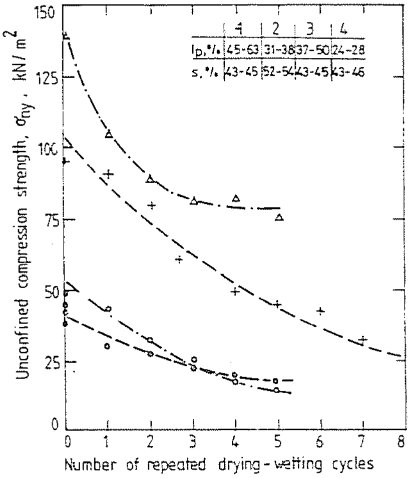

Fig. 16. Effect of wetting-drying cycles on unconfined compression strength. 1 — dark grey rich clay; 2 — reddish grey rich clay; 3 — black-grey rich clay; 4 — greenish-grey rich clay

recover the value after the first wetting. Drying-wetting cycles were repeated five times (for one type of clay six times), testing one sample after each cycle (wetting). Results are seen in Fig. 16. Shear strength values are seen to have decreased after each cycle, but at a slowing rate. After the first two or three dryings, compressive strengths of all the four clay types about halved.

Remind, however, that such an exsiccation is inexistent in subsoils of slopes of cuts; there the restructuration, hence the strength loss, is much slighter.

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