of the Great Western Railway, for the permission to use results of investigations carried out in his Office.

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THE RATE OF SOFTENING IN STIFF FISSURED CLAYS, WITH SPECIAL REFERENCE TO LONDON CLAY

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A.W. SKEMPTON M.Sc., A.M.I.C.E., F.G.S.

University Reader in Soil Mechanics and Assistant Professor at Imperial College, University of London.

INTRODUCTION.

During the construction of the early railways in the London district, engineers such as Gregory (1844) and geologists such as Sir Henry Delabeche (1844) observed that the London Clay was fissured and that water percolated along these fissures, causing a progressive softening of the clay. In this way Gregory accounted for the fact that several of the slips which he had encountered in cuttings took place several years after the cuttings had been excavated. At the same period Alexandre Collin (1846) in his classic study of the slips in the Canal de Bourgoyne suggested that, in the course of time, clay slopes would progressively flatten until they approached the slopes found in natural hillsides in clay strata.

These valuable observations were not followed up, and in the author's opinion, one of the reasons for the long delay in the development of soil mechanics can be found in the apparently "treacherous" and unpredictable behaviour of stiff-fissured clays: especially since these are very wide-spread in south east England and in France.

No real advance was in fact made until 1936 when Terzaghi presented a clear account of the softening action in stiff-fissured clays and (equally important) pointed to the great differences between fissured and non-fissured on "intact" clays. This account has been substantiated by direct field observations, and it is of great practical importance. Yet before any help of more than a general character can be given to the engineer it is necessary that at least an approximate time scale for the softening process should be obtained. Thus, in the London Clay for example, a cutting 20 ft. deep could be made with vertical sides and remain stable for a few weeks or months, but at a slope of 2:1 this depth would probably remain stable for 10 or 20 years, while at 3:1 or 4:1 it would remain stable for perhaps 50 years or more. In the London Clay an inclination of about 10° is the steepest found in natural slopes, and this is presumably the limiting value for very long periods of time.

In the present paper the author attempts to find a time scale for the rate of softening of London Clay. This attempt is tentative and as more evidence is obtained it will almost certainly have to be modified. But the data, even in its present form, seems to be of some value and for that reason it has been presented to the Conference for discussion.

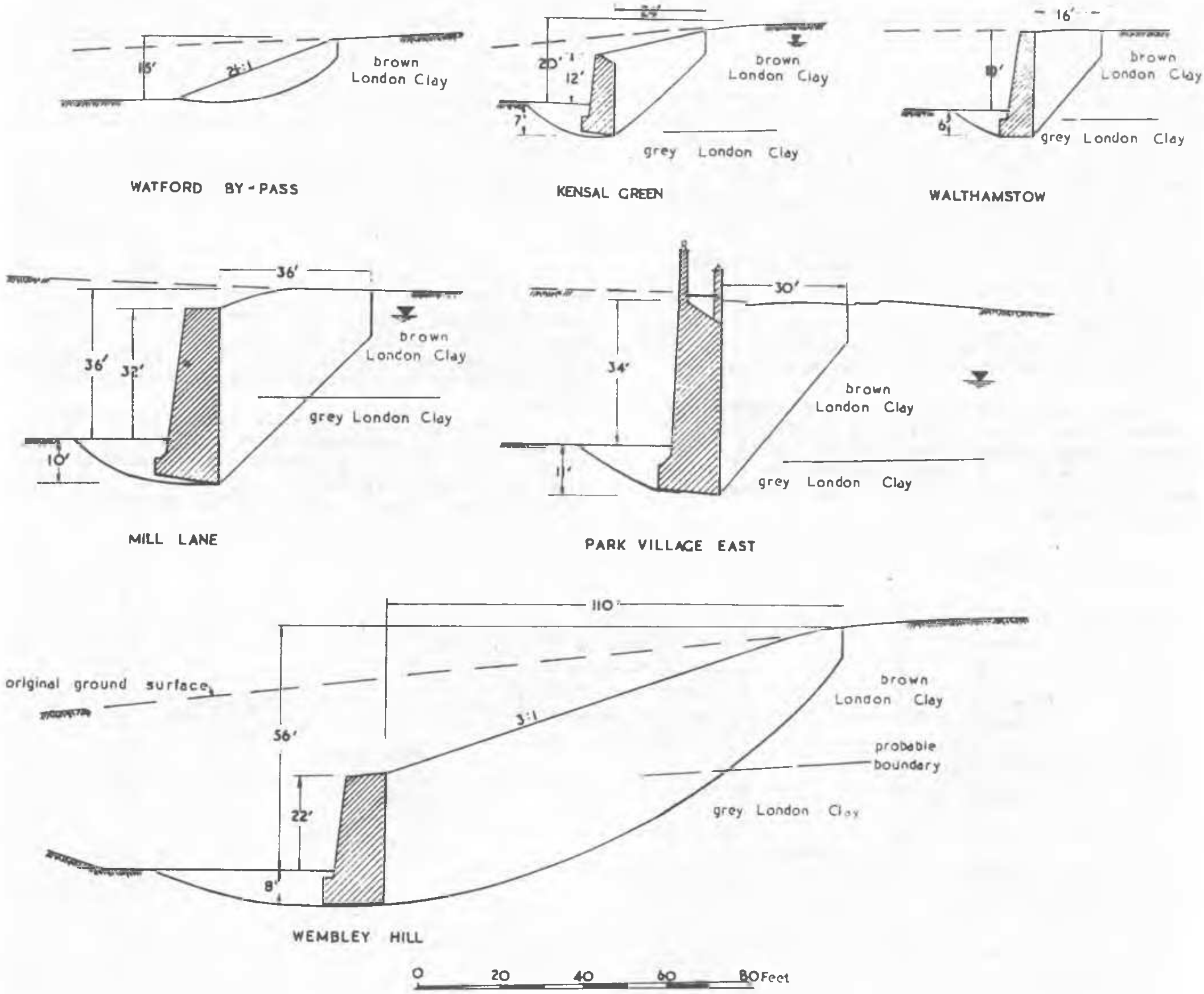
TERZAGHI'S EXPLANATION OF THE SOFTENING OF STIFF-FISSURED CLAYS.

In its simplest terms Terzaghi's explanation is as follows: In a stiff fissured clay the fissures are normally closed, but when a cutting is made there is an opportunity for lateral expansion towards the slopes. This allows some of the fissures to open and, owing to the high strength of the clay itself, the fissures can remain open at considerable depths. Water will then start percolating through the open fissures and the clay exposed on the faces of the fissures will start softening by absorbing water. This softening will, in its turn, lead to further slight movements and consequently more fissures will be opened. The progressive nature of the process may lead eventually to a slip.

In his paper of 1936 Terzaghi gave four examples of slips in stiff fissured clays and quoted the average shear strength of the clay along the slip surface at the time of failure. These shear strengths are, of course, not necessarily the fully softened strength of the clay since a slip will in general take place before the softening process is complete. Nevertheless, the four examples all showed strengths in the order of 500 to 700 lb/ft^2: an order of strength far less than the original unsoftened strength of the clay.

FIELD EVIDENCE IN LONDON CLAY.

a) Watford By-Pass. Fig. 1(a). This cutting was made in 1927. Several slips occurred between 5 and 10 years later. The average strength at failure, calculated on the $\varphi = 0$ assumption (see Skempton 1948), was about 220 lb/ft^2. Borings were made in the undisturbed ground behind the slip and the unsoftened strength at the average depth of the slip surface was found to be about 1.000 lb/ft^2.



Sections through various slips in London clay

FIG.1

b) Kensal Green. Fig. 1(b). In 1912 the wall was built in trench. Failure took place in 1941, the wall moving forward about 18 inches and cracking. The average shear strength at failure was calculated to be about 340 lb/ft^2 while tests made on samples taken from borings at the site indicated that the original unsoftened strength was roughly 1300 lb/ft^2.

Detailed investigations made by the author in a trial pit opened up behind the wall revealed the existence of fissures, with soft clay on their surfaces. This thin layer of soft clay had a strength of about 250 lb/ft^2. Free water was also found in the fissures, but the depth of softening extended no more than $\frac{1}{4}$ inch from the fissure into the clay.

c) Walthamstow. Fig. 1(c). This wall was built in 1895 and became cracked in 1936. By 1942 the movement was considerable. The average shear strengths along the slip surface at failure was calculated to be 390 lb/ft^2. The original strength, deduced from tests and borings at the site, was roughly 1500 lb/ft^2.

d) Mill Lane. Fig. 1(d). This wall was built in 1902. Movement first occurred in 1930 but in 1943 the wall moved forward quite rapidly for a distance of 3 ft. The average shear strength along the slip surface was estimated to be roughly 2.300 lb/ft^2. Several samples were taken on the actual slip surface. They had strengths of 500 to 800 lb/ft^2.

e) Park Village East. Fig. 1(e). This wall was built in 1901. In 1920 appreciable movements were observed. The remedial measures adopted were of only temporary value and in 1941 further serious movements occurred. At this date investigations were made. The average shear strength along the slip surface was calculated at 800 lb/ft^2 and from tests and borings the original strength was estimated at about 2700 lb/ft^2.

f) Wembley Hill. Fig. 1(f). The cutting and retaining wall at this site were constructed in 1905 and complete failure occurred in 1919. The slip surface is not known accurately, nor have borings been made at the site. As very rough estimates the shear strength along the slip surface has been estimated at 880 lb/ft^2 and the original strength at 2.500 lb/ft^2.

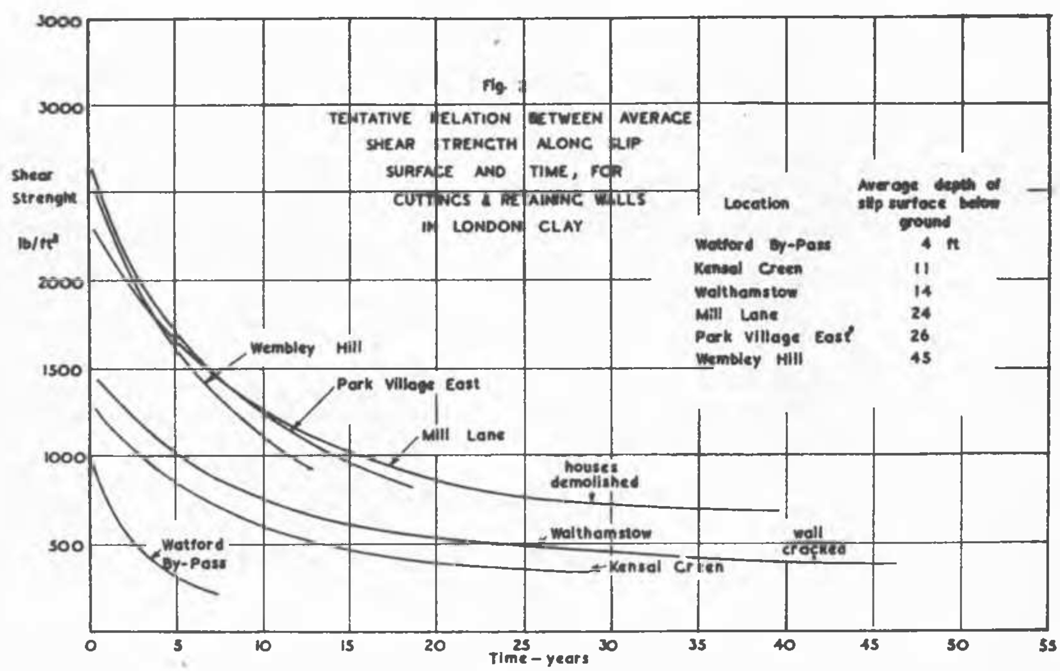
TIME-SCALE GRAPH.

From these observations a graph relating shear strength and time can be plotted as shown in Fig. 2.

In the case of Mill Lane the date of failure has been taken as 1943. Yet movements had been noticed 13 years earlier. As a consequence it is probably justifiable to draw the curve with only a small decrease in strength over this period. It will then be seen that the three slips with comparatively deep slip surfaces (average depth of about 25 ft.) are moderately concordant.

In the same way the two slips at Kensal Green and Walthamstow, with slip surfaces at an average depth of about 13 ft. are similar to each other, though distinct from the deeper group. The shallow slip on Watford By-Pass is, again, quite distinct from the other results.

Each curve has been drawn as asymptotic to some final value, which is presumably the average shear strength of the softened clay in the fissures. It seems reasonable to suppose that this final strength is greater at greater depths.



Tentative relation between average shear strength along slip surface and time, for cuttings & retaining walls in London clay.

FIG.2

Whether this is correct or not, it is at once clear from Fig. 2 that the strengths at failure is in excess of the final value for any particular case. The strength of the clay at failure is therefore not a particular value which can be used to characterise the clay: it is merely the strength corresponding to a factor of safety of unity in the given cutting or retaining wall. This strength will be an average value depending on the final strength, the strength of the unsoftened clay and the proportion of the slip surface which passes through the fully softened clay.

If the average strength at any time after construction is c then, according to the above mentioned conception

$$c = f.\ c_0 + (1 - f)c_1$$

where c_0 is the fully softened strength of the clay in the fissures, c_1 is the original unsoftened strength of the clay, and f is the proportion of the slip surface which passes through the softened clay at this time. The author proposes to define f as the "percentage of fissure surface".

In calculating f the following values of c_0 have been assumed x):

Average depth of slip surface	c_0
25 ft.	400 lb/ft^2
13	250
4	150

The resulting values of f are plotted against time in Fig. 3. With the exception of the slip on the Watford By-Pass there is a promising degree of similarity between the various cases.

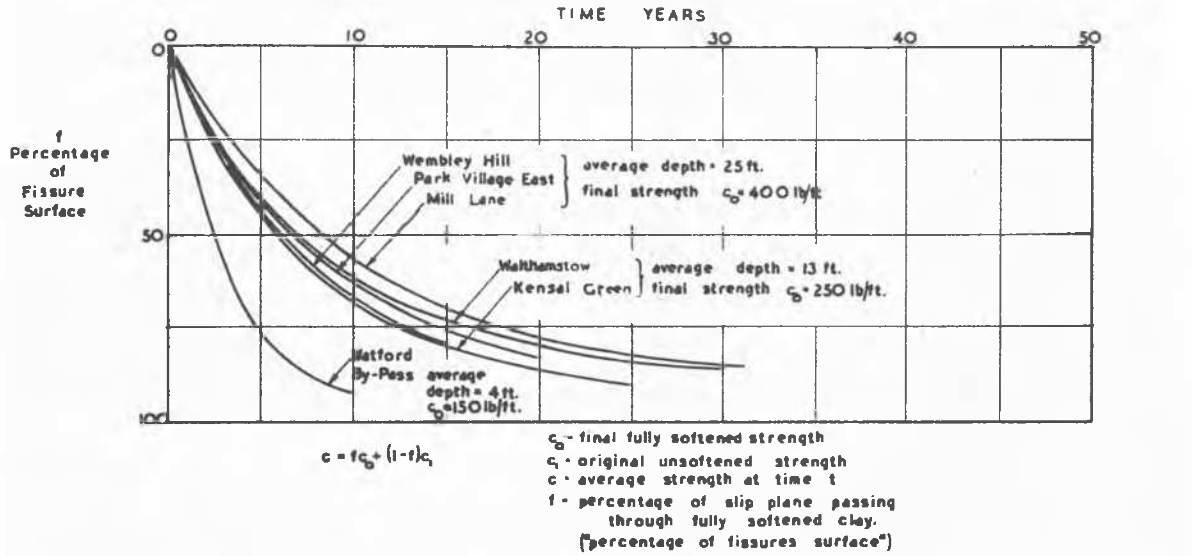
From Fig. 3 it appears that, in London Clay, for slip surfaces more than 12 ft. deep, 50 per cent of the potential slip surface is passing through softened clay in the fissures after about 7 years, while after about 15 years the proportion is 75 per cent.

It is probable that in shallows slips, such as that on the Watford By-Pass the rate of softening is considerably greater owing to the influence of weathering, and seasonal variations.

CONCLUSIONS.

It is concluded that at least a rough idea of the rate of softening of stiff-fissured clays may be gained from field studies.

x) It should be noted that c_0 for a depth of 13 ft. is equal to the strength actually observed on the fissure surfaces at Kensal Green.



Relation between Percentage of Fissure Surface and Time.

FIG.3

The essential information necessary for the solution of the problem includes the original strength, the fully softened strength, the average strength at failure, the time interval between construction and failure, and the depth of the slip surface. A collection of such information for many different stiff-fissured clays, together with an analysis such as that suggested by the author (modified if necessary as a result of experience), should prove of considerable value to the civil engineer.

ACKNOWLEDGMENTS.

The field work was carried out by the author while at the Building Research Station, Department of Scientific and Industrial Research. The results are published by permission of the Director of Building Research.

The investigations could not have been made without the generous cooperation of the Chief Engineers of the London Midland and Scottish Railway and the London North Eastern Railway.

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