Stability of Natural Slopes in London Clay

Stabilité des Talus Naturelles en Argile Londonienne

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Summary

In several areas of the London clay north of the Thames the natural hillsides are not yet in final equilibrium. Where the ground water level reaches the surface in winter, slips can occur on 10 degree slopes, but all slopes flatter than 10 degrees are stable, although subject to soil creep. This critical slope is in agreement with an analysis of stability based upon the laboratory value for the angle of shearing resistance $\phi' = 20$ degrees, provided the cohesion intercept c' is taken as zero.

Sommaire

Dans quelques régions du London clay au nord de la Tamise le talus naturel ne se trouve pas encore en équilibre définitif. Aux endroits où le niveau phréatique arrive jusqu'à la surface en hiver des glissements peuvent se produire sur les pentes de 10 degrés. Toutes les pentes de moins de 10 degrés sont stables, bien que sujettes au fluage. Cette pente critique est en accord avec une analyse de stabilité calculée d'après la valeur au laboratoire de l'angle de la résistance au cisaillement $\phi' = 20$ degrés; pourvu que la cohésion soit zéro.

Introduction

A number of landslides in natural clay slopes have been analysed and the results published; these have, however, been treated necessarily as individual cases and no data appear to be available concerning a wide survey of the slopes in any particular clay stratum. The London clay provides excellent opportunities for such a survey, owing to the great area which it covers and its exceptional uniformity, coupled with the fact that both stable and unstable slopes can be found. The present paper summarizes the information so far obtained on natural slopes in the London clay. It is to be regarded as an interim report since work is still in progress, but already a remarkably clear and significant pattern has emerged from this survey.

In 1953 an analysis of a landslide in the stiff-fissured clays of the Coal Measures in the River Severn valley in Shropshire led to the conclusion that stability depended solely upon the angle of shearing resistance ϕ' and that the clay behaved as if its cohesion intercept c' was zero (HENKEL and SKEMPTON, 1954). This analysis, carried out in terms of effective stresses, also showed the great importance of the position of the water table; and if the water table rises to ground surface then, with $c' = 0$, the maximum stable slope is equal to about $\frac{1}{2}\phi'$.

At the same time drained tests were being made on London clay, and it was found that $\phi' = 20$ degrees for this material.

Now a few isolated observations had already indicated that the limiting slope was about 10 degrees in the London clay (SKEMPTON, 1945). Previously the quantitative significance of this result had not been apparent, but it was now realized that this slope was in fact closely equal to $\frac{1}{2}\phi'$. It therefore became worth while to undertake a more systematic survey.

Areas Studied

Reconnaissance by GRAVES (1954) revealed three promising localities, near Elstree, at Sewardstone (between Chingford and Waltham Abbey) and near Potters Bar. These are all north of the Thames, and more recently Mr W. H. Ward has drawn the authors' attention to another northern area of great value, at Childerditch near Brentwood in Essex. A foundation investigation on the slope of Sydenham Hill (SKEMPTON and HENKEL, 1955) provided a locality south of the river, and Telegraph Hill, near Chessington, appeared to present a second interesting site in the south.

The detailed investigations at Sydenham, however, had revealed that the upper and steeper parts of the slope consisted of the sandy clays of the Claygate Beds, although these were not plotted on the 6 in. Geological Survey map. Telegraph Hill is likewise plotted as London clay, but it stands out so conspicuously in the landscape, and its slopes are comparatively so steep, that we felt it also might owe its existence to a capping of Claygate Beds; and a hand auger hole proved this to be the case. Consequently, as the steepest parts of the sites south of the Thames had to be eliminated, we have obtained no critical data from this region. Indeed, the topography of the London clay south of the Thames is in general noticeably flatter than north of the river.

The steeper slopes in the northern part of the London clay are probably due to the valleys having been deeply eroded by melt water from the ice sheets which, about 150,000 years ago, deposited the 'Older Drift' boulder clay much of which can still be seen a few miles north of the localities mentioned above. The melt water, however, would enter the Thames and therefore not influence the country to the south. The whole area was probably heavily eroded again, under periglacial conditions, about 50,000 years ago, following the period of the 'Newer Drift' boulder clays of northern England; and possibly the slope adjustment which is still occurring today may result partly from a fresh disturbance caused by the de-forestation which has taken place since mediaeval times. These later effects would be superimposed on the major topographical pattern left by the older interglacial erosion.

Field Observations

Inclinations were measured with a vernier clinometer, one observer sighting on the eyes of another standing not less than 50 yards away down the slope. At least 2 and often 4 or 5 observations were made at each site and the average value recorded, as well as the precise (numbered) location, on the 6 in. maps.

At selected sites a hand boring was made and the water content and Atterberg limits determined on a sample from a depth of about 5 ft.

The Clay

All the slopes recorded in this paper are in the 'brown' London clay, the weathered zone about 20 ft. to 30 ft. thick, of the London clay. The clay in these slopes has the following average properties:

water content . .	$w = 33$
liquid limit . .	LL = 80
plastic limit . .	PL = 29
density . . .	$\gamma = 119$ lb./cu. ft.

Values of c' and ϕ' have been measured in drained tests on undisturbed samples from a number of localities (see Appendix) with the following results:

angle of shearing resistance . .	$\phi' = 20$ degrees
cohesion intercept	$c' = 250$ lb./sq. ft.

The average water content and Atterberg limits of these samples are not significantly different from those of the clay in the slopes, and the above values of c' and ϕ' are therefore sufficiently accurate for our purpose.

The London clay has a total thickness of at least 100 ft. It is a stiff fissured clay, as defined by TERZAGHI (1936).

Stability Analysis

Slips which take place in the relatively flat natural clay slopes are typically quite shallow and take the form essentially of a sheet of material sliding down hill on a slip surface parallel to the ground. Moreover the length of the slipping mass, measured up the slope, is usually great compared with its depth.

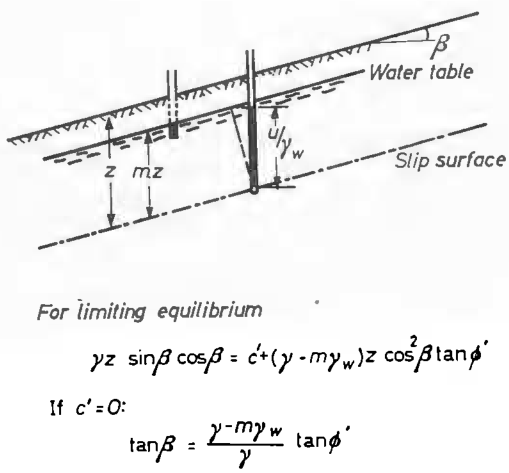

Fig. 1 Stability analysis
Analyse de la stabilité

Hence the problem can be treated on the assumption that the slip surface is a plane.

Referring to Fig. 1, let the inclination of the slope be β, the depth to the slip surface z and the depth of ground water above the slip surface mz. Then the shear stress acting on the slip surface is

$$\tau = \gamma z \sin\beta\cos\beta \qquad \ldots. \ (1)$$

where γ is the saturated density of the clay. The effective normal pressure on the slip surface is

$$\sigma' = (\gamma - m.\gamma_w)z\cos^2\beta$$

where γ_w is the density of water. Consequently, if the shear strength parameters of the clay, in terms of effective stresses, as measured in the drained test, are c' and ϕ' then the shear resistance that can be mobilized on the slip surface is

$$s = c' + (\gamma - m.\gamma_w)z\cos^2\beta.\tan\phi' \qquad \ldots. \ (2)$$

Thus the factor of safety is

$$F = \frac{c' + (\gamma - m.\gamma_w)z\cos^2\beta.\tan\phi'}{\gamma z \sin\beta\cos\beta} \qquad \ldots. \ (3)$$

and for the special case where $c' = 0$ the critical slope is given by the expression

$$\tan\beta_c = \frac{\gamma - m.\gamma_w}{\gamma}.\tan\phi' \qquad \ldots. \ (4)$$

If, in addition, $m = 1$ (i.e. ground water level coincides with ground surface), then

$$\tan\beta_c = \frac{\gamma'}{\gamma}.\tan\phi' \qquad \ldots. \ (5)$$

where γ' is the submerged density of the clay. With the foregoing values of γ and ϕ', but assuming that $c' = 0$, the critical slope of London clay in accordance with equation 5 is $9\frac{3}{4}$ degrees. When ground water level is below surface the maximum stable slope will be greater than this value. For example if $m = \frac{3}{4}$, then $\beta_c = 12\frac{1}{2}$ degrees.

Unstable Slopes

A certain number of the slopes which have been measured are difficult to classify with regard to their stability. Some of these, although apparently stable, show signs of having slipped in the distant past and others show a somewhat wavy surface,

Fig. 2 Elstree No. 1. 10 degree slope, slump
Talus à 10 degrés, affaisement

probably indicative of soil creep. There are, however, seven cases of definite instability and these are listed in Table 1.

Table 1
Unstable slopes in London clay
Talus instables dans l'argile de Londres

Site	*Slope degrees*	*w*	*LL*	*PL*	*Remarks*
Childerditch 5	$11\frac{3}{4}$	36	78	30	Moderately large slip
9	$10\frac{3}{4}$				High G. W. L.
1	$10\frac{1}{2}$	33	78	29	Active slip
Sewardstone 6a	$10\frac{1}{2}$				Slip in 1913
Childerditch 2	$10\frac{1}{4}$				
Elstree 1	10	31	80	28	G. W. L. at surface
Sewardstone 1	10	36	84	28	G. W. L. at surface

The last two cases in Table 1 are of especial interest since there can be little doubt that in winter the water table at both these sites is very close to the ground surface. At each locality a cattle pond has been formed at the top of the slope and marshy grass is widespread. At Elstree No. 1 the slope is extremely uneven and the movement may well be described as a slump (Fig. 2). At Sewardstone No. 1 there is a definite slip, the toe of which forms a sharp ridge several feet high.

At the other five sites recorded in Table 1 we cannot be certain that the ground water coincides with the surface, although it is likely that in the winter it is not more than 2 or 3 ft.

Fig. 3. Childerditch No. 1. 10½ degree slope, active slip
Talus à 10½ degrés, glissement en course

deep. At sites Nos. 1, 2 and 5 at Childerditch, instability takes the form of a very pronounced slip (Fig. 3) and Sewardstone

Fig. 4 Sewardstone No. 6. 10½ degree slope, old slip
Talus à 10½ degrés, ancien glissement

No. 6 was the scene of a large slip in 1913, although this has now been partially obscured by ploughing and there has been

Fig. 5. Sewardstone No. 5. 10 degree slope, stable
Talus à 10 degrés, stable

no recent movement (Fig. 4). All the sites in Table 1 are in grass pasture.

Stable Slopes

Details concerning 20 slopes which are undoubtedly stable will be found in Table 2.

Table 2

Stable slopes in London clay
Talus stables dans l'argile de Londres

Site	*Slope degrees*	*w*	*LL*	*PL*	*Remarks*
Childerditch 6	11½	—	—	—	Wooded slope
10	10½				
12	10½	—	—	—	High G. W. L.
Sewardstone 6c	10¼				
7	10¼				
5	10				
4b	9½	—	—	—	Probably low G. W. L.
2	9¼	28	79	27	
8b	9¼	30	81	29	
Elstree 4	9¼				
3	9	—	—	—	Probably high G. W. L.
Potters Bar 2a	9				
Sydenham A(5)	8¼	31	90	30	G. W. L. about 3 ft. deep
Sewardstone 8a	8				
Potters Bar 5	8				
2b	7¾				
Elstree 2	7¾				There are a vast number of stable slopes flatter than 7 degrees
Potters Bar 1	7½				
3	7¼				
4	7¼				

Childerditch No. 6, with an inclination of 11½ degrees, is the steepest stable slope recorded and, significantly, it is heavily wooded. The other slopes in Table 2 are all in pasture fields. There are five cases with slopes of 10 to 10½ degrees and their

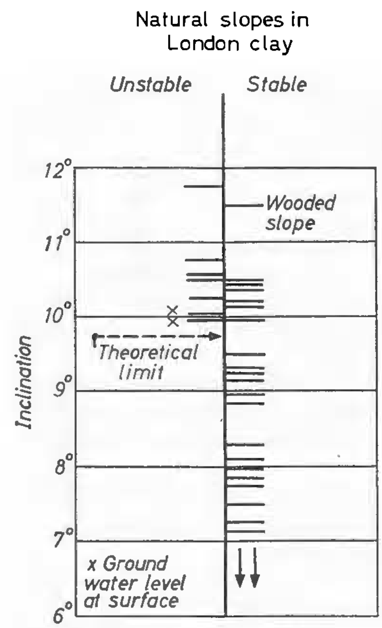

Fig. 6 Summary of observations
Resumé des observations

stability is probably due to the fact that although the water table may be high it is not at the surface and, as we have seen, if the factor m falls from 1 to ¾, the maximum stable slope increases from 9¾ to 12½ degrees.

Most of the slopes recorded in Table 2 are essentially plane over a substantial length (Fig. 5). The well known S-shaped profile seems to be a characteristic of slopes which are more mature than the majority of those found in the present survey.

Conclusions

The data in Tables 1 and 2 are expressed graphically in Fig. 6. The three most striking features of this survey are: (1) no slopes have yet been found which are steeper than 12 degrees; (2) all the unstable slopes have inclinations between 10 and 12 degrees; and (3) all slopes flatter than 10 degrees are stable.

It therefore appears that 10 degrees is a critical angle for natural slopes in the London clay, and this agrees with the value obtained theoretically on the assumption that the water table is at the surface and that $c' = 0$. It will be recalled that this result was also obtained from the analysis of the landslide in Shropshire.

There is, consequently, rather strong evidence suggesting that, on a geological time scale, stiff-fissured clays in natural slopes behave as if $c' = 0$. More investigations are necessary before this can be held to be a result of general validity, but the very consistent data obtained from the present study indicate that further work of this nature is likely to prove fruitful.

Appendix

Slow drained triaxial tests have been made, under the supervision of the authors' colleague Mr D. J. Henkel, on undisturbed samples of brown London clay from five localities. The specimens were $1\frac{1}{2}$ in. diameter and 3 in. long, with a porous plate at the lower end and filter strips up the sides, to accelerate the dissipation of pore water pressures. The rate of strain was arranged so that the time to failure was about 2 days.

Location	w	*LL*	*PL*	c' lb./sq. ft.	ϕ' *degrees*
Chingford	34	82	29	230	19
Sydenham Hill	32	83	26	220	19
Uxbridge	28	82	28	280	21
Queen Victoria Street	33	89	26	220	22
Gresham Street	29	86	27	280	19
Average	31	84	27	250	20

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