4/22

Stress Distribution beneath Pavements of Different Rigidities

Distribution des contraintes sous des revêtements de différentes rigidités

by George F. Sowers, Professor of Civil Engineering, Georgia Institute of Technology and Consulting Soil Engineer, Law Engineering Testing Co., Atlanta, Georgia, U.S.A.
and
Aleksandar B. Vesić, Associate Professor of Civil Engineering, Georgia Institute Of Technology Atlanta, Georgia, U.S.A.

Summary

Full-scale tests have been made of single, dual and dual-tandem static tire loads on flexible pavements in order to determine the actual stress distribution in the subgrade and to evaluate the relative load spreading ability of different base course materials now in use.

A comparison of the test results with stresses computed for a homogeneous, isotropic soil by the Boussinesq theory indicates that base courses that do not possess tensile strength have limited load spreading ability. However a soil-cement base course, having some tensile strength, was much more effective in load spreading. The distribution pattern in this case was similar to that computed by the Burmister-theory of multi-layered systems.

Sommaire

Des essais à grande échelle ont été exécutés avec différents pneus chargés (pneus individuels, jumelés et jumelés en tandem) sur revêtement flexibles en vue de déterminer la distribution réelle des contraintes dans la fondation et d'évaluer la capacité relative de répartition des charges des différents matériaux utilisés pour les couches de base.

Les résultats des essais indiquent que les couches de base qui n'ont pas de résistance à la traction ont une capacité très limitée de répartition des charges. La répartition des contraintes dans les revêtements avec de telles couches de base, suit en général la théorie de Boussinesq pour sols homogènes. Par contre une couche de base en sol-ciment, ayant une certaine résistance à la traction, est beaucoup plus efficace pour répartir les charges. La répartition des contraintes dans ce cas est analogue à celle calculée par la théorie des couches multiples de Burmister.

Introduction

The primary function of a pavement is to spread concentrated loads from vehicle tires into the subgrade soil so that they do not cause shear failure or excessive deflection. Therefore any rational design of a pavement system must be based on an analysis of stresses and deformations in the system. Such analyses have been made possible by the solutions based on theory of elasticity of the problem of layered systems (Burmister, 1943, 1945; Fox, 1948; Hank and Scrivner, 1948; Acum and Fox, 1951).

A flexible pavement system can be represented by three layers (Fig. 1) each having different elastic properties described by the moduli of elasticity E and Poisson's ratio ν. In many cases the surface course has a rigidity comparable to that of the base so that for the purpose of analysis a two-layer system is considered.

The stress analyses in layered systems are generally based on the following simplifying assumptions :

(a) The materials in each layer are perfectly elastic, homogeneous and isotropic, having different elasticity moduli and the same constant Poisson's ratio of 0·50.

(b) All the layers are of infinite extent in the horizontal direction ; the subgrade layer is infinite in extent also in the vertical direction.

(c) Interfaces between layers are either perfectly rough or perfectly smooth.

(d) Load is acting on the surface layer uniformly distributed over a flexible circular bearing area.

These assumptions, to a greater or a lesser degree, always deviate from the actual conditions encountered in pavement systems. First, none of the materials are perfectly elastic : they have non-linear stress-strain relationships, they exhibit hysteresis and have variable E and ν. In addition the properties of these materials are different in tension than in compression (some of them do not have tensile strength at all). Second, the layers are not perfectly homogeneous and isotropic. The surface, base and the compacted part of the subgrade are likely to be reasonably homogeneous but laminated, while the subgrade is likely to change its properties with both depth

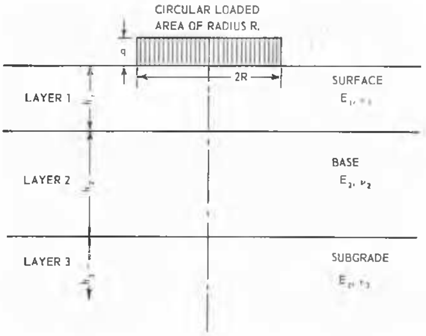

Fig. 1 A flexible pavement system.
Couches dans un revêtement flexible.

and location. Third, the usual conditions at the interface are between the two theoretical cases (perfect continuity or perfect lack of continuity). Fourth, surface layers are finite in extent in the horizontal direction; subgrade may be also finite in extent in the vertical direction. Fifth, the load applied is neither uniform nor circular.

Although many of the mentioned differences between the actual conditions and the assumptions for analysis are not likely to cause important discrepancies, it is reasonable to expect that some of them may cause serious deviations in stress distribution. Unfortunately, there is still practically no experimental data available on the stresses actually produced in layered pavement systems.

The purpose of this investigation was to determine the stresses produced in subgrades by wheel loads comparable to those of the heaviest highway vehicles and to evaluate the load spreading ability of different base course materials now in use.

Experimental apparatus

Full scale test sections of pavements were built with earth pressure cells in the subgrade. These were static-loaded with tires to simulate vehicle loadings and the stresses and deflections were measured.

The pavement and subgrade were constructed in a concrete test pit 8 ft. wide, 12 ft. long and 7 ft. deep as shown in Fig. 2.

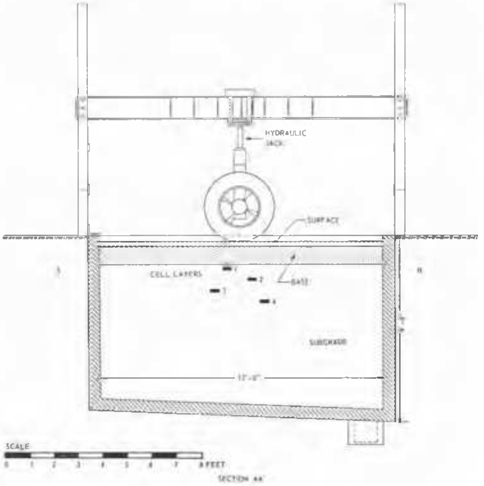

Fig. 2 Cross-section of the test pit showing position of layers of pressure cells and the loading equipment.

Coupe transversale de la fosse d'essai montrant la position des couches, des cellules de pression et de l'installation de chargement.

A steel loading frame was attached to the pit with a heavy beam from one end to the other. A hydraulic jack mounted on a carriage riding on the beam could be easily positioned to apply load anywhere on the pit center line (Fig. 3).

Four different wheel assemblies were used, similar to present heavy truck design : single, dual, and dual tandem. Nine inch tires on 20 in. diameter rims were mounted on the assemblies and inflated to pressures of 80 to 90 lb. per sq. in., depending on the tire load*.

Twenty-five earth pressure cells were employed to measure the stresses. Each consisted of a thin circular aluminium diaphragm mounted on a heavier base plate. The earth pressure caused the diaphragm to bend and stretch, and these deformations were measured by electric *SR*-4 strain gauges mounted on the diaphragm and on the base. The cells and the wires leading from them were sealed with polyvinyl cement. Each cell was individually calibrated in soil by applying a uniform pressure to the soil surface with an air-loaded membrane.

Fig. 3 General view of the model with the loading equipment and strain-measuring apparatus.

Vue générale du modèle avec l'installation de chargement et l'appareil de mesure des déformations.

The cells were placed at different levels in staggered rows across the pit so as to minimize any interference between them. The row locations are shown in the cross section, Fig. 2.

Subgrade and pavement

The subgrade soil was a micaceous sandy silt with a liquid limit of 45, plasticity index of 8 and approximately 40 per cent finer than 0·074 mm. The optimum moisture was 25 per cent and the maximum density 94·5 lb. per cu. ft. by the standard Proctor (ASTM D698-58 T) compaction test. The deepest 3 ft. of subgrade was compacted in the pit with no control to simulate a natural subgrade; and above it was placed 3 ft. of controlled subgrade compacted in thin layers to 95 per cent of the maximum to simulate the compacted subgrades now used in highway work.

Three different base courses have been tested ;

(a) Silty, well-graded sand. Maximum density 128 lb. per cu. ft., optimum moisture 10 per cent.

(b) Soil bound macadam, 40 per cent soil, 60 per cent crushed stone from 38·2 mm to 4·76 mm.

(c) Soil cement — soil bound macadam plus four per cent portland cement.

All three were compacted to 100 per cent of their maximum density in thin layers to form an 8 in. thick base course.

A three inch thick asphaltic concrete wearing surface completed the pavement.

---

* The design load for such a tire is 9 000 lb. but a 50 per cent over load is permissible under some conditions.

Test procedure

The pressure cells were installed during the subgrade compaction so that each cell was imbedded in soil having the same elastic properties as the greater mass of the subgrade. The base and pavement followed immediately.

Each different pavement system was loaded according to the following schedule :

(a) Ten positions of the load on the longitudinal axis of the pit : center, 3 in., 6 in., 12 in. and 24 in. each side of the center and 36 in. on one side of the center.

(b) Single tire : 2 500, 5 000, 9 000, 13 500 lb. loading at each position ; dual tire : 5 000, 9 000, 13 500, 18 000 lb. at each position. A few tests were made using a dual tandem load with 48 in. spacing center to center of wheels as is standard on highway trucks in the United States.

Pressure readings were made with all the cells for each load and for each position. Deflections of the pavement were measured by micrometer dial gauges for a limited number of positions and loads.

After each pavement test was complete, moisture and density tests were made in the base and subgrade. Undisturbed samples were taken of the controlled top 3 ft. of subgrade and in the silty sand base. (It was impossible to make undisturbed samples of the bases containing the crushed stone.

Plate load tests were made on the top surfaces of the base and the subgrade, using circular and square plates.

Triaxial shear tests were performed on the 4″ diameter undisturbed samples of subgrade and base to determine the moduli of elasticity. Similar tests were made on 8″ in diameter specimens of compacted macadam and soil-cement bases, prepared at the same density as in the actual model.

Test results

The tire prints for different loadings are shown in Fig. 4. At very small loads the tire exerts a nearly circular load but at high loads the area is a rectangle whose length is more than twice its width.

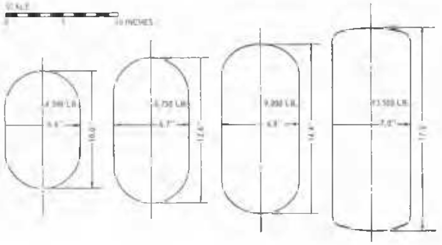

Fig. 4 Tire prints for different loadings on a 9 inch tire on 20 inch rim. Tire pressure 86 lb/in². Design load 9 000 lb.

Empreintes des pneus pour differentes charge (9-inch pneu on 20-inch jante) pression de gonflement 86 lb/in². Charge de projet du pneu 9 000 lb.

Typical test results of stresses in the subgrade are shown on Figs. 5, 6, 7, 8, and 9. These give the pressure increase at each depth and for different horizontal distance from the center of the load. Also shown on each graph is the theoretical pressure computed by the elastic theory of a homogeneous isotropic soil (Boussinesq analysis) and a uniformly loaded rectangular area. For the soil cement base, curves are plotted also showing stress distribution computed by the two-layer theory assuming the base and surface courses to have the same E.

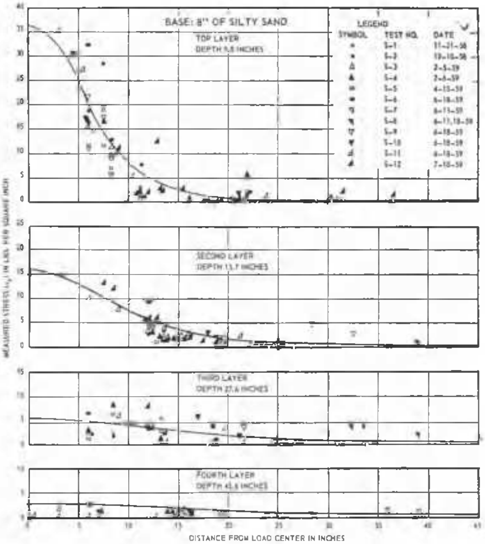

Fig. 5 Measured stresses for a single wheel load of 9 000 lb. Base : silty sand. Curves show stress distribution for homogeneous soil.

Contraintes mesurées sous une charge de 9 000 lb sur un pneu individuel. Base : sable-limon. Les courbes montrent la distribution théorique des contraintes dans un sol homogène.

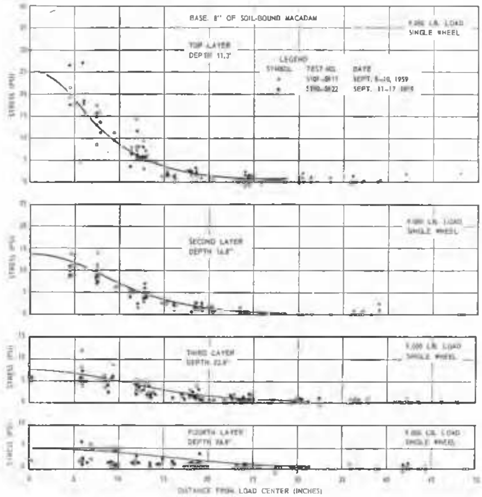

Fig. 6 Measured stresses for a single wheel load of 9 000 lb. Base : soil-bound macadam. Curves show stress distribution for homogeneous soil.

Contraintes mesurées sous une charge individuelle de 9 000 lb. Base : macadam, lié par le sol. Les courbes montrent la distribution théorique des contraintes dans un sol homogène.

The results for the silty sand base (Fig. 5) show a stress distribution pattern close to that computed by the Boussinesq theory. This indicates that the load spreading ability of such a base is no better than that of a homogeneous soil. However the ratio of the elasticity moduli obtained by triaxial and plate-load tests was 8, so that the stresses beneath the center of the load according to the two-layer theory should be considerably lower. Similar results were obtained for the soil-bound macadam base, where the ratio of elasticity moduli was 9. (Fig. 6 and 7).

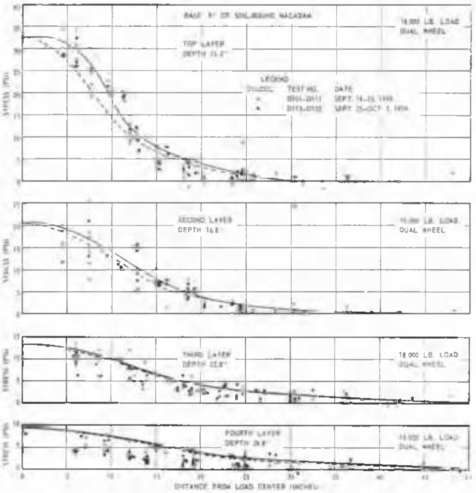

Fig. 7 Measured stresses for a dual wheel load of 18 000 lb. Base : soil-bound macadam. Curves show stress distribution in homogeneous soil for two median sections N.-S. (Solid line) and E.-W. (dotted line).

Contraintes mesurées sous une charge de 18 000 lb. sur pneux jumelés. Base : macadam, lié par le sol. Les courbes montrent la distribution théorique des contraintes dans un sol homogène pour deux sections médianes N.-S. et E.-O.

The observed disagreement with the two-layer theory may be explained by the lack of tensile strength of the upper layer. It supports to a certain extent a common practice in design of flexible pavements (CBR) of neglecting any effect of base course rigidity in determining the required pavement thickness.

As shown by the results, Figs. 8 and 9, the soil cement base is much more efficient in spreading the wheel load than the other two bases tested*. The results show the same trend as do the stresses computed by the elastic layer theory (laboratory and plate load tests indicated a ratio of elasticity moduli of 100). Better agreement with the Burmister theory is explained by the fact that the soil-cement base tested has a remarkable tensile strength.

Concerning the stresses produced by the dual tandem tires it was found, both analytically and by model tests, that they were no different than those produced by the dual tires with the same tire load. The 48 in. spacing is sufficiently

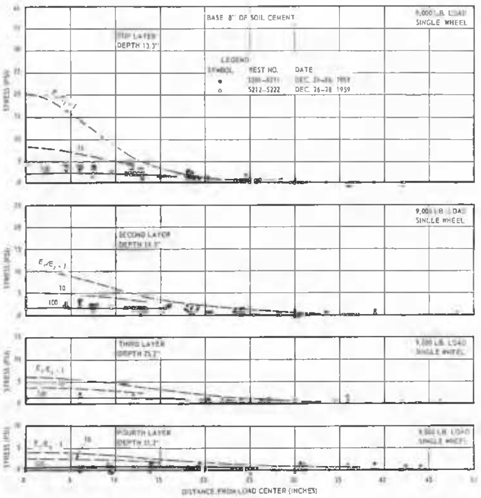

Fig. 8 Measured stresses for a single wheel load of 9 000 lb. Base : soil-cement. Curves show theoretical stress distribution for a two-layer system with rough interface and various ratios E_1/E_2.

Contraintes mesurées sous une charge individuelle de 9 000 lb. Base : sol-ciment. Les courbes montrent la distribution théorique des contraintes dans un sol composé de deux couches avec interface rugueuse et pour different rapports E_1/E_2.

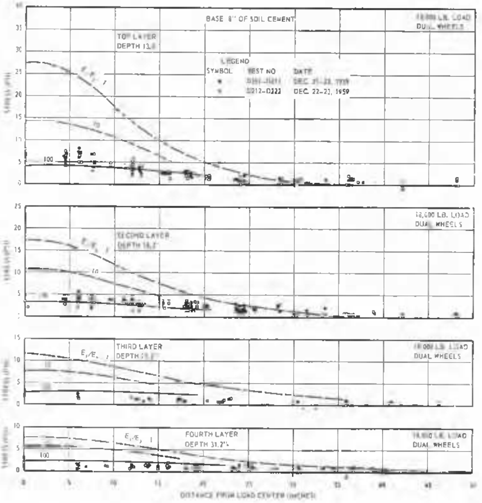

Fig. 9 Measured stresses for a dual wheel load of 18 000 lb. Base : soil-cement. Curves show theoretical stress distribution for a two-layer system with rough interface and various ratios E_1/E_2.

Contraintes mesurées sous une charge de 18 000 lb. sur pneus jumelés. Base : sol-ciment. Les courbes montrent la distribution théorique des contraintes dans un sol composé de deux couches avec interface rugueuse et pour différents rapports E_1/E_2.

---

* The permanence of this greater load spreading ability of soil cement must be investigated before final conclusions are reached. Experience shows that soil cement bases develop cracks after repeated loading. These might lead to behaviour similar to that of bases without tensile strength.

large that the load from one pair of tires does not contribute to the stresses beneath the other set in the upper 3 feet. Below three feet their interference increases; however, the stresses at that level are not sufficiently great for truck tire loads to be of concern in pavement design.

Acknowledgement

This work was sponsored by the Georgia State Highway Department, the U.S. Bureau of Public Roads, and the Engineering Experiment Station of the Georgia Institute of Technology.

The authors are indebted to Messrs. C. E. Hedges, W. H. Johnson, F. Chabrol, C. E. Snepp, W. L. Boyd, R. E. Housworth, M. J. Grandolfi and B. E. Cox, Graduate Research Assistants for their assistance in the investigations.

References

[1] Burmister D. M. (1943). The theory of stresses and displacements in layered systems and application to the design of airport runways. *Proceedings, Highway Research Board,* vol. 23 (1943), p. 126.

[2] — (1945) The general theory of stresses and displacements in layered systems, *Journal of Applied Physics*, vol. 16, 1945, p. 296.

[3] Fox L. (1948). Computation of traffic stresses in a simple road structure, *Road Research Paper 9*, Road Research Laboratory, H. M. Stationery Office, London, 1948.

[4] Hanck and Scrivner (1948), Some numerical solutions of stresses in two and three layered systems, *Proceedings Highway Research Board*, vol. 28, 1948, p. 457.

[5] Acum W. E. A. and L. Fox (1951). Computation of load stresses in a three layered elastic system, *Geotechnique*, vol. II, No. 4, Dec. 1951, p. 293.