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A Study of the Sensitivity Resulting from Consolidation of a Remoulded Clay

Étude de la Sensibilité d'une Argile Remaniée Résultant de la Consolidation

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Summary

The remoulded clay used in these investigations is shown to acquire a sensitivity as a result of the process of consolidation. When the clay is remoulded after having been consolidated it can be further consolidated under the original pressure. During this process it again acquires a sensitivity the magnitude of which, however, is less than before. By continued remoulding and reconsolidation water contents approaching the plastic limit are shown to be attainable under extremely low consolidation pressures. The c/p ratio of the consolidated clay is about 0·35 whereas that of the clay in its remoulded state is shown to be of the order of 3, a value which is without precedent.

To account for these experimental results, it is suggested that: (a) the consolidation process causes a reversible increase in both the true cohesion and the force of repulsion between the particles, and (b) the as-consolidated and remoulded shear strengths consist predominantly if not entirely of true cohesion.

Sommaire

L'argile remaniée utilisée au cours de ces recherches acquiert une sensibilité à la suite du processus de consolidation. Lorsque l'argile est remaniée après consolidation, on peut encore la consolider sous la même charge. Pendant ce processus, elle acquiert de nouveau une sensibilité dont l'importance est cependant plus faible que précédemment. Par des remaniements et des consolidations successives, des teneurs en eau approchant la limite de plasticité peuvent être obtenues avec des pressions de consolidation extrêmement faibles. Le rapport c/p de l'argile consolidée est environ 0·35 alors que celui de l'argile remaniée atteint 3, chiffre sans précédent.

Pour expliquer ces résultats, l'auteur suggère que (a) la consolidation provoque une augmentation réversible à la fois de la cohésion vraie et des forces de répulsion entre particules et que les résistances au cisaillement de l'argile consolidée et de l'argile remaniée sont dûes surtout sinon entièrement à la cohésion vraie.

Introduction

In the course of shear strength measurements on samples of Waterview and Whangamarino clay, described in an earlier paper (NEWLAND and ALLELY, 1956), remoulded samples were found to have acquired a sensitivity after having been consolidated. The impression was also gained, when samples were moulded in the fingers, that the consolidated clay had a greater rigidity than the same clay after it had been remoulded without change in water content.

In order to make a more careful study of the phenomenon the experiments described below were undertaken. A description of the properties of the Whangamarino clay and of the apparatus used in these investigations has already been given (NEWLAND and ALLELY, 1956).

Experimental Programme

A large sample of Whangamarino clay (LL = 136, PL = 61) was made up to a water content of 152 per cent and its shear strength measured with a laboratory vane apparatus.

The first set of experiments was then carried out on samples taken from this bulk supply. One sample was dried out to a water content of 140 per cent and another was wetted up to 160 per cent; both samples were then consolidated in the usual way under increasing pressure. These tests served as control tests. A further sample from the bulk supply was then consolidated under a pressure of 0·21 ton/sq. ft., remoulded without change in water content and reconsolidated in the ordinary way without further remoulding. This procedure was repeated on another sample using a consolidation pressure of 1·07 tons/sq. ft. prior to remoulding. The results of this set of tests are shown in Fig. 1.

The remainder of the bulk supply was used in the second set of experiments. A sample was allowed to consolidate under a selected pressure until such time as primary consolidation was complete, i.e. no appreciable secondary consolidation was permitted. At this stage the shear strength was measured. The sample was then remoulded and its shear strength again measured. After a small sample had been extracted for moisture content determination, the remainder was moulded back into the consolidation machine and reconsolidated under the same pressure. When primary consolidation was complete, the as-consolidated and remoulded shear strengths were

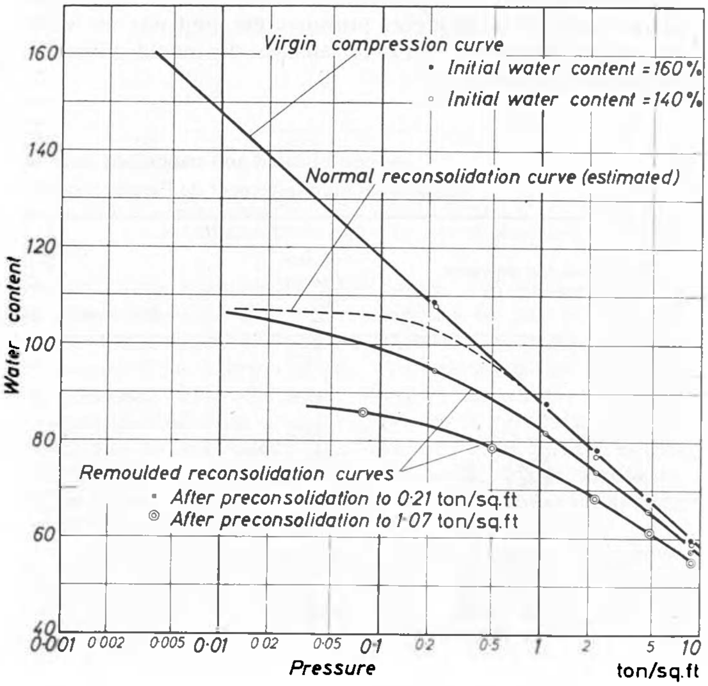

Fig. 1 Consolidation test results: variation of water content with pressure

Résultats des essais de consolidation: variation de la teneur en eau avec la pression

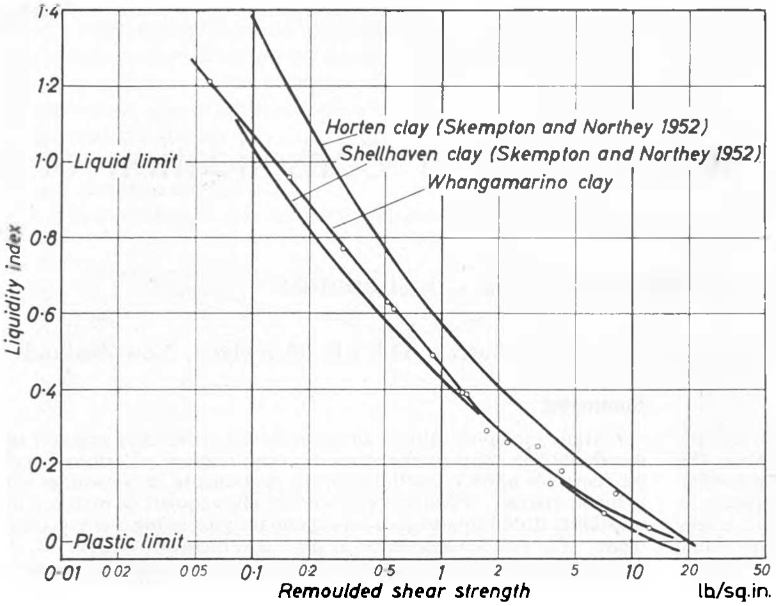

Fig. 2 The relationship between remoulded shear strength and liquidity index. Figures obtained elsewhere are included for comparison

Rapport entre la résistance au cisaillement de l'argile remoulée et l'indice de liquidité. Les résultats provenant d'autres essais sont inclus afin de permettre la comparaison

again measured. The above procedure was repeated for as many cycles as possible under a single pressure, and other samples were subjected to the same treatment under different pressures.

The initial thickness of the sample used was about 1¾ in. Each sample tested under a single pressure became progressively thinner with each cycle because of the expulsion of water by consolidation and the depletion due to extraction of samples for moisture content determination. Thus the limit to the possible number of cycles for the lighter pressures was set when the sample became too thin to enable satisfactory shear tests to be carried out. For the higher pressures the limit was set when the sample became too stiff to be satisfactorily moulded into the consolidation machine.

Most of the shear strength measurements were made with the laboratory vane apparatus. For higher strengths a vane with blades ½ in. in length was substituted for the one with ¾ in. blades. Several measurements were also made with the unconfined compression apparatus. Samples for these tests were obtained by forcing a thin-walled brass tube with a diameter of about 0·9 in. into the sample contained in the consolidation machine. Two or three such samples were placed one on top of the other to obtain a sample of suitable overall length. Remoulded samples for unconfined compression tests were obtained by moulding the sample into a 1½ in. diameter tube. The results of this set of tests are presented in Table 1.

In Fig. 2 the remoulded shear strengths obtained in all the tests irrespective of the stress history are plotted against the

Table 1

As-consolidated and remoulded shear strengths obtained after cyclic consolidation

Résistances au cisaillement de l'argile consolidée et remaniée après des cycles de consolidation

Consolidation pressure p_{ac} tons/sq. ft.		*Water content* $W\%$	*Shear strength*—lb./sq. in.		*Sensitivity* c_{ac}/c_r	$\frac{c_{ac}}{p_{ac}}$
			As-consolidated c_{ac}	*Remoulded* c_r		
Initial		152·0		0·059	1·0	
0·03		133·0	0·33	0·154	2·15	0·70
0·076	1st Cycle	119·0	0·52	0·30	1·75	0·44
	2nd Cycle	108·1	0·80	0·52	1·55	0·68
	3rd Cycle	97·8	1·29	0·90	1·45	1·09
	4th Cycle	90·0	1·71	1·34	1·30	1·45
	5th Cycle	83·0	2·08	1·73	1·20	1·76
0·215	1st Cycle	107·0	1·22	0·56	2·20	0·37
	2nd Cycle	90·4	2·28	1·30	1·75	0·68
	3rd Cycle	80·5	3·15	2·25	1·40	0·94
	4th Cycle	72·4	5·5*	3·75	1·45	1·65
0·76	1st Cycle	90·6	4·12	1·35	3·05	0·35
	2nd Cycle	74·8	7·8	4·3	1·80	0·66
	3rd Cycle	66·4	11·1†	7·2	1·55	0·94
2·25	1st Cycle	79·8	12·4	3·2	3·9	0·35
	2nd Cycle	63·5	20·8† ($\alpha = 60°$)	12·6†	1·65	0·60
0·75		70·2	20·2†	8·35†	2·40	0·27

* Average of vane and unconfined compression tests.
† Only unconfined compression tests done.

liquidity index of the clay for comparison with the results of Horten and Shellhaven clays presented by SKEMPTON and NORTHEY (1952).

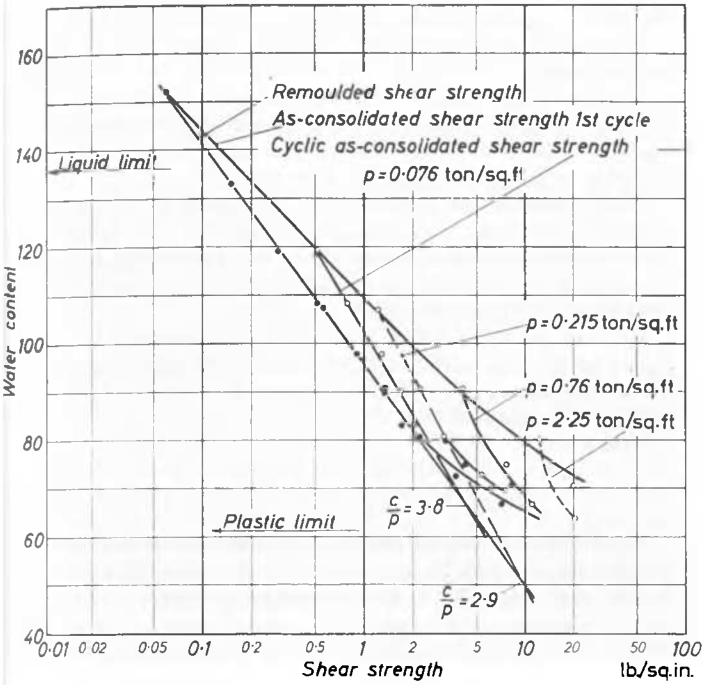

Fig. 3 The variation of as-consolidated and remoulded shear strengths with water content
Résistances au cisaillement de l'argile consolidée et de l'argile remaniée en fonction de la teneur en eau

In Fig. 3, as-consolidated and remoulded shear strengths are plotted against water content.

Discussion of Results

Referring to Fig. 1, it will be seen that the consolidation curves obtained from tests on samples with initial water contents of 140 and 160 per cent are practically identical over the range concerned. The points obtained in the second set of tests after the first direct loading under selected pressures are not shown, but they will be found to lie close to the same curve.

The two reconsolidation curves for the remoulded samples will be seen to have the general appearance of reconsolidation curves for samples which have not been remoulded; they are curved about the preconsolidation pressure and eventually become asymptotic to the virgin compression curve. An estimated reconsolidation curve for a sample which has not been remoulded is shown dotted on the illustration for comparison.

Referring to Table 1 and Fig. 3, the following points may be observed:

(1) There is a linear relationship between the logarithm of remoulded shear strength and water content which is independent of the loading history of the clay. This relationship holds over the range of water content from somewhat above the liquid limit to a water content approaching the plastic limit. Beyond this point, despite the scatter in results, there is a fairly definite change in slope in the curve.

(2) Over the same range of water contents there is also a linear relationship between water content and logarithm of as-consolidated shear strength obtained (a) at the end of the first cycle under each of the selected pressures and (b) at the end of each cycle under a single pressure, giving what will be called the cyclic as-consolidated curve.

The exception to 2 (a) is the point obtained after consolidation under 0·03 ton/sq. ft. Perhaps because of the low value of the pressure, coupled with the thickness of the samples used, this sample did not consolidate in the uniform manner in which the remainder of the samples did. To allow the sample to attain the water content indicated by the pressure-water content relationship, the sample was left in the machine for a period of 10 days as compared with a maximum of 30 hours for the other samples. The high shear strength is attributed in part to thixotropic hardening, a property which the clay is known to possess to some degree.

(3) The clay acquires a sensitivity as a result of consolidation. The magnitude of this sensitivity increases with increasing consolidation pressure so that the as-consolidated and remoulded shear strength curves diverge from the initial point. On the other hand, the sensitivity decreases with each succeeding cycle under a given pressure so that the cyclic as-consolidated shear strength curve converges on the remoulded curve.

(4) Surprisingly low water contents are attainable under quite low pressures after several cycles of remoulding and reconsolidation.

(5) The as-consolidated shear strength attained under a given pressure increases with decrease in water content. In other words, the cyclic c/p ratio gradually increases, and as Table 1 shows, some surprisingly high figures are obtained. Since at the same time the cyclic sensitivity is decreasing, it is evident that the c/p ratio of the remoulded clay will be higher than any of the figures quoted. An estimate of its value may be obtained from the shear strength at which the cyclic as-consolidated shear strength curve for a particular pressure intersects the remoulded curve. An alternative method is that given in Fig. 4 where c/p is plotted against cyclic sensitivity. The c/p ratio for the remoulded clay is found by extrapolating this curve to the point where the sensitivity equals unity.

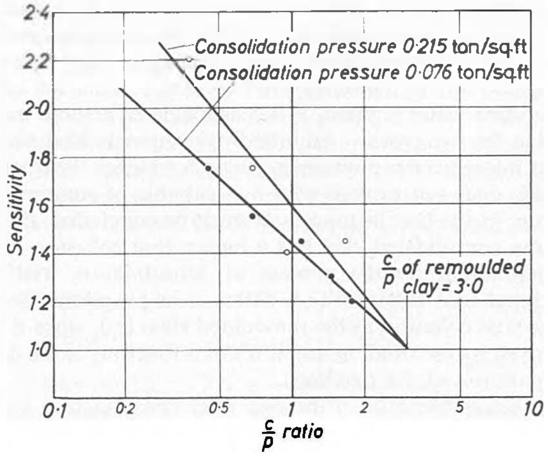

Fig. 4 The relationship between c/p ratio and sensitivity
Relation entre le rapport c/p et la sensibilité

Extremely high values are obtained by either method; however, they can only be taken to give its order of magnitude since the remoulded shear strength curve never attains the co-ordinates to which this c/p ratio corresponds. This is due to the change in slope of this curve which has been referred to earlier.

(6) The c/p ratio of samples after the first cycle of consolidation shows a gradual decrease with increase in pressure, but the range is relatively speaking quite small.

BJERRUM (1951) has pointed out that the water content reached under a given consolidation pressure and the shear strength at a given water content depend on the initial water content of the clay.

Analysis and Conclusions

The above results show that the consolidated clay is capable of supporting a higher consolidation pressure than the remoulded clay at the same water content, i.e. it has a greater resistance to consolidation. We may assume that this resistance to consolidation is entirely independent of the shear strength of the clay, whether it be consolidated or remoulded. This would require the mechanism of consolidation to be such that the shear resistance available between particles is not overcome in any way; in other words, consolidation must take place by a deformation of particle lattices without any sliding of one particle relative to another or any reduction in their distance of separation.

For reasons which, in the interests of brevity, will not be discussed here, the above assumption is discarded in favour of the more reasonable one that the resistance to consolidation does depend on the shear strength of the clay. In simplified form, the shear strength c of a clay is given by:

$$c = c_e + p \tan \phi_e \qquad \ldots. \ (1)$$

where $p =$ the intergranular pressure which in an undrained test may be taken to be approximately equal to the pressure to which the clay has been consolidated; $c_e =$ the true cohesion; $\phi_e =$ the true angle of internal friction.

The first question that may now be asked is, which component of the shear strength c gives the consolidated clay a resistance to consolidation which is higher than that of the remoulded clay at the same water content. Since the clays are at the same water content, it is reasonable to assume that ϕ_e is equal in the two cases. Admittedly the consolidated clay has a higher intergranular pressure p, giving it a higher shear strength, but this does not explain why it is capable of supporting this pressure in the first instance. It must be concluded, therefore, that the consolidated clay has a higher true cohesion which is brought about by the process of consolidation itself. The additional true cohesion $(c_e)_c$ differs in its properties from that of the true cohesion in the remoulded state $(c_e)_r$ since it can be destroyed by remoulding and it is not a function of the distance of separation of the particles.

The shear strengths of the clay after consolidation and after remoulding at the same water content are respectively given by:

$$c_{ac} = (c_e)_{ac} + p_{ac} \tan \phi_e \qquad \ldots. \ (2a)$$

where $(c_e)_{ac} = (c_e)_c + (c_e)_r$

and

$$c_r = (c_e)_r + p_r \tan \phi_e \qquad \ldots. \ (2b)$$

The next question for consideration is the quantitative relationship between the shear strength of the clay and the consolidation pressure; in other words the c/p ratio. In line with the assumption that has been adopted, the applied pressure p overcomes the shear resistance available between particles. As consolidation proceeds, the shear strength increases until such time as it reaches a value which enables it to resist further shear failure. At this point, if thixotropic effects are excluded, the clay is in a state of incipient failure since a small increase in pressure will cause further consolidation. Thus p may be considered to be equivalent to the maximum shear stress and if we consider planes of sliding within the mass making angles $((\pi/2) - \theta)$ to the direction of p, then:

$$c = \tfrac{1}{2} p \sin 2\theta \qquad \ldots. \ (3)$$

It will be noted that this relationship is independent of the fundamental components c_e and ϕ_e.

In the case of solid contact between particles, these planes may be tangent to the point of contact between particles. If the state of packing in the two clays at the same water content is assumed to be the same, then the values of θ will be the same in both cases.

On the other hand, if the particles are separated by an adsorbed phase, θ will depend on the value of ϕ_e for this phase. Again θ will be the same for the two clays if ϕ_e is assumed constant or is equal to zero in both cases.

Thus, whether the particles are considered to be in solid contact or not, there is a strong probability that c/p is constant; but, as the experimental results show, this ratio varies between wide limits, its value for the remoulded clay being much higher than for the consolidated clay.

We may account for this anomaly by postulating a force of repulsion between particles which reduces the applied pressure p by an amount p_R to an effective pressure p'. Thus $p = p_R + p'$ and c/p' is a constant.

Hence

$$\frac{c}{p} = \frac{c}{p' + p_R} = \frac{c/p'}{1 + p_R/p'} \qquad \ldots. \ (4)$$

To obtain complete agreement with the experimental results, the ratio p_R/p' must be greater for the consolidated clay than for the remoulded clay at the same water content,

i.e.

$$\left(\frac{p_R}{p'}\right)_{ac} > \left(\frac{p_R}{p'}\right)_r \qquad \ldots. \ (5)$$

It is of interest to note that the above concept favours the idea that the clay particles are separated by a film of adsorbed water, i.e. they are not in solid contact. Summarizing, the process of consolidation causes not only an increase in true cohesion but also an increase in repulsion between particles satisfying equation 5, and both the additional true cohesion and repulsive forces may be destroyed by remoulding.

Equations 2a and 2b now become, respectively

$$c_{ac} = (c_e)_{ac} + p'_{ac} \tan \phi_e \qquad \ldots. \ (6a)$$

and

$$c_r = (c_e)_r + p'_r \tan \phi_e \qquad \ldots. \ 6b)$$

We have seen from the experimental results that the value of the consolidation pressure p_r which the remoulded clay can support is extremely low even at very low water contents. Thus even if $(p_R)_r = 0$, making $p'_r = p_r$, it is evident from equation 6b that the shear strength of the remoulded clay consists largely of true cohesion.

Further, we have seen that the consolidated clay has a higher true cohesion and that the value of $(p_R)_{ac}$ must be appreciably greater to account for the very much lower c/p ratio. Hence, p'_{ac} will be relatively small so that the shear strength of the consolidated clay will also consist mainly of true cohesion.

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