shear test is due to the influence of the intermediate principal stress. According to the Author's tests (Kjellman, 1936) the internal friction of sand seems to depend on this principal stress to about the same degree as on the other two. Probably the same is true of the frictional part of the shear strength of clay. It seems reasonable to assume that the same is true also of the cohesive part of the strength, because this part is a function of the pore volume. Thus the total shear strength probably depends roughly equally on all three principal stresses. Consequently, the triaxial test probably gives values for the shear strength which are too low in the drained case.

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DISCUSSION

The Chairman, in opening the discussion, said that he had been very interested in Mr Kjellman's review of the methods used in Sweden for determining the shear strength of clay. It was no mean achievement for the Swedes to have constructed recently the vane borer and also the direct shear apparatus with loose rings. Besides the triaxial and unconfined compression devices those apparatuses constituted, probably, the most reliable means known at present for determining the shear strength of clays.

Before discussing the relative merits of the different tests, he thought it would be useful to make quite clear what engineers wanted to know about the soil, and how it should be possible to obtain the information required.

When a stability analysis should be carried out for a structure founded on clay, it was in most cases necessary to know the undrained shear strength of the clay along any potential sliding surface.

Until quite recently it had been more or less commonly assumed that the undrained shear strength of a clay at any given point was a non-directional quantity which might be measured either in situ or by means of undrained tests on undisturbed samples. However, as shown by Gibson and himself,¹ the behaviour of actual clays could not be quite so simple as that. Most natural clays had been consolidated under different vertical and horizontal pressures, and the result was that the undrained shear strength in situ depended on the inclination of the sliding surface. The first consequence of which was that, even under ideal conditions, the vane-test results could not be expected to agree perfectly with the shear strengths developed by actual slides. However, the difference might be rather small and probably was generally on the safe side, as, theoretically, the vane strength should very nearly be equal to the minimum strength developed by slides.

¹ HANSEN, J. BRINCH, and GIBSON, R. E., 1949. "Undrained shear strengths of anisotropically consolidated clays." *Géotechnique*. 1: 189-204.

Further, it could be shown that, even under ideal sampling conditions when the sample was structurally undisturbed and undrained, its internal stresses would have decreased considerably. Consequently undrained tests on samples must give values of the shear strength which would generally be lower than the ground strengths developed by slides. Moreover, different tests must give different shear strengths, and the result might even be dependent on the orientation of the sample when tested. That, together with the fact that actual samples would always be more or less disturbed before and during the extraction, and would often lose some water before and during the testing, made it questionable whether the results of tests on samples bore any definite relationship at all to the ground strengths, which were the ultimate objects of the investigation.

Theoretically, the triaxial and unconfined compression tests should give results within the range of the actual ground strengths, and under favourable conditions approximate agreement had been found to exist in a number of cases, as shown by Skempton and Golder. More often, however, and especially where greater depths were concerned, the laboratory tests had given far too small a value for the shear strength, as Mr Kjellman had demonstrated in his Paper.

In most of the cases where vane tests had been compared with actual slides in Sweden, a reasonably good agreement, according to Cadling and Odenstad, had been found to exist. Mr Kjellman had, therefore, concluded that under Swedish soil conditions the vane test seemed to be more reliable than any other test. Unfortunately, opinion seemed to differ somewhat on that point, even within Sweden. In a recent and extraordinarily interesting lecture in Copenhagen, Fellenius had related the results of almost a hundred pile loading tests in Gothenburg clay, probably the most extensive series of pile loading tests ever made. He had stated that the measured bearing capacities agreed well with the results of cone tests on samples, whereas the results of vane tests would lead to considerably too high values for the bearing capacities. Thus it seemed still to be an unsolved question whether in-situ tests or sample tests provided the best agreement with actual conditions.

With regard to the Swedish cone test, that was probably an excellent means of determining the shear strength of clays for which a calibration curve had been obtained by comparison with actual slides. Unfortunately, a different calibration curve seemed to be required for each different clay, which limited the usefulness of that test considerably.

The fact remained that at present no testing method was known which, for every clay, would be sure to yield a shear strength sufficiently close to the actual ground strengths. That was all the more deplorable in view of the small safety factors normally used in earth stability calculations, although presumably the error was generally on the safe side.

The effect of anisotropic consolidation and of sample disturbance must both tend to increase the actual factor of safety. On the other hand, as Dr Skempton had already pointed out, the effects of the rate of strain and of creep and progressive failure would tend to decrease the actual safety factor.

All that should be evident, and the individual effects could be investigated separately; but it seemed rather strange that the combined effects should counterbalance each other perfectly or, at least, with a deviation of only a small percentage. But, as was well known, that was what had been found in practically every case of failure which had been investigated. It might be a coincidence, but it was certainly a most fortunate one.

The Chairman asked Mr Kjellman whether he had any data available enabling a comparison to be made between the results obtained in the direct shear apparatus with loose rings, and the results obtained in the ordinary shear box. He also asked whether the results of tests in the new apparatus had been compared with the results of unconfined compression tests.

Dr L. J. Murdock described tests carried out in the estuarine deposits at Grangemouth, Scotland, in 1948, in which about one hundred vane tests were compared with a similar

number of unconfined compression tests in some sixteen boreholes. Curves drawn for shear strength against depth for the two methods of testing were in close agreement. However, it was thought that the average of the shear strength results given by the unconfined compression tests might have been a little high, since a number of samples were too soft to test by that method.

The soil was laminated clay, silt, and fine sand, with wide variations in water content. The vane used was $1\frac{1}{2}$ inch long and $\frac{3}{4}$ inch in diameter. Wide scatter was obtained in the results, and there were a few very low strengths registered by the vane, possibly owing to a ($\phi = 0$) condition being set up in a saturated silt.

Agreement was also obtained between in-situ vane tests and unconfined compression tests made more recently on soft clay in the Humber estuary. However, the results were not always in agreement; as in tests in the Thames estuary, the vane test gave results roughly twice those given by unconfined compression tests at all depths.

After excavating at Grangemouth to various depths, vane tests were made immediately below the excavation. It was shown that excavation by hand or mechanical grab caused considerable disturbance, with a distinct drop in strength, for depths up to about 4–5 feet below the excavation level; that required some consideration in foundation design in such soils.

Mr E. C. W. A. Geuze expressed interest in the consolidation carried out in the Swedish shear box and said that he himself had been trying for five years to do the same thing, but with no success—perhaps because Dutch clays were much softer than Swedish clays. He wondered if these consolidation tests had shown any marked differences from those carried out in the standard apparatus. Tests carried out at Delft had shown that in the standard oedometer wall friction might take up to 25 per cent. of the applied load.

He thought that it must be very difficult to compute the distribution of shearing stresses across a circular shear section: even more so than for the square section.

Mr T. K. Huizinga asked whether, in the Swedish research apparatus, there was minimum strength as the vertical was passed, when the samples were sheared from about 3 degrees on one side of the vertical to the same amount on the other side.

Professor A. H. Naylor expressed the view that the distribution of shear stress across the circular section of the Swedish shear test was rather uncertain. The rings, with the uncertain rigidity of the rubber in between them and the specimen, complicated the issue. A circular section subject to pure shear had a shear stress distribution which was unequal, but of known pattern. The rings could not rectify that since, for instance, on the leading edge no tension could be exerted between ring and sample. Any maldistribution should, being an edge effect, be diminished by reduction in thickness of the sample or by the adoption of a rectangular section with the long edge in the direction of shear.

Mr E. E. de Beer said that he considered the in situ “pull” test described by Mr Kjellman to be a form of the cone test. Like the cone test, it gave values of shear strength lower than the vane test and the unconfined compression test, and would probably give good agreement with the pile loading tests of Fellenius, already referred to by the Chairman. In his opinion the deep sounding cone gave direct and reliable results for deep foundations.

Mr W. Kjellman, in replying to the discussion, referred to the Fellenius pile tests. In driving piles into the soil in question, there would have been a loss in strength due to remoulding, and then a gain in strength due to thixotropy and consolidation. No conclusions could possibly be drawn from pile loading tests as to the shear strength of the soil, and any agreement with the cone test would be fortuitous.

No comparison had been made between the standard Swedish shear test and tests with other boxes. The test was compared some years ago with the unconfined compression test and generally gave results some 20 per cent. lower. That might have been due to the grids slipping on the surface of the sample in the shear box. If the gelatine-seal technique referred to in the Paper were used, the agreement would possibly be complete.

With regard to Dr Murdock's final remarks about the drop in strength due to decrease of overburden pressure beneath the excavation, that showed no fundamental error in the test. The soil conditions had altered.

In reply to Mr Geuze, in ordinary cases, where consolidation was small, a 0.1-millimetre space was left between the rings, and the bulging had no effect on the rubber membrane, which was 0.05 millimetre in thickness. An error was introduced where a large space had to be left.

The distribution of stress across the sample in shear depended very much upon the dimensions of the sample. If the height was small compared with the area, uniform distribution could be assumed. That condition held equally for square and circular areas. The apparatus gave pure shear with comparative simplicity. In that test there had not been found to be any drop in shearing resistance as the sample became vertical, as Mr Huizinga had suggested.

In reply to Mr de Beer he pointed out that remoulding occurred in both the "pull" test and in the deep sounding cone test, but not in the vane test. It was, therefore, important not to use the former tests with soils having any appreciable sensitivity. As a matter of principle, the stress and strain conditions should be ascertained as accurately as possible in any test, whether laboratory or field. With the deep sounding cone, there was a large element of uncertainty.

He was aware of the error in the cone test due to neglecting the rigidity of the soil, and would attempt to take that into account in future tests.