

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The Colloidal “Activity” of Clays

L’Activité colloïdale des argiles

by A.W. SKEMPTON, D.Sc., A.M.I.C.E., F.G.S., University Reader in Soil Mechanics and Assistant Professor at Imperial College, University of London, England

Summary

In any particular clay stratum the ratio of the plasticity index to the clay fraction content is approximately constant, and may be defined as the “activity” of the clay. Values of activity are given for many clays and also for the more common minerals. It is shown that activity is related to the mineralogy and geological history of clays, and to the proportion of their shear strength contributed by true cohesion. Field data is presented which indicates that the difficulties of taking satisfactory undisturbed samples in deep beds of sensitive clay are restricted to those clays with an activity of less than 0.75.

Introduction

The properties of a clay are determined fundamentally by the physico-chemical characteristics of the various constituent minerals and by the relative proportions in which the minerals are present. The determination of these characteristics is a lengthy and difficult process requiring the use of an X-ray spectrometer, thermal analysis, etc., and it is evident that such techniques can never become part of the normal laboratory procedure in soil mechanics. Some simple tests are therefore required that give a quantitative measure of the composite effects of all the basic properties of a clay and, as is well known, the Atterberg limits fulfill this function in large measure. But they are not wholly sufficient, and in the present paper evidence is given which shows that valuable additional information is provided by an index property combining the Atterberg limits and the particle size distribution of a clay; yet requiring for its determination only the results of these routine tests.

The Ratio: PI /Clay Fraction

If a number of samples are taken from a particular clay stratum and the clay fraction content (percentage by weight of particles finer than 2 microns) and the Atterberg plasticity index (PI) are determined for each sample, then there is gene-

Sommaire

Dans une couche d’argile le rapport de l’indice de plasticité à la proportion d’argile (moins de 2 microns) est presque constant et peut être défini comme «l’activité» de la couche. Les valeurs de cette activité sont données pour diverses argiles et aussi pour les minéraux les plus répandus. Il est démontré que l’activité dépend de la minéralogie et de la géologie des argiles et de leur résistance au cisaillement due à la cohésion vraie. Les observations sur le terrain montrent que l’extraction d’échantillons satisfaisants, dans de profondes couches d’argile sensitive, ne présentent des difficultés que pour les argiles dont l’activité est inférieure à 0,75.

rally a quite wide range in the numerical values for both properties. Yet if the plasticity index is plotted against clay fraction it will be found that the points lie about a straight line which extrapolates back to the origin. Typical sets of results obtained from such tests on four clays are given in Fig. 1. The degree of scatter about the mean line is presumably a measure of the variations in composition within the stratum.

Now it is widely recognised that the higher the plasticity index the more pronounced are the colloidal properties of a clay. Moreover the colloidal properties are contributed largely by the finest particles and, in particular, by the “clay fraction”. But reference to Fig. 1 will at once show that two clays which may have the same content of clay fraction can have widely different plastic indexes, and it would seem logical to assume that the clay with the higher PI , for a given clay fraction content, is more colloiddally active than the clay with a lower PI , for the same given clay fraction content.

The direct linear relationship between PI and clay fraction content for any particular clay enables this degree of colloidal activity to be expressed very simply by the ratio:—

$$\text{activity} = \frac{\text{plasticity index}}{\text{clay fraction}}$$

This ratio is, in fact, the slope of the lines such as those in Fig. 1; and it provides a convenient single-valued parameter for any particular clay.

The above definition of activity was given by the author in 1950, and is a development of an earlier conception (*Skempton, 1948c*) in which liquid limit was plotted against clay fraction.

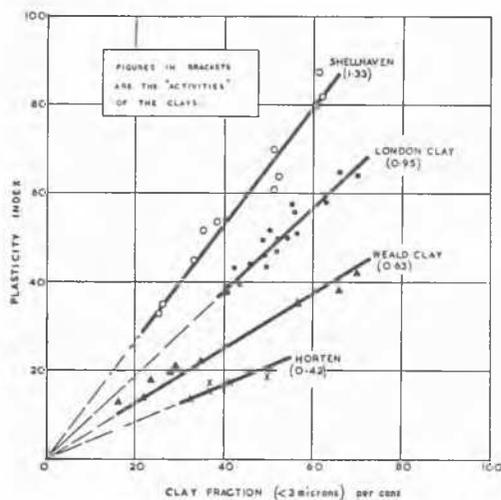


Fig. 1 Relation Between Plasticity Index and Clay Fraction
Relation entre l'indice de plasticité et le pourcentage d'argile

In the 1948 paper three classes of clay were recognised, from this point of view, namely "inactive", "normal" and "active". Data obtained subsequently has not lead to any essential change in this classification which, in terms of the ratio $PI/clay$ fraction, may be stated as follows:—

- inactive clays — activity < 0.75
- normal clays — activity 0.75 to 1.25
- active clay — activity > 1.25

The relation between liquid limit and clay fraction, although linear, is not one of direct proportion and is therefore less convenient than the ratio $PI/clay$ fraction. For the idea of plotting clay fraction against plasticity index rather than liquid limit, the author is indebted to a graph in a paper by *A. Casagrande and Shannon (1948)*.

Activity of Various Minerals

In examining more fully the significance of activity it is in the first place of interest to discover the values of $PI/clay$ fraction for the commonly occurring minerals in clays. The principal data are assembled in Table 1.

Table 1 Values of $PI/Clay$ Fraction for some Clay-Minerals

Mineral	Activity	Reference
Quartz	0.0	<i>von Moos (1938)</i>
Calcite	0.18	<i>von Moos (1938)</i>
Mica (muscovite)	0.23	<i>von Moos (1938)</i>
Kaolinite	0.33	<i>Northey (1950)</i>
	0.46	<i>Samuels (1950)</i>
Illite	0.90	<i>Northey (1950)</i>
Ca-montmorillonite	1.5	<i>Samuels (1950)</i>
Na-montmorillonite	7.2	<i>Samuels (1950)</i>

The three minerals quartz, calcite and mica, tested by *von Moos*, were ground to a very small particle size and the PI then determined on the fraction finer than 2 microns. The activity of these minerals is low, as might be expected from their relatively simple crystal structure. Of the true clay minerals so far examined kaolinite has the lowest activity. Illite is probably the most widespread of all clay minerals but it usually occurs in conjunction with other minerals. Fortunately, however, a clay shale exists in Illinois, the clay fraction of which consists almost entirely of illite. A large sample of this material was kindly sent by Professor *Grim* and the average result of tests carried out by Dr. *Northey*, in the author's laboratory, is given in Table 1. The clay known as bentonite consists almost exclusively of the mineral montmorillonite. In its natural state bentonite is usually a sodium clay and, in this state, it has a very exceptionally high activity. By effecting a base exchange from sodium (monovalent) to calcium (bivalent), *Samuels (1950)* has shown by repeated tests that the activity is considerably lowered; although even the Ca-bentonite has a high activity. He has also shown that bentonite carrying a tri-valent base Al has an activity of about 1.3. In contrast, *Samuels (1950)* found that base exchange has only a minor influence on kaolinite. No base exchange tests appear to have been made on illite but, since this mineral shows moderate activity, the effect would probably be appreciable.

It is clear from the above results that activity is, broadly speaking, related to the structural complexity of the minerals; ranging from quartz through kaolin up to montmorillonite.

Activity and Geological History

Information concerning 27 clays is given in Table 2, from which it may be deduced that there is some degree of correlation between activity and the mineralogy and geological history of a clay.

The "inactive" clays (activity less than 0.75) seem to possess one or more of the following characteristics:—

- (a) clay fraction either consists predominantly of kaolinite, or contains little true clay mineral;
- (b) deposition in fresh water;
- (c) deposition in salt water, but subsequently leached by percolation of fresh water.

Clays combining the characteristics (a) and (b) or (a) and (c) form the least active group I (activity less than 0.5). Apart from kaolin the typical members of this group are late-glacial clays derived largely by mechanical erosion of non-argillaceous rocks by ice-sheets, and deposited in ice-dammed lakes; and post-glacial marine or estuarine clays which have subsequently been leached by fresh water, usually following isostatic uplift. There is evidence, both from the field and the laboratory, that many of the extra sensitive clays belong to this category of leached post-glacial marine deposits (*Rosenquist, 1946; Skempton and Northey, 1952*). Clays formed by normal weathering and deposited in fresh water seem to fall into the group 2 with activities between about 0.5 and 0.75.

The largest group is that with activities between 0.75 and 1.25, and it includes the marine and estuarine clays with illite as the predominant clay mineral. Only 8 examples are given in Table 2, but many more clays could be included ranging in geological age from the Jurassic to the post-glacial periods.

Group 4, the members of which may be described as "active" clays, consists of deposits which contain an appreciable amount of organic colloids, although in other respects they would be classed as "normal". It may be expected that clays containing

Table 2 Correlation between Activity and the Mineralogy and Geology of Some Clays

Group	Range of Activity	Location	Geology	Mineralogy of Clay Fraction		Activity	Authority
				Major	Minor		
Inactive 1	less than 0.5	St. Thuribe, near Quebec	Post Glacial marine or estuarine, leached	Q	Mi	0.33	Peck et al., Grim
		Cornwall, England	Formed in situ by pneumatolysis (kaolin)	k	—	0.39	Northey
		Chicago, U.S.A.	Late Glacial, lacustrine	---	---	0.41	Rutledge
		Boston, U.S.A.	Late Glacial, marine	---	---	0.42	Taylor
		Horten, Norway	Post Glacial, marine, leached	Q Mi i	mo k	0.42	Hansen, Northey, Grim
Inactive 2	0.5 to 0.75	Detroit, U.S.A.	Late Glacial, lacustrine	Mi i C	Q mo	0.49	Peck, Grim
		Wrexham, Wales	Late Glacial, probably lacustrine	---	---	0.54	B.R.S.
		R. Lidan, Sweden	Post Glacial, probably as Horten	---	---	0.58	Cadling
		Weald (various sites), England	Weald Clay, Cretaceous, lacustrine	i k	vermiculite	0.63	B.R.S., A.O.R.G.
		Reading, England	Reading Clay, Eocene, fresh-water	---	---	0.72	B.R.S.
		Seagrove Bay, I.O.W., Engl.	Oligocene, fresh-water	---	---	0.73	Skempton
		Grangemouth, Scotland	Late Glacial, Estuarine	---	---	0.74	Skempton
Normal 3	0.75 to 1.25	Peterborough, England	Oxford Clay, Jurassic, marine	---	---	0.86	B.R.S.
		Gosport, England	Post Glacial, marine	i	h	0.88	Skempton, Nagelschmit
		Grundy County, Ill., U.S.A.	Upper Carboniferous (illite.)	i	—	0.90	Northey, Grim
		Aylesbury, England	Kimmeridge Clay, Jurassic, marine	---	---	0.93	B.R.S.
		London (various sites)	London Clay, Eocene, marine	i	k mo	0.95	Cooling, Skempton, Grim
		Various sites, S.E. England	Gault Clay, Cretaceous, marine	i k	mo	0.96	B.R.S., A.O.R.G.
		Norfolk Fens, England	Post Glacial, marine and estuarine	---	---	1.06	B.R.S.
		Vienna, Austria	Wiener Tegel, Miocene, marine	---	---	1.08	Hvorslev
		Klein-Belt, Denmark	Klein-Belt-Ton, Eocene, marine	---	---	1.18	Hvorslev
		Active 4	1.25 to 2.0	Shellhaven, England	Post Glacial, organic and estuarine	i	k
La Guardia Airport, New York	Post Glacial, organic, marine			---	---	1.45	Harris et al.
R. Shannon, Eire	Recent river alluvium, organic			---	---	1.5	B.R.S.
Belfast, N. Ireland	Post Glacial, organic, estuarine			---	---	1.6	B.R.S.
Chingford, England	Recent river alluvium, organic			---	---	1.7	B.R.S.
Panama, Central America	Recent organic, marine			---	---	1.75	Casagrande
Active 5	more than 2.0	Mexico City	Bentonite Clay	mo	---	4.3	Marsal et al.
		Wyoming, U.S.A.	Bentonite	mo	—	6.3	Samuels, Northey

C = Calcite	h = Halloysite	}	clay minerals	— negligible	
Mi = Mica	i = Illite			---	not determined
Q = Quartz	k = Kaolinite				
	mo = Montmorillonite				

Ca-montmorillonite would also fall into this group, but the author does not know of any data on such materials. Group 5 includes only bentonitic clays, no others are known with such high activity values; and the reason is immediately apparent from the fact that they consist predominantly of Na-montmorillonite (see Table 1).

Boulder clays have not been given in Table 2 since they can vary between Groups 1 to 4, depending upon the nature of the ground from which the glacier or ice-sheet derived the material. Thus the boulder clays of East Anglia, being derived from the Jurassic and Cretaceous clays of the southern and eastern Midlands, fall into group 3. But some of the boulder clays of northern England and Scotland fall into groups 1 or 2 as they consist largely of finely ground rock minerals with little if any true clay minerals incorporated in the matrix.

Activity and True Cohesion

The shear strength of a clay is made up of two parts, the cohesion c_r and the coefficient of internal friction $\tan \varphi_r$, according to the expression (Hvorslev, 1937)

$$\tau_f = c_r + \sigma_n' \tan \varphi_r$$

where σ_n' is the effective pressure normal to the shear plane. If a clay is normally-consolidated from a slurry under a pressure σ_n' and is then sheared sufficiently slowly for all the pore water pressure to be fully dissipated (a "drained" shear test), then:

$$\tau_f = \sigma_n' \tan \varphi_d$$

where φ_d is the angle of shearing resistance in the "drained" state. If, moreover, c_r is the cohesion of the clay at the water content at failure in the drained shear test, then the proportion of the shear strength due to cohesion is

$$\frac{c_r}{\sigma_n' \tan \varphi_d}$$

and the proportion due to internal friction is

$$\frac{\tan \varphi_r}{\tan \varphi_d} = 1 - \left[\frac{c_r}{\sigma_n' \tan \varphi_d} \right]$$

In Fig. 2 the components of shear strength in 8 normally-consolidated materials are plotted against their activity. It is

not to be expected that there would be an exact correlation, but the results show beyond doubt that the greater the activity the greater the contribution of cohesion to the shear strength. Of these tests two clays were investigated by *Hvorslev* in his

is either negligible or non-existent (for example *Taylor, 1943*) and the latter maintaining, with *Hvorslev*, that true cohesion must, in general, be present in clays (for example *Skempton and Bishop, 1950; Bjerrum, 1950*).

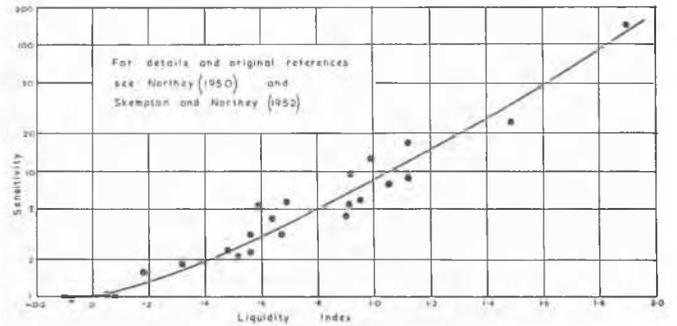
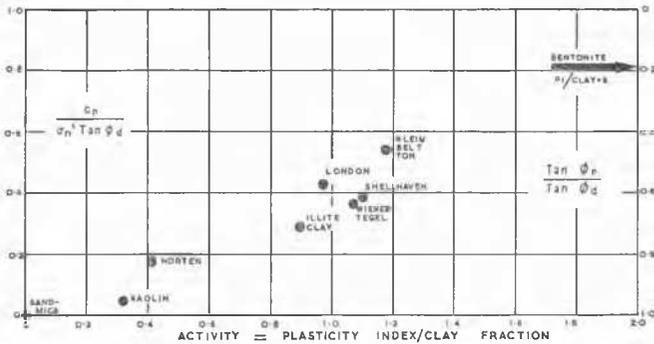


Fig. 2 Relation Between the Components of Shear Strength and the Activity of Normally Consolidated Clays
Relation entre les composantes de la résistance au cisaillement et l'activité d'argiles normalement consolidés

Fig. 3 Relation Between Sensitivity and Liquidity Index
Relation entre la sensivité et l'indice de liquidité

classic research (1937) and the others have been studied by *Gibson (1951)*, working at Imperial College.

Fig. 2 provides evidence supporting the suggestion made in an earlier paper (*Skempton, 1948c*) that there is likely to be a correlation between the cohesion of clays and their mineralogy and, in particular, that the true cohesion in some of the North American clays (Boston Clay, Massena Clay, Chicago Clay, etc.) is probably only a small proportion of their shear strength. This conclusion may go far towards resolving an apparent conflict in viewpoint between some investigators working in America and those working in Europe; the former maintaining that in normally consolidated clays true cohesion

Activity and Sampling Difficulties

From the investigations of *Carlson (1948)*, *Skempton (1948b)* and especially *Cadling and Odenstad (1950)*, it is known that there are a number of normally-consolidated clays in which it seems to be impossible to take satisfactory samples from depths of more than about 20 or 30 ft.; even with the best available sampling techniques. In contrast, cases have been reported by *Skempton (1948a)*, *Harris, Mueser and Porter (1948)* and others where it proved to be possible to obtain satisfactory samples from depths of 40 ft. to 70 ft. in normally-consolidated clays. It may be mentioned that no difficulties in this respect have been encountered in any over-consolidated clays.

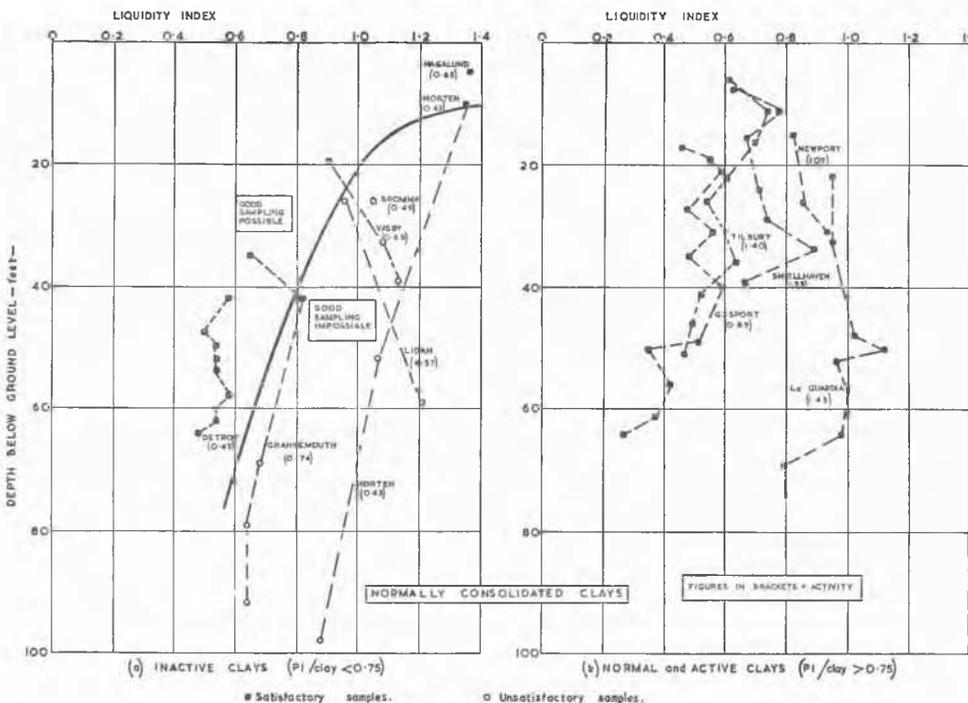


Fig. 4 Relation Between Depth, Liquidity Index and Activity and Feasibility of Sampling
Relation entre la profondeur, l'indice de liquidité, l'activité et la possibilité d'obtenir des échantillons

Now although in all normally-consolidated clays (including those from which satisfactory samples cannot be obtained at depth) the in-situ vane test gives a sufficiently correct measure of undrained shear strength, it is nevertheless generally desirable to take samples in order to carry out tests for the determination of properties other than the undrained shear strength. Consequently it is important to understand as far as possible the reasons for the sampling difficulties mentioned above. This problem was briefly considered in an earlier paper (Skempton, 1948b) and subsequently some valuable data from Sweden has become available (Cadling and Odenstad, 1950) which can be used to throw more light on the subject. The most obvious suggestion is that satisfactory sampling at depths of more than about 20 ft. to 30 ft. becomes increasingly difficult as the sensitivity¹⁾ of the clay increases. As shown in Fig. 3 the liquidity index may be used as a simple measure of sensitivity, where (Terzaghi, 1936)

$$\text{liquidity index} = \frac{\text{water content} - \text{plastic limit}}{\text{plasticity index}}$$

If the liquidity index of a sample is plotted against the depth from which the sample was taken, and if the point is given a symbol showing whether the sample was satisfactory or not, then it becomes clear that the unsatisfactory samples all lie to the right of the heavy line shown in Fig. 4. But it is also found that in this zone there are a number of perfectly satisfactory samples. Some other factor must therefore be involved, and this appears to be the activity of the clay since, in the cases known to the author, the unsatisfactory samples all have an activity of less than 0.75, while the satisfactory samples lying in the zone to the right of the line in Fig. 4 all have an activity of more than 1.0. In order to make this apparent the data has been separated, in Fig. 4, into two graphs (a) for inactive and (b) for normal and active clays.

The information at present available is not sufficient to enable any detailed or final deductions to be made, but the evidence does at least suggest that the sampling difficulties at depth, in normally consolidated clays, may be restricted to sensitive clays of low activity; and that neither sensitivity or activity are by themselves a sufficient criterion. The importance of sensitivity is evident, and the influence of activity may perhaps be explained by the proportionately low cohesion in clays of low activity, see Fig. 2. It seems not unreasonable to assume that in sampling two clays of the same sensitivity, and at the same depth, more difficulty would be experienced with the clay in which the majority of the strength derived from internal friction, and less difficulty with the clay between the particles of which there were appreciable cohesion forces. The clarification of the problem, however, awaits further research and the publication of additional case records of field investigations.

¹⁾ Defined by Terzaghi (1944) as $\frac{\text{undisturbed strength}}{\text{remoulded strength}}$

Acknowledgments

The author is indebted to many friends who have supplied data during the past years. Professor Grim, Dr. Nagelschmit and Dr. Honeyborne have given great help in connection with mineralogical analyses, Mr. Smith and Mr. Evans of the Army Operational Research Group have contributed information on activities measured by them at various sites. Professor Peck has very kindly sent many results supplementing those in his own and his students' publications. The data attributed to the B.R.S. has been included by permission of the Director of Building Research, Department of Scientific and Industrial Research.

References

- Bjerrum, L. (1951): Fundamental considerations on the shear strength of soil. *Géotechnique*, Vol. 2, p. 209.
- Cadling, L. and Odenstad, S. (1950): The vane borer. *Proc. Roy. Swedish Geot. Inst. No. 2* (Stockholm).
- Carlson, L. (1948): Determination in situ of the shear strength of undisturbed clay. *Proc. 2nd Int. Conf. S.M.*, Vol. I, p. 265.
- Casagrande, A. and Shannon, W. L. (1948): Research on stress-deformation and strength under transient loading. *Grad. School Eng. Publ. No. 447*. (Harvard Univ.)
- Gibson, R. E. (1951): An investigation of the fundamental shear strength characteristics of clays. Ph.D. Thesis Faculty of Eng. University of London. (See also paper to 3rd Int. Conf. Soil Mechanics.)
- Grim, R. E. (1949): Mineralogical composition in relation to the properties of certain soils. *Géotechnique*, Vol. 1, p. 139.
- Harris, F. R., Mueser, W. H. and Porter, O. J. (1948): Report of Board of Consultants . . . on La Guardia Field Test Section. *Port of New York Authority* (New York).
- Hvorslev, M. J. (1937): Über die Festigkeitseigenschaften gestörter bindiger Böden. *Ingeniørridenskabelige Skr. A No. 5* (Copenhagen).
- Moos, A. von (1938): Geotechnische Eigenschaften und Untersuchungsmethoden der Lockergesteine. *Erdbaukurs der E.T.H. No. 4* (Zurich).
- Northey, R. D. (1950): An experimental study of the structural sensitivity of clays. Ph.D. Thesis Faculty of Science. University of London.
- Rosenquist, I. T. (1947): Om de norske kvikkleirers egenskaper og mineralogiske sammensetning. *N.I.M. 3 Forhaudlingar*, Vol. 10, p. 1. (Stockholm).
- Samuels, S. G. (1950): The effect of base exchange on the engineering properties of soils. *Building Res. Station Note*, No. C176 (Watford).
- Skempton, A. W. (1948a): A deep stratum of post-glacial clay at Gosport. *Proc. 2nd Int. Conf. S.M.*, Vol. I, p. 45.
- Skempton, A. W. (1948b): Vane tests in the alluvial plane of the River Forth near Grangemouth. *Géotechnique*, Vol. I, p. 111.
- Skempton, A. W. (1948c): A possible relationship between true cohesion and the mineralogy of clays. *Proc. 2nd Int. Conf. S.M.*, Vol. 7, p. 45.
- Skempton, A. W. (1950): Soil Mechanics in relation to geology. *Yorkshire Geological Soc.* (in press).
- Skempton, A. W. and Bishop, A. W. (1950): The measurement of the shear strength of soils. *Géotechnique*, Vol. 2, p. 90.
- Skempton, A. W. and Northey, R. D. (1952): The sensitivity of clays. *Géotechnique*, Vol. 3, p. 30.
- Taylor, D. W. (1943): Discussion of factors affecting shearing strengths of clays. *Ninth Progress Report, Triaxial Shear Research Supplement*. M.I.T. (Cambridge, Mass.).
- Terzaghi, K. (1936): Stability of slopes of natural clay. *Proc. 1st Int. Conf. S.M.*, Vol. 1, p. 161.
- Terzaghi, K. (1944): Ends and means in soil mechanics. *Grad. School Eng. Publ. No. 402* (Harvard University).