CORRESPONDENCE

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Paper No. 5292.

"Soil Mechanics and Site Exploration." †

By LEONARD FRANK COOLING, M.Sc.

Paper No. 5297.

"Soil Mechanics in Road and Aerodrome Construction." *

By ALFRED HERBERT DORLENCOURT MARKWICK, M.Sc., Assoc. M. Inst. C.E.

Correspondence.

Mr. H. Q. Golder observed that in his Paper on "The Ultimate Bearing Pressure of Rectangular Footings [1]", he had cited the conclusion arrived at by Fellenius in 1929 [2], that "On a purely frictional soil the maximum possible load per unit area of a rectangular or elliptical area is determined by the smallest dimension of the area and is proportional to this dimension." That conclusion had been substantiated by the tests of Kögler and Meischeider. In other words, the tests of these three investigators had shown that the ultimate bearing pressure on a circular area was approximately the same as that on a square area of the same width.

In his contribution to the oral discussion [3] Mr. Golder had assumed, for the sake of brevity, that Mr. Markwick was aware of that fact, and therefore he had stated that "a square (or circular) area on a frictional soil will support only the same pressure as a strip of the same width." The evidence, therefore, could not be considered inconclusive.

† Journal Inst. C.E., vol. 18 (1941–42), p. 37 (Mar. 1942).
* *Ibid.*, vol. 18 (1941–42), p. 62 (Mar. 1942).
[1] *Ibid.*, vol. 17 (1941–42), p. 161 (Dec. 1941).
[2] See reference [1] p. 51, *ante*.
[3] P. 173, *ante*.

The results quoted by Terzaghi [1], to which Mr. Markwick had referred, were irrelevant, since they related only to tests on circular areas. The theoretical result obtained by Terzaghi (in 1925), that a circle was twice as strong as a strip, was not supported by experimental evidence. Unfortunately the statement was repeated by Kögler (1938), in spite of Fellenius' evidence to the contrary.

The point which Mr. Golder had made in the oral discussion, and which, because of Mr. Markwick's reply, he wished to repeat, was that all the available evidence showed that on a frictional soil the ultimate bearing pressure on a square or a circle was the same as on a strip of the same width. Until that evidence was refuted by further tests, the statement that a square or circle was twice as strong as a strip should be considered untrue.

Dr. B. H. Knight observed, with regard to Mr. Markwick's statement (p. 65, *ante*), that the liquid limits and plasticity indexes of soils increased roughly in proportion to the "clay" content of the particular soil, that the writing of the word "clay" in inverted commas was welcomed; in the Civil Engineering Laboratories of the University of the Witwatersrand, Johannesburg, the term "clay fraction" was used, since it was now known that clay fractions of differing mineralogical properties possessed widely differing physical properties, according to the nature of the minerals present in such fraction. Research in those laboratories had given results in accordance with those mentioned by the Author, but it had been found that the presence of micaceous particles in the clay fraction did not always have the effect of increasing the liquid and plasticity index of the soil. Thus a shale soil, whose clay fraction was predominantly talcose, had been found to possess quite a low liquid limit and plasticity index (21·0 and 1·5 respectively, with a volume change of only 5 per cent.).

Mr. Markwick had further stated that those indexes were probably affected by "changes" in the mineral composition of the clays. Did he mean, for the word "changes," the word "differences"? Work in the university laboratories tended to show that mechanical analysis only was not a safe indication of the physical properties of a soil, since it had been found that soils with much the same mechanical analysis might possess either an expansive or a non-expansive type of clay fraction, giving completely different physical properties in each case. For that reason the clay fraction was divided into three main types:

1. Non-expansive (usually of a quartzose type, neither absorptive nor expansive).
2. Moderately expansive (containing markedly absorptive minerals such as limonitic, calcareous, and kaolinitic clay fractions).
3. Very expansive (containing a clay fraction which was both absorptive and expansive, such as the montmorillonite clays).

[1] See reference (23), p. 87, *ante*.

A simple colour test for distinguishing between those types of clay fraction had been developed in the University laboratories, using a 1/5,000 solution of malachite green. The non-expansive type of clay fraction had little or no effect on that solution, whilst the other two groups removed the colour according to their degree of expansive property.

Professor R. F. Legget observed that the Papers jointly gave an admirable review of the present status of Soil Mechanics. Considered in association with Dr. Terzaghi's "James Forrest" lecture [1], they would enable British civil engineers to see the progress that had been made in the scientific study of soils; to appreciate that, despite the possibly unfortunate selection of name, Soil Mechanics had valuable contributions to offer to both design and constructional work; and to realize that valuable and original work in that relatively new field had already been carried out in Great Britain.

Earlier contributions to technical literature by the Authors and their colleagues testified to the work they had done and were doing. Mr. Cooling had presented a Paper at the First International Conference on Soil Mechanics and Foundation Engineering, held at Harvard University in 1936 [2], which marked the first formal recognition of Soil Mechanics. He was the only representative of Great Britain in an international group of about two hundred engineers, and by his presence, as his Paper, he had shown that more would be heard of soil studies in Great Britain, despite a relatively late start. That promise had been well fulfilled.

It was particularly fitting that study of those properties of soils of importance in engineering should be pursued with vigour, and upon a wide scale, in Great Britain, for probably no country of comparable size exhibited such a wide variety of soil types and arrangements. That variety was intimately linked with the geology of the British Isles. Professor Legget considered that both Authors might profitably have acknowledged in their Papers the necessity for at least a general correlation of soil studies in the laboratory with the geology of the corresponding soil stratum in the field. In the case of glacial soils (so widespread in Canada) that was of special importance, but the Authors would probably agree that geology and soil mechanics were studies inevitably complementary, in all localities.

Agricultural soil studies could be profitably linked with engineering investigations of soils. In certain parts of the United States a close correlation had been worked out between so-called engineering properties of soils and recognized agricultural soil classifications. Possibly the most notable example was the work of the Michigan State Highway Depart-

[1] "Soil Mechanics: A New Chapter in Engineering Science", Journal Inst. C.E., vol. 12 (1938–39), p. 106, June 1939.

[2] "The Shearing Resistance of Soils", L. F. Cooling and D. B. Smith, Proc. First Int. Conf. on Soil Mechanics and Found. Eng., vol. 1, p. 37, Cambridge, Mass., 1936.

ment, an excellent account of which had been published[1]. In view of the agricultural soil maps so generally available, that type of correlation seemed to be of unusual value.

Mention of agricultural soil maps in relation to engineering practice would serve to emphasize the apparent simplicity of modern soil investigations, an impression conveyed by the Papers, from which practically all trace of mathematics had been carefully removed! Possibly that undue simplification—for such it was—represented a laudable attempt to make a new subject palatable to those engineers who protested publicly their ignorance of mathematics. If such members of the profession ever stopped to realize the harm done by their protestations when read by engineering students, already impatient at the rigours of mathematical study, they would inevitably refrain from thus adding to the difficulties of engineering educators. Correspondingly, the picture of modern soil studies presented by the Authors would be more complete if they would indicate in their replies, however briefly, something of the impetus given to such studies by the powerful aid of mathematical analysis.

An interesting feature of the Papers, as of other British papers on soil problems, was the attention necessarily devoted to studies of failures—necessarily, because in the first applications of new methods they must inevitably be tried out on problems the answers to which could be checked. Professor Legget hoped that the useful and accurate work done in connexion with failures, notably by the staff of the Building Research Station, would lead British engineers to venture the application of similar procedures to new problems. In one of the most concise descriptions of such an application of Soil Mechanics known to Professor Legget, Mr. R. F. Dawson[2] had described soil tests, the application of test results to design, and actual and calculated settlements of a large memorial tower in Texas.

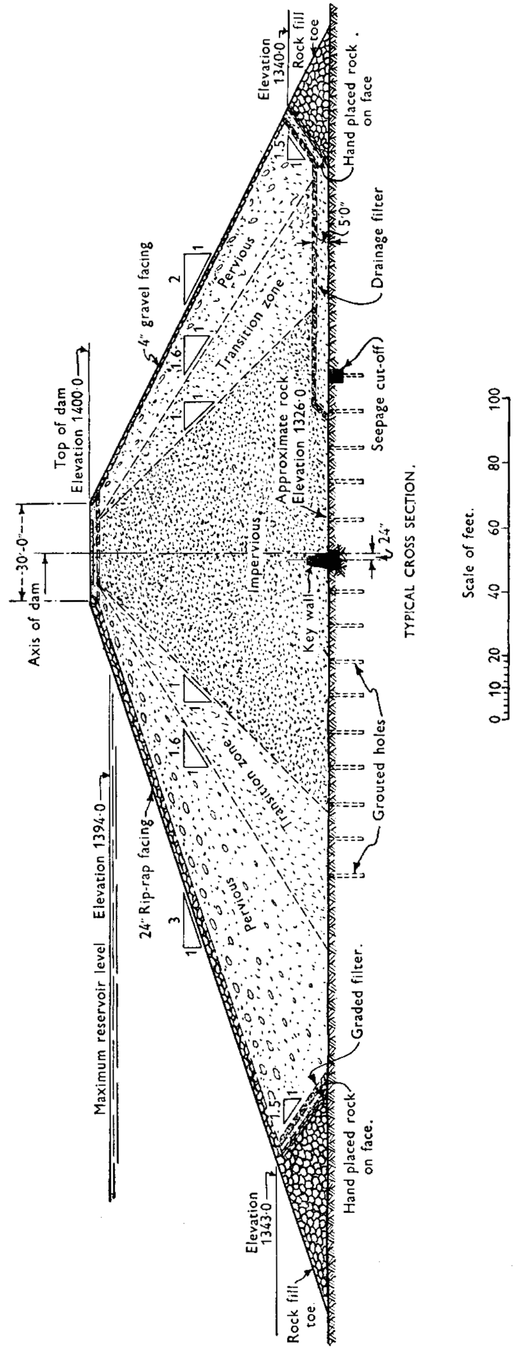
Mr. Markwick had referred briefly to the data now available on the compaction of soils, and had included the usual American statement about the pioneer work of Mr. R. R. Proctor. Professor Legget, whilst acknowledging the value of Mr. Proctor's great contribution to practical soil work, wished to point out that a part at least of his work had been anticipated by Mr. A. E. Kelso, Assoc. M. Inst. C.E., in a Paper[3] that had yet to receive the attention is deserved. The knowledge now rendered available through soil studies in regard to the correct placing of soils in embankments and the economical and efficient design of so-called earth dams, appeared to Professor Legget to form a major contribution of Soil Mechanics to the practice of civil engineering.

[1] O. L. Stokstad, " Soil Type as a factor in Highway Engineering ", Proc. Purdue Conference on Soil Mechanics and its Applications, p. 371. Lafayette, Indiana, July 1940.

[2] " Settlement Studies on San Jacinto Monument ", *Civil Engineering* (New York), vol. 8, p. 589, Sept. 1938.

[3] " The Construction of the Silvan Dam, Melbourne Water-supply ", Min. Proc. Inst. C.E., vol. 239, p. 403, 1936.

Fig. 1.



TYPICAL CROSS SECTION.

Possibly because of lack of a suitable example in Great Britain, modern earth dam design had not been dealt with in the Papers. *Fig. 1*, p. 510, *ante*, showed a cross-section of the Shand dam of the Grand River Conservation Commission, on the Grand river in south-western Ontario. The cross-section differed considerably from conventional British practice, there being no core-wall, and the section marked "impervious" being constructed of the local glacial till properly compacted at optimum moisture-content. A full account of the design and construction of the dam had been given [1], by two members of the staff of the consulting engineer, Dr. H. G. Acres, M. Inst. C.E., by whose permission *Fig. 1* was reproduced. Professor Legget had been associated with the soil tests, which were carried out at the University of Toronto.

The references cited had been given with the dual purpose of amplifying his remarks and of directing attention to some typical examples of the literature on modern soil studies. That was voluminous, but a recently published bibliography (of 350 items, selected from about 1,000) could serve as a guide to those who wished to pursue the subject further [2]. Despite the quantity of material already published, the Papers formed a notable addition to the literature, and Professor Legget hoped that they were but the precursors of many similar contributions to the "Journal."

Mr. D. Lloyd observed that on p. 74, *ante*, Mr. Markwick had given some data of flow in subsoil drainage in winter, the values being $\frac{5}{16}$ inch to $\frac{3}{8}$ inch per 24 hours, presumably immediately after a fall of rain. Some of the causative rainfall might have been added to the subsoil water at the place where the observations were made, for on a small area larger values of drainage had been recorded in England. In winter, the drainage formed a high proportion of the rainfall. According to Messrs. H. L. Penman and R. K. Schofield [3], the drainage recorded in the automatic recorders in the drain-gauge at the Rothamsted Experimental Station on 8–10 November, 1926, was 1·35 inch from a rainfall of 1·41 inch. Of this 1·09 inch was delivered in 24 hours from 1·22 inch of rain.

If 2 inches was regarded as a heavy fall likely to occur on any winter day, the drainage system at an important site like an aerodrome should be designed to accommodate a large proportion of it, or untimely waterlogging might occur.

As soil physicists had shown, there was another aspect of the characteristics of soil in reference to the passage of water, in addition to that mentioned on p. 74. In the zone of saturation the permeability of the material was largely related to the size of particles ; but in the zone of aeration, in which soil was usually situate, the passage of water was not related to

[1] "Soil Mechanics at the Shand Dam," by A. W. F. McQueen, and R. C. McCordie, *Engineering Journal*, vol. 23, p. 16, Montreal, April 1940.

[2] "Selected Bibliography of Soil Mechanics," Manual No. 18 of the American Society of Civil Engineers ($1.00), New York, 1940.

[3] H. L. Penman and R. K. Schofield, *J. Agric. Sci.*, 31, 74–109. 1941.

grain-size, but to the many factors applicable to colloidal aggregates. The low rate of seepage was the cause of difficulties in draining the surface, and any method of expediting the drainage that could be mentioned would add to the value of the Paper.

Mr. G. E. Scott observed that, having had some experience of landing-grounds under trying climatic conditions in Burma, with a rainfall ranging up to 250 inches per annum, and occasionally as much as 20 inches per day, he could confirm Mr. Markwick's remarks on p. 71, *ante*, that the deflexion in the ground increased as the machine slowed down. It was frequently found that the heavy commercial passenger planes—for example, the Douglas D.C.3's weighing 18–20 tons—would sink into the ground when taxi-ing, but never when landing, in spite of the excessive impact then occurring. The Author had stated that the case was analogous to that of a skater on thin ice, but that principle seemed to apply equally to all cases of impact, which appeared to be contrary to the accepted principle that the impact effect was inversely proportional to the length of span. That was, perhaps, a subject into which some research by mathematicians was required.

In Wartime Building Bulletin No. 9 a case of comparatively light runway surfacing was mentioned, which stood up very well indeed under trying conditions.

It would seem that for soil surveys borings were almost a *sine qua non*, but that was not always so, as there could be no dispute that for making the necessary analysis trial pits were preferable.. But for the ordinary work, for example, a small bridge, the cost of trial pits was considerable, almost amounting to the cost of the excavation of the foundations of the work itself, so that it might be necessary to postpone the soil examination until the work was ready to start.

An interesting case of that had occurred to Mr. Scott when an enthusiast for soil mechanics reported, as a result of borings, that the ground was sand, and proceeded to design the foundations of a bridge accordingly, but on the excavations being made it was found that the ground was actually soft rock—sandstone.

Mr. E. G. Walker considered that of the Papers which had been brought before The Institution during recent years on the subject of soil mechanics Mr. Cooling's was one of the most useful from the point of view of the practising engineer. He regretted, therefore, that limitations of space seemed to have induced greater condensation than was good for a full exposition. The five examples showed the range of problems that could be treated by a practical study of field conditions. The initial conditions of the problems and the conclusions derived from the studies had been given clearly, but more details of the steps by which the results were obtained were essential if full use was to be made of the work of the Building Research Station on the subject. The object of the Paper, as set out in the third paragraph on p. 38, *ante*, had been achieved in that the

Author had drawn attention to the sort of study which should be undertaken in examining sites for prospective foundations, so far as the procedure had been deduced from the successful diagnosis of the causes of failures. Mr. Walker's plaint was rather that it was necessary to develop more fully the details of procedure for such study.

The Author had drawn attention, on p. 43, *ante*, to the desirability of improvement in making and examining borings. The choice between test-pits and borings was determined in most cases by the depth to which examination had to be carried. For investigation to shallow depths test-pits normally would be preferable by reason of their convenience and the much better facilities for inspection which they afforded. In the large majority of cases a practical limit of depth for test-pits was soon reached, and below that boring was essential. There was no doubt that much boring that was made did not provide all the data which could be obtained from that method of exploration, and that, at rather higher expense, the taking of undisturbed samples on the lines described by the Author should be employed to a much greater extent.

The references in the Paper to indirect methods of investigation were not extensive. It was questionable how far they were of value for the detailed examination which was required for such problems as had been dealt with. For the general determination of the distribution of strata over an area there was every likelihood that geophysical methods would be employed more extensively in the future. The Author did not appear to have considered the accuracy of the sounding or penetration method to be of a very high order. It would be of interest to learn to what orders of depth it was likely to yield good results.

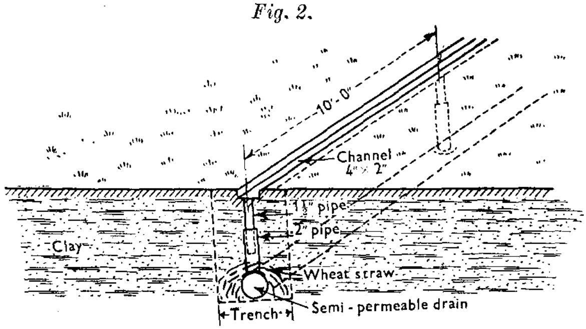
In the section dealing with the ultimate bearing capacity of footings on clay (p. 51, *ante*) no comparison had been given of the relative merits of the assumptions made by the different investigators whose results were summarized in the formulas giving bearing capacity as a multiple of shearing strength. If the work of Bell, now about 30 years old, were omitted, the dispersal of the numerical factors was within a workable range (5·14 to 6) and the average was more nearly $5\frac{1}{2}$, the factor given by Fellenius, than the value 5 suggested as a rough generality by the Author. In example I analysis by the method of Fellenius furnished an exact estimate of the load which caused failure. The result might be fortuitous or might arise from the greater correctness of the Fellenius analysis. As a number of theories had been evolved it would be well to have some recorded comparison of them so that their individual suitability for practical application might be assessed.

The significance of the "yield-load," referred to in connexion with the loading tests on small areas, was not clear. That load was said to be about three times the shearing stress, and so was a little more than half the ultimate bearing capacity. The ultimate capacity was defined by the Author as "the intensity of loading which will cause failure of the soil in shear." Was the "yield-point load" an intensity of loading at which deformation began to increase at some defined greater rate, or at which incipient failure of the soil occured, or had it some other significance ?

Mr. J. H. Walker observed that the statement of Hogentogler and Terzaghi, cited on p. 71, *ante*, that "the mean intensity of pressure on the ground beneath a flexible surfacing may attain eight times the mean pressure under a concrete surfacing", combined with Mr. Markwick's qualification : "Flexible surfacings are, however, less affected by settlements than are rigid slabs", substantiated the practice of many Government, county, municipal, and dock engineers, in the casting of "flexible concrete surfacings" for roads.

Such surfacings consisted of small slabs, preferably about 10 feet square, which, flexibly interlocked together, mutually assisted one another

Fig. 2.



to support wheel loads traversing the joints. Where the ground settled the slabs conformed to the settlement like links in a coat of mail.

Whereas settlements could sometimes be ascertained only by the use of a level and staff, at other times they might be obvious, as in the case of a 5-mile stretch of main road laid in 1932. Part of it, on bad ground, sank more than 2 feet, but, being a flexible concrete surfacing, the road remained in first-class condition with even joints and no cracks. When desired it could be reinstated to its original level, by pumping water and ashes under the slabs through holes jumped in the concrete.

Notwithstanding that flexible concrete surfacings in roads were subjected to maximum wheel loads of only 4 tons, they would seem to be the obvious and only solution for runways destined to carry wheel loads many times as great. To attempt to do so with rigid concrete surfacings, cast on bare ground and consisting of large slabs, with butt joints, filled perhaps with expansion-joint material, was futile for the reason that concrete shrank in setting.

The shrinkage of the base of a slab was restrained by friction with the ground, whilst the top was free to shrink. Therefore the area of the surface became less than that of the base. Consequently, a large slab—say 30 feet by 18 feet—warped up at the edges, out of contact with the ground, and cracked across the centre, both ways, through sheer inability to support the weight of its uplifted perimeter.

Originally the Air Ministry intended to make the runways of flexible concrete surfacings, but only a few were so constructed, because, owing to the vital necessity for speed, the contractors were allowed to cast slabs of large dimensions in hundreds of miles of new runways. Recently the relative speeds of the two systems were compared on an aerodrome, when it was found that the second runway, of 80,000 square yards of flexible concrete surfacing, was quicker and cheaper to construct than the runway made of inefficient large slabs, unsuited even for the comparatively light wheel loads on roads [1].

Mr. Lyddon's concluding remark in the discussion, that "One still came back to that unfortunate material clay" (p. 158, *ante*) was much to the point.

The usual practice was to lay drain-pipes in rubble-filled trenches, which in clay soils merely took run-off water, as did ditches and mole drains. None of them extracted water from the clay sub-soil.

One way of draining a clay soil, originated about 1650, was to lay faggots of hazel, willow, thorn, etc., in the bottom of a trench refilled with the excavated clay, well wetted and punned. A modern method used for draining derelict clay lands was to lay in similarly clay-filled trenches semi-permeable pipes, jacketed with wheat straw. Those pipes slowly but continuously sucked the water out of the sub-soil, which, thus de-watered, could re-absorb up to 25 inches of rain-water per annum, 15 inches of which would evaporate or be transpired by plant life.

With heavier rainfalls, provision had to be made to remove most of the precipitation as run-off water, leaving the semi-permeable drains to suck about 10 to 15 inches per annum. For example, in a grass runway on a slope, where the rainfall was 80 inches per annum, the semi-permeable drains should be located on the contour-lines. Vertically above such a drain was a channel, from which, at 10-foot intervals, pipes descended into the semi-permeable drain below (*Fig. 2*, p. 514, *ante*). The vertical pipes were suitably telescopic, and at the top ranged from $1\frac{1}{2}$-inch diameter to the diameter of a hole in a golf putting-green.

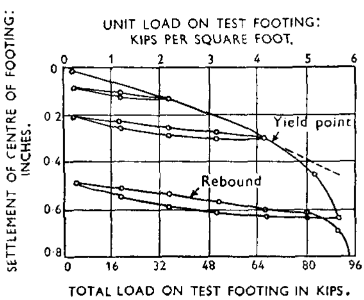
Such pipes, at similar distances, had been used for 20 years by the Port of London Authority, to drain the centre channel in the level inverted concrete roads in the docks, thereby dispensing with unsightly longitudinal graded channels.

Mr. Cooling, in reply, said he was glad that Mr. E. G. Walker, as a practising engineer, had found the Paper useful. He understood Mr.

[1] J. H. Walker, "Concrete Runways at Aerodromes", *Concrete and Constructional Engineering*, vol. 37, p. 38 (Jan. 1942).

Walker's plea for more details of the procedure adopted in studying soil problems, but as indicated in the second paragraph on p. 50, the details varied with different problems and could really be discussed only in relation to specific practical cases. He thought, however, that the point had been met to a certain extent by subsequent Papers which had been, or would be, published in the Journal of The Institution. For instance, the details asked for in relation to Example I (see footnote 1, p. 53) had been given in a Paper by Mr. A. W. Skempton, Assoc. M. Inst. C.E.[1]. In that Paper the various methods used for calculating bearing capacity were critically examined in regard to their applicability in the particular practical example described. Details relating to Example III would be published in a forthcoming Paper by the Author and Mr. H. Q.

Fig. 3.



Golder, Assoc. M. Inst. C.E., entitled " The Analysis of the Failure of an Earth Dam during Construction." [2]

Mr. Cooling did not understand Mr. Walker's reference to the accuracy of sounding or penetration methods, since he could see no reason why the penetration resistance could not be measured accurately at any depth likely to be required. The point which he had tried to make was that, in his opinion, measurements of penetration resistance could not by themselves be expected to give a basis for the design of structures. When interpreted in the light of knowledge of the soil strata obtained from geological records or from borings they could provide valuable information. A particular application in conjunction with boreholes was in obtaining rapidly a more detailed picture of the variation in thickness of soil strata over an extensive site.

As to the term " yield-point " load, he agreed that its meaning was not very clear from the text of the Paper, but it had been quoted from the Paper by Mr. T. R. Dames [3] to which reference had been made. To indicate its significance a typical load settlement curve given in Mr. Dames'

[1] " An investigation of the Bearing Capacity of a Soft Clay Soil", Journal Inst. C.E., vol. 18 (1941–42), p. 307 (June 1942).
[2] To be published in the November, 1942, Journal.
[3] See footnote (1), p. 55, *ante*.

Paper was reproduced in *Fig. 3*, p. 516, *ante*. Load-settlement curves were normally smooth throughout, with no evidence of a definite yield point as was found, for instance, in tests on steel specimens. The choice of a "yield-point" was therefore a matter of personal judgement in assessing the load at which the deflexion began to increase unduly. From the practical point of view, however, the range of choice was not wide. Mr. Dames had carried out a large number of tests and had found by an analysis of the results that the most probable ratio between the "yield-point" load and the corresponding shear strength was 3·25, in comparison with the theoretical value of π at which plastic yield of the soil commenced.

Mr. Cooling welcomed Professor Legget's contribution and wished to thank him for his kind references to the work of the Building Research Station. In reply he would like to take the opportunity of further emphasizing two important points which had been touched upon already. The first concerned the importance of the application of geology to the study of civil engineering problems, a subject which had been treated admirably in Professor Legget's book on "Geology and Engineering." [1] Mr. Cooling agreed that geology and soil mechanics were complementary studies and should be linked together wherever possible. The second point related to the part played by mathematics in the study of soil problems. In soil mechanics laboratory tests were employed to obtain quantitative measurements of soil characteristics which could be used in the analysis of engineering problems for purposes of design. In common with other design problems, for example, structural design, mathematical methods were inevitably involved, and as Professor Legget had stated, progress in soil mechanics had been closely linked with the application of mathematical methods to the study of soil problems and soil properties. However, since Mr. Cooling's Paper had been concerned with site exploration he had not thought it necessary to introduce details of that aspect of the subject. Finally, although most of the examples quoted in the Paper had been concerned with failures, Mr. Cooling was pleased to be able to reassure Professor Legget of the increasing importance which was being attached by engineers in Great Britain to the application of soil mechanics methods to the consideration of soil problems at the design stage.

Mr. Markwick, in reply, observed that he wished first to refer again to the question of impact of aeroplane wheels. He had cited, on p. 69, an American report that impact loads from landing aeroplanes might approach four times the static wheel load. He now believed that that estimate was excessive, since when a plane first landed, much of the load was still air-borne. The relative softness of the tires and the flexibility of the landing gear also limited the impact loads which could arise from surface irregularities and from deformation of the foundation. The consensus of American opinion now seemed to be that impact loads would not

[1] "Geology and Engineering", McGraw Hill Publishing Co., 1939.

exceed 25–50 per cent. of the total wheel load, and that value seemed to him to be much more likely. Experience had shown that, owing to vibration, aprons and standings where planes warmed up were more heavily stressed than were runways or perimeter tracks, and he felt that the importance of impact on runways had possibly been over-emphasized.

Mr. Scott had suggested that impact conditions when an aeroplane landed were analogous to impact conditions on a bridge. Impact on a bridge, however, depended on its elastic deflexion and was especially important in the case of railways, especially when heavy hammer-blows were applied by the locomotive. Mr. Markwick did not feel that the elastic deformation of the soil or runway could seriously affect the applied wheel loads, since quite appreciable surface irregularities could be tolerated on a grass field without landing becoming unpleasant.

He had been pleased to note that Mr. Scott's observations of the behaviour of aeroplanes on soft landing-grounds confirmed the remarks made on p. 71, *ante*. That behaviour was easier to understand if impact loads were relatively unimportant. He had noted Mr. Golder's remarks, but he was still not entirely happy about the evidence cited in Mr. Golder's Paper [1], for it did not appear that any direct comparison had been made between a circular area and a long rectangular strip of equal width. He felt that a more comprehensive investigation was desirable, especially as there was the possibility that non-uniform distribution of pressure on footings (if it occurred) might invalidate calculations which assumed a uniform pressure-distribution. However, assuming that a circle and a square gave the same ultimate pressure, the formulas given in the Appendix were apparently in agreement with experiment, for Mr. Golder had stated that *Figs. 13* (p. 83, *ante*), agreed with Prandtl's formula for a strip footing [2], and that formula agreed with Mr. Golder's experiments [3] on square and rectangular footings.

The Appendix had been included in the Paper, not as an exact analysis, but primarily to illustrate how the various factors contributed to the bearing capacity of soil under an aeroplane tire, and the main conclusion (*Fig. 14*, p. 84, *ante*) was the striking effect on stability of internal friction. Mr. Scott had cited from Wartime Building Bulletin No. 9 (p. 9) an interesting case in point, where runways composed of 6–9 inches of 2-inch crushed brick were laid on a subgrade composed of 18 inches of sandy clay on sand, and carried wheel loads of up to 20,000 lb. Thus a base possessing high internal friction had been laid on a subsoil possessing frictional qualities.

Mr. Markwick would also like to draw attention to the American practice of thoroughly compacting the subgrade beneath flexible-type bases. That practice seemed entirely logical in view of the fact that the tires of large aeroplanes stressed the soil to appreciable depths and dense compaction obviously increased the stability of the subgrade.

[1] See ref. (1), p. 504, *ante*. [2] P. 173, *ante*. [3] See ref. (1), p. 173, *ante*.

In referring to "flexible concrete" surfacings, Mr. J. H. Walker had used the term "flexible" in a rather different sense from that defined in the Paper (p. 71, *ante*) in which "flexible bases" referred to types such as hardcore which lacked flexural rigidity. Mr. Walker's type of surfacing thus involved questions of concrete slab design which were rather outside the scope of the Paper.

Mr. Markwick agreed with Dr. Knight that both the mineralogical nature of the clay fraction and the quantity of "clay" present (as determined by the mechanical analysis) affected the values of the liquid and plastic limits of a soil. When the liquid and plastic limits were plotted against the "clay"-content, the points for British soils [1] were fairly widely scattered, although they showed a general linear tendency. When, however, the investigation was restricted to clays of three definite types—London clay, Wealden clay, and clays from the lower Yorkshire Ouse—the points lay along three separate pairs of lines. That suggested a mineralogical similarity between clays of similar origin, and that under those conditions the liquid and plastic limits were a linear function of the "clay"-content of the soil. In all the British soils so far tested, the "clay"-content had had an appreciable, though varied, influence upon the plasticity index of the soil.

Mr. Lloyd had suggested a rainfall of 2 inches per 24 hours as the basis of design for aerodrome drainage systems. Although Mr. Markwick had no definite figures, that did not seem unreasonable for a continuous downpour lasting, say, 24 hours. In a combined stormwater and subsoil water drainage system, however, the stormwater discharge from paved areas probably governed the sizes of drains, and since the time of concentration for the paved area on aerodromes was in general less than about an hour (p. 73), it was necessary to consider the higher intensities of rainfall which occurred over short periods. The Meteorological Office had recently furnished the Road Research Laboratory with a chart * (*Fig. 4*, p. 520, *post*), which gave the relation between the duration of rainfall and the maximum total rainfall likely to occur once per year and once in various periods up to 160 years. That chart was similar to those used in the United States [2], but British intentities were lower than the American, and in the case of the Gulf Coast area of South-Eastern America were only about one-third of the corresponding American figures. For design purposes it had been recommended [3] that the intensity of rainfall adopted should not exceed the 10-year figure.

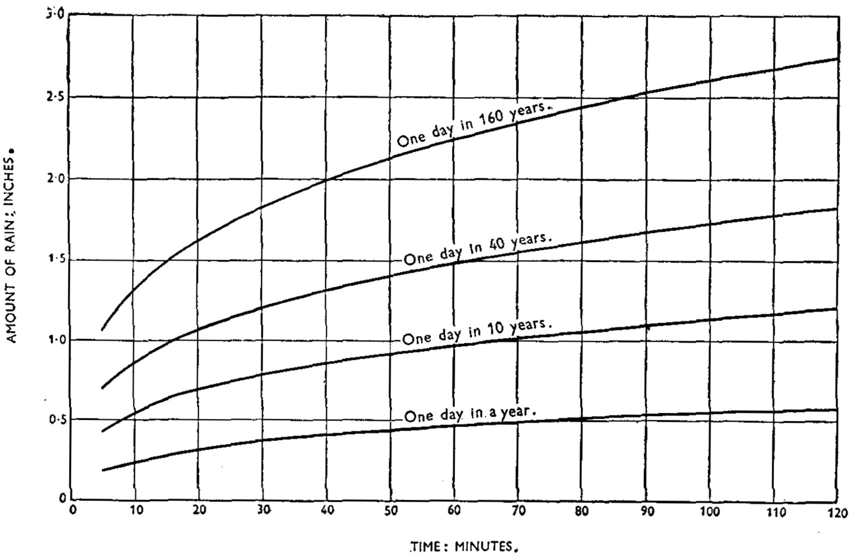
Mr. Markwick agreed with Mr. Lloyd that in winter the run-off ultimately formed a high percentage of the incident rainfall, but he did not

[1] See Ref. (3), p. 86.
* Reproduced from *British Rainfall*, 1935, p. 275, by permission of the Controller of H.M. Stationery Office. Crown copyright reserved.
[2] "Handbook of Culvert and Drainage Practice." London, 1938, p. 173. Armco, Ltd..
[3] See ref. (7), p. 86.

think that there was necessarily any discrepancy between the maximum precipitation and the maximum rate of outflow of subsoil water mentioned in the Paper (5/16 inch to 3/8 inch) because of the important effects of storage in the ground and in the drainage system. Over a large catchment such as the Fens it had been usual to take a run-off of $\frac{1}{4}$ inch per 24 hours.[1] Whilst that figure would be rather greater for small areas, it had not been possible, under wartime conditions, to obtain any experimental data in Great Britain.

Several correspondents had referred to the drainage of clay soils, and Mr. Lloyd had mentioned the difficulty which attended the passage of water through the pores of unsaturated clay. On that point Mr. Markwick would refer to a recent summary of the physics of soil moisture by

Fig. 4.



Dr. Keen [2], where the matter was explained in quite a simple manner. It arose because of the cellular structure of the pore-space, and the result was that soil moisture in the pores of cohesive soils tended to be static and moved only with difficulty. It was for that reason (as pointed out on p. 157, *ante*) that cracks and fissures were of particular importance in providing channels in clay soils for the passage of water to the drains. Experimental evidence had been cited [3] to show that water soaked rapidly

[1] Adkin, B. W., "Land Drainage in Great Britain." London, 1933, p. 177. Estates Gazette, Ltd.

[2] Keen, B. A., "Soil Physics: Theory and Practice." J. Royal Soc. Arts, 1942, **90** (4618), 552–7.

[3] Adkin, B. W., "Land Drainage in Great Britain" London, 1933, p. 248. Estates Gazette, Ltd.

through the soil in the drainage trenches where it had been disturbed, but only slowly through undisturbed soil. In the case of mole drains on heavy soil the water tended to run down to the drains through the slots made by the mole plough rather than by percolation. That suggested that on heavy soils it was important not to space the drains too far apart, and that on such soils there was little point in placing the drains at depths to which the water could not readily penetrate.

For the reasons outlined above, Mr. Markwick had found it difficult to visualize how Mr. J. H. Walker's drains sucked water out of the clay, but the design illustrated seemed well adapted to deal with water before it could enter the pores of the clay. The well-wetted clay back-fill would certainly open up into cracks in the summer, especially as a wide trench was used with straw beneath, whilst the location of drains along the contours which Mr. Walker mentioned would also assist in the disposal of surface water. Mr. Markwick understood that tests were in progress on Mr. Walker's system of drainage; the results would be of considerable interest.

Professor Legget, whose kind remarks were appreciated, had pointed out that the engineering study of soils was intimately related to geology as well as to agricultural studies of soil, and there was, of course, a basic unity underlying all three. It was, however, the behaviour of the soil which was of primary interest to engineers, and the subject was considerably simplified if attention were centred on the mechanical and other properties of soils irrespective of their mineralogical nature and origins. The Author did not think that that unduly simplified the investigation. It was true that, in Michigan, soil investigations for roads had been based very largely upon the agricultural soil maps, but the Author believed that in Michigan there was a basic pattern in the various successions of soil deposits which extended over practically the whole State. These were special conditions that did not occur in Britain, where soils were very varied and the basic pattern of the successions more complex and on a smaller scale. On the other hand, agricultural soil studies were particularly useful in soil drainage problems.

Lastly, Mr. Markwick would like to refer again to the question of compaction of earthworks. During a recent visit to the United States he had been greatly impressed at the extent to which controlled compaction of embankments was becoming standard practice in America. He had been told that the majority of the forty-eight States made use of some form of field control in constructing road embankments, whilst on earth dams it was almost universal. Although at first contractors had felt that technical control might hinder progress, they soon found from experience that controlled compaction worked to their advantage, since on densely compacted fills plant could be employed in weather when it would otherwise have been unusable.