while a heavy clay soil compacted to Standard density will require nearly three times this percentage for saturation. The subgrade soils encountered in the two investigations were found to belong to the A2 non plastic and plastic, A4, A7-5, and A7 Subgrade Groups, as classified by the Public Roads Administration,and the moisture percentages were found to vary more with the type of subgrade than with the seasons of the year. A preliminary examination of the data obtained to date indicates that, in general, the moisture contents of subgrade soils belonging to the A2 and A4 groups stay below the point of saturation the year around, and in the majority of cases do not exceed the optimum moisture for Standard Compaction, which is the moisture contents used in the soils that have been tested for bearing capacity by load tests. The moisture contents of the subgrade soils belonging to the A7-5 and A7 groups ,however,were found to approach the saturation point, which exceeded the optimum moisture for Standard Compaction. In some cases this excess was quite appreciable, which will in all probability necessitate corrections to be made to the load test values obtained on these type of soils. Future load tests made on soils of these types will be conducted at higher moisture contents than in the past. Just how much higher moisture contents will be used and their relation to the saturation point of the compacted soil, the optimum moisture for Standard compaction, the Plastic Limit, or any other test value is yet to be determined by a careful study of the data obtained from the two investigations. It is not expected that this change will materially affect the values used in present design practices in this State as they are somewhat conservative due to the lack of exact information concerning moisture conditions at the time the values were tentatively adopted.

CONCLUSIONS

The evaluation of highway subgrades can be accurately done by the use if plate bearing tests if the proper testing technique is followed and the results correctly analysed. The testing technique described and the analysis of the data obtained in which stress reactions and soil coefficients are used to calculate bearing capacity seem to the writer to be sound, and while the work required seems to be considerable, when compared with that required by some other methods, the results achieved are more reliable and useful in bearing capacity determinations.

Conditions of moisture to be encountered is a most important factor in placing the correct evaluation on a subgrade, since this factor has much influence on bearing capacity.Assumptions not based on factual data obtained from thorough investigations may lead to errors of some magnitude.

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FLEXIBLE PAVEMENT DESIGN CRITERIA FOR VERY HEAVY MULTIPLE WHEEL LOAD ASSEMBLIES

VIII b 10

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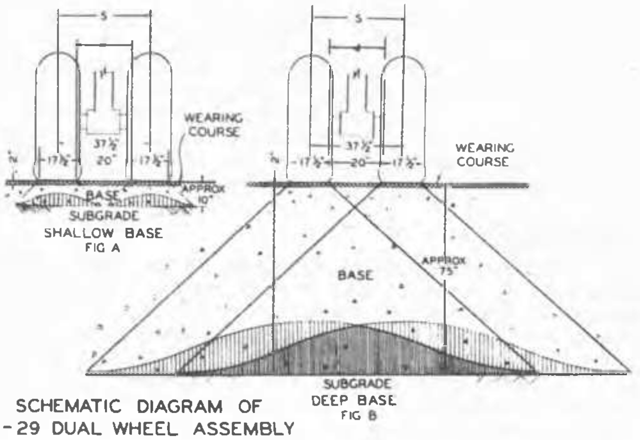
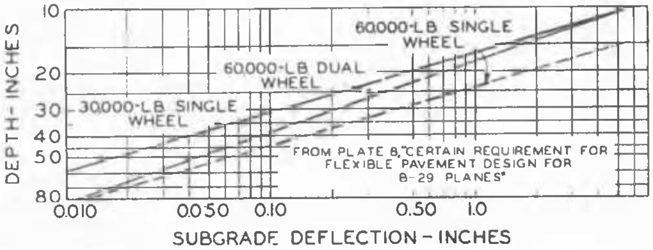
The present trend in landing gear assemblies for the very heavy airplanes is toward multiple wheels..It is expected for the near future that these planes will have their weight carried by two principal wheel assemblies,each composed of a twin-tandem arrangment of wheels with the tires inflated to as high as 200 psi with 300-psi pressures a possibility. This paper will present the method used by the Corps of Engineers to develop flexible pavement design criteria considered satisfactory to support this type of wheel load. It is recognized that complete design criteria will include requirements as to the type and quality of the several component parts of the pavement structure, and compaction requirements to prevent detrimental settlement. However, this discussion will be limited to the development of total thickness requirements of base and pavement to prevent shear failure in the underlying subgrade soil.

To date, the Corps of Engineers has no factual data relative to requirements for high pressure tires and for twin-tandem assemblies. Single wheel design curves for wheel loads up to 200,000 lb have been developed and are believed reasonable for tire pressures of about 100 psi. These curves are presented in Part XII of the Engineering Manual published by the Office, Chief of Engineers, and their development has been the subject of numerous papers. 1), 2). Data are available and an analysis has been made for twin wheels as a result of a special study to determine the flexible pavement requirements for the B-29 Superfortress.3) A method of design for any multiple wheel assembly and for tires inflated to 100 psi has also been presented. 4) Therefore, although the method of design which will be presented must be considered as tentative and will require validation, it is not entirely theoretical since it does have some foundation of ac-



SCHEMATIC DIAGRAM OF B-29 DUAL WHEEL ASSEMBLY

FIG. 1



SUBGRADE DEFLECTIONS
SINGLE VS DUAL WHEELS

FIG. 2

tual test background. This paper will (1) briefly review the development of design curves for multiple wheel loads based on single wheel load curves designed for tires inflated to 100 psi, (2) present the development of single wheel load curves for tires inflated to pressures up to 300 psi, and (3) present design curves for high pressures tires of a specific twin-tandem assembly for the purpose of illustration.

As previously noted, a complete explanation of the development of multiple wheel design curves may be found in the referenced Waterways Experiment Station Bulletin No. 29. Since this bulletin has not received wide distribution the method will be reviewed very briefly. Figure 1 is a schematic diagram of the B-29 twin wheel assembly on a thin and a thick flexible pavement. The design load on the twin assembly of the B-29 plane is 60,000 lb -- 30,000 on each tire, which is inflated to about 80-lb pressure. The diagram on the left refers to the case of a shallow base and implies that the subgrade is strong.

The diagram on the right refers to the case of the thick base and implies that the subgrade is weak. On each diagram shading is shown beneath each tire to suggest the distribution of induced stresses in the subgrade. Whether or not the distribution is correctly shown, it must be conceded that at some shallow base thickness the two wheels of the twin assembly will stress the subgrade as practically independent 30,000-lb units with little overlapping of stresses. With reference to the diagram on the right under a very deep base the stresses overlap considerably from the two wheel loads. It is believed that there is a depth where the overlapping of stresses would be so great that the stress induced in the subgrade from the twin wheel assembly would be, for all practical purposes, the same as that induced by a single 60,000-lb wheel load. Thus it was reasoned that the thickness design curves for the B-29 plane must range between the curves for the 30,000- and 60,000-lb single wheels. The problem of determining design curves for the B-29 twin wheel was narrowed to finding:

a The thickness at which each tire stresses the subgrade as an independent unit.

b The thickness at which the two tires stress the subgrade as one single unit.

It was further reasoned that if these two thicknesses could be determined, thickness requirements between the two values would vary in an orderly manner.

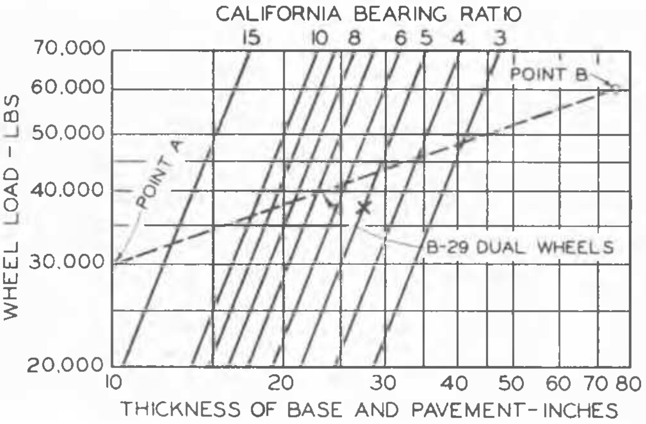
The thickness at which each tire of the B-29 twin assembly acts as an independent unit and the thickness at which the two tires act as a single unit were determined by comparison of vertical stresses, shearing stresses and deflections. The computations for the vertical and shearing stresses were made using Boussinesq's formulas assuming homogeneous material. Such computations are not new and will not be presented in this paper. The comparisons based on deflections are from actual test data utilizing a B-24 plane for single and a B-29 plane for twin wheel loads. The method of comparison will be briefly described in the following paragraphs.

Figure 2 is a plot of subgrade deflections under different loads of single and twin wheels. The bold parts of the curves represent the range of the actual test data. For a given wheel load the deflection decreases as the thickness of base and pavement increases; or for a given thickness, the greater load produces the greater deflection.

It will be noted that the deflection data plot as straight lines on the logarithmic graph. The curves for the two single wheel loads are parallel. The curve for the twin wheel lies between the two at a steeper slope. It was reasoned that by extending these curves upward, the intersection would represent depths at which the twins would act as independent 30,000-lb wheel loads. Also by extending the curves downward the intersection with the single 60,000-lb wheel load curve would represent the point at which the twin tires stress the subgrades as a single 60,000-lb wheel load. Such an extension is shown on the chart by the light lines. The curve for the twin wheel intersects the 30,000-lb single at about 10 in; the twin and the 60,000-lb single at about 80 in. Other deflection data for conditions not shown indicate depths of about 10 and 75 in. The computations of both vertical and shearing stresses showed the latter values to be reasonable and they were adopted.

The next step in the problem was to develop from these limits a design curve for the B-29 plane. In developing this curve single wheel load design curves were used. They were plotted in a special form suited to this analysis as shown on figure 3. The B-29 curve is developed as follows: The thickness at which the tires act as independent units, 10 in., and the tire load, 30,000 lb, is indicated as point A. The thickness at which the twins act as one tire, 75 in., and the total 60,000 lb, is indicated as point B. Between these two points it was reasoned that the thickness requirements would vary in a logical manner and they were therefore joined by a straight line. The intercepts of this line with each CBR curve determine the thickness requirement for the B-29 curve.

The next step was to extend the method to



DEVELOPMENT OF DESIGN CURVES-60,000 LB LOAD ON B-29 DUAL WHEELS

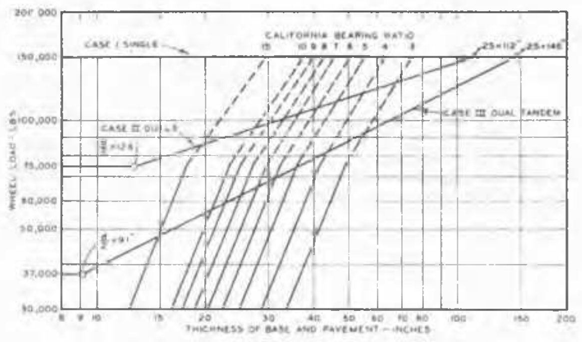
FIG. 3

cover any multiple wheel assembly. This was done simply by resolving the two thicknesses-the shallow depth at which each twin acts separately and the greater depth where they act as a single wheel -- into ratios of appropriate dimensions of the assembly. Without further discussion it may be said that the shallow depth may be expressed as one-half of the clear distance between the contact of the two nearest tires, while the greater depth is computed to be twice the greatest distance, centre to centre, between tires of the assembly.

An example of the method of developing curves for multiple wheel loads is shown on figure 4. Assume a total wheel load of 150,000 lb supported by a twin-tandem assembly with the wheels spaced 40 in. center to centre and the axles 61 in. apart. For this case assume circular contact areas with the tire inflation pressure 100 psi. From these data a value of 9.1 in. is obtained for the shallow depth and 146 in. for the great depth (diagonal centre to centre spacing between a front tire and an opposite rear tire). The design curve for the assembly is obtained by joining the point at 9.1 in. at 37.500-lb wheel load with the point at 146 in. and 150,000-lb wheel load. The intersections of this line with the CBR curves determine the thickness requirements. A curve is also shown on the figure for the same load carried on twin wheels spaced 56 in. centre to centre.

It is believed that the method of developing multiple wheel load curves is applicable for any tire inflation pressure. However, the single wheel CBR design curves must be based on the same tire inflation pressure as contemplated for use in the multiple wheel assembly. It is necessary, therefore, to produce single wheel design curves for tire inflation pressures of the desired amount. The adjustments made to the existing single wheel curves and the reasons therefore are presented in succeeding paragraphs.

For any given load and thickness of base and pavement, an increase in the tire contact pressure will produce an increase in the stress induced in the subgrade and the deflections this stress will produce. If the base thickness is relatively large, the increase in both stress and deflection will be small. If, however, the base thickness is relatively small, the increase will be of considerable magnitude.



TENTATIVE METHOD OF COMPARING THICKNESS REQUIREMENTS FOR VARIOUS WHEEL LOAD ASSEMBLIES

FIG. 4

For any given wheel load and subgrade condition, the maximum stress induced and the deflections produced at the subgrade level can be maintained constant for a range of tire pressures by varying the thickness of base and pavement above the subgrade. The adjustment of the single wheel design curves for higher contact pressures has been accomplished by increasing the required thickness of base and pavement for any fiven CBR value a sufficient amount so that the theoretical subgrade deflections produced by the tire with the higher pressure will equal the theoretical deflections produced by the tire with lower pressures. Deflections were used for this study because the computations are simpler than for stresses.

The adjustment of thickness to give equal subgrade deflections under the center of the load is based on the following formula which is applicable to an elastic solid with Poisson's ratio of 0.5. Under the centre of a uniform circular load, the total deflection

$$W = \frac{3\,P}{2\pi E\,(r^2 + z^2)^{1/2}}$$

where

P = total load

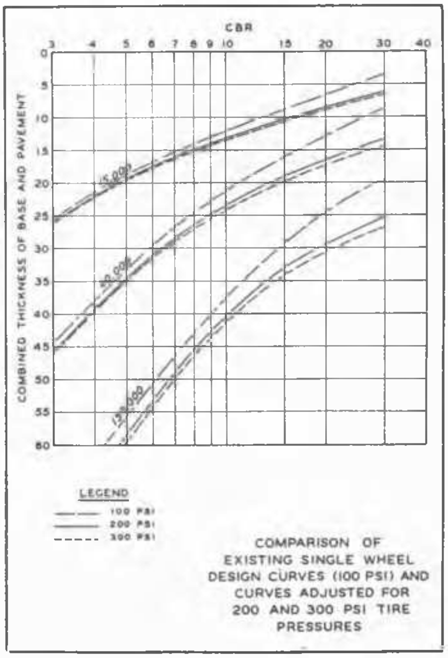
E = the modulus of elasticity

r = the radius of the loaded area (circular contact areas have been assumed)

z = the depth from the surface to the subgrade.

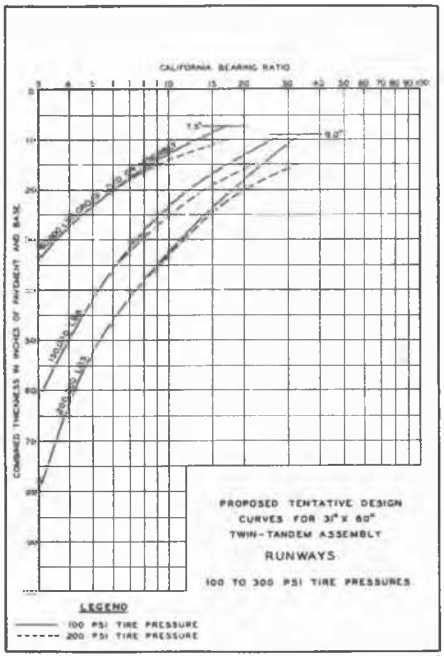
This formula was obtained by integrating and simplifying the formula for the deflection produced by a point load which is given by S. Timoshenko. 5) In applying this formula, a homogeneous, elastic solid with the other usually stated properties is assumed. The formula given above is equivalent to a formula of slightly different form presented by Nathan M. Newmark. 6).

In using the formula given in the previous paragraph to adjust the thickness requirements for a single wheel at several tire pressures, it is not necessary to assume any specific values of deflection or modulus of elasticity. The only assumption necessary is that the deflection and modulus of elasticity are equal for all conditions of tire pressures. The assumption of equal deflection is basic in that it was the starting premise. The assumption of equal moduli of elasticity is probably slightly in error under thin bases since the modulus



COMPARISON OF EXISTING SINGLE WHEEL DESIGN CURVES (100 PSI) AND CURVES ADJUSTED FOR 200 AND 300 PSI TIRE PRESSURES

FIG. 5

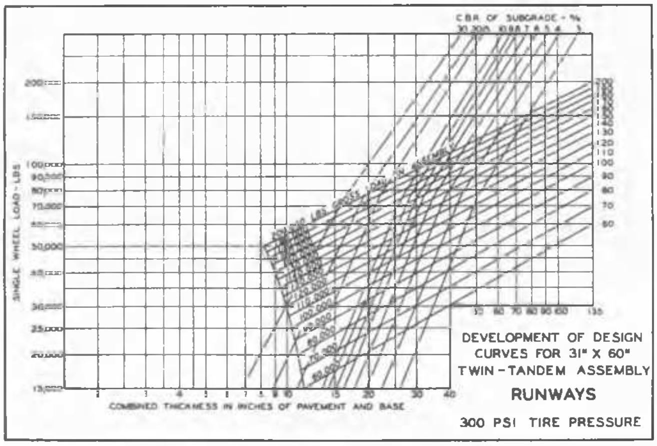


PROPOSED TENTATIVE DESIGN CURVES FOR 31" X 60" TWIN-TANDEM ASSEMBLY

RUNWAYS

100 TO 300 PSI TIRE PRESSURES

FIG. 7



DEVELOPMENT OF DESIGN CURVES FOR 31" X 60" TWIN-TANDEM ASSEMBLY

RUNWAYS

300 PSI TIRE PRESSURE

FIG. 6

of elasticity for soil may vary with the unit stress; however, the error involved in using this assumption is considered to be small. The only remaining variables in the equation given in the preceding paragraph are r and z. If r and z represent values for 100-psi tire pressures and r_1 and z_1 are values for any given higher pressure, then at equal deflections:

$$r^2 + z^2 = r_1^2 + z_1^2$$

Values for r and r_1 are obtained from the total load and tire pressure. Values for z are obtained from the total load and the existing single wheel CBR design curves. The value of z_1, the adjusted thickness for the higher contact pressure, can then be computed.

As previously stated all comparisons under the centre of the loaded area assume that equal deflection at this point would indicate equivalent stress condition in the subgrade. Although not presented here, the entire deflection profiles produced by each loaded area were computed and compared. It was found that if the deflections beneath the centre of the loaded area were equal, then the deflection profiles, though at different subgrade elevations, were also approximately equal. On this basis it was considered that an adjustment based on equal deflections under the centre of the loaded area was reasonable. Figure 5 shows a comparison of thickness requirements for 15, 60, and 150,000 lb single wheel loads for 100-, 200-, and 300-psi tire pressures. It is seen that for the lighter wheel loads and the lower CBR values (thick bases) there is very little difference in the three curves. For the heavier loads and higher CBR values (thinner bases), the thickness requirements for the 200- and 300-psi pressures are as much as 20 per cent in excess of the required thicknesses for the 100-psi pressures.

With single wheel curves developed for high pressure tires, curves for multiple wheel loads can be produced for any given condition in accordance with the method outlined earlier in this paper. Figure 6 shows a typical development of curves for a twin-tandem assembly assuming 300-psi tire pressure 31 in. centre to centre of tires and 60 in. between axles. This spacing has been tentatively designated for the B-36 airplane. Computation for 200-lb tire pressure has also been made for the case cited. In general the difference between the requirements for 200- and 300-lb tires is not sufficient to warrant separate curves. Figure 7 shows the developed design curves for the 31-in. By 60-in. assembly for three loads. The solid curves on figure 7 represent requirements for a 100-psi tire pressure. Where the requirements for the higher tire pressures differ, they are shown by dashed curves. The dashed curve for each load represents the requirements for tire pressures ranging from 200 to 300 psi. It should be noted that the minimum thickness requirements which ranged from 7.5 in. to 9 in. for the 100-psi tire pressure have been increased to 10 in. to 15 in. for the higher tire pressures.

It is believed that the method of developing design criteria as just presented is logical and gives an entirely reasonable solution to the problem. However, it is again stressed that the method is tentative and will be used as a temporary expedient until actual prototype experience is available for verification.

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VIII b11

RUNWAY STRENGTH CORRELATION BETWEEN THE DISTRIBUTION OF STRESSES IN THE SOIL DERIVED FROM:

1) THE C.B.R. METHOD OF THE DETERMINATION OF RUNWAY THICKNESS;

2) THE THEORY OF BOUSSINESQ

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SUMMARY OF THE FRENCH REPORT

The U.S. Corps of Engineers adopted for runway design the method used by the Californian Highway Administration.

It is known that this method is as follows:

A) Determine the strength of each layer of material by penetration of a piston into a sample of the said material. The testing device and the conditions of the test being standardized. The California Bearing Ratio is thus equal to the quotient of the piston-load producing in the tested material a given penetration, by the load causing the same penetration in a reference material.

B) Determine the minimum depth at which the upper face of a layer of a given bearing ratio must be, in terms of the intensity of the load applied upon the free surface of the work.

The relation between the wheel-load, the thickness of the different courses and the bearing-ratio of the materials is expressed by a diagram, obtained experimentally after a long series of tests carried out on the runways at Stockton, Vicksburgh...etc., where deflection and the wear of the runways under the effect of moving loads were carefully studied.

If it is admitted that :

1) good behaviour of a runway under service implies that stresses in the tested materials do not exceed their elastic limit;
2) the elastic limit of a given material is,on the whole, proportional to its bearing ratio;
3) the distribution of stresses in the runway under the effect of loads transmitted by the tires, is in accordance with Boussinesq's law, established for a semi-indefinite, homogenous and isotropic solid.

A diagram, very much like the empirical one of the U.S. Engineers, but established rationally, can then be plotted. By means of slight corrections, taking into account the difference which exists between a homogenous medium and a medium made up of several layers, the compressibility of which varies according to its bearing-ratio, it is possible to ascertain that the superposition of the curves obtained on the new diagram with those of the experimental American one, is very close.

From this very close correlation between the results obtained with the empirical method and the theoretical one, based on the theory of elasticity, it is possible to draw the conclusion that the distribution of stresses, throughout flexible pavements, under the action of dynamic loads transmitted by tires, differs little from that which takes place in a semi-indefinite, homogenous and isotropic medium.

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