SECTION VIII

PROBLEMS IN ROAD AND RUNWAY CONSTRUCTION

GENERAL REPORT

G. WILSON (England)

GENERAL

In this section of the conference we have a number of papers on the design of pavements, both rigid and flexible, a series of examples of actual designs, some papers on drainage and frost effects, a few on failures of road foundations and of road and railway embankments and cuttings, two papers on soils classification, one on the formation of corrugations, and one on the trafficability of soil.

PAVEMENT DESIGN

Let us first consider the most numerous class of papers, that on the design of pavements.

There are theories for flexible pavements, theories for rigid pavements, theories that consider only the pavement, theories that consider only the soil below the pavement, and, finally, theories that consider both the pavement and the soil beneath it.

However, there is an underlying trend in one direction and it may be hoped that another twelve years will see a great unification in design methods. It seems reasonable to hope for a correlation between the C.B.R. method and the Burmeister theory that will be applicable both to flexible and to rigid pavements.

At the time of the first conference, twelve years ago, Engeneers had available the Westergaard method for the design of rigid pavements and some empirical rules connecting the thickness of concrete pavements with the soils classification of the U.S. Bureau of Public Roads. Flexible pavements were designed by rule of thumb.

The most important developments that have taken place since that time are the C.B.R. system for the design of flexible pavements and the Burmeister theory of layered elastic systems.

These are important because they consider both the soil and the pavement: the C.B.R. method consists, in essence, of comparing the experimentally found bearing capacity of the soil with the thickness of pavement which has, in practice, prevented failure. The Burmeister theory allows of the calculation of the stresses and displacements at any point in the pavement or the subsoil.

Other theories have been put forward by Housel and by Glossop and Golder. These theories require that the normal pressure between the pavement and the subsoil, found on the assumption that the load is dispersed through the pavement at a given angle, is less than the bearing capacity of the soil as determined by a particular theory. Thus neither method really takes into account the strength and flexibility of the pavement.

FLEXIBLE PAVEMENTS

The California Bearing Ratio test was first devised in 1929 and, as reported by O.J. Porter to the Highway Research Board of the U.S.A. in 1938, subsequent extensive investigation of flexible pavements indicated that failures usually did not occur when the total thickness of pavement, including surface and base, was equal to certain values dependent on the C.B.R.

This method was subsequently extended, to allow for the heavier wheel loads on airports, by Middlebrooks and Bertram, in collaboration with Porter and Professor A. Casagrande, as reported to the Highway Research Board in 1942.

Seven papers, those by Messrs. Russel and Olinger, Lewis, Loxton, Beavis and McNicholl, McFadden and Pringle, Olmstead and Willis, McLeod and Turnbull, Boyd and Foster discuss the C.B.R. method, or modifications thereof, and one, that by de l'Hortet, shows that there is a close correlation between the C.B.R. method and a design based on the assumption that the soil and pavement are identical in physical properties and form part of an elastic half space in which the stresses and displacements may be found by Boussinesq's theory, which is also the method adopted by Glossop and Golder, as far as the soil is concerned.

De l'Hortet's paper is valuable, and his proposals for further work on this subject are to be commended. In any further work attention might profitably be given to the following points:-

1) The effect of the vertical and lateral stresses in the soil due to its own weight and that of the pavement, due to rolling (as mentioned in the paper) and due to past geological compression or extension of the stratum:
2) Comparisons with the results of Burmeister's theory, of which de l'Hortet appears unaware: and
3) The relationship between the total deformation in the test proposed by de l'Hortet and the flexibility of the pavement.

Considering broadly and together the five papers on the C.B.R. method, the principal criticism contained in them is that C.B.R. tests on soaked specimens are an unwarrantably severe basis for design. This is a fair criticism: a design on such a basis will always be safe, but often uneconomical. The criticism is not, however, a justification for the abandonment of the method, as proposed by Mr. McLeod: what is needed, as pointed out by McFadden and Pringle, is a method by which soil samples may be produced for test in the weakest state to which they will attain naturally: Loxton, Beavis and McNicholl propose such a method, but much more extended experience will be needed to justify its general adoption.
A comparison of this method with the Wyoming "group index" method reported by Russell and Olinger would be valuable. An important paper by Lewis points out the undoubtedly great benefit that can be obtained by the subjection of the subgrade to traffic, but it is necessary to point out that this would not be the case in wet weather.

Four papers, those by Messrs. Hicks, Palmer and Thomson, McLeod and Netter and Becker, are based on the Housel method of design. Hicks describes the laboratory technique, but gives no correlation with experience and his conclusion that the method is satisfactory is not proven by his paper. It has already been pointed out that the real conclusion from McLeod's paper is that actual subgrades often do not attain as week a condition as soaked samples: with regard to his proposals it is not clear why the arbitrary deflection limits of 0.5 and 0.225 inch for 10 repetitions were chosen. Palmer and Thompson give a lot of information, but appear to have missed the opportunity to correlate the relation of the C.B.R. of the material in place to that of soaked specimens with local conditions: they do not appear to have correlated plate bearing tests with the border line between success and failure. Netter and Becker give the results of many plate bearing tests, but no conclusions as to their possible application.

Olmstead and Willis not only give an excellent appreciation of the factors affecting the condition, and therefore the strength and C.B.R. value of the soil, but they call attention to a number of important points: the effect of the moisture content during compaction on the subsequent soil properties, the danger that may arise from over-compaction, and the utility of the pedological soil classification and of aerial photographs in assessing the quality of the soil as a subgrade.

The paper by Turnbull, Boyd and Foster on the extension of the C.B.R. method of design to very heavy multiple wheel load assemblies appears, as claimed, to be logical and reasonable. It is also refreshing to find such a statement as "such computations are not new and will not be presented in this paper".

The State Highway Commission of Kansas report a design method based on triaxial tests, but give no correlation with experience: it is not clear from the paper how pavement thickness would vary with wheel load.

RIGID PAVEMENTS

Experience over the past 12 years appears to have confirmed that the Westergaard method of design is satisfactory in cases where the pavement fails before the subsoil. It was always recognised by Westergaard that the "modulus of subgrade reaction" is a purely fictitious quantity and he demonstrated that a large change in this modulus leads to only a small change in pavement thickness.

De Kruyf, v.d. Poel and Timman have extended the Westergaard theory so as to include for sandwich construction and dual wheels, and their work will no doubt be of value to many Engineers. Docker and McFeeters have collected and calculated a number of design curves for use with Westergaard's theory, but their paper appears to contain nothing novel from the Soil Mechanics point of view.

Glossop and Golder are right in pointing out that the Westergaard theory takes no account of the strength of the subsoil, but they go as far in the opposite direction by neglecting the strength and elasticity of the pavement: they are correct in comparing stresses in plastic soils with the shear strength of the material, but they neglect the stresses which may have existed in the soil prior to the application of the load.

RIGID AND FLEXIBLE PAVEMENTS

If it is assumed, as indicated by de l'Hortet and, to some extent, confirmed by Glossop and Golder, that the satisfactory performance of pavement can be ensured by design such that the elastic range of stress is not exceeded in either the pavement or the soil, it is obvious that a knowledge of the stresses in layered systems is most important. It is, of course, a fact that there is no true elastic range in soils, concrete or bituminous pavements, but it would probably be conceded that there is a practical elastic range in all these materials, when loads of short duration are concerned. This appears to be confirmed in respect of asphaltic carpets, by v.d. Poel.

A.H.A. Hogg, in 1938, published in the Philosophical Magazine, a paper entitled "Equilibrium of a thin plate, symmetrically loaded, resting on an elastic foundation of infinite depth". He followed this, in 1944, with a further paper, in the same journal, on "The equilibrium of a thin slab on an elastic foundation of finite depth".

D.W. Burmister, in 1943, published his paper, "The Theory of Stresses and Displacements in layered systems and applications to the design of airport runways" in the Proceedings of the Highway Research Board of the U.S.A.,

Hogg's pavement has stiffness, but no thickness, whereas Burmister's has thickness as well as stiffness and the latter's theory is therefore more truly representative of actual conditions.

L. Fox, in a paper to this conference, has calculated and plotted the stresses at various points in both layers, pavement and subsoil, by Burmister's theory. On the basis of his work it would be possible to determine whether the soil or the pavement will fail first and what load will cause this failure. Your Reporter believes that this is likely to be a more reliable criterion for the design of pavements than the deflection criterion proposed by Burmister, and he has done a certain amount of work, in collaboration with his colleague G.M.J. Williams, in order to produce design charts, a typical one of which is reproduced in figure 1. Your Reporter and his Colleague are preparing a paper on this subject and they hope to publish it before long.

Referring to Figure 1: -

- q - Tyre pressure
- a - Radius of circle having an area equal to the contact area between the tyre and the pavement
- σ_c - Maximum permissible tensile stress at bottom of concrete
- h - Thickness of concrete pavement
- c - Cohesion of subgrade soil
- γ - Density of subgrade soil
- ϕ - Angle of internal friction of the subgrade soil

This particular example is for the case when the angle of internal friction is zero, the coefficient of earth pressure at rest is equal to 0.5 and the ratio of the modulus of elasticity for the concrete to that for the soil is 100. Thus, if for a given case, the loading is such that $\frac{q}{\gamma a} = 150$ and the soil is such that $\frac{c}{\gamma a} = 5$, a point A is defined on the chart corresponding to $\frac{h}{a} = 0.71$. This means that the pavement thickness must be at least equal to 0.71a to prevent soil failure, provided that this occurs before the concrete fails.

Suppose the concrete is such that $\frac{c}{\gamma a} = 900$. This and the value of 150 for $\frac{q}{\gamma a}$ define point B corresponding to $\frac{h}{a} = 0.58$ and showing that

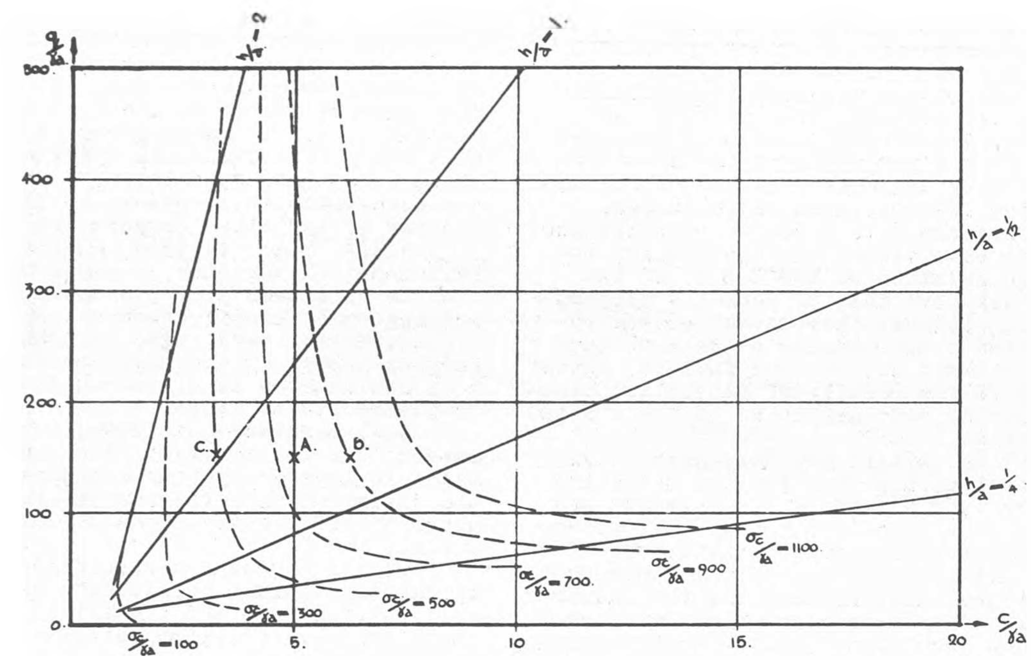

FIG. 1

to prevent failure of the concrete the thickness must be at least 0.58a. The fact that the pavement thickness to prevent soil failure is greater means that for this particular combination of loading and materials the soil will fail before the concrete, and that the thickness must be at least 0.71a to prevent either from failing. If, on the other hand, $\frac{\sigma_c}{\gamma a} = 500$, the other variables remaining unaltered, point C is obtained where $\frac{h}{a} = 1$, so that to prevent concrete failure the slab thickness must be at least equal to a. This is greater than the thickness to prevent soil failure which is still given by point A where h = 0.71a, so that in this case the concrete will fail first and the thickness to prevent this must be equal to 1.0a.

It is realised that this design method is only applicable to the middle parts of the area of a slab and that stresses, both in the slab and in the subsoil, due to the action of wheel loads on edges and corners, are much more important. Such stresses might be evaluated by the method of three-dimensional photoelasticity. Adoption of the Schiphol sandwich form of construction would, of course, obviate the need for consideration of edges and corners.

The paper by Turnbull, Boyd and Fergus describing the arrangements for the measurement of stresses in the soil, is appetising and Engineers will await the results with interest. It is particularly to be hoped that the attempt to measure the stresses existing in the subgrade prior to the application of the transport load will be successful.

TENSILE MEMBRANE SURFACES

Mr. Pollitt has reported some most interesting tests on the influence of thin tensile surfacing on the traffic carrying capacity of soil.

EXAMPLES OF PAVEMENT DESIGN AND CONSTRUCTION

In this section we have five papers, two on the aerodrome Schiphol, one on that at Zurich, one on aerodromes in Hongkong and one on an unidentified aerodrome.

The most outstanding paper is that by Clerx and Weinberg on the conception of the new and original design for the runways at Schiphol. By "Sandwich" construction the concrete pavement is not only protected from stresses due to changes of temperature and humidity, but is enabled to carry a greater load owing to the spreading action of the upper layers of construction. This type of pavement seems destined to widespread use.

The paper by Weinberg, Begemann, Lit and Carstens on the tests made to check the bearing capacity of these "sandwich" construction runways at Schiphol shows that excellent agreement with the design requirements was attained. Their findings that the modulus of subgrade reaction varies inversely with the diameter of the plate accords with Haefeli's equation, as reported by Germann and Eng, and with the conclusions of Netter and Becker. However, the stresses in the soil below the concrete slab do not appear to have been considered.

Germann and Eng report on a design based on plate bearing tests. It appears to your Reporter that Haefeli's "modulus of plasticity" can be directly computed from the California Bearing Ratio (diameter of test load = 1.94 inches penetration = 0.1 inch) this gives M_E = 14 x C.B.R. The curve of thicknesses required according to the C.B.R. method of design has the same general shape as that given by the authors in their figure 4. If, further, we assume with Henry and Grace that a rigid pavement has the effect of twice the thickness of flexible pavement, we obtain the following comparison for a 67.5 ton wheel load:-

1.	M_E	35	42	56
2.	Construction thickness, cm	133	110	78
3.	do. allowing concrete as double thickness	163	140	108
4.	C.B.R. corresponding to M_E	2.5	3	4

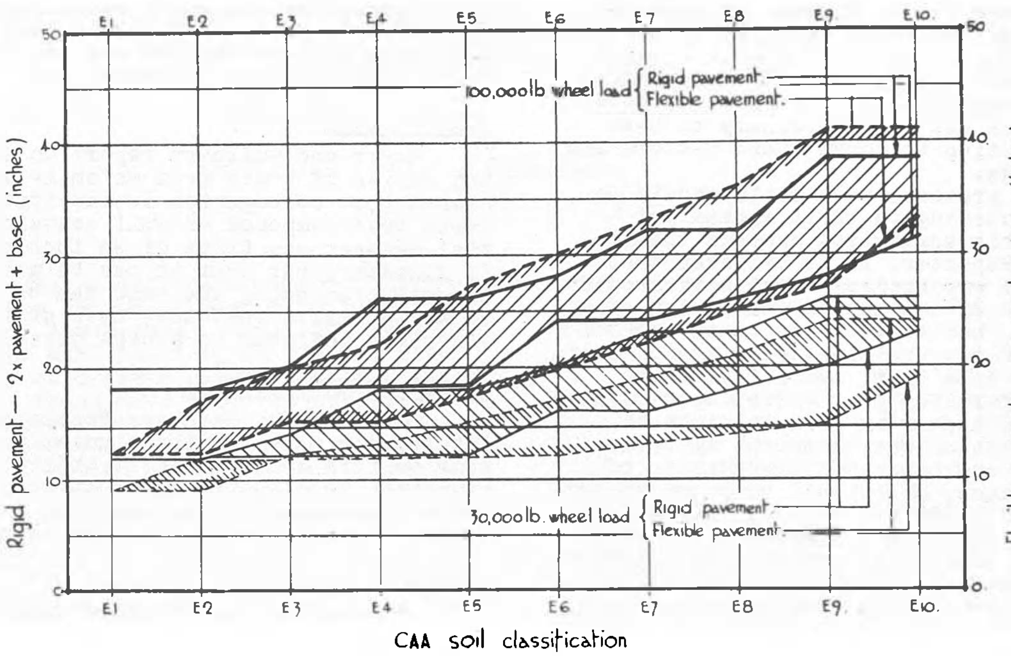

FIG. 2

5.	Construction thickness, cm	210	180	144
6.	Ratio $\frac{\text{line 5}}{\text{line 3}}$	1.3	1.3	1.3

Thus the thickness calculated by Henry and Grace's modification to the C.B.R. method bears a constant ratio to the thickness calculated by the modulus of plasticity: this ratio could have been unity had a different critical deflection been selected by Haefeli.

Henry and Grace have reported a case where estimation of the worst condition of the soil for use with the C.B.R. method of design instead of taking the strength of soaked specimens as a basis, has been successful.

CLASSIFICATION OF SOILS

Aaron reports on the C.A.A. Classification of soils. This classification appears to comprise a direct method of design. To your Reporter it seems too easy.

The physical properties of each type of soil must vary over quite a wide range and it does not seem, therefore, that to each type of soil there should correspond only one thickness of pavement: this would lead either to failures or to extravagances.

Judgement of classification systems must always to a certain extent depend on personal prediliction, but it would seem a pity to abandon the helpful mnemonics of the A.C. Classification. The A.C. Classification can readily be carried out in the field, largely by eyes and feel. As to the number of tests required, the A.C. system relies on the same tests for confirmation of field examination and it is then usual to base flexible pavement thicknesses on C.B.R. tests, which can be performed with quite simple apparatus which can be improvised wherever a carpenter and a blacksmith are available.

Aaron's paper permits of a check on Henry and Grace's suggestion that the thickness of a rigid pavement may be counted double. Figure 2, prepared from Aaron's data, appears to confirm their supposition.

Figure 3 shows a comparison of the C.A.A. and A.C. systems of classification in which

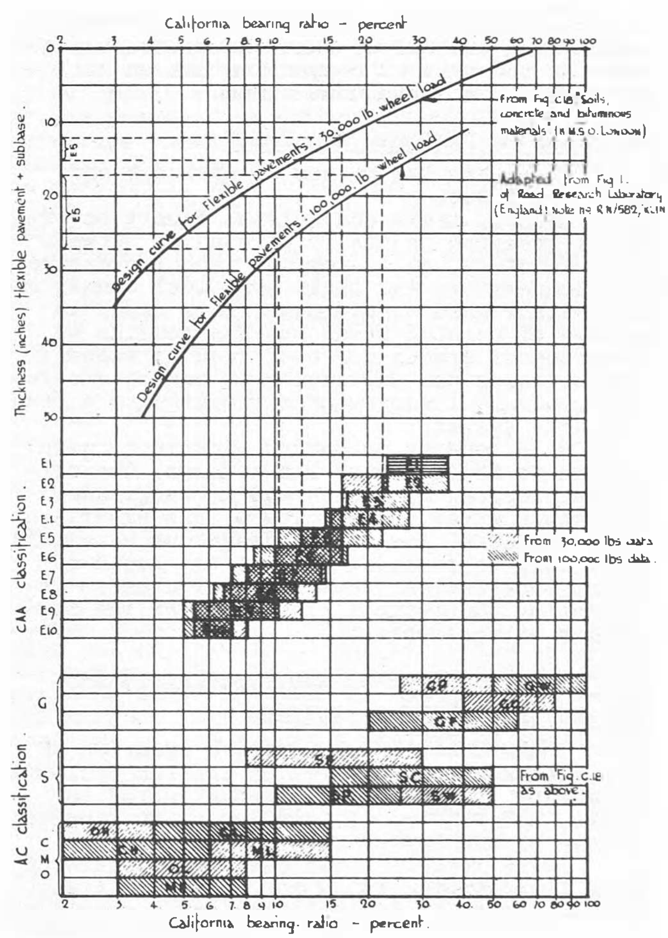

FIG. 3

the range of C.A.A. soils have been plotted from the thicknesses required according to Figure 2. It will be seen that, apparently, no soil, other than peat and muck, would have a C.B.R. less than 5, according to this classification, whereas, actually, many plastic clays have lower C.B.R. values. It appears generally, that the range of soil types is too narrow.

The Author's remarks on the importance of turf and crops on aerdromes are appreciated, but it does not seem necessary to have one classification to cover these factors and runway loadings.

McDowell proposes that soils should be classified according to their mechanical properties. This suggestion appears inadvisable to your Reporter. It is believed that the mechanical properties of the soil should form the basis of the mechanical design of the pavements, but that they are not adapted as a yardstick for the classification of soils.

It would seem that, according to the method of preparation of the test specimens, any soil could appear in more than one of McDowell's classes. The treatment of the soil in the field, and hence the preparation of the test specimen, might well vary according to the type of pavement proposed, and we might then be faced with two different classifications for the same soil. On the other hand, soils quite dissimilar by origin and nature would have to be classed together, whereas the origin and nature of the soils are important characteristics when considering the behaviour of the pavement in service, drainage, danger from frost, etc.

McDowell also, with Olmstead and Willis, calls attention to a number of important facts concerning the effect that the moisture content at the time of compaction has on soil properties at subsequent times.

PROBLEMS OF DRAINAGE AND FROST

There are two papers on drainage and three on frost.

Croney, Lewis and Coleman report on original research on the relationships between soil moisture, soil suction, vapour pressure and temperature and their practical consequences with regard to drainage. This paper is worthy of careful study and its remarks on interceptor drains are confirmed by McNeal; who stresses the importance of making a careful geological survey before designing a road drainage system.

Riis reports on Danish experience with regard to frost damage and confirms the criteria proposed by Beskow and A. Casagrande. Godskesen gives the results of his experience which indicate that frost-dangerous materials need only be replaced to half the depth of frost penetration. Ruckli contributes an interesting theoretical discussion of the formation of ice-lenses.

STABILITY OF CUTTINGS AND EMBANKMENTS AND RAILWAY ENGINEERING PROBLEMS

Thoms contributes numerous examples of the treatment of failures on British Railways including instability of tracks, slips in banks, and soft spots, and Thornburn reports a case of the latter from the U.S.A.

Lewis reports three cases of failure of road foundations: it is not, however, clear why he adopts in his calculations a wheel load 33% above the legal limit, especially as the same conclusions would be reached by assuming the latter load.

COMPACTION

R. R. Proctor's paper on "The Preparation of Subgrades of Compacted Soils for Paving or Structures", appears to belong more to Section A.IX than to this Section and it will be reviewed in the Report thereon.

CORRUGATIONS

Mayer and Guilbert report on an interesting series of tests from which it may be concluded that corrugation is inevitable in an earth road composed of soil containing material between one fifth of an inch and one inch in diameter, but that it can be mitigated if the vehicles using the road can be controlled so as to ensure that they have stiff springs and tyres inflated to a high pressure.

TRAFFICABILITY OF SOIL

Schoolcraft, Boyd and Foster present an interesting paper on the studies they have made on this subject. Their object appears to have been to classify types of ground according to the types of vehicle that can make 25 trips across it before bogging down.

RECOMMENDATIONS

It appears that valuable results would be obtained if the Authorities which have made evaluations of the strenght of roads and runways were to extend their investigations in the period preceeding the next conference to provide the data necessary for the evaluation by the various theories adopted by others and were this information to be made available to a small committee of this conference for consideration and recommemdation of a standard method for the evaluation of the bearing capacity of pavements.

AT THE COMBINED SESSION OF SECTIONS VIII AND IX, Mr. WILSON MADE YET THE FOLLOWING REMARKS:

I should like to speak of the two big related problems, one of which is dealt with in Section VIII and the other in Section IX. I refer, of course, to the design of pavements and to the compaction of the soil. I would like to treat them together not only because they are related, but also because it appears to me that the means by which further progress can best be attained are similar in the two cases. The value of this Conference is that it has presented so many different points of view. Now that we have all been able to see one another's points of view it is time not to attempt to form a final judgement but to put the various theories, hypotheses and ideas to the test. Both these big subjects are still in a state of flux and what we need is more experience.

We shall not obtain the greatest benefit from our experience unless we all of us take sufficient measurements to enable each job with which we are connected to be judged by all the various theories and not only by that which we may individually and for very good reason consider to be the best or the most applicable to the case in question. If we do this we shall, of course, also provide the material for the converse action: the judgement of the various theories by the various practical cases. At the moment we are losing experience because Engineers are apt only to take the measurements required by the theory which they have selected for the design of the job in question.

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SUB-SECTION VIII b

METHODS OF FLEXIBLE PAVEMENT DESIGN

VIII b 12

DISCUSSION

O.J. PORTER (U.S.A.)

My discussion will cover several points concerning the matter of design of flexible pavements for heavy wheel loads. Before discussing these matters, I would like to comment briefly on a few misunderstandings which have arisen. These have been previously discussed by Andrew MacLeod and others as described in Paper VIIIb 8.

In interpreting results of all pavement tests, the changes in moisture content over a long period of time beneath the pavement must be considered. Many highways have been in excellent condition for four or five years, but have failed thereafter due to the development of a higher moisture content beneath the pavement. It is interesting to comment on Mr. MacLeod's paper which deals with airports in Canada. According to his description the subgrade was 85% saturated or more over a short wet period, and the degree of saturation was 10% or 15% during longer dry periods. It is my opinion that we should pay more attention to the few local cases where our construction methods have failed than to the many cases where good performance has been observed over a period of years. Normally the figures found by experience in a few local areas when they are taken for a basis for larger often indicate that complete reconstruction is needed. I think this is particularly true of airfield taxiways. It is proper to comment that Mr. MacLeod's comparison in the excellent work he has done in correlating CBR with loading tests shows substantial agreement between the two design curves. In fact I suspect that the plate loading test would be more conservative than the CBR design for taxiways and aprons, especially when very heavy wheel loads of 10 to 100 tons are being considered. There are three or four design methods used for aprons, taxiways and runways. One of these designs is based on construction of test sections with limited amounts of traffic. We are not justified for a temporary installation in the theatre of operations in building a substantial foundation at considerable additional expense when the installation may be wasted or may soon be made inactive. The Corp of Engineers, U.S. Army, provided for a reduction in required pavement thickness during the war for all military fields in the theatres of operation, and also for fields that would not be permanently needed for heavy airplanes. It is quite obvious that in some cases the required thickness might be a great deal less than indicated by the CBR design curves if the field were to be used for a limited period of time especially if the moisture content beneath the pavement did not increase rapidly or of the traffic were light. I think the curves derived from Mr. MacLeod's work for aprons and taxiways are desirable. However, I think the curves for runways are too greatly reduced in comparison with the requirements for taxiways. Certainly we can reduce the section of our runways to make them thinner than taxiways, but it is always possible that the runways will be used as taxiways and on many military fields this is true for about 80% of the operations.

Another design is based on deflection. This is a complicated problem but we can discuss it briefly. The plastic deformation of the subgrade is a very small amount and at a very low percent of strain. With a given thickness of pavement and base course we can summarize that the permissible deflection will depend on the type of deformation and whether it is progressively increasing or decreasing. It is obvious to all soil mechanics people that the amount of the deflection will vary with the size of the loaded area. Therefore, we cannot in my opinion fix a definite amount of allowable deflection for all loads, as this procedure does not take into account effect of the size of the loaded area. In fact it is probable that the load carrying capacity of the pavement is a function of the radius of curvature under load. We have reached the conclusion that the permissible deflection will be very small when designing for light wheel loads of 10,000 pounds, but will be rather large, perhaps 0.5 inch in the case of 200,000 pound wheel loads and greater. Those responsible for the design of runways will not be able to keep up with the pace which is being set by the airplane designers in building heavier and heavier planes, but they must try. I think that deflection measurements really show that safe designs for light wheel loads require subgrade deflections of 0.05 inch or less, but that an allowable deflection of 0.2 to 0.3 inch might not be excessive for a wheel load of 100 tons.

The CBR method has been widely discussed and has been used extensively. A detailed discussion of it is beyond the scope of this talk. I only want to say that I have prepared a paper that you will all receive in the next few months which is part of a rather thick symposium edited by Colonel Hardin of the Corps of Engineers, U.S. Army, on the history and progress of investigations of design based on the CBR method. This will be published in the Proceedings of the American Society of Civil Engineers in the near future.

I want to mention briefly the test for determination of flexible pavement requirements for 200,000 pound wheel loads at Stockton, California. This is an extensive study which includes comprehensive pressure and deflection measurements. The report on these tests is now in process of publication by the Office, Chief of Engineers, U.S. Army.

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DISCUSSION

N.W. MACLEOD (Canada)

The Reporters for the 12 sections of the Conference deserve our sympathetic understanding. It is not an easy task to read through and abstract the various important ideas which the many different papers are intended to express, some times probably with not too great clarity.

There are several points in Mr. Wilson's review with regard to my own paper, VIIIb 5, on which I would like to comment.

1. Mr. Wilson has remarked that "it is not clear why the arbitrary deflection limits of 0,5 and 0,225 inch for 10 repetitions were chosen" as criteria for the required thickness of flexible pavements .
The required thickness of flexible pavements for runways for capacity operations was based upon 0,5 inch deflection for 10 repetitions of load, because this platebearing value appeared to correspond to the maximum aeroplane wheel loads which the runways at the different airports had been carrying without sign of distress, and with very little maintenance. Experience has demonstrated that taxiways, aprons and turnarounds require greater thickness than the runways themselves. In Canada and elsewhere some years ago, runways and taxiways were constructed of the same thickness. The taxiways frequently failed under wheel loads which the runways carried without distress. If flexible pavements have a yield point, it is important that this yield point should not be exeeded by aircraft parked on aprons or taxiways. The average yield point deflection for the flexible pavements included in the Canadian runway testing program,was found to the 0,225 inch, according to a method of analysis devised by Housel. Consequently, 0,225 inch deflection for 10 repetitions of load, was selected as the criterion for the required thickness of flexible pavement for taxiways, aprons and turnarounds, for capacity operations.

The same deflections, but for 1 repetition of load, are suggested for limited operations.

It is believed that the thicknesses given by these design criteria, although much less than those required by the U.S. Corps of Engineers, may still be too conservative.

2. Mr. Wilson has stated that our paper, VIII b 5, is based upon the Housel method of design.

If the Reporter is referring to the procedure for determining the required thickness of flexible pavement, we would like to emphasize that the method of design which have been developed from the Canadian investigation, is entirely different from that proposed by Prof. Housel some years ago.

That it is completely different in both conceptions and form can be seen from the following:

$$t = \frac{r(p-s)}{m} \qquad (1)$$

and

$$t = K \log \frac{p}{s} \qquad (2)$$

Where equation (1) is the Housel equation in its simplest form, and equation (2) was derived from the Department of Transport's investigation. The symbol "t" represents required thickness, "p" and "s" are unit applied load and unit subgrade support, respectively, and refer to the same contact area, "m" is pavement shearing resistance, "r" is radius of contact area, and "K" is an inverse measure of the supporting value of the base course per inch of thickness.

It is obvious therefore, that equations (1) and (2) are based upon entirely different concepts.

3. Earlier in the investigation, it was thought that the symbol "K" of equation (2) above, was independent of the size of bearing plate. More recently, it has been found that this is not so. As nearly as can be determined, a straight line relationship occurs, when log K is plotted versus the perimeter area ratios of bearing plates of different sizes.
K appears to have a value of 65 for a 30 inch bearing plate, and 35 for a 12 inch plate, for normal granular base course construction for airports.

4. We are pleased to observe from Mr. Wilson's report, and from paper VIIIb 8 by Mc Fadden and Pringle, that consideration is being given to the determination of a method for making C.B.R. tests on subgrade soils in their weakest state, rather than after soaking. This would be a very worth-while advance. As indicated in our paper VIIIb 5, the flexible pavement thickness requirements obtained from the U.S. Corps of Engineers design curves based on the C.B.R. ratings of soaked subgrade samples,are very much greater than Canadian airport engineers could justify on the basis of their own considerable experience with the construction and operation of several hundred airports.

Examples of airports in Canada which are carrying considerable traffic of aeroplane wheel loads that are several times greater than the U.S.Corps of Engineers design would permit, are contained in our paper.

At no Canadian airport which has been tested as far, could the thicknesses of flexible pavement required by the U.S.Corps of Engineers' design be justified.

We believe this is due to the fact that the moisture contents in the top inch soaked C.B.R. samples were from 40-140 percent higher than the actual subgrade moisture contents measured in the field for runways that had been paved for several years, and in which moisture conditions had therefore probably attained equilibrium.

The results of the Canadian investigation appear to be in general agreement with those obtained by the Bureau of Yards and Docks of the U.S. Navy, who have tested a large number of airports in the U.S.A.

We are inclined to believe that the way would be opened for more rapid progress in the field of airport and highway engineering, if for the C.B.R. test there could be substituted one or more tests which provide more fundamental information on the properties of subgrade, base course, and flexible pavement. The triaxial compression test is suggested as one of these.

While we are not in agreement with their present requirements for pavement thicknesses, it is a pleasure to pay tribute to the large amount of very fine investigational work in many phases of soil mechanics which the U.S. Corps of Engineers has undertaken.

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VIII b 14

DISCUSSION

L.J.H. WEINBERG (Netherlands)

In the first place I want to remember a moment Mr. Carstens of the public works department of Amsterdam, with whom I cooperated in writing a report for the proceedings of this conference on Schiphol, our biggest airport, and who recently met with a sudden death during a testloading at the airport.

In this discussion I like to say that concerning the determination of the bearing capacity of flexible runways to my opinion the most practical methods are the C.B.R. method of Mr. Porter and the method proposed in 1943 by the committee on flexible pavement disign of the American H.R.B., which method determines the bearing capacity by means of loading tests on test sections. At the tests at Schiphol our biggest airport, it appeared that the results of both methods agreed very well, if limited, and capacity operation on runways according to the C.B.R. method would be taken as corresponding to respectively 10 and 1000 repetitions of static loads on the same identical area according to the H.R.B. method. This is already stated in a report for this conference by Mr. Clerx and myself.

Now Mr. MacLeod has stated that in Canada the results of the C.B.R. method are too conservative. However Mr. Mc.Leod has soaked his test-samples whereas he states that the subsoils of his runways are far from saturated. Now the C.B.R. method requires that moisture conditions during the test must be simular to the most unfavourable conditions in the field to be expected. Moreover in the concerning chapter of the Engineering Manual it is said that in arid or semi-arid regions where the annual rainfall is less than 15" and the water table is at least 15 feet below the surface, the danger of saturation is reduced, so that the required thickness of pavement and base may be reduced to an amount of 20%.

At the H.R.B. method the crucial point is that the deformation of the pavement is kept within reasonable limits for the traffic concerned. Generally speaking these deformations are caused by compression or plastic deformation of base and subgrade. At repetitional loading the compression in considerably decreasing whereas the deformations caused by lateral displacement increase and these last deformations appear to be the main cause of failures.

The H.R.B. method points out that the greater part of the compression will occur at the first loading and also that the corresponding settlement should not be taken into account for the bearing capacity. On the contrary the great importance of repetitional loading is emphasized and here the deflection after the first settlement should not exceed o.2" an emperical value.

Mr. MacLeod uses the H.R.B. method at ten repetitions, but he does not consider the settlement at the first loading, but goes by a total deflection 0.5", which seems not quite correct to me.

Finally I want to point out that at test loading the problem is always what should be considered as a permissable deflection and up to now this is an empirical question. Of course besides the total deformation also the ouvature of the pavement and the diameter of the loaded area are influencing factors. I hope that during these discussions some more light will be shed on this problem and particularly whether members are of the opinion that the recommended deflection of 0.2" is correct or not.

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VIII b 15

WRITTEN DISCUSSION ON PAPER VIIIb 4

E.H. DAVIS and J.A. CAUWOOD (England)

The simplifications involved in the Authors' method of design for pavements on purely cohesive subgrades give rise to two main inaccuracies which tend to cancel one another. On the one hand, by using the Boussinesq distribution of stress for a homogeneous elastic solid (and thus assuming the pavement has only the same rigidity as the subgrade), the stresses in the subgrade are over-estimated. On the other hand, by neglecting the effect of repeated wheel loads and using the ultimate shear strength instead of some form of yield strength, the strength of the subgrade is also over-estimated.

The method has been proved satisfactory for a not very wide range of wheel loads and for a range of soil strengths limited to that of saturated or near saturated clays, and it may well be inaccurate when applied to soils far from saturation and to high wheel loads. This is shown by the example quoted by the Authors in which the distribution of shear stress in a two-layered elastic system had to be used by Skempton to give a reasonable design thickness for a 150,000 lb. wheel load; an analysis such as that originally found satisfactory by the Authors gave nearly double the thickness. The limitations of the Authors' method are also indicated by Table I in which there is good agreement between the C.B.R. method and the Authors' method III for smaller but not for higher wheel loads on soft clay. The selection by the Authors of a unique value of strength of stiff clay to correspond with a range of values of C.B.R. makes comparison between the Authors' method II and the C.B.R. method difficult for this soil.

The Authors' method for designing pavements on subgrades having both cohesive and frictional properties is open to a number of objections as can be seen from the discussion following the original publication of the method in 1946 (Authors' ref. 2). Since they considered an elastic distribution of stress (either two-layer or homogeneous) to be satisfactory for pavement design on clay foundations, the Authors might have extended their methods to cover the case of C - φ materials without recourse to an ultimate bearing capacity formula. The horizontal and vertical stresses on the axis are principal stresses, therefore the state of stress on the axis at any depth may be defined by a Mohr circle construction. Thus failure at any point on the axis can be prevented by ensuring that at no depth is this Mohr circle cut by the line $S = C + p \tan \varphi$ using values of C and φ determined for the soil at that depth. I might be necessary to check that more critical conditions did not occur away from the axis although from a few trial calculations this seems unlikely. It would probably also be necessary to include in the horizontal and vertical stresses a component for the stress due to the dead weight of the material above, especially in the case of soils having little or no cohesion.

However, we do not consider the use of such a theoretical method of pavement design advisable until sufficient actual measurements of stresses in layered systems have been made to determine what modifications to existing theories of stress distribution are necessary in order to take account of the non-elastic behaviour of the materials of the pavement and the soil underneath and also until it can be decided how the strength properties of the soil can best be evaluated in order to take account of repetitions of load. For the time being the most reliable pavement design method is surely an empirical one such as the C.B.R. which is now based on a considerable amount of experience for wheel loads up to 150,000 lb.

In the Authors' Table I, there is little agreement between method I (Westergaard) and method II (C.B.R.) or, for that matter, between method I and the Authors' methods III and IV. This might be expected since Westergaard assumes the subgrade to have certain loaddeflection characteristics but an unspecified ultimate bearing capacity and designs the thickness of concrete slab so that the stresses in this slab are not excessive. The C.B.R. method on the other hand is mainly for flexible pavements and designs the overall thickness of construction so that the stresses in the subgrade are not excessive. For concrete pavements the overall thickness of concrete and base or sub-base may be calculated by the C.B.R. method or for clay subgrades, by the Authors' method III. The proportion of this overall thickness to be made of concrete can then be determined by Westergaard's method using a value of the modulus of subgrade reaction probably to be obtained on top of the base sub-base. Of course, for a complete design it is also necessary to check that secondary stresses in the concrete due to temperature and moisture changes are not excessive.

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SUB-SECTION VIII c

METHODS OF RIGID PAVEMENT DESIGN

VIII c 4

DISCUSSION

N. CARILLO (Mexico)

"I am reporting on another paper not included in the general report. It deals with the problem mentioned Wednesday by Prof. Terzaghi, in his closing remarks. He said that the value of the average settlement of a building is much less important than the distribution of deflections and the "bearing capacity" of the building to the deformation. And that this problem has received little or no attention from soil mechanics.

In this paper, the theoretical skeleton of the problem is presented, assuming that the building is equivalent to "an equivalent slab" as far as strength to deformation is concerned. Also, the soil is assumed to be perfectly elastic.

Under these assumptions, various rectangular areas loaded by uniformly heavy "buildings" (slabs) are analysed. The average bending of the slab, the critical length, the maximum moment, the minimum radius of curvature and the stress concentrations at the corners of the rectangles are presented in a table.

To properly determine the "equivalent slab" of a building structure, it is important to take into account not only elasticity but also plasticity considerations, which in turn have to do with the consolidation characteristics of the soil. The method of construction, i.e. the time rate of the building up to the structural strength, is also important.

The elastic constants of the soil have to be determined by soil testing and settlement analyses, in correlation with actual settlement observations at the site under considerations.

Only through all these investigations in proper correlation can a reasonable settlement-analysis of a building be made."

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VIII c 5

DISCUSSION

J.N. McFEETERS (England)

I propose to refer to two papers on concrete runways which Mr. Docker and I have contributed, VIII c 2 and VIII d 2 and to the general report. First I want to make a correction to volume 2 page 250 figure 4 where equations 6 and 7 should be numbered 5 and 6. We recommend number 6. We ventured to hope that without specific reference to soil mechanics our papers might be a contribution to Foundation Engineering to which this conference is also devoted, for a runway is merely an extended foundation carrying live load only. But nevertheless soilmechanics and soil tests are "just around the corner", for, above all, we want to avoid the misconception that after employing the methods we have detailed or any other series of mathematical calculations, however refined, the plans can be sent out from the designer's board for "fabrication" as in the case of buildings.

We took this for granted but the emphasis on theoretical methods in the general report makes me wish to add a few explanatiory remarks on our papers. Initially we have developed individually our theories, because I belong to the Ministery of Works and Mr. Docker to the Air Ministery; afterwards when we got close contact we found that we had come to think alike on concrete runways.

I can just touch briefly on two principal matters out of many which I should like to discuss. The first is this: Concrete runway design consists in the design of edges and corners. The stresses in these parts of the concrete slabs may be twice and in the soil below may be three times those at the interior of slabs. The design of concrete runway slabs is, therefore, not soluble by improvement in the delicacy of the mathematical calculations on the surface for infinitely extended slabs, because first of all the stresses obtained in that manner are unimportant. But in addition, the foundation of the runway - the soil and the base course - is so variable, due to local conditions, that the so-called "inherent properties of the soil" the modulus of elasticity, Poisson's Ratio etc. for the many variations of soil type, soil moisture, soil density, to say nothing of similar variations in the base course and concrete, these inherent properties are never likely to be obtainable in practice; especially when it is recollected that it is not the value of these properties in the laboratory which is required, but their values in site and all over the site. Now you can eliminate corners fairly readily but to eliminate edges you must either prestress or produce a composite runway, so integral that it acts as an infinite slab. However this is not so easy and I should like to know whether at Schiphol the same results were obtained.

What is required then is a simple field test for the soil and base course in situ, and a theoretical or if you like an empirical means for drawing conclusions from this test as to the stress in the concrete in the edges and corners and in the soil under edges and corners. I repeat that edges and corners whether free, joined by dowels or plates, covered with asphalt or other material, or support from below.

The best test is a simple penetration test, analogous in many ways to the deep penetration tests we have seen at Delft and valid for the special problems to which it is applied. We use the well known 30 inch diameter plate test and obtain the "modulus of subgrade reaction" described in our reference 20 to which Mr. Docker contributed. The theoretical analogue we use is Westergaard's treatment of load stresses, made complete only in 1947 by his edge formula which is of major importance to runway designers. We have extended this theory to cover pressures on the soil, temperature stresses, and design of dowels. We have also given the experimental evidence for accepting these procedures as reasonably valid and a framework for future experimental results. But we do not claim that this procedure produces the runway design.

In each of our two Ministeries we have arrived at something like the following procedure. A detailed soil survey is taken of the site and general problems of earthworks and consolidation are settled. This may be the major feature of the design, but it is not relevant just now. Next, a plate bearing test survey is carried out, leading to broad choices of the average moduli of subgrade reaction in various parts of the site. A tentative design is got out, together with the design of a base course which will distribute the pressures below the slabs in such a manner that failure or deterioration of the soil will not occur. I use Mr. Glossop and Mr. Golder's methods here, to compare the shear strength of the soil with the shear stress, but based on the pressures calculated beneath the slabs by the formulae which I suggested in 1946, which are quoted in our paper.

Next an area of the site, which the Air Ministry calls: "a guinea-pig area" is selected and base courses are laid for further plate tests, leading to a new modulus of subgrade reaction and a more detailed slab design. Concrete slabs are then constructed on the base courses, and after curing, are tested up to the designed load and usually beyond, to destruction. At least, loads and deflections are measured during these tests but in the latest runway carried out for my Ministery, strains in the concrete were also measured by extensometers in considerable details. It is only as a result of these practical tests that the runway design is settled.

Now it is clear that such tests are expensive, somewhat difficult, and take considerable time. Therefore we cannot afford to be far wrong with our trial designs. We have found the system we propose in our papers to be a good approach to the design of our trial slabs; certainly it is the best we know and we would welcome criticism by engineers practising concrete runway work; we cant test results especially.

That is our standard method of approach via field tests, tentative design, and final tests. I feel that it corresponds to that so strongly urged on us by our President in his adresses.

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VIII c 6

DISCUSSION

T.P. O'SULLIVAN (England)

In the first place I should like to comment whom the paper by de Kruif, van der Poel and Timman, referring to the novel composite flexible rigid construction applied to the runways at Schiphol airport. However it seems to me that the principle runs counter to the conception of a construction which increases consistently in strength from bottom to top as exemplified in the CBR-method of design.

Another paper I want to refer is the paper of Messrs. Dockers & Mc Feeters, calling attention to the fact that load transference by dowels tends to equalise mid span edge and corner moments, thus rendering unnecessary any desire to thicken the slab at the edges.

At last I want to refer to the design of the Hall Floor and Apron for the Brabazon Aircraft being constructed by the Bristol Aerplane Company. The design is based upon the use of the Glossop and Golder method to determine the total thickness of construction together with the revised Westergaard theory for checking the stresses in the high grade concrete slab.

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SUB-SECTION VIII e

INVESTIGATIONS ON FAILURES, DRAINAGE AND FROST ACTION

VIII e 9

DISCUSSION

A. MAYER (France)

The very comprehensive study on washboard waves we have made during the last years only referred to the waves obtained under traffic on dirt roads in dry climates. These waves consist of loose granular material which accumulates along transverse lines, generally 1 metre apart, giving the road the general aspect of a washboard. The term "corrugation", in that case, is not correct, as the firm soil, under the waves, remains intact, and as it is possible to get rod of the waves simply by sweeping the surface.

These waves are very frequent in dry countries. I observed them personally very often in North and West Africa, but I heard they also existed in South Africa and Australia. Even in Sweden I was told of such a formation of waves. I very much wondered how this could happen until I came to that country and noticed how dry the air was in summer.

A model study was made in Paris on a 15 m diameter circular track. Films were taken, and conclusions were drawn as to the means of preventing the waves. The length of the waves corresponds to the vibration of the vehicle due to the elasticity of the tyres.

The best way is to have a bound surface but that is expensive in a country where there are not very much more than two cars a day on the road. There must not be loose granular material on the soil. On layers of fine sand you do not get the waves because the cars simply spread the sand away.

In a lateritic country, the red clay which generally lies under the superficial hard crust can be used as a surface material. It hardens in the sun and wears out regularly producing dust and no waves.

With pebbles that are too heavy to be thrown in the air you have nothing at all. The main conclusion is that the stabilisation of the soil does not prevent waves. On the contrary as soon as the weather is dry you have a formation of loose material on the roads and get the waves after a very short time. This is all I want to say about these waves.

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SUB-SECTION VIII f

MISCELLANEOUS

VIII f 9

ADDITIONAL REMARKS (BY LETTER) ON PAPER VIIIf 2

A.H. TOMS (England)

The paragraphs at the foot of page 233 relating to the treatment of unstable track formations may give an impression that the use of precast concrete slabs is now the most usual methods of treatment on the Southern Region of British Railways.

As a result of research carried out by Mr. L.R. Waddington, of the Chief Civil Engineers Research Section, the use of slabs has been discontinued in favour of the less costly method of excavation to a depth determined as shown in fig. 24, and backfilling with consolidated fine rock crusher waste, on top of which the normal track ballast is placed, with a thin layer of intermediate size chippings, in between to prevent the penetration of ballast into the rock dust.

Research is being actively pursued on this very important problem.

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CLOSING DISCUSSION

Prof. K. TERZAGHI (U.S.A.)

The subject matter of sections VIII and IX has been so thoroughly covered by the general reporter and the discussers, that nothing of any consequence can be added at the present. However, the following incident may be of interest.

Some time ago I had to express an opinion on the adequacy of the subbase for the runways on an exceptionally large airdrome. The subbase consisted of very coarse sand and gravel, containing cobblestones with a diameter up to four inches. Previously, attempts were made to determine the quality of the subbase by means of CBR tests. I protested against this procedure because the size of the loaded area is very much smaller than the largest cobbles contained in the subbase; and I proposed the performance of large-scale loading tests with repeated load application. The tests were successfully carried out, but when I inquired about the maximum deflection which the designers of the airdrome are willing to tolerate, I could not get a satisfactory answer. Considering this awkward situation, I felt like a tailor who is requested to make a pair of trousers without being told how long and how wide the trousers should be.

Remembering this incident I was very pleased to learn from the discussions by McLeod, Middlebrooks, Porter and others that the length and width of the trousers begins to receive the attention which it deserves.

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