Relationships between deflection, settlement and elastic deformation for subgrades and flexible pavements provided by plate bearing tests at Canadian airports - Relations expériementales entre la deflection totale, le tassement et la déflection élastique, des sols de foundation et des revêtements souples, lors d'essais de chargement à la plaque sur des aéroports Canadiens

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Relationships Between Deflection, Settlement and Elastic Deformation for Subgrades and Flexible Pavements Provided by Plate Bearing Tests at Canadian Airports

Relations Expérimentales entre la Deflection Totale, le Tassement et la Deflection Elastique, des Sols de Fondation et des Revêtements Souples, lors d'Essais de Chargement à la Plaque sur des Aéroports Canadiens

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Summary

For its investigation of airport runway design and evaluation, the Canadian Department of Transport employs plate-bearing test procedure that enables deflection, settlement and elastic deformation of the loaded material to be evaluated. Analysis of the load test data indicates that simple relationships exist between deflection, settlement and elastic deformation for the subgrade soils under Canadian airport runways for deflections ranging from 0 to 0·7 in. These relationships are noticeably different in sandy and in cohesive subgrade soils. Relationships between deflection, settlement and elastic deformation for flexible pavement surface load tests are very similar to those for the subgrade soils on which the pavement has been placed. In all cases, the ratio of settlement to deflection increases, and the ratio of elastic deformation to deflection decreases, as the deflection of the bearing plate under load is increased. Relationships between deflection, settlement and elastic deformation appear to be relatively constant, regardless of the diameter of the bearing plate. For any given total deflection, the ratio of settlement to deflection increases with the number of repetitions of load required to attain that deflection.

Sommaire

Dans ses recherches sur le calcul et l'évaluation de la force portante des pistes d'envol, le Ministère des Transports du Gouvernement canadien utilise l'essai de chargement à la plaque. Cela permet d'évaluer la déflection totale, la déflection élastique, et la deflection plastique. L'analyse des résultats obtenus par cet essai de chargement montre que des relations simples existent entre ces trois déflections pour les sols de fondation des aéroports canadiens, tout au moins pour des déflections allant de 0 à 1·75 cm. Ces relations sont notablement différentes, selon que le sol de fondation est argileux ou sablonneux. Par contre, ces mêmes relations ayant trait aux essais de chargement effectués à la surface des revêtements souples sont très semblables à celles obtenues pour leurs sols de fondation. Ces relations semblent être relativement constantes et indépendantes du diamètre de la plaque de chargement. Pour une déflection totale donnée, le rapport déflection plastique sur déflection totale augmente avec le nombre de répétitions de chargement nécessaires pour obtenir ces déflections.

Introduction

It is the principal purpose of this paper to point out the relationships between deflection, settlement and elastic deformation that have resulted from an analysis of data obtained from plate bearing tests performed by the Canadian Department of Transport on the subgrades and surfaces of flexible pavements at major airports in Canada. This is a matter of considerable interest because it has been suggested by some that 'elastic deformation', and by others that 'settlement', should be employed instead of 'deflection' as the basis for establishing flexible pavement thickness requirements. An earlier paper (McLeod, 1948a) provided some of this information for a 30 in. diameter bearing plate for 10 repetitions of load. The present paper extends this earlier study to cover the influence of other bearing plate diameters, and the effect of 1, 10, 100 and 1000 repetitions of load.

Fig. 1 illustrates the definitions of the terms 'deflection', 'settlement' and 'elastic deformation', as they are used in this paper. All three terms refer to movement of the bearing plate in the vertical direction. When the subgrade soil, or the surface of a flexible pavement, is subjected to a plate bearing test, the loaded area is depressed below its original elevation when the load is applied (Fig. 1). When the load is completely removed, the loaded area rebounds but does not return to its original datum or elevation. The term 'deflection' is given to the total vertical deformation that occurs when the load is applied while the residual vertical deformation, remaining after the load has been released, is designated 'settlement'. The difference between 'deflection' and 'settlement' as the load is applied and removed is defined as 'elastic deformation'. Consequently, 'elastic deformation' represents the rebound of the bearing plate when the load is released.

Relationships between Deflection, Settlement and Elastic Deformation

Since the beginning of its investigation of airport runway design and evaluation in 1945, the Canadian Department of Transport has employed a repetitive load test procedure for plate bearing tests that has been described elsewhere (McLeod,

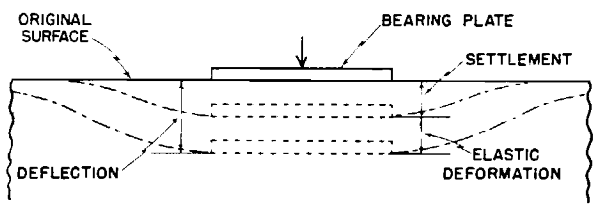

Fig. 1 Diagram illustrating deflection, settlement and elastic deformation
Diagramme illustrant la déformation, le tassement et le rebondissement

1947a, 1947b, 1948b, 1949), and which now conforms to A.S.T.M. D 1195–52T.

Very briefly, a load giving a deflection of about 0·04 in. is first applied, a stop watch is started, and the same load is maintained until the increment in deflection is 0·001 in./min. or

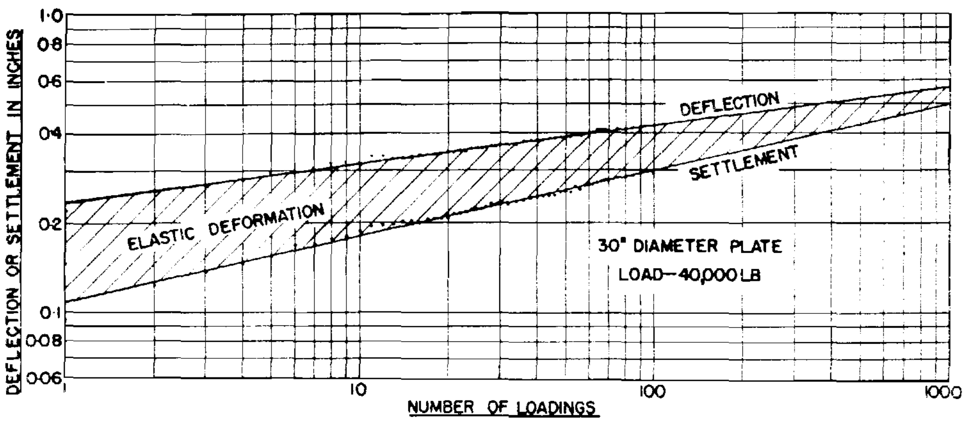

Fig. 2 Increase in deflection and settlement resulting from repetitions of a given load
Augmentation de la déformation et du tassement résultant de la répétition d'une charge donnée

less for three successive minutes. The load is then released, and is left off until the rate of rebound of the bearing plate is 0·001 in./min. or less for three successive minutes. The same load is applied and released six times in this manner. The load is next increased to give a deflection of about 0·2 in., and the same operations for application and release of load are repeated six times. Finally the load is increased to give a deflection of about 0·4 in. and, as before, is applied and released six times. Readings of the deflection gauges on the bearing plate are made at the end of every minute following application and release of load, and are entered in field notebooks as a permanent record.

These data have been analysed for possible relationships between deflection, settlement and elastic deformation for both subgrade and surface load tests for each airport, and for possible overall relationships between these variables for the 12 major airports extending across Canada for which these data have been investigated.

When the same load is repeated a number of times, both the deflection and settlement gradually increase. At a considerable number of test locations on both the subgrade and surface of flexible pavements a given load was applied and released 100 times. This usually requires a continuous testing period of about 18 hours. Fig. 2 illustrates the gradual increase in deflection and settlement that occurred when a load of 40,000 lb. on a 30 in. diameter bearing plate was applied and released 100 times. The end-point deflection rate for each application and each release of load was 0·001 in./min. or less for each of three successive minutes. It is apparent from Fig. 2 that the relationship between the number of repetitions of a given load *versus* both deflection and settlement can be expressed as a straight line on a log–log graph. Fig. 2 shows that elastic deformation is represented by the difference between deflection and settlement measurements for any given number of repetitions of load.

The data of Fig. 2 appear to plot as straight lines equally well on either a log–log or semi-log graph. However, a log–log graph represents a more conservative relationship between deflection or settlement *versus* the number of repetitions of a given load.

Fig. 2 shows that the best straight line through points for the first six applications is also the best straight line through the points representing deflection and settlement for the first 100 repetitions of load. Consequently, it appears quite valid to extrapolate the best straight line through the points representing deflection and settlement for each of the first six applications of load to at least 100 repetitions, and probably to 1000 or more repetitions of load.

As previously mentioned, for the repetitive load test procedure, employed by the Canadian Department of Transport, six applications and six releases of each of three different loads are made at each test location. This requires a continuous testing period of about six hours on the average. For each load, deflection and settlement values for each of the six repetitions are plotted *versus* the number of repetitions on either a semi-log or log–log graph like that of Fig. 2. Best straight lines are drawn through the 6 points in each case and extrapolated to 10, 100 and 1000 repetitions of load (McLeod, 1947a, 1947b, 1948b, 1949). The data from this semi-log or log–log plot are then used to prepare a graph of load *versus* deflection

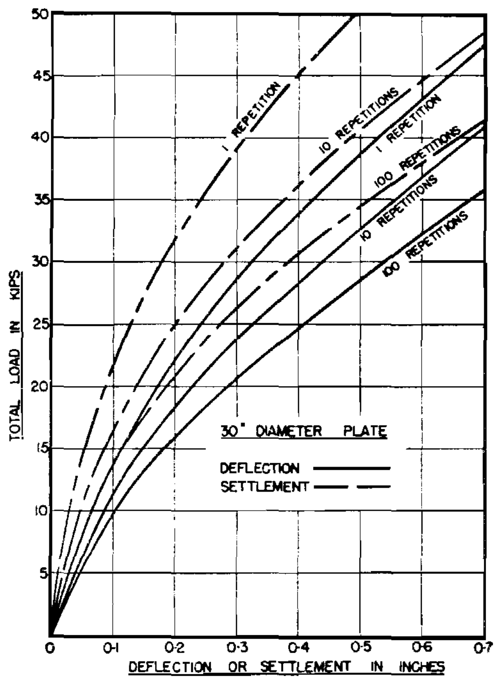

Fig. 3 Load *versus* deflection and settlement for 1, 10 and 100 repetitions of load
Charge *versus* deformation et tassement pour 1, 10 et 100 répétitions de la charge

and settlement for 1, 10, 100, 1000, etc., repetitions of load (Fig. 3).

Diagrams similar to Fig. 3 have been plotted for a large number of test locations on subgrades and surfaces of flexible pavements for bearing plates 12, 24, 30 and 36 in. diameter. Some load tests have been made with bearing plates 18 and 42 in. diameter, but their number is too small to provide representative data.

Relationships between deflection, settlement, and elastic deformation for a 30 in. diameter bearing plate for 10 repetitions of load—Up to the present time, the largest amount of data on the relationships between deflection, settlement and elastic deformation has been obtained for a 30 in. diameter bearing plate for 10 repetitions of load. More load tests have been made with the 30 in. bearing plate than that of any other diameter, and it is believed that extrapolation to 10 repetitions of load can be made accurately with a minimum of error.

From curves of load *versus* deflection and settlement at each test location for a 30 in. bearing plate for 10 repetitions of load, the ratio of settlement to deflection for each value of deflection can be obtained. For example, from Fig. 3, for a load of 25,000 lb. the deflection for 10 repetitions of load is 0·325 in., while the corresponding settlement for 10 repetitions of load is 0·2 in. Consequently, for a deflection of 0·325 in., the corresponding ratio of settlement to deflection is $0{\cdot}2/0{\cdot}325 = 0{\cdot}615$. Expressed in another way, for the conditions given, the settlement is 61·5 per cent of the deflection.

Average values for the ratio of settlement to deflection, corresponding to each value of deflection, have been obtained for the subgrade soils at each airport, and have been compared with the subgrades for different airports. Fig. 4 shows this

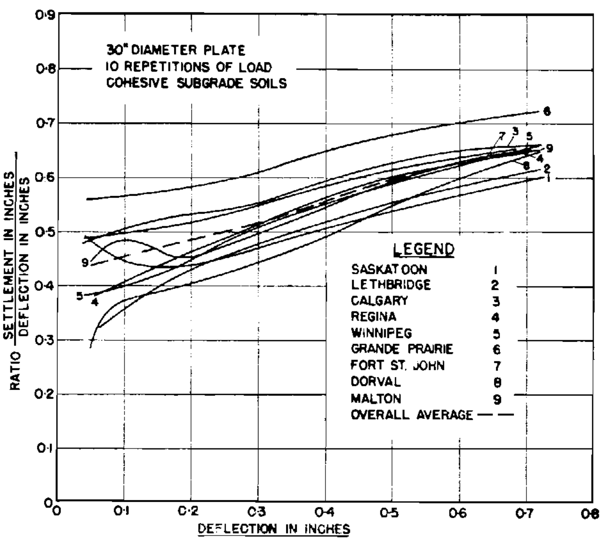

Fig. 4 Relationships between deflection and settlement for cohesive subgrade soils

Relations entre la déformation et le tassement pour terrains de fondation argileux

comparison for subgrade load tests at nine Canadian airports having cohesive subgrade soils. The broken line curve represents the overall average relationship between the ratio of settlement to deflection *versus* deflection for subgrade load tests at the nine airports.

In spite of the fact that these airports are distributed over a distance of at least 2000 miles, Fig. 4 shows that, for any given deflection, the ratios of settlement to deflection for the individual airports are all reasonably close to the broken line curve representing the overall average ratio. At 0·2 in. deflection the maximum deviation is 15 per cent, and at 0·5 in. deflection the maximum deviation is 9 per cent.

The overall average relationship, provided by the broken line curve of Fig. 4, has been utilized in the preparation of Fig. 5, which indicates the average value of settlement and of elastic deformation corresponding to any given deflection between 0 and 0·7 in. Fig. 5 shows that, for a deflection of 0·2 in., caused by 10 repetitions of load on a 30 in. bearing plate on these cohesive subgrade soils, the corresponding settlement and deflection will each be approximately 0·1 in. on the average. When the deflection is 0·5 in. under these conditions of load, the corresponding settlement and elastic deformation will average about 0·3 and 0·2 in., respectively. Fig. 5 also demonstrates that to obtain an elastic deformation, or a settlement of about 0·2 in. for a cohesive subgrade soil, the load required is, respectively, 1·6 times and 1·4 times the load that will give a deflection of 0·2 in.

Diagrams similar to Figs. 4 and 5 have been prepared from data for load tests on flexible pavements on cohesive subgrades, for load tests on sand subgrades, and for load tests on flexible pavements on sand subgrades, and are reported elsewhere (McLeod, 1948a).

Influence of bearing plate diameter on relationships between deflection, settlement and elastic deformation for 10 repetitions of load—In Figs. 4 and 5, relationships between deflection, settlement and elastic deformation for subgrades under flexible pavements have been presented on the basis of data for load tests on a 30 in. diameter bearing plate at 10 repetitions of load.

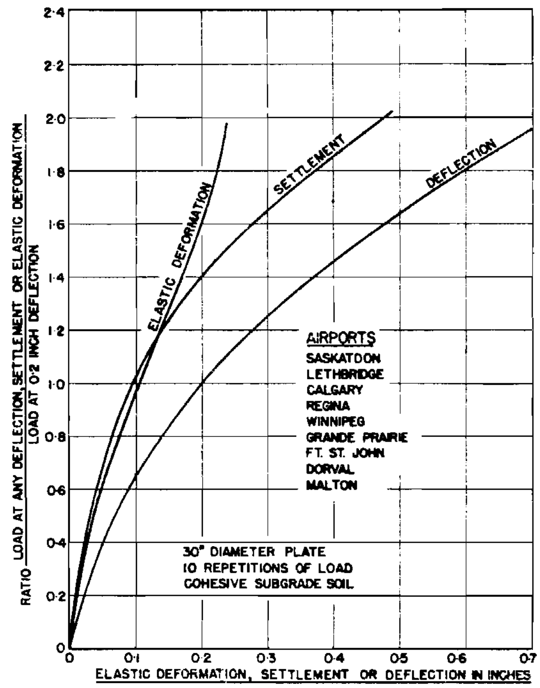

Fig. 5 Relationships between deflection, settlement and elastic deformation (cohesive subgrade soils)

Relations entre la déformation, le tassement et le rebondissement (terrains de fondation argileux)

In Figs. 6, 7, 8 and 9, the relationships between deflection, settlement and elastic deformation, provided by load tests on bearing plates with diameters of 12, 24 and 36 in., for 10 repetitions of load, are compared with those for load tests on the 30 in. diameter plate at 10 repetitions of load.

Fig. 6 compares the values of the ratio of settlement to deflection at each deflection for load tests on bearing plates, with diameters of 12, 24, 30 and 36 in. on the subgrades at airports with cohesive subgrade soils. Similar information is provided (Fig. 7) for load tests on the surfaces of flexible pavements at airports with cohesive subgrade soils. Fig. 8 is similar to Fig. 6, but pertains to subgrade load tests with bearing plates 24, 30 and 36 in. in diameter at airports with sand subgrades. Fig. 9 is similar to Fig. 7, but is concerned with load tests on the surfaces of flexible pavements at airports with sand subgrades. No test data for the 12 in. bearing plate were available for inclusion in Figs. 8 and 9.

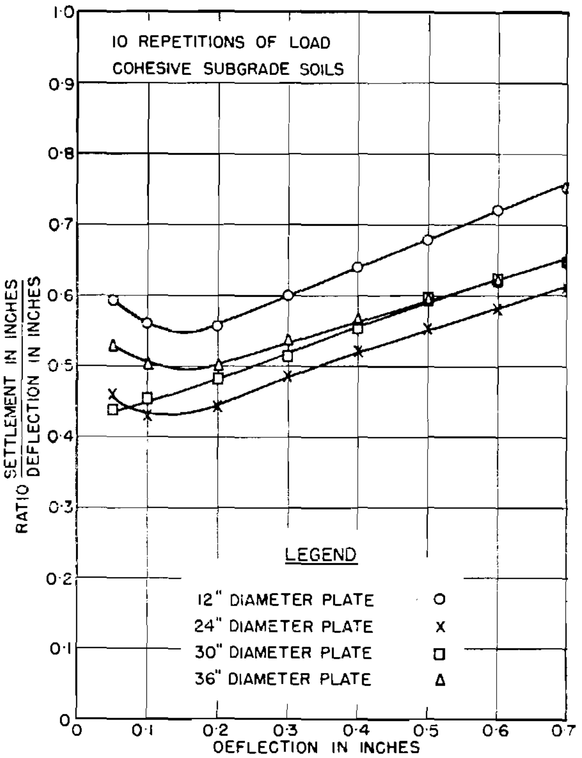

Fig. 6 Influence of diameter of bearing plate on the relationships between deflection and settlement for cohesive subgrade soils

Influence du diamètre du plateau de chargement sur les relations entre la déformation et le tassement pour terrains de fondation argileux

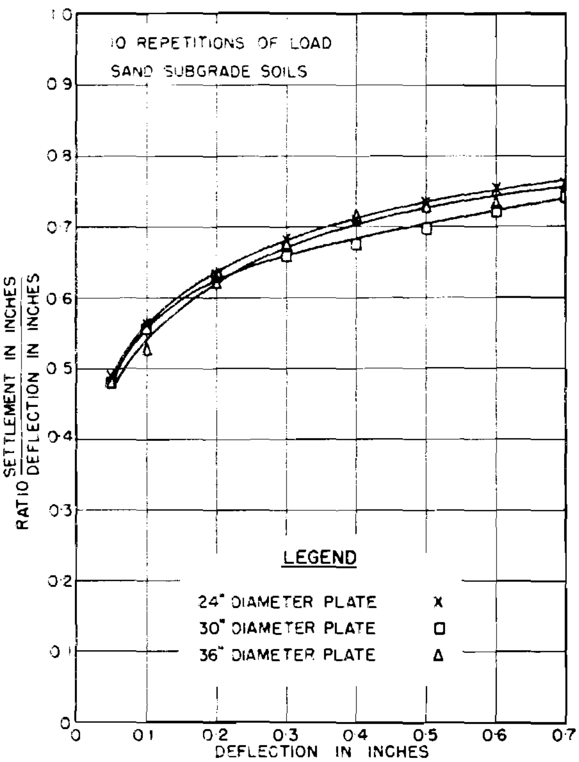

Fig. 8 Influence of diameter of bearing plate on the relationships between deflection and settlement for sand subgrade soils

Influence du diamètre du plateau de chargement sur les relations entre la déformation et le tassement pour terrains de fondation sablonneux

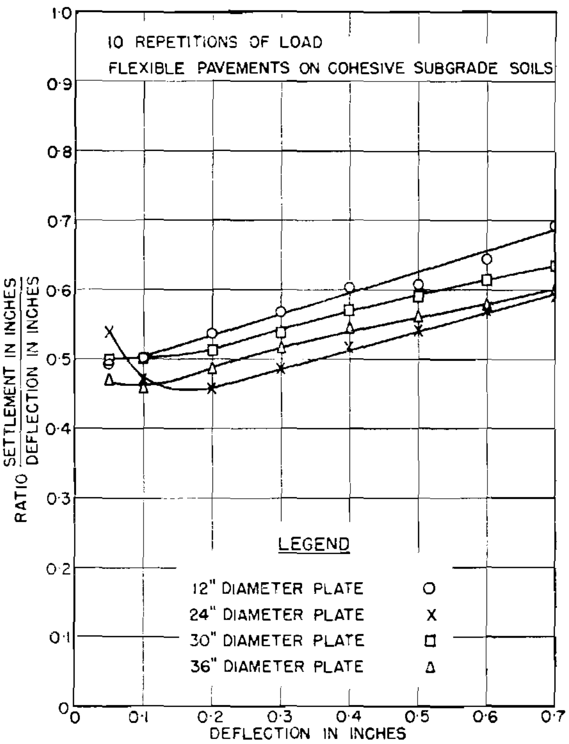

Fig. 7 Influence of diameter of bearing plate on the relationships between deflection and settlement for flexible pavements on cohesive subgrade soils

Influence du diamètre du plateau de chargement sur les relations entre la déformation et le tassement pour dallages flexibles sur terrains de fondation argileux

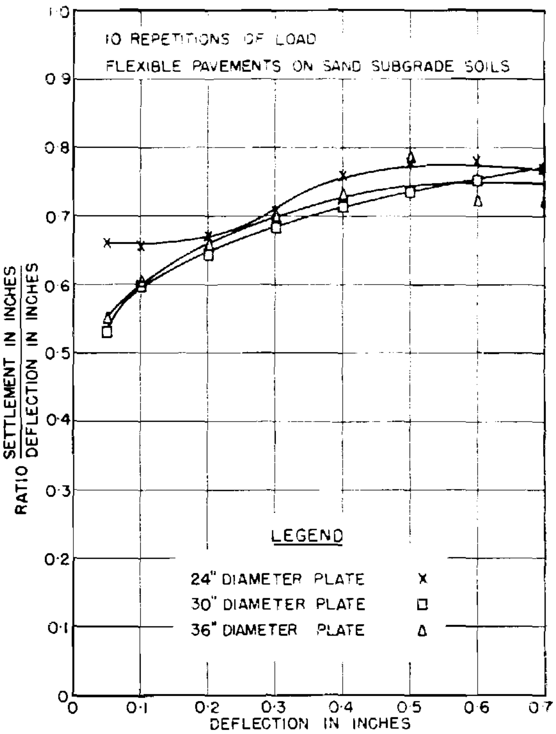

Fig. 9 Influence of diameter of bearing plate on the relationships between deflection and settlement for flexible pavements on sand subgrade soils

Influence du diamètre du plateau de chargement sur les relations entre la déformation et le tassement pour dallages flexibles sur terrains de fondation sablonneux

By comparing Fig. 6 with Fig. 7, it will be seen that for any given deflection the ratio of settlement to deflection for load tests on cohesive subgrade soils is very similar to that for load tests on the surfaces of flexible pavements over these cohesive subgrade soils. This is also true for Figs. 8 and 9 for load tests on sand subgrades, and on the surfaces of flexible pavements over these sand subgrades.

It is clear from Figs. 6, 7, 8 and 9 that there is no consistent tendency for values of the ratio of settlement to deflection at any given deflection, to either increase or decrease with increasing bearing plate diameter. Consequently, as a general conclusion, Figs. 6, 7, 8 and 9 tend to indicate that insofar as bearing plate size by itself is concerned, the value of the ratio of settlement to deflection for any given deflection is independent of the diameter of the bearing plate. This in turn implies that for 10 repetitions of load the relationships between deflection, settlement and elastic deformation, illustrated by Fig. 5, for load tests with the 30-in. diameter bearing plate on cohesive subgrade soils, represent those for other bearing plate sizes, at least over the range of 12 to 36 in. in diameter.

Influence of number of repetitions of load on relationships between deflection, settlement and elastic deformation—In Figs. 10, 11, 12 and 13 the influence of 1, 10, 100 and 1000 repetitions of load on a 36 in. diameter bearing plate is illustrated for load tests on cohesive subgrade soils, on surfaces of flexible pavements over cohesive subgrade soils, on sand subgrade soils, and on surfaces of flexible pavements over sand subgrades, respectively.

In each case, it is clear that for any given deflection the value of the ratio of settlement to deflection increases with the number of repetitions of load required to attain the deflection specified. Similar conclusions are provided by the load test data obtained for other bearing plate diameters.

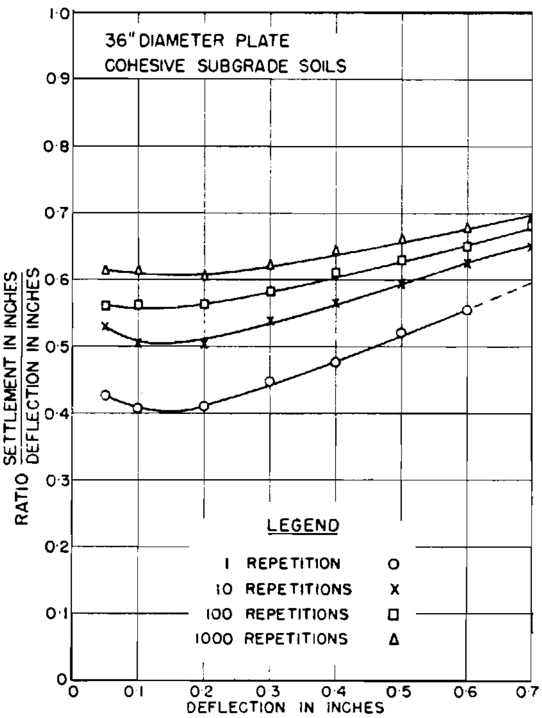

Fig. 10 Influence of number of repetitions of load on a 36 in. diameter bearing plate on the relationships between deflection and settlement for cohesive subgrade soils

Influence du nombre de répétitions de la charge sur un plateau de chargement de 36 pouces de diamètre sur les relations entre la déformation et le tassement pour terrains de fondation argileux

It should be pointed out that for any given deflection the applied load becomes smaller as the number of repetitions of load is increased. This is illustrated by Fig. 3, where a deflection of about 0·325 in. develops under 1 repetition of a load of 30,000 lb., or under 10 repetitions of a load of 25,000 lb., or under 100 repetitions of a load of about 21,600 lb.

The remarkable similarity of the corresponding curves for 1, 10, 100 and 1000 repetitions of load in Figs. 10 and 11 should be noted. Fig. 10 pertains to load tests on cohesive subgrade soils and Fig. 11 to load tests on the surfaces of flexible pavements over cohesive subgrade soils. The curves for 1, 10, 100 and 1000 repetitions of load in Fig. 10 almost overlap the corresponding curves in Fig. 11. With the exception of the curve for 1 repetition of load (Fig. 12) this is also generally true for the curves in Figs. 12 and 13. This provides further evidence that the relationships between deflection, settlement and elastic deformation provided by load tests on the surface of flexible pavements are controlled by the deflection, settlement and elastic deformation characteristics of the underlying subgrade.

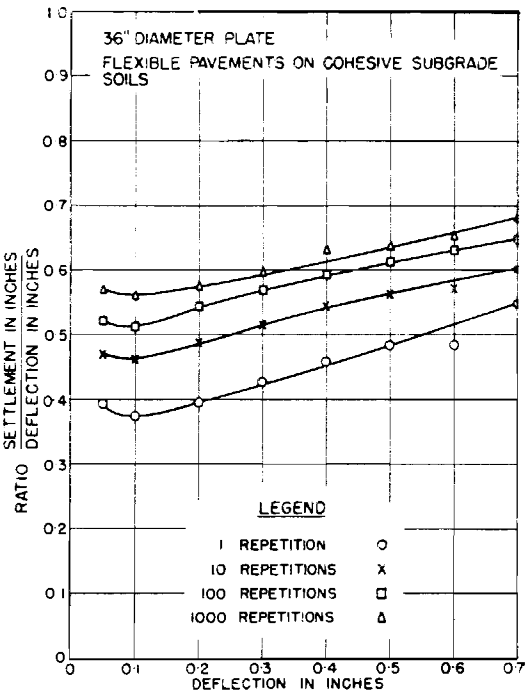

Fig. 11 Influence of number of repetitions of load on a 36 in. diameter bearing plate on the relationships between deflection and settlement for flexible pavements on cohesive subgrade soils

Influence du nombre de répétitions de la charge sur un plateau de chargement de 36 pouces de diametre sur les relations entre la déformation et le tassement pour dallages flexibles sur terrains de fondation argileux

Summary and Conclusions

The data that have just been presented seem to lead to several clearly defined conclusions, at least on the basis of the repetitive plate bearing test procedure employed by the Canadian Department of Transport.

(1) For any given number of repetitions of load, plate bearing test data indicate that certain simple relationships exist between the deflection, settlement and elastic deformation characteristics of subgrade soils, and of flexible pavements, e.g. Fig. 5.

(2) In all cases, the ratio of settlement to deflection increases, and the ratio of elastic deformation to deflection decreases, as the deflection of the bearing plate under load increases, e.g. Figs. 4, 6–10, etc.

(3) These relationships are different in cohesive and in sand subgrade soils. Other factors being equal, for any given deflection, the ratio of settlement to deflection is smaller, and the ratio of elastic deformation to deflection is greater for cohesive than for sand subgrade soils, e.g. compare Figs. 6 and 8, and Figs. 10 and 12. Expressed more simply, cohesive subgrade soils behave somewhat more elastically than sand subgrade soils under the load test procedure employed.

(4) The relationships between deflection, settlement and elastic deformation provided by load tests on the surface of a flexible pavement are almost identical with, and appear to be controlled by, the deflection, settlement and elastic deformation characteristics of the underlying subgrade, e.g. compare Figs. 6 and 7, 8 and 9, 10 and 11, 12 and 13.

(5) For any given subgrade soil, and for any given number of repetitions of load, the relationships between deflection, settlement and elastic deformation appear to be independent of the size of the bearing plate, at least for bearing plates from 12 to 36 in. in diameter, Figs. 6, 7, 8 and 9.

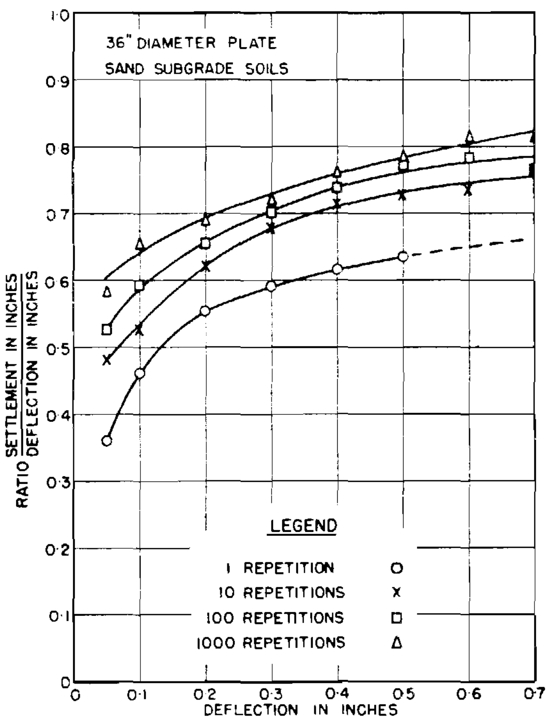

Fig. 12 Influence of number of repetitions of load on a 36 in. diameter bearing plate on the relationships between deflection and settlement for sand subgrade soils

Influence du nombre de répétitions de la charge sur un plateau de chargement de 36 pouces de diamètre sur les relations entre la déformation et le tassement pour terrains de fondation sablonneux

(6) For any given subgrade soil, the relationships between deflection, settlement and elastic deformation vary with the number of repetitions of load. They vary in such a way, that for any given deflection the ratio of settlement to deflection increases and the ratio of elastic deformation to deflection decreases, as the number of repetitions of load required to attain the given deflection is increased, Figs. 10, 11, 12 and 13.

(7) It has been proposed that instead of basing the thickness design of flexible pavements on deflection criteria it should be established upon certain settlement values. It has also been suggested that elastic deformation is the only adequate basis of design for flexible pavement thickness requirements. The data presented in this paper indicate that since for any given subgrade, the deflection, settlement and elastic deformation characteristics appear to be closely related, it makes no difference which one of these three vertical deformation properties is selected as the basis for flexible pavement thickness design. However, since deflection is probably the easiest of these three vertical deformation characteristics to measure accurately during a plate bearing test, it is suggested that flexible pavement thickness requirements continue to be based on deflection criteria.

(8) It is to be emphasized that the relationships between deflection, settlement and elastic deformation for cohesive subgrade soils, for flexible pavements on cohesive subgrade soils, for sand subgrades, and for flexible pavements on sand subgrades that have been presented in this paper are based upon the particular load test procedure employed by the Canadian Department of Transport, and pertain to flexible pavements on Canadian soils. For other load test procedures, and for flexible pavements in other areas, particularly in dissimilar geographical areas, quite different relationships may be obtained.

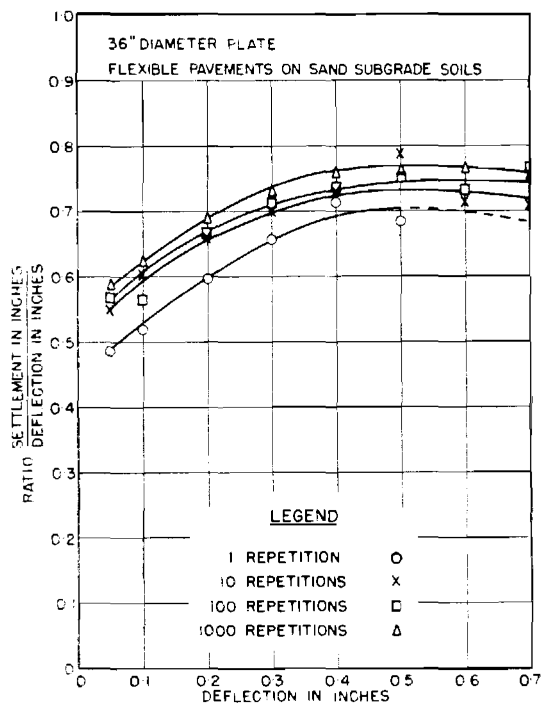

Fig. 13 Influence of number of repetitions of load on a 36 in. diameter bearing plate on the relationships between deflection and settlement for flexible pavements on sand subgrade soils

Influence du nombre de répétitions de la charge sur un plateau de chargement de 36 pouces de diamètre sur les relations entre la déformation et le tassement pour dallages flexibles sur terrains de fondation sablonneux

The material presented in this paper forms part of an extensive investigation of airports in Canada that was begun by the Canadian Department of Transport in 1945. Air Vice-Marshal A. de Niverville, Director of Air Services, is responsible for the general administration of this investigation. It comes under the direct administration of Mr Harold J. Connolly, Chief Construction Engineer, Mr George W. Smith, Assistant Chief Construction Engineer, and Mr D. A. Lane. In their respective districts the investigation is carried on with the generous co-operation of District Airway Engineers G. T. Chillcott, E. B. Wilkins, L. Millidge, R. A. Bradley, F. L. Davis and W. D. G. Stratton.

In the preparation of the material on which this paper is based, special mention should be made of the able assistance provided *by Mr C. L. Perkins, Mr A. Douglas, Mr J. Hvodanski, and Mr D. Segal. Mr Perkins' skill and care in drafting the diagrams is also acknowledged.*

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