ACKNOWLEDGEMENT.

The Author wishes to express his thanks to Mr. R. Glossop for help in the preparation of the Paper.

Discussion.

The Author introduced the Paper with a brief summary of its contents.

Sir Jonathan Davidson considered that until a few years ago engineers in Great Britain who had had to construct embankments had not troubled unduly about scientific tests of the shear strength, the moisture-content, and the liquid limit of the materials to be used. They knew that with certain materials their banks would stand up, and when they found materials which by eye and by touch were similar they did not hesitate to use them. Even to-day some old practical men determined the quantity of sand or grit in a clay by biting a piece of it, and a stout ash walking-stick was very useful in testing the consolidation of a bank. Some of the most eminent soil experts placed considerable reliance on the feel of a sample of clay when rubbed between the thumb and finger.

If he might offer a word of criticism, he thought that the Author had interpreted his subject in a rather narrow sense. The title was general in scope, but, for instance, no mention had been made of the construction of railway embankments, which were very often constructed by end tipping, the material being brought out from an adjoining cutting at the top level of the bank. The Paper, as it stood, however, offered a wide field for discussion.

The Author had wisely drawn attention, in the case of non-cohesive material, such as fine sand, which had a low permeability, to the danger of loose packing; it was essential that such material should be spread in thin layers and thoroughly consolidated by rolling. In the United States of America many high embankments for reservoir purposes had been built entirely of non-cohesive materials without any watertight wall. In such cases very careful proportioning and mixing of the materials, careful control of the moisture-content, and thorough consolidation were essential. Sheep's-foot rollers were used, usually arranged in threes in arrow-head formation, towed by a tractor, and it was perhaps interesting to recall the origin of the sheep's-foot roller. A century and a half ago it was common practice in Scotland to arrange hurdles on each side of a bank and to drive a flock of sheep backward and forward along its length in order to consolidate it.

The Author, in dealing with cohesive materials, had recommended that no account should be taken of the increase in strength due to load. That was a safe rule in most cases, but sometimes the bank might have beneath it a thin layer of clay with ballast or some other permeable strata above and below into which the water could readily escape; and in such cases a considerable increase in the strength of the clay might occur owing to the excess moisture being squeezed out. Experiment had shown that in one case, where a 2-foot layer of a very soft yellow clay existed under a bank which was erected to a height of 20 feet—equivalent to just over 1 ton per square foot of load—the shear strength increased during twelve months from 2·78 lb. per square inch to 4·34 lb. per square inch. Sir Jonathan thought that in such a case an engineer was quite entitled to take advantage of that increase in strength, which would make a very perceptible difference in the factor of safety to which he was working.

He agreed that sampling was of primary importance; but boring was a very slow process and in the case of a long bank with a wide base the time-factor imposed a limitation upon the number of bore-holes that could be put down. He always liked to have also a fair proportion of trial-pits; it was much more satisfactory to see the material actually growing than a sample that had been pulled up from below the surface of the ground.

In sampling care should be taken in two respects. Firstly, for cohesive materials, such as clay, the sample must be absolutely fresh. A dry sample of clay was very misleading: apparently it might contain a high proportion of sand and grit, but no evidence was provided of its moisture-content, which made all the difference between a stable and an unstable bank. Secondly, for cohesive materials such as ballast, particularly when the water-table was only a few feet below the surface, samples were very misleading because no sand was obtained with them, and the sample-boxes might be labelled "ballast" or "gravel" when 60 or 70 per cent. of sand might be included with the ballast in the ground.

In Great Britain the majority of banks that had been successfully constructed had had a factor of safety lower than 1·5—quite unknown to those responsible for the construction.

With regard to the methods of construction, the essential factor was that the bank should be brought up evenly over as great a length as possible; and for that reason the old method of using locomotives and tipping-wagons on rails had an advantage over more modern machinery, because with tractor-scrapers and tracklaying tipping-wagons a great temptation existed to bring a bank up in short sections, in order to shorten the length of haul.

When the material of which the bank was to be formed was found in layers, such as ballast above, then clay, and then ballast again, it was very difficult to produce a homogeneous bank with the use of either tractor-scrapers or grader-elevators, both of which skimmed off a thin horizontal slice; and it was preferable to use machines which excavated vertically instead of horizontally, such as the dragline or mechanical shovel, as a much better mixture was obtained.

The Author had stated that overhead cableways could deposit material evenly over a considerable area of bank; but Sir Jonathan's experience was that they deposited it in great heaps on the bank because the "stopper" on the cableway which tipped the bucket could not be moved readily.

The practice of strengthening clay by the addition of ballast was known to engineers in the middle of the last century. It was quite common practice in foundation works under retaining walls, where extra bearing strength was required, to use what the old engineers called "gravel puddle", which was simply a mixture of broken stone or ballast in clay; in other words, instead of using cement and sand for concrete, they used clay.

Mr. A. W. Skempton *said that the construction of embankments was* a practical job, but certain principles had to be understood if it was to be carried through well and economically. The great value of the Paper lay in the fact that it brought out those principles and related them to the practical aspects of the problem. One of the most important of those principles was the need for a high degree of compaction in the banking material. Just as in building a concrete dam only the best quality of concrete obtainable would be used, and very frequent control tests would be applied as the concrete was being placed, so in building an earth dam or an important embankment the soil should be well compacted and tested frequently during the process of construction, because only by compaction could the best use be made of the material available locally.

A high degree of compaction was very important for clay soils, because, if air voids were left, rain water would penetrate into them and would soften the clay by increasing its water-content. A comparatively small increase in water-content could cause a rather alarming decrease in shear strength, especially with the low-liquid-limit clay to which the Author had referred. That such softening might be very important in some cases was illustrated by the following example. A large earth dam was being built of boulder clay, and before it was completed serious signs of deformation became evident. Trial pits were opened up, and it was found that the material that had been placed during the earlier stages of construction was remarkably soft; in fact, it was so soft that the machinery which had been used in depositing the clay could not have run over it in the condition in which it was found in the trial pits. The only explanation was that the clay had softened subsequently, and some tests were therefore made to determine its characteristics. In the borrow pits the material was firm boulder clay with a liquid limit of 43 and a water-content of 16·5, whilst its compression strength was 35 lb. per square inch. A sample tested in the laboratory showed that the maximum dry density obtained by the Proctor test was 116 lb. per cubic foot. The criterion adopted by the United States Bureau of Reclamation was that the density of the soil as placed in the bank should be not less than 98 per cent. of the Proctor maximum density[1], and Mr. Skempton believed that that was readily attainable with the modern equipment used in America. Had the clay in the case cited above been placed in accordance with that criterion, the water-content would have been increased from 16·5 in the borrow pits to 18·5 in the bank, which would have left the clay with a compression strength of 20 lb. per square inch. Actually the clay found in the trial pits had a water-content of 23 and a compression strength of only 5 lb. per square inch—that was, about a quarter of what it might have had with a really good compaction. A simple calculation would show that, to produce softening to that degree, the clay had been originally laid down with a density of not more than 90 per cent. of the Proctor maximum. The bank was to have been a high one, and the degree of compaction should have been correspondingly good.

The sequence of events could be visualized as follows. With the light equipment used, the material included about 12 per cent. by volume of air voids, which later became filled with rain water; but the softening process was slow, and without much effect, probably, for a few weeks. Therefore when the equipment returned to deposit the next layer the clay was still in a reasonable condition—especially if the surface had been dried by wind or sun during the interval. Nevertheless the clay beneath the surface still included voids full of water, and after a few weeks it might have become quite soft; but by that time several feet of new material had been placed, which was still firm and would support the equipment. Thus the bank seemed satisfactory, although the material a few feet below the working surface was far too soft for stability. As a result remedial measures had to be put in hand.

That experience demonstrated the value of a high degree of compaction, and probably it could best be effected by the use of heavy rolling equipment. From the theoretical point of view, heavy rolling had many advantages, and he would like to ask whether the Author knew of any practical objection to the use of heavy equipment on the construction of important banks and earth dams.

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[1] F. F. Smith, "Consolidation and Pressure Observations in Existing Earth Dams and Their Influence on Future Placement Control", Highway Conference, University of Colorado, 1941, p. 65.

Mr. H. Q. Golder said that on reading the Paper he had been reminded of the old trick question: "Is a thing lost if you know where it is?" He would like to ask: "Can a thing be called treacherous if it does what you expect?" If the measured strength of a clay was, for instance, 2 lb. per square inch and it failed when the stresses were equal to 2 lb. per square inch, it was hardly fair to call that clay treacherous. His view was that to call a soil treacherous was not so much a reflexion on the soil as a reflexion on one's own understanding of its properties. What was required was not an increase in the loyalty of soils, but an increase of understanding of their properties by engineers.

The one great merit of earth banks was that they could be built of the local material, and it was probably untrue to say that such and such a material was unsuitable for earth bank building. Some materials might be more suitable than others, but the design had to be adapted to the material which was available in the particular neighbourhood.

The site and height of a bank were normally fixed by considerations over which the designing engineer had no control, and the first thing to be determined was the strength of the foundation material and that of the material in the borrow pits in the condition in which it would be likely to exist when placed in the bank with adequate construction methods, due allowance being made for possible softening caused by rain or flooding. He agreed with Mr. Skempton that compaction was necessary, but he thought that at any one time the engineer should specify only the degree of compaction which a contractor could effect with the most efficient construction equipment then in general use. There was no point in specifying extraordinary degrees of compaction which most contractors would be unable to produce. Having determined the strength of the material, the engineer could then design a cross-section to show the necessary conditions. The circular method of analysis would be found useful, but simpler methods of analysis should not be despised; for example, methods based on straight lines and wedges would be found useful. Every possible way in which the bank could fail should be considered, and the factor of safety decided upon should provide against all possible means of failure. Very small differences in the values of factors of safety should not be regarded. All the methods used were approximate, and anything closer than 10 per cent. should not be looked for; for example, 1·4 was a lower factor of safety than 1·5, but a value of 1·45 was certainly too close for the difference to be considered.

The cross-section having been obtained, the economics of the design had to be considered. It might be that the section obtained was quite uneconomic, and various methods might be adopted to improve it. The Author had mentioned most of those methods, such as forming berms or, in cases where time was not important, allowing some consolidation of the earth underground to take place. It might still appear, however, that the earth bank was not an economic proposition; and if it were found that by the use of the methods suggested and the employment of every artifice an economic section could not be produced, it would become necessary to consider fundamental matters, such as a change of site, an alteration in height, or the use of either concrete or steel, depending upon the purpose for which the bank was required.

Mr. R. Glossop observed that the Paper emphasized the importance of a thorough sub-surface exploration for purposes of design. He considered that the responsibility for obtaining and publishing such information should be laid directly upon those responsible for designing the bank. The practice, sometimes met with, of shifting the responsibility for determining the nature of the ground to the contractor, when tendering—the engineer accepting no responsibility for the results of boring—was obviously indefensible, *for unless such information was comprehensive and trust*worthy, the design itself could not have been made in a proper manner. Apart from questions of design, it was possible, from such information, to decide upon the best type of plant for excavation and bank building, with certainty, and to draw up a programme for the work with a reasonable prospect of its being adhered to. Not only would much time and money be wasted if a change-over of plant were found necessary after work had started, but also conditions on the site might have been rendered very inconvenient to the efficient working of the machines finally decided upon.

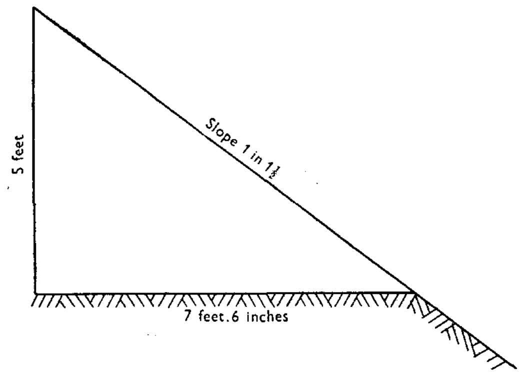
In mechanized muck-shifting, as much as in mechanized warfare, detailed preliminary staff work was the secret of success. In planning the execution of large-scale works, not only had the type of soil and the type of plant to be considered, but also climate and weather conditions; configuration of the site; drainage; access; transport; and the location and equipment of repair-shops.

The last-mentioned item was very important, for as every action was balanced by an equal and opposite reaction, the high output of modern heavy excavating plant could be obtained only as the result of heavy wear and tear on the machines, and a first-rate maintenance organization was essential to economy.

Mr. A. C. Whiffin, referring to the Proctor maximum density, said that in the United States the soil was normally fairly dry, and it was therefore easy to add water to bring it to the optimum value; but in Great Britain the soil was usually much too wet and one had to be content with working lower down the Proctor curve. He had carried out some tests on embankments, and had found that usually the density was much below the value on the Proctor curve—the average ranging from 85 to 93 per cent.—which meant that settlement would occur and trouble would arise through water getting into the soil. Measurements had been made of the settlements on various sites and showed that if there was a differential settlement of $\frac{3}{8}$ inch in 25 feet the concrete surface was uncracked, but with a settlement of the order of 1 inch—which after all was not very much—the concrete began to crack and, between 1 inch and 4 inches it became very bad. Moreover, where a tunnel passed through an embankment the settlements at the approaches were greater than the settlements immediately above the tunnel. That meant that the concrete slabs had cracked because of the differential settlement.

In Great Britain the practice was to put down 3-foot layers or 6-foot layers, just tipping the material out and running the lorries over it, and hoping for the best, whereas in the United States the practice was to put 7-inch, 8-inch, or 9-inch layers and compact each layer thoroughly, using pneumatic-tired and sheep's-foot rollers if necessary. He thought that much more attention should be devoted to the problem in Great Britain, where banks were designed properly but no trouble was taken to build them properly.

Fig. 1.



Mr. H. G. Lloyd said that on a job of which he had been in charge he had learned from a navvy a very useful method of ascertaining the slope of a bank. The method (*Fig. 1*), depended upon knowing the height of one's eye above ground-level and making a number of paces of a certain length. For instance, if the height of the eye was 5 feet above ground-level and the number of paces, each 3 feet in length, was 2½, the slope of the embankment as seen from the top was 1 in 1½.

He had found that method very useful when supervising embankments some miles in length, and he thought that many younger engineers might be very glad to know of it.

Mr. A. H. Toms said that he wished to make one comment on Mr. Golder's remark with regard to suiting the design to the material. That was, of course, the logical process where the space available for the construction of a bank was ample and the use of the local material was economic. In the case of railway projects it appeared that in some instances the cost of purchasing land and property had restricted the width available for the construction of both banks and cuttings and had consequently determined the side slopes which were adopted. Some bank slips had occurred as a combined result of such enforced limitations and the use of local materials.

Some banks and cuttings which had remained stable for a long period after construction had given trouble suddenly owing to gradual absorption of water and swelling of the clay.

In 1940 Mr. George Ellson, M. Inst. C.E.[1], had described slips which had been experienced on cuttings on the Southern Railway, driven through stiff fissured clays having a very high shear strength in the unfissured portions. Those cuttings, after standing stable for a period of many years, had undergone a gradual disintegration due to the swelling of the clay on account of the penetration of water into the fissures, and the shear strength on the slip surface was found to be only a small fraction of the measured shear strength of the unfissured material.

Reference had been made to compaction in relation to a moisture-content of some definite proportion of the Proctor limit, which was an experimental result. Was any evidence yet available as to whether if a bank were consolidated with a sheep's-foot roller, say, 90 per cent. of the Proctor value, that condition would be stable and the bank would not ultimately soften owing to the gradual penetration of rain? He was thinking in terms of the weather conditions in Great Britain.

In certain types of clay around London the outcrop was rather loamy, and slips were being experienced which did not settle down until the overall angle was of the order of 10 degrees, which meant a very low shear strength on the slip surface. Had any experiments been made in treating the surfaces of banks and cuttings in order to render them more impervious; and, if so, had any satisfactory solution been arrived at in regard to providing some surface of that nature, to shed water off the bank and prevent it getting in, which was sufficiently resistant to frost heaving?

In the event of side slips on railway banks the first consideration was to re-establish traffic on the line, and the quickest method was to load ashes on the top of the slip and drive the bank out, if sufficient space were available, until it settled down to a flatter slope. The original surface of the top at the depressed level inclined inward towards the middle of the bank, and therefore if the slip went, say, half-way through the formation, a depression containing ashes was left in which water collected. In several instances, after a bank had remained stable in that condition for several years, the slip had extended owing to the softening action of the water which had accumulated in the ashes. In such cases it appeared to be important to drain the depression in order to eliminate any accumulation of water.

Mr. R. Glossop observed that fissured clays presented a very difficult problem in the case of cuttings. He understood that in Germany, shortly

[1] Journal Inst. C.E., vol. 14 (1939–40), p. 429 (Oct. 1940).

before the war, cement grout was used to seal the fissures on deep cuttings in a canal passing through stiff fissured clays. He did not know how far that had been successful, but it was possible that it might provide a simple and effective solution of the problem of making deep cuttings through stiff fissured clays.

Mr. E. E. H. Bate said there was one point with which he had expected the Author would deal a little more fully, namely, the degree of testing the compaction in building an embankment. In the case mentioned by Mr. Skempton, the clay apparently had softened in the bank after deposition. He thought he was correct in saying that, in that particular case, if the conditions which were found had been general the bank would not have stood at all, but would have failed completely: only because those conditions were purely local was the failure merely partial. Therefore it was obviously very important to know how near one should go in taking the samples of compaction. Information regarding the compaction which was obtained on the bank to which Mr. Skempton had referred, elsewhere than the positions where the soft material was found, would be of interest.

Mr. A. W. Skempton observed that Mr. Proctor, who started the study of the theory and testing of compaction, had recommended in 1933 [1] that a field density test should be carried out in every thousand yards of material placed in a bank. He did not know whether the same recommendation was made now.

In certain other parts of the dam to which he had referred the clay was well compacted and approached much nearer to the criterion laid down by the U.S. Bureau of Reclamation, namely, 98 per cent. of the Proctor maximum; but he thought that in those cases the compaction had been done with rather heavier machinery at a later stage. When heavier machinery was put on to the same clay a rather better state of affairs resulted.

Mr. G. E. Scott observed that in road construction on hillsides, one cut and filled from the cutting immediately. Fortunately that problem did not often arise, but when it did arise it was rather difficult. Unless considerable care was taken it was not uncommon, when the weather became at all wet, for the filling part of the embankment to slide down the hill.

Could the Author give any idea of the maximum and minimum heights of embankments that should be ordinarily used. Mr. Scott believed that, even under the most favourable conditions, about 50 feet was considered to be the maximum, whilst the minimum was open to discussion.

Mr. W. J. Sinclair considered that not only the physical conditions of the soil in any embankment should be considered, but also the natural

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[1] R. R. Proctor, *Engng. News-Rec.*, vol. 111, pp. 245, 286, 348, 372 (1933); *Engng. Abstracts* 58, No. 73 (Jan. 1934).

contents of that soil. In the case of a cut and fill job, the top soil was deposited in the bottom of the cutting, and by the ordinary laws of nature in certain depths of that soil certain microbes and insects lived. If they were placed below the depth of their usual environment their mode of living might be considerably changed, with a consequent alteration of the condition of the soil. For example, in an embankment all the insects were put there in their natural condition, but as the bank grew they were not working on the soil under natural conditions, and they endeavoured to return to the surface. Possibly, therefore, something might be happening in that soil from a natural point of view, which was changing its condition as time passed.

The Chairman observed that Mr. Scott had mentioned a fact which some members knew only too well, namely, that in road construction in particular one had to balance one's cut and fill, so that the choice of material for the embankment was very limited, if it existed at all.

In his own experience, a very marked improvement in the consolidation of embankments had resulted from the use of heavy plant, provided that the embankment was properly constructed under proper supervision, was not brought up in too deep layers, and that they were levelled off properly in the longest practicable lengths.

He had been interested in Sir Jonathan Davidson's explanation of the origin of the sheep's-foot roller. He had heard of banks being compacted on the west coast of Africa by the feet of natives in the same way as people trampled on the grapes in the wine-presses in days gone by.

The Author had mentioned the need of constructing temporary surfaces on roads on embankments. That might not be the case if the embankment were properly constructed under proper supervision, except perhaps in the near neighbourhood of bridges (where naturally little, if any, settlement would be expected), and perhaps of culverts the height of which bore any serious relation to the height of the embankment.

The Author, in reply, remarked that a good deal had been said about cut and fill and end-tipping. The great point in connexion with end-tipping was that if tbe material was not compacted settlements would inevitably occur. Part of the trouble with railway-banks that had subsequently slipped was no doubt that they were not properly compacted, that the density of the material was low, and that water entered in course of time. It was a very slow process : the material softened, and long after the banks had been built they slipped. There was no reason why, with proper end-tipping, the compaction should not be done as the work progressed. It was incorrect to imagine that the layers must always be horizontal ; but whether the bank was built horizontally or not, the layers must be shallow ; thick layers could not be compacted properly. With modern angledozers, and similar equipment, the material could be spread, whether it was tipped over the end of the bank or whether it was tipped on the flat, if enough trouble were taken ; and if the layers were thin, one layer would merge into another as the material was compacted, so that no cleavage-plane would develop between them. That was important also from the point of view of drainage. The bank must be arranged so that the water would drain off it during construction and also when it was finished.

The maximum height for banks depended very largely upon the type of material used, and if the bank was homogeneous could be calculated fairly accurately from the strength of the material. Limitation to a certain type of material because it had to come out of a cutting, or for some other similar reason, would automatically limit the height of the bank, if the soil were of a cohesive type, and it might be necessary to change the level of the road or the height of the embankment to suit the material available for building the bank.

Sir Jonathan Davidson had remarked that many banks had been constructed with factors of safety of less than 1·5. That was not surprising. Banks until recently were built by trial and error. If the bank stood up, well and good; if it failed it was replaced. That such banks stood was no argument against choosing a reasonable factor of safety. Factors of safety were often called factors of ignorance. Enough was known now about the behaviour of soils to show how complicated a problem they presented and that compared with the knowledge of steel, for instance, the ignorance of soils was enormous; and the failure of a dam might well have much more serious consequences than the failure of a steel building.

He could not agree with Sir Jonathan that tractor-scraper outfits were not useful for building banks when the material in the borrow-pit was in layers. It should be remembered that it was not necessary to run all of those machines at the same level. If the borrow-pit was worked properly, some of the scrapers would be digging one material, whilst others would be digging another. Alternatively the cutting could be on a slope; in fact, it was better to use the machines in question on a slope, as they then dug faster and filled themselves better.

He could not think of any disadvantages in obtaining a high degree of compaction. The important point, as Mr. Whiffin had said, was to have the layers thin. Professor Terzhagi had told him that with the most modern German vibrating equipment consisting of 25-ton machines, no greater thickness than 1 foot could be compacted. Tractors, scrapers, and angledozers were very useful, because with them the material used could be spread out thinly.

The dependence of a railway-bank upon the cost of the land was purely a matter of economics. The prime cost of the land had to be offset against the possible running costs of continuous disorganization of traffic by slip. If a railway-bank did slip any serious result was very unlikely; it would be an extraordinary coincidence if the slip occurred just when a train was passing over that part of the track. In Sweden, where enormous slides took place, electrical devices were used on the railway-tracks to indicate when a slip had occurred.

Mr. Skempton's interesting example of material which months later was found to be very much weaker than it was when laid down showed the danger of keeping a bank badly drained and allowing water to penetrate into the hearting. That was one reason why he had advocated in his Paper that the top of the bank should be kept convex instead of concave. The idea of the concave top was that there would be no sliding planes, but he did not believe that they would occur with a properly-rolled bank, or that any planes at all would exist between the layers. In any event, he was quite sure that the advantage of proper drainage far outweighed the disadvantage of a very slight plane of weakness.