Some Concepts on the Use of Deflection Measurements for Evaluating Flexible Pavements

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INTRODUCTION

The amount of flexible pavement deflects under load indicates, in part, its adequacy insofar as structural capacity is concerned. Repeated deflection may cause the pavement to crack and distort as a result of fatigue, excessive bending stresses, accumulated plastic deformation, and other factors.

The deflection of a flexible pavement is partly elastic in character, but it is also made up of plastic strains. Elastic strains are regained upon removal of an applied load whereas plastic strains are not. Thus, the accumulation of these non-recoverable plastic strains with repeated applications of load can result in distortion of the paving surface.

It must be recognized at the outset that performance of a flexible pavement is influenced by many factors and their possible combinations. These include gross load, tire pressure, repetition of load, thickness and quality of the various pavement components, and the elastic-plastic properties of the pavement components (particularly the subgrade soil). Pavement failure may result from excessive shear stresses, vertical deflection, or a combination of these.

Several methods of flexible pavement design are based upon limiting deflection criteria. These include procedures adopted by the Kansas State Highway Department and the Navy Department. Both of these methods of design are predicated in part upon theoretical considerations that relate pavement stresses and deflections to the applied load. Certain simplifying assumptions are made regarding the shape of the tire imprint upon the pavement surface, the relationship between tire pressure and contact pressure, and homogeneity and isotrophy of the structural system.

Many engineers use deflection measurements to evaluate the adequacy of existing pavements. The literature contains numerous references to deflection measurements, including the work done on the WASHO and AASHO Road Tests. Deflection measurements are but one tool that can be used by the researcher to formulate concepts regarding the behavior of flexible and rigid pavements. Deflection measurements are subject to many limitations and therefore must be considered to be a means towards an end rather than an end within themselves.

PAVEMENT DISTRESS

Before consideration can be given to the effect of pavement deformations on performance, it is necessary to consider the matter of pavement distress. One of the biggest questions that must be considered is "what constitutes a failure?" This single factor probably affects the variation in design thicknesses obtained by the various design methods as much as any other. It is the intent at this point to illustrate various types of pavement distress with the hypothesis that ultimate design criteria should be based upon pavement performance.

There is no exact definition in existence at the present time that states the ultimate desired performance of pavements. Engineers differ widely in their concepts of acceptable performance. If one is willing to accept the assumption that the purpose of the pavement is to carry vehicles over it through all weather conditions with maximum comfort and minimum inconvenience to the user, this immediately implies design criteria that will insure relatively smooth surfaces, accident-free roads, and economic operation of vehicles over the pavement. It leaves the definition of ultimate failure open to the opinion of the pavement user.

Distinction will be made here between two types of failure. The first, structural failure, is the collapse of the pavement structure or a breakdown of one or more of the pavement components of such magnitude to make the pavement incapable of sustaining the loads imposed upon its surface. The second, classified as functional failure, may or may not be accompanied by structural failure, but is such that the pavement, due to its roughness, will not carry out its intended function without causing discomfort to passengers or without causing high stresses in the vehicles that pass over it.

Obviously the degree of distress for both categories is gradational and the severity of distress in any pavement is largely a matter of opinion of the person observing the distress. However, the difference between the two types of failure is important and the engineer must be able to distinguish between them. For example, consider a rigid highway pavement that has been resurfaced with an asphaltic overlay. The surface may develop rough spots as a result of breakup in the bituminous overlay (functional failure) without structural breakdown of the overall structure. On the other hand, the same pavement may crack and breakup as a result of over load (structural failure). Maintenance measures for the first situation may consist of resurfacing to restore smooth riding qualities of the pavement. However, the structural type of failure may require complete rebuilding.

The difference between functional and structural failure can also be demonstrated by considering airport pavements. The rapid development of jet aircraft in recent years has had a profound effect on pavement design concepts. Historically, design engineers have had uppermost in mind the effect of vehicular traffic upon the pavement. In contrast, present day requirements necessitate that consideration be given to the effect of the pavement upon the aircraft, as well as the effect of the aircraft on the pavement. Jet engines are easily damaged by debris sucked into the air intakes. Thus, much research has gone into the design of shoulders adjacent to taxiways and areas adjacent to runway ends to make them resistant to erosion from jet blast. Also, the pavement must be resistant to the effects of fuel spillage and heat.

What were once considered minor changes in longitudinal grade now, because of the ground operating characteristics of aircraft such as the B-47, can cause the vehicle to "porpoise" or undulate. This motion is inimical to safe operation and must be avoided. Thus it is seen that functional failure can precede structural failure.

Since the ultimate design criteria should include a measure of the relative smoothness of pavement, it follows that a knowledge of the pavements strain characteristics is essential to good design practices. This is true from the standpoint of both functional and structural characteristics of the pavement. The structural designer is perhaps more interested than others in pavement deflection characteristics since he must design a pavement which will not deform permanently and cause a rough surface to result.

PURPOSE OF DEFLECTION MEASUREMENTS

The primary purpose of determining the deflection of an existing pavement, insofar as structural adequacy is concerned, is to obtain basic data, either by inference or direct measurement, relative to the stress-strain properties of the pavement materials. Mere measurement of gross deflection at the pavement surface may not yield the desired results.

Such factors as radius of banding and the visco-elastic properties of the pavement components must also be evaluated.

To be of maximum benefit to the engineer, deflection measurements must be planned so that a large amount of information is obtained without resorting to elaborate field installations. This is true inasmuch as the time required to install deflection gauges in pavements is great, which in turn limits the amount of measurements that can be obtained. Thus, a need exists for evaluation deflection measurements on a rational basis.

DEFLECTION PATTERNS

Figure 1 indicates an idealized profile of deflection under dual tires. Several factors are worth discussing at this point. First, surface deflection is made up of cumulative deflections of all the pavement components, including the subgrade. Second, for the usual case a

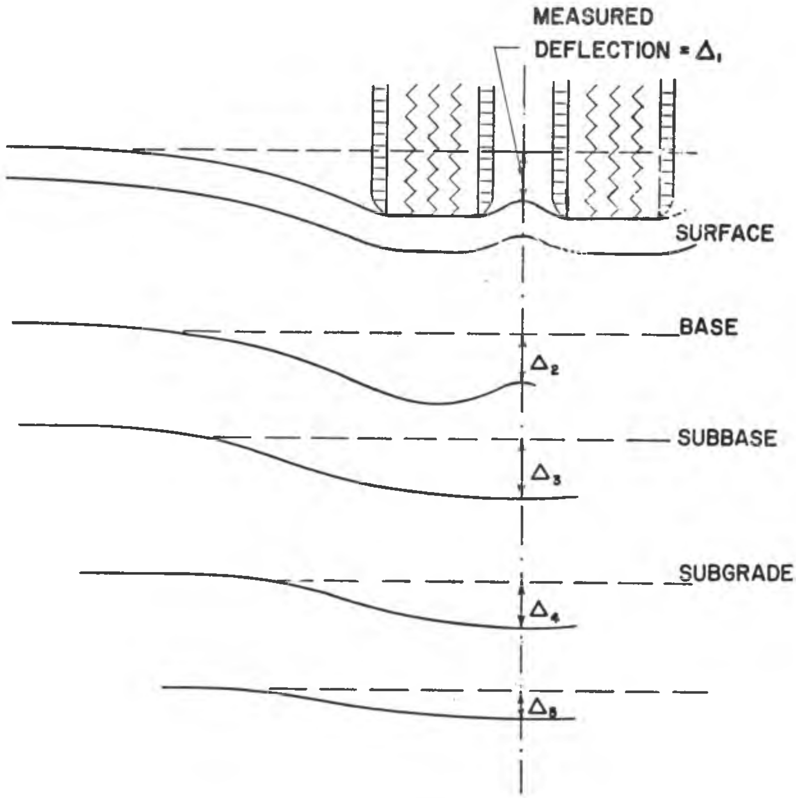

Fig. 1. Deflection profiles under dual wheels.

large portion of the deflection occurs in the subgrade. It is to be noted that the pavement may tend to "heave" both between and outside the dual wheels.

As depth increases, the profile of banding changes from that found immediately under the wheels and is saucer shaped. Surface deflection is an accumulation of strains from the surface downward; the distance a particle moves when a load is applied at the surface decreases with depth.

Pavement distress as evidenced by rutting, cracking, etc., can be caused by excessive *total* deflection but distress can also result from sharp radii of bending. For example consider the wearing course in Figure 1. It is noted that shoving between the wheels could cause ruts to form (due to sharp radii, or an effect that can be visualized as "punching" through the surface) even though total vertical movements are slight.

Figure 2 shows the deflection patterns as determined by tests* as well as deflection patterns which are obtained by theoretical considerations. It should be noted first that deflection is plotted on the abscissa as a per cent of the surface deflection rather than absolute values of deflection. The purpose of plotting the curves in this manner is that even though deflection depends upon the elastic properties of the pavement and subgrade, these cancel out in the ratio.

The deflection of a circular flexible plate on a flexible pavement can be expressed as follows:

$$\Delta = 1.5 \times p \times a \times \frac{F}{E_2}$$

where: Δ = deflection

p = contact pressure

a = radius of contact

E_2 = modulus of elasticity of the subgrade

F = a dissensionless quantity which depends upon two ratios, $\frac{z}{a}$ and $\frac{E_2}{E_1}$ where z is depth below surface and E_1 is the modulus of elasticity of the pavement.

It is important to note that for a given contact pressure and given total load (which fix the radius), vertical deflection is dependent upon a settlement factor F which is in turn dependent upon the ratio of z/a.

* See paper by Geldmacher, *et al.* "Subgrade Support Characteristics Experimental and Theoretical," Report to the Advisory Board of the Joint Highway Research Project, December, 1956.

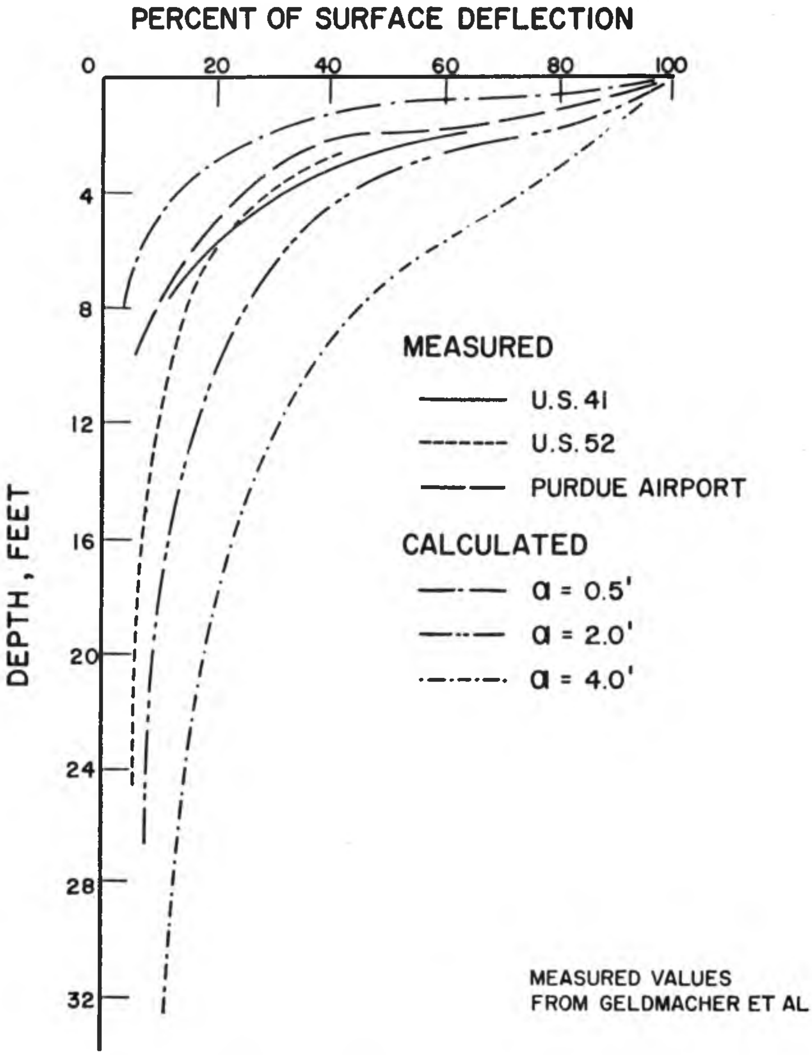

Fig. 2. **Deflection patterns—measured and calculated.**

The above equation was developed using certain boundary conditions which will not be discussed here. Considering the theoretical or calculated values in Figure 2, depth of influence of deflection for various plate sizes is shown. For example, circular plates with large diameters cause greater depths of influence than plates of smaller diameter. (Compare the curves for a = 4, a = 2, and a = 0.5.)

Also plotted on Figure 2 are deflection patterns obtained by tests which were made on rigid pavements. The similarity between the patterns obtained by tests with the theoretical values is striking. Thus, it may be concluded that even though values of deflection as measured by tests may not be numerically equal to those obtained by theory, the *measured deflection patterns are quite similar to the calculated values.* The test values shown in Figure 2 were obtained under rigid pavements and therefore it is difficult to make direct numerical comparisons of measured deflection with the theory since the relative radius of contact of the pavement and the base course is difficult to determine. The depth of influence, it is noted, extends for great depths.

LIMITATIONS OF DEFLECTION MEASUREMENTS

As previously stated, measurement of deflection is a tool that can be used by the engineer and researcher for evaluating pavements. However, it must be remembered that gross deflection of the pavement structure is of value only if the deflection profile is measured (see Figures 3 and 4). Also, ideally at least, these measurements should be made with the end point of evaluating the elastic-plastic properties of the pavement components.

METHOD OF ANALYSIS

Several methods of analysis can be adopted; each of these will be discussed briefly in subsequent paragraphs.

1. Measurement of gross deflection.
2. Measurement of gross deflection along with measurement of the deflection of each component layer of the pavement.
3. Measurement of deflection profiles and contours.
4. Determination of unit deformation of each layer (total deflection divided by height).
5. Determination of a constant or constants which define the stress-strain properties of the materials.

The measurement of gross deflection will not, in most cases, yield the desired results. Determination of the deflection of the pavement components will yield relative data which can be used in a qualitative sense. However, since deflection is dependent upon depth as well as type of material, it is necessary to analyze the data in light of the depth of the component below the pavement surface. Utilization of deflection profiles offers some potential in the analysis of the data.

Figures 3 and 4 show longitudinal and transverse deflection curves for the U. S. 31 Test Road near Columbus, Indiana (flexible pave-

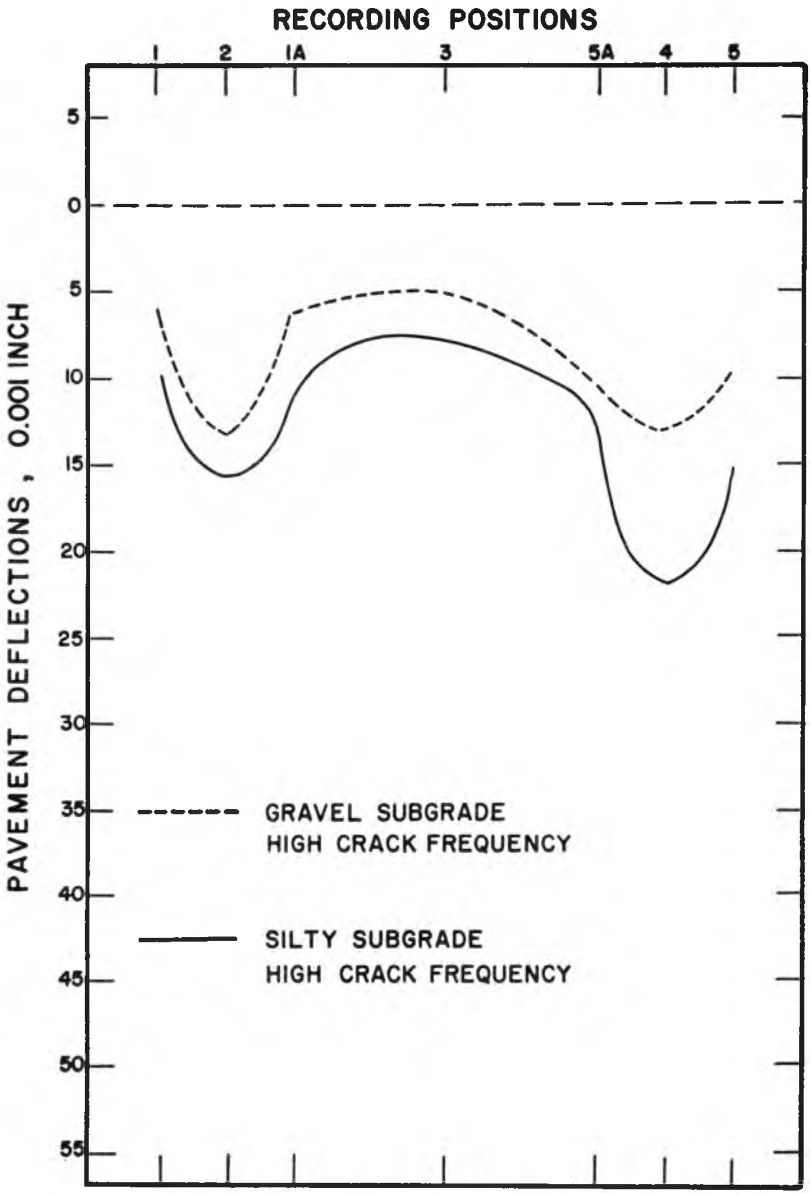

Fig. 3. Typical transverse deflection curves.

ment). The flexible pavement on this test road has shown some rutting and longitudinal cracking; however, signs of neither functional nor structural failure are evident on the road surface.

Deflection data were obtained in areas of high crack frequency as well as in areas showing low occurrence of cracks. Figure 3 shows data for pavement built over a gravel subgrade as well as that built over a silty subgrade. It is to be noted that the gravel subgrade (high crack frquency) resulted in less deflection than the silty subgrade with high crack frequency. No significant correlation was found between total deflection and crack frequency.

Figures 3 and 4 indicate an interesting feature of the deflection patterns. In each case the granular subgrade showed less total deflection than the silty subgrade. However, the radius of bending of the pavement

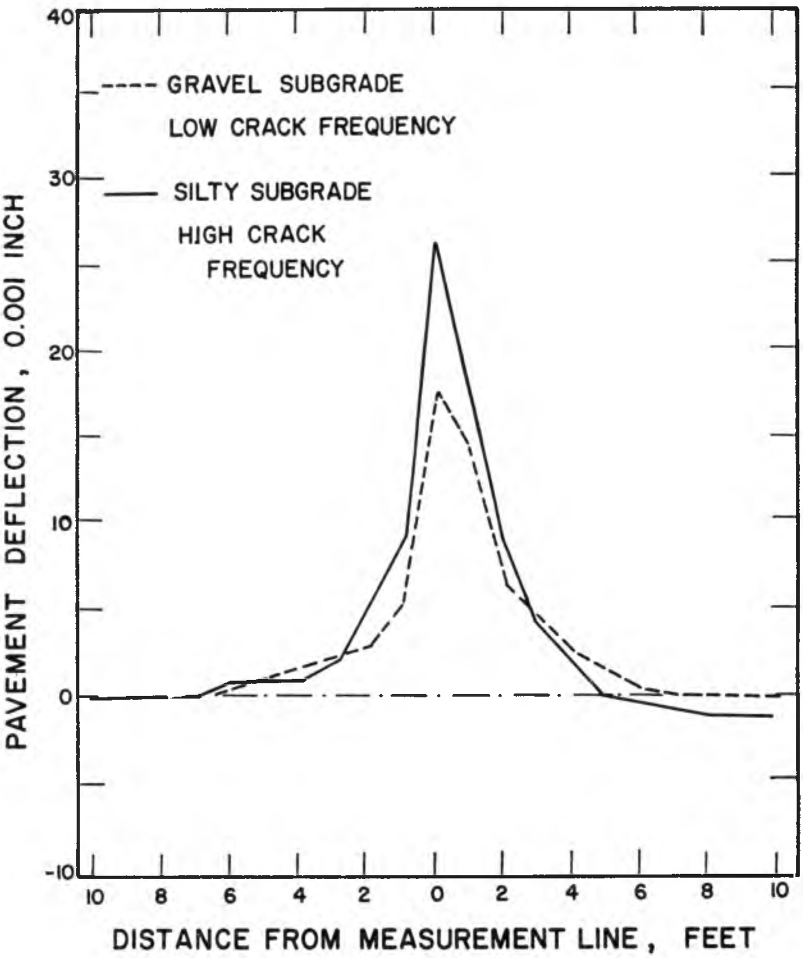

Fig. 4. Typical longitudinal deflection curves.

built over the gravel subgrade was generally smaller than the radius of bending for comparable pavements built over the silty subgrade. Small radii of bending indicate high stress concentrations and thus one may expect that pavements with low radii of bending will crack more frequently than those with larger radii of bending. Analysis of the data for this test road, however, did not indicate a significant correlation between radius of bending and pavement distress.

Use of unit deformations (deflection of the layer divided by the thickness of the layer) is subject to the restriction that deflection is dependent upon depth below the surface as well as type of material. Thus, it becomes necessary to exercise a degree of caution in computing unit deformations since they do not take into account stresses that exist on any given layer of the pavement.

The last method of analysis deals with determination of certain elastic constants which define the stress-strain properties of the pavement materials. The constant which first comes to mind is the modulus of elasticity (sometimes called modulus of deformation). Poisson's ratio is also a significant property of the material that must be considered.

Figure 5 indicates the stress inducing factors which cause a material to deform. The equation shown in the lower right-hand

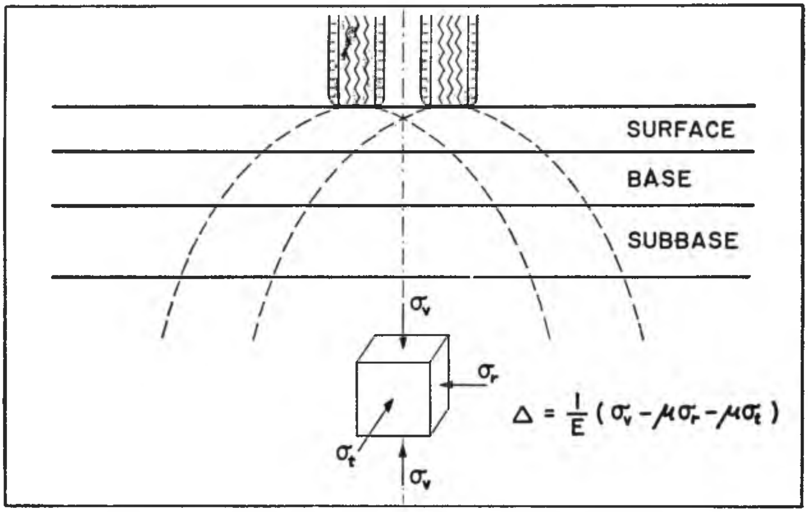

Fig. 5. Idealized stresses and strain under dual wheels.

portion of the figure is an expression that relates stress and strain in terms of two elastic constants. Ideally in this type of analysis one should measure stresses and strains. It then becomes a simple matter to solve for modulus of elasticity. Unfortunately, this requires a great deal of instrumentation.

Figure 6 shows variation of vertical stress with depth as measured by pressure cells below a 12-inch crushed stone base coarse. Theoretical values of stress are also plotted against depth. It is noted that although numerical values of calculated stresses vary from the theoretical values

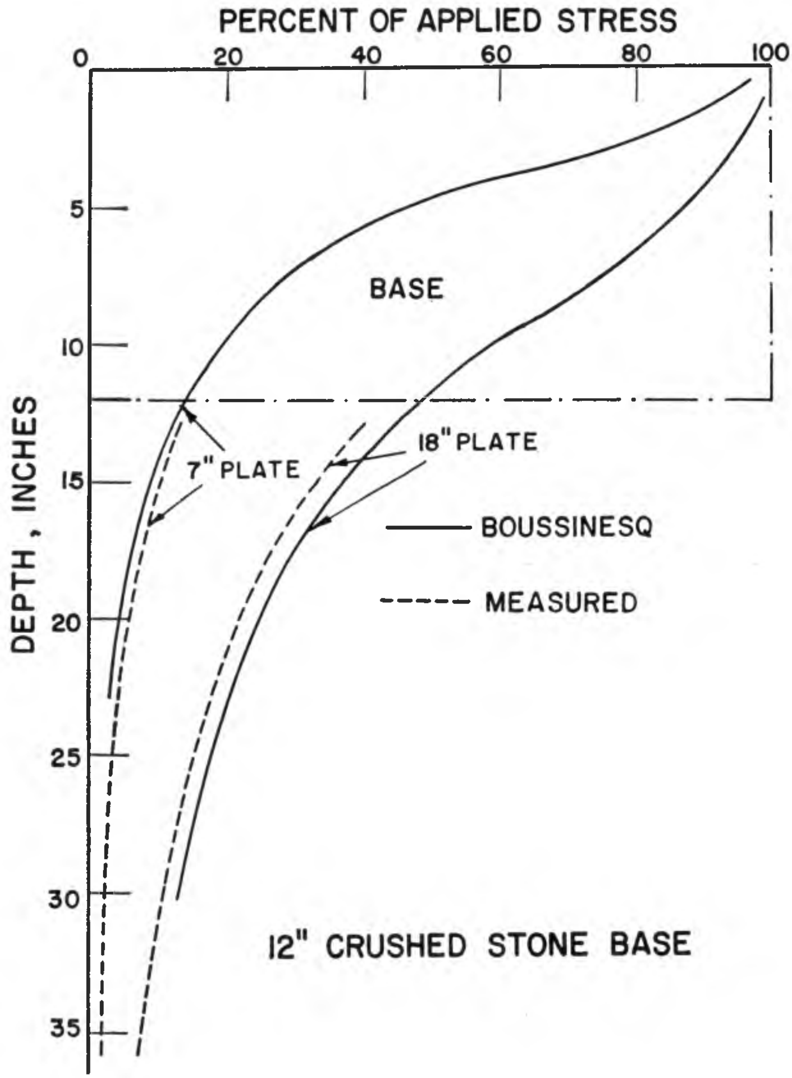

Fig. 6. Measured and calculated stresses below a circular plate—12 inches of crushed stone base.

the stress patterns for both cases are similar. Since for a given component layer of a pavement it is necessary to use only *change* of stress with depth to compute an elastic constant, it appears that use of theoretical equations for estimating stresses is warranted.

STRAIN CHARACTERISTICS

Using the hypothesis that a relative modulus value which defines the stress-strain properties of the material can be determined by estimating theoretical stresses, a research program was set-up to ascertain if significant differences in modulus values could be obtained for various components.

A research project was established wherein layer deflections were measured on the U. S. 31 Test Pavement using the Benkelman Beam. Figure 7 shows a diagrammatic sketch of this beam. The probe at the

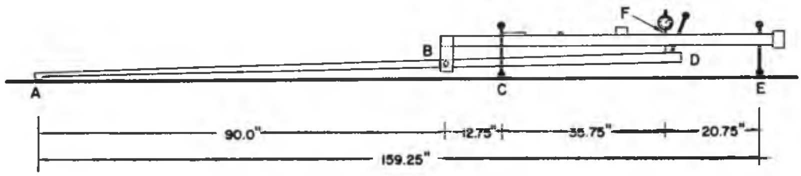

Fig. 7. Diagrammatic sketch of Benkelman Beam.

extreme left-hand side is placed between a set of dual wheels and then as the truck moves away from the probe, deflection is indicated by means of the dial on the right.

Figure 8 shows the set-up for measuring the layer deflections. The test pavement consists of asphaltic concrete, water-bound macadam, and granular subbase resting upon the grade. Holes were drilled through the asphaltic concrete and plates were set on each pavement layer.

Figure 9 shows typical relative modulus values which were calculated for two locations. It was found that crack frequency could not be correlated with subgrade modulus values, but a relatively good correlation was established between crack frequency and subbase values. In Figure 9 it is seen that the base course had relatively high modulus values whereas the modulus for the subbase, in general, was less than that of the silty subgrade.

SUMMARY

The amount a pavement deflects determines to a major extent the potential structural performance of the pavement. Highway engi-

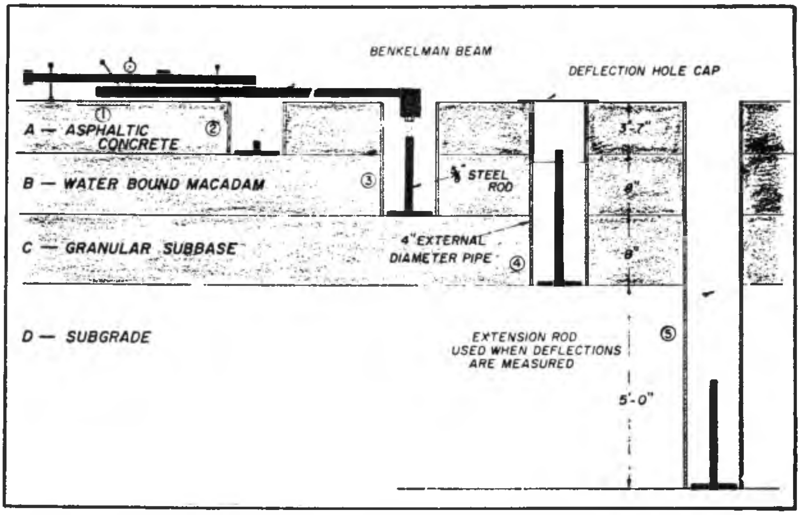

Fig. 8. Use of Benkelman Beam for layered system deflection study.

neers have been measuring pavement deflection under various loading conditions for many years. It has been the purpose of this paper to present a discussion of the factors which affect analysis of deflection measurements.

Total deflection values are influenced to a great extent by subgrade type. Thus it is possible to infer potential performance from deflection measurements if the performance will be influenced to any extent by type of subgrade. However, in cases where other components of the pavement contribute to performances, deflection measurements can be misleading. This was brought out in the study made on the U. S. 31 Test Road wherein crack frequency could not be correlated with total deflections but a high degree of correlation was indicated between occurrence of cracking and layer deflection. It was not possible to formulate definite conclusions relative to radii of bending as it affects performance; nevertheless, stress analysis indicates that such a relationship should exist.

Previous paragraphs have shown theoretical relationships between deflection patterns and depth for relatively homogenious materials. Data are also presented which indicate deflection patterns as determined by measurement under prototype pavements. A marked degree of similarity is apparent when considering the theoretical and measured values. The results of the layer deflection measurements have indicated the feasibility of determining a constant which defines the stress-strain properties of each pavement material.

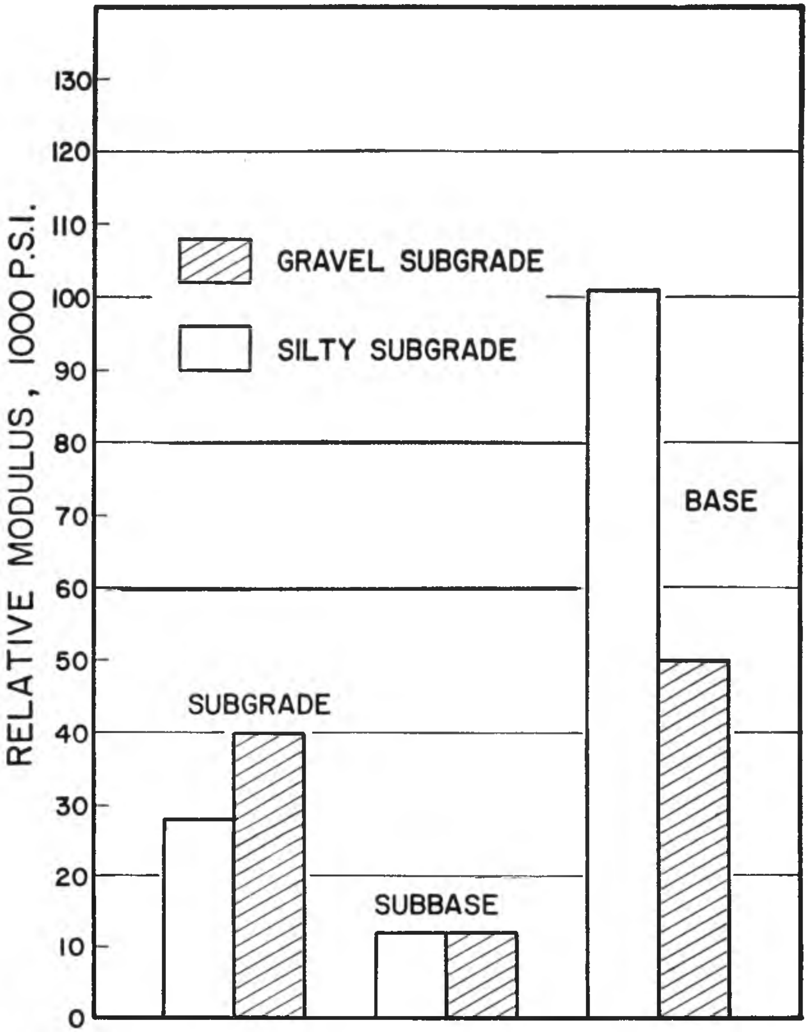

Fig. 9. Relative modulus of pavement layers—11,250 pound dual wheel load.

It is apparent that determination of a relative modulus depends upon a knowledge of the stress conditions and Poisson's ratio. Since it is desired to obtain *relative* values of modulii of pavement layers, the importance of determining the exact value of Poisson's ratio decreases. An assumption that Poisson's ratio is equal to 0.5 appears to be justified for most cases since this value results when there is no volume change under load. For new pavements Poisson's ratio is probably less than 0.5; however, after a pavement is open to traffic for a long period of time the assumption that no volume change occurs under any increment of load is probably correct.

A major obstacle which must be overcome is that regarding the stresses which are used in the calculations. This can be circumvented by actual field measurement of stresses; however, since only relative values are desired, and since the stress and deflection patterns follow the ideal, theoretical stress computations can be utilized with a relatively high degree of accuracy.