

Research Report
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CORRELATION OF ROAD RATER AND BENKELMAN BEAM DEFLECTIONS

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0. Abstract

The Benkelman beam is commonly used to measure surface deflections of highway and airfield pavements. The Benkelman beam is based on a simple lever-arm principal and uses dial gauges to measure surface deflections under an applied axleload. The Road Rater is an electro-hydraulic testing device that applies a sinusoidal force to the pavement at a fixed amplitude and frequency; surface wave velocities are measured and electronically integrated to obtain surface deflections. Road Rater and Benkelman beam deflections have been successfully simulated using elastic theory and the Chevron N-layer computer program. The analyses presented in this paper illustrate relationships between Road Rater deflections and the more commonly used Benkelman beam deflections.

1. Introduction

The Road Rater and Benkelman beam are comparable in the sense that both measure surface deflections of pavements. The Road Rater loading was dynamic and consisted of a vibrating load that impulsed the pavement. Frequency and amplitude of vibration were pre-selected variables that controlled the dynamic load induced by the Road Rater. The forced motion of the pavement due to the vibratory load was measured by velocity pickup sensors located at various distances from the center of the test head. Deflection measurements for each sensor were displayed on meter scales and were read directly by the operator.

The Benkelman beam operated on a simple level-arm principal and used dial mechanisms to measure surface deflections. Benkelman beam tests were conducted at a creep speed of the test vehicle (0.5 Hz to 1.0 Hz). The test vehicle consisted of a two-axle, six-tire dump truck with a load of 80 kN (18 kips) on the rear axle. Two Benkelman beams were used, with the tips of the beams placed between the two dual tires at each end of the axle. The maximum surface deflection was read as the vehicle tires rolled past the tips (points) of the Benkelman beams. The movement of the pavement was measured by dial mechanisms attached to the beams.

2. Simulation of Benkelman Beam Test Results

Benkelman beam deflections have been simulated by elastic theory using the Chevron N-layer computer program. Assuming equal load distribution, each rear tire of the test truck applied a 20-kN (4.5-kip) load to the pavement. Superpositioning principles were used to compute the deflections between the two tires of the rear duals. Superpositioning is applicable provided the deformations are small and do not substantially affect the action of external forces. For the principles of superpositioning to apply, a linear relationship between displacement and external force must exist or be assumed to exist [5]. Thus, the deflection sensed by the Benkelman beam is the sum of deflections caused by each of

the four tires on the rear axle at their respective distances from the point of measurement. This approach was used to calculate deflections at any location on the pavement and for any axle configuration and loading.

An array of conditions (thicknesses of asphaltic concrete, dense-graded aggregate thicknesses, and moduli of elasticity for asphaltic concrete, dense-graded aggregate, and subgrade) was used in the Benkelman beam simulation. Estimation of the modulus of the crushed stone layer was obtained from the relationship $E_2 = F \times E_3$, in which there is an inverse linear relationship between $\log F$ and $\log E_3$. The ratio of the modulus of the base (E_2) to the modulus of the subgrade (E_3) is equal to 2.8 at a California Bearing Ratio (CBR) of 7 and is equal to one when the modulus of the asphaltic concrete (E_1) and the subgrade modulus (E_3) are equal: $E_1 = E_2 = E_3$. Subgrade moduli (E_3) in psi may be approximated by the product of the CBR and 1500. This appears adequate for normal design considerations up to a CBR of 18 to 20. Other inputs used in the simulation [1] included the following:

Poisson's ratio: Asphaltic Concrete: $\mu = 0.40$

Granular Base: $\mu = 0.40$

Subgrade: $\mu = 0.45$

Load per tire: 20 kN (4.5 kips)

Tire (contact) pressure: 0.55 MPa (80 psi)

Analyses [3] have shown that changes in Poisson's ratio and tire pressure have relatively insignificant effects upon the calculated deflections. An example of results of the simulation of Benkelman beam deflections is illustrated in Figure 1.

3. Simulation of Road Rater Tests Results

The testing head on the Kentucky Road Rater, mounted on the front bumper of a 1971 International Travelall, consisted of a vibrating mass weighing 72.6 kg (160 pounds), which impulses the pavement; the forced motion of the pavement is measured by velocity sensors normally located at 0 mm (0 feet), 305 mm (1 foot), 610 mm (2 feet), and 914 mm (2 feet) from the center of the test head. The vibrating mass was suspended by a system of rubber bellows. A second set of bellows housed in the test head distributes the dynamic load equally to two "feet". Frequency of the vibratory loading may be chosen from pre-selected frequencies of 10, 20, 25, 30, and 40 Hz. The vibrating mass was lowered to the pavement by a hydraulic system. Optimum and resonant frequencies were a function of the location of the test head, the dynamic force, the location of the load-bearing "feet", and the pavement structure. The dynamic force was a function of frequency and amplitude of vibration and the pressure in the hydraulic system. At a hydraulic pressure of 4.82 MPa (700 psi), the static load for the Kentucky unit was 7.43 kN (1,670 pounds).

A frequency of 25 Hz and an amplitude of vibration of 1.524 mm (0.06 inch) resulted in a peak to peak dynamic force of 2.67 kN (600 pounds). Once the dynamic force was set for a given frequency and amplitude, the other preset frequencies will vary the amplitude of the vibrating mass such that the dynamic force remains constant for all pre-selected frequencies. The composite loading consisted of a static load of 7.43 kN (1,670 pounds) with a dynamic force of 2.67 kN (600 pounds), peak to peak, oscillating about the static load. The loading was transmitted to the pavement by two "feet" symmetrically located on either side of a beam extending ahead and supporting the sensors.

Superposition principles are applicable in computing the deflection at each sensor location. Applying superposition principles to the Road Rater, the deflection resulting from the load applied to one "foot" must be added to the deflection due to the load applied by the other "foot". For the symmetrical conditions of the Road Rater, deflection calculations only need to be made for one "foot" and radii corresponding to each sensor location.

The dynamic loading (sine wave) of the Road Rater can be approximated by a square wave. For short time periods, this is representative of a steady-state condition that approximates a static load. The peak-to-peak loadings of the Road Rater are 8.37 kN (1,882 pounds) and 6.49 kN (1,458 pounds). From symmetry, the loads on each "foot" of the test head are equal to 4.19 kN (941 pounds) and 3.24 kN (729 pounds). The dynamic deflection is the difference between the

calculated deflections caused by the 8.32-kN (1,882-pound) and 6.49-kN (1,458-pound) loads.

Simulated deflections for Road Rater loadings were obtained using the Chevron N-layered computer program, which are based on elastic theory [1]. The contact pressure of the low and high loads were inputted to maintain the correct area for each "foot". The following constants were used in simulating the Road Rater deflections [1]:

Poisson's ratio: Asphaltic Concrete $\mu = 0.40$
 Granular Base $\mu = 0.40$
 Subgrade $\mu = 0.45$

Load = 4.186 kN (941 pounds); Contact pressure = 0.231 MPa (33.5 psi)

Load = 3.243 kN (729 pounds); Contact Pressure = 0.183 MPa (26.5 psi)

An array of asphaltic concrete and crushed stone thicknesses and moduli for the asphalt, crushed stone, and subgrade layers was used in the simulation [1].

4. Comparison of Road Rater and Penkelman Beam Deflections

A log-log plot of Benkelman beam versus Road Rater No. 1 Sensor deflections (both computed (simulated) by elastic theory) for equivalent conditions is illustrated in Figure 2 and shows the effects of total thickness and thickness of asphaltic concrete to be a family of curves. Road Rater and Benkelman beam deflections were obtained from the results of the simulation previously described. A similar relationship exists for field measured deflections (Figure 3). The dashed lines in Figure 3 represent theoretical lines (from Figure 2) for specific pavement structures. Deflections were plotted to an arithmetic scale in Figure 3 while log scales were used in Figure 2. The points on Figure 3 represent pairs of field measured Road Rater No. 1 Sensor deflections and Benkelman beam deflections. Both Road Rater and Benkelman beam deflections were adjusted to the moduli of the asphaltic concrete corresponding to the mean pavement temperature and their respective test frequencies [1].

The Figures 4-8 compare field measured pairs of Road Rater and Benkelman beam deflections with their corresponding theoretical values. These values have been adjusted to a 21.1°C (70°F) reference [4]. Initial comparisons indicated unreasonable amounts of scatter. However, when the limits of operator error in reading the dials of the Benkelman beam and the meters of the Road Rater were considered, much of the scatter was explained.

Road Rater deflections were displayed on meter scales ranging from 0 to 100 with divisions for every two units. Normal reading error is ± 1 unit on the meter. The true deflection is determined by multiplying the meter reading by the scale factor. In most instances, the scale factor is 2.54×10^{-4} mm (1×10^{-5} inches).

Benkelman beam deflections were recorded by dial gauges. The number of divisions on the dial face was a major contributor to operator error. Also, since the Benkelman beam functions on lever-arm principles, the location of the fulcrum must also be considered. For the Kentucky Benkelman beam, the dial was located 1.22 m (4 feet) from the fulcrum, and the tip of the beam was 2.43 m (8 feet) from the fulcrum. Therefore, a dial reading for the Kentucky Benkelman beam was multiplied by 2 to obtain the true deflection. One division on the dial was 2.54×10^{-2} mm (1×10^{-3} inches). For an error of ± 1 division, the error in deflection is $\pm 5.08 \times 10^{-2}$ mm (2×10^{-3} inches). The solid lines in Figures 4-8 illustrate theoretical relationships between Road Rater No. 1 Sensor deflections and Benkelman Beam deflections as determined by simulations using elastic theory.

The dashed lines on Figures 4-8 illustrate different levels of error in Benkelman beam deflections with corresponding levels of error for the Road Rater. The figures indicate that an operator error of ± 1 division in dial reading of the Benkelman beam is more significant than an error of ± 1 unit on the Road Rater meter scale for a scale factor of 2.54×10^{-4} mm (1×10^{-5} inches). All Road Rater deflections were determined using a scale factor of 2.54×10^{-4} mm (1×10^{-5} inches). When plots of Benkelman beam deflection versus Road Rater deflections were compared with the theoretical relationships and the reading tolerance (dashed lines) superimposed on each plot, the following results were obtained: 45

percent of the points were within $\pm 2.54 \times 10^{-2}$ mm (1×10^{-3} inches) of the theoretical Benkelman beam deflection; 71 percent were within $\pm 5.08 \times 10^{-2}$ mm (2×10^{-3} inches) and 84 percent were within $\pm 7.62 \times 10^{-2}$ mm (3×10^{-3} inches) of the theoretical deflections. The remaining points were analyzed individually using Road Rater deflection data for Sensors 1, 2, and 3 [1, 2]. When the Road Rater deflection basins were evaluated, every point indicated some type of abnormal behavior. In most cases, a foundation material problem was indicated. Only ten percent of the abnormal points indicated a problem in the bound layer. This was not surprising since the pavement was only 1 year old at the time of testing.

In most cases when Benkelman beam deflections were plotted versus Road Rater deflections, most points indicating foundation problems plotted below the theoretical line. On the other hand, deficiencies on the bound layer normally plotted above the line. There were only three exceptions noted in this general pattern. Circled points indicate foundation material deficiencies and points inside squares indicate possible bound-layer problems.

One possible explanation for the separation of the two problem types may be related to the deflection basin. The Road Rater applies a relatively small load and measures surface deflections at specified distances from the load. A plot of the deflection basin for the Road Rater can readily be developed. Benkelman beam deflections are measured as the vehicle creeps past the tips of the beams. A surface deflection is measured, but the location of that deflection on the deflection bowl is not known. For the Kentucky test procedure, rebound is considered and sufficient time is allowed for the dial to cease moving. Therefore, the deflection approaches a maximum deflection.

One example of an abnormal situation resulted from concurrent Road Rater and Benkelman beam tests for a site in Kentucky. Tests were taken on a layer of compacted subgrade overlying a layer of soft soil of known high moisture content overlying bedrock. Geologic and topographic conditions of the area made drainage less than adequate. Road Rater tests indicated abnormally high deflection values, but Benkelman beam deflections at the same site were relatively low. Cracking and subsidence of the entire testing area was observed when the truck for the Benkelman beam test was driven onto the test site. When the truck was removed, the Benkelman beam indicated very little movement, yet rebound of the compacted subgrade could be visually observed. The load due to the test truck was distributed over a very large area such that both the truck and the Benkelman beam were completely within the deflection bowl.

5. References

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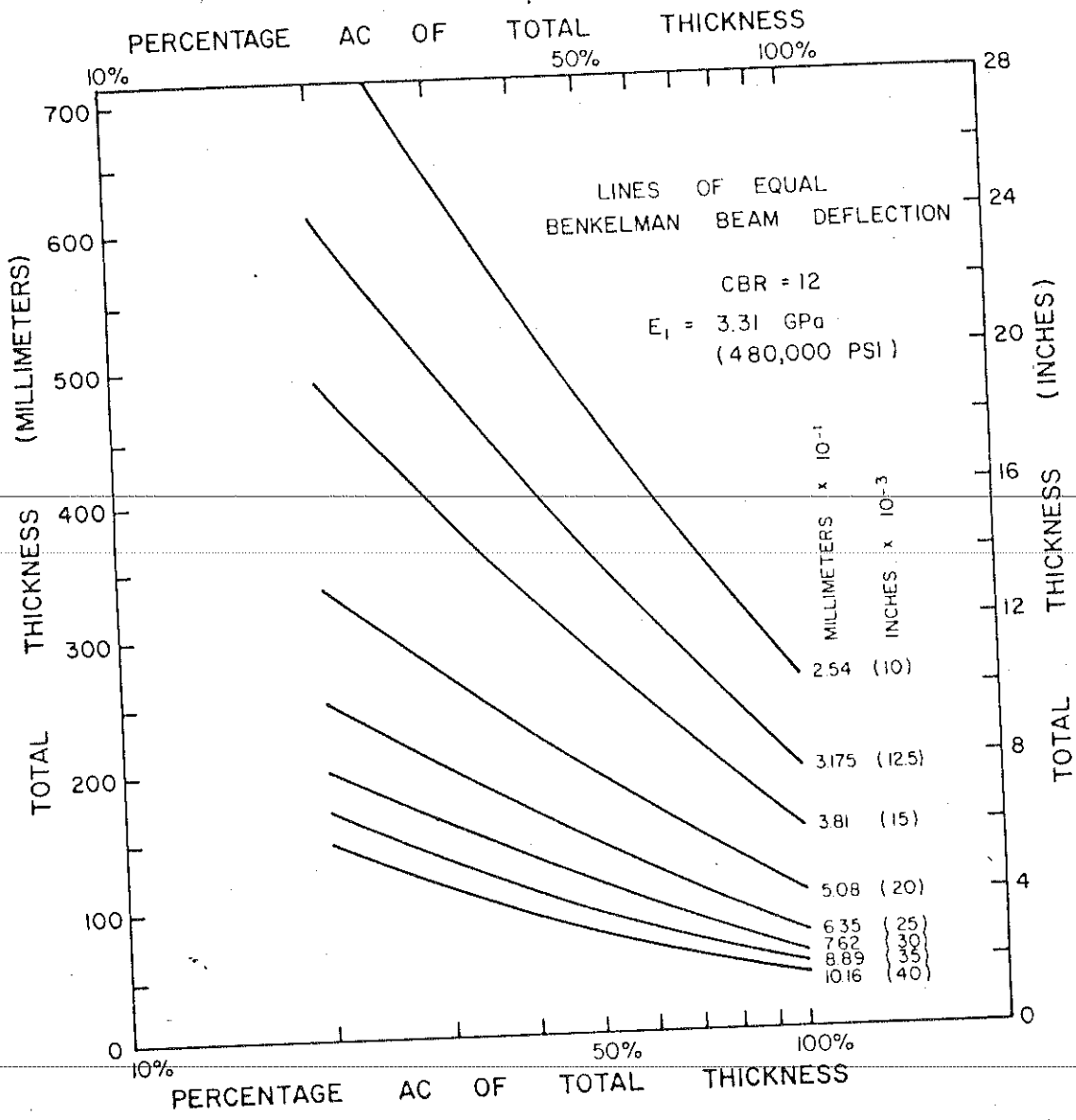


Figure 1. Theoretical Deflections for Penkelman Beam Tests.

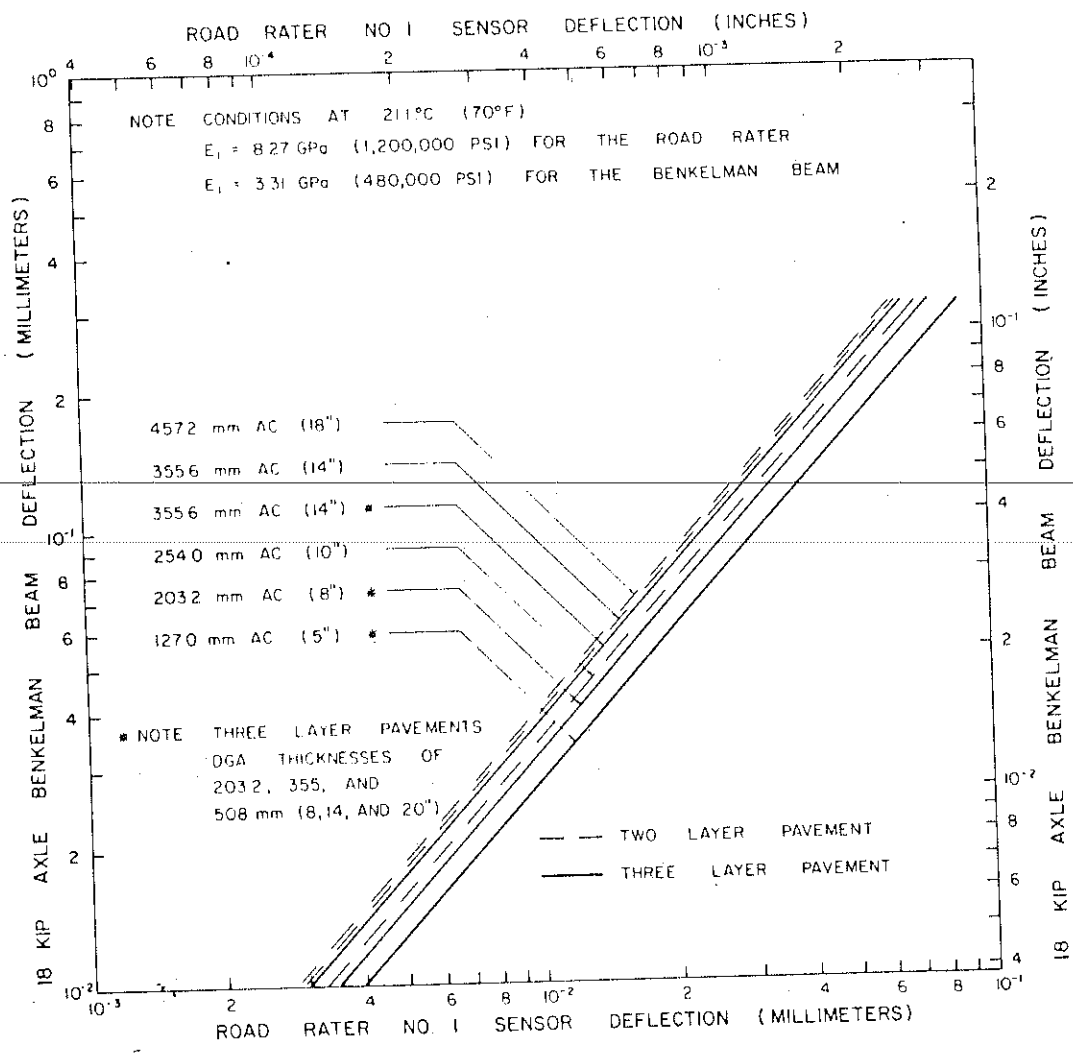


Figure 2. Theoretical Deflections: Benkelman Beam Deflections for an 80-kN (18-kip) Axleload versus Road Pater No. 1 Sensor Deflections.

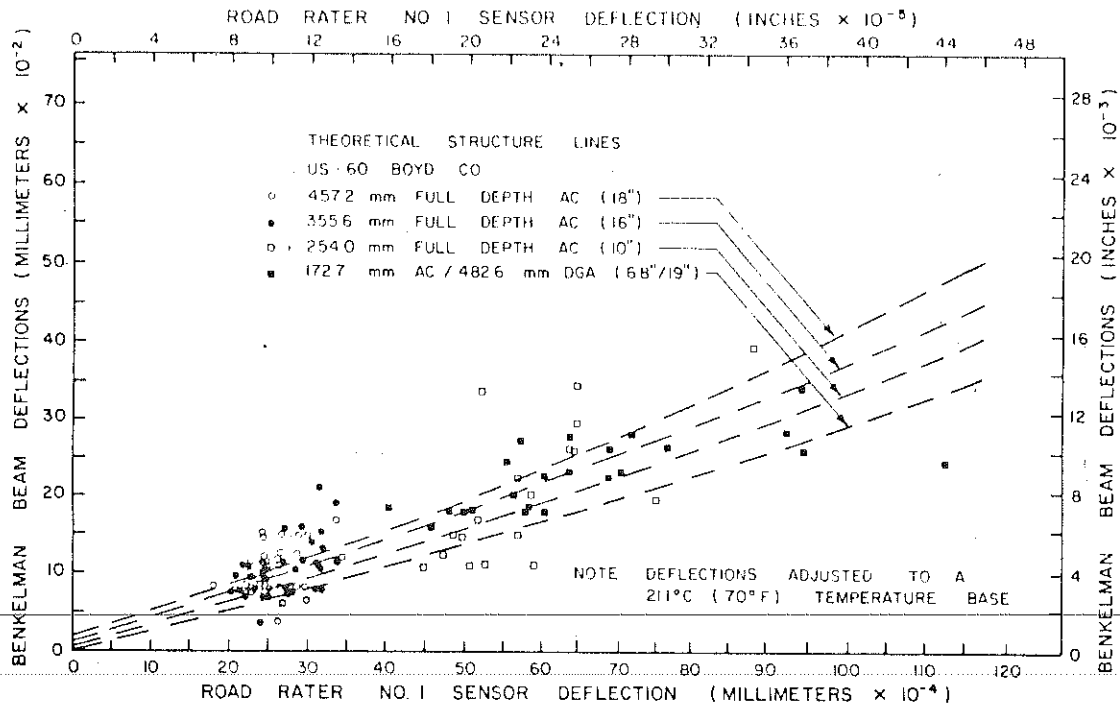


Figure 3. Benkelman Beam Deflections for an 80-kN (18-kip) Axleload versus Road Rater No. 1 Sensor Deflections: Dashed Lines Represent Theoretical Deflections and Points Represent Field Measurements.

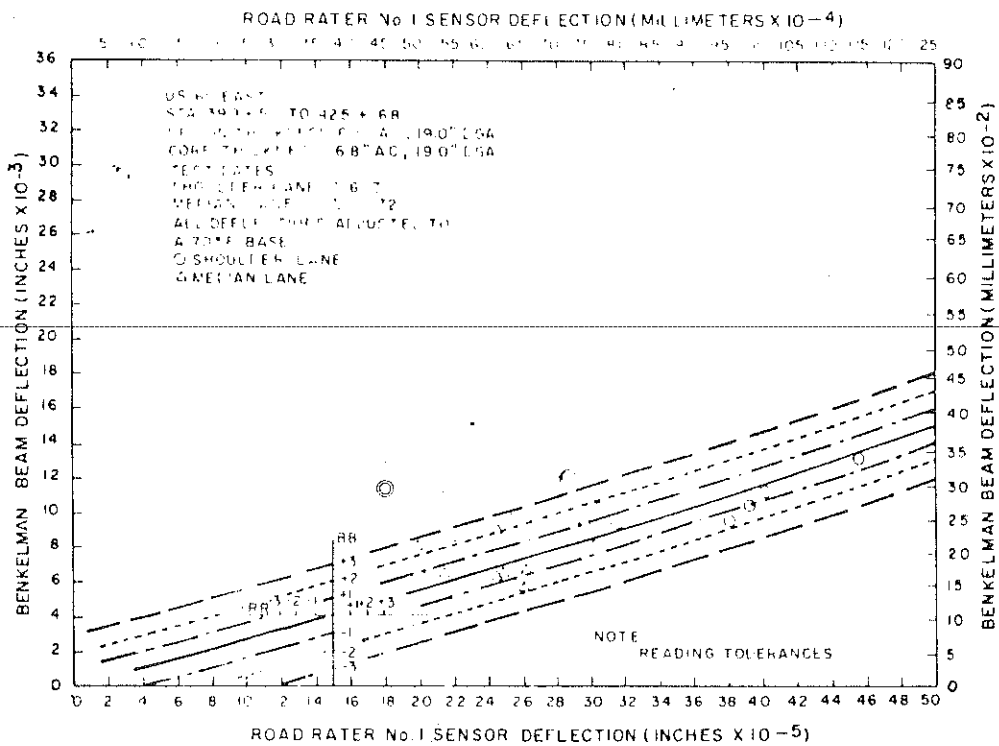


Figure 4. Plot of Road Rater No. 1 Deflection versus Benkelman Beam Deflections for 173 mm (6.8 inches) of Asphaltic Concrete on 483 mm (19 inches) Dense-Graded Aggregate.

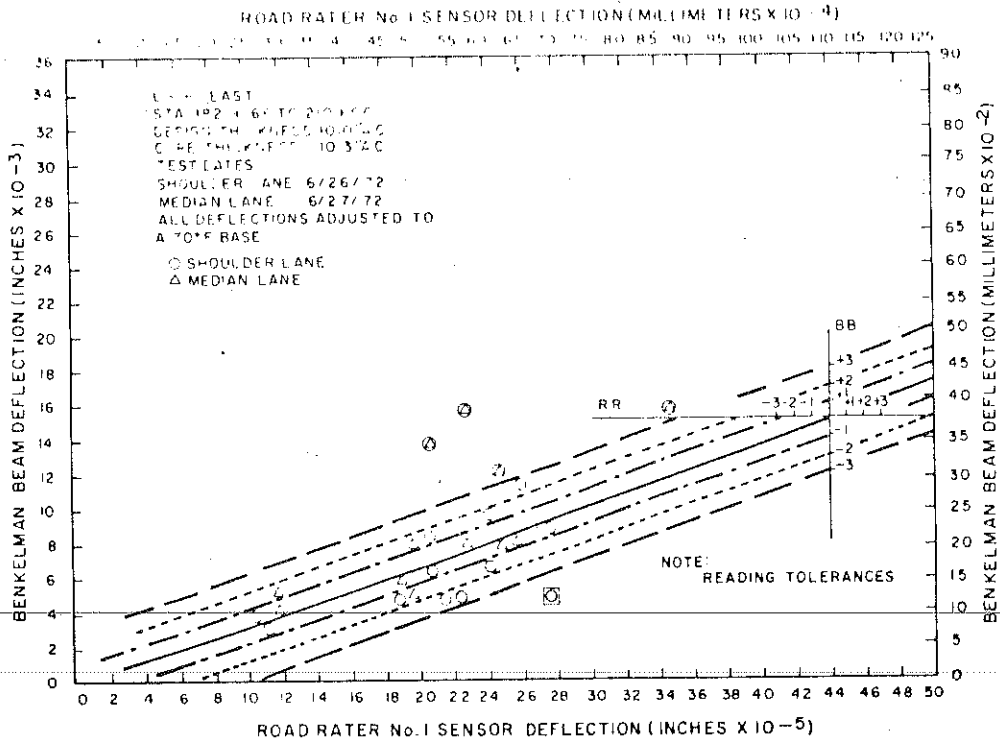


Figure 5. Plot of Road Rater No. 1 Deflection versus Benkelman Beam Deflections for 254 mm (10 inches) of Full-Depth Asphaltic Concrete.

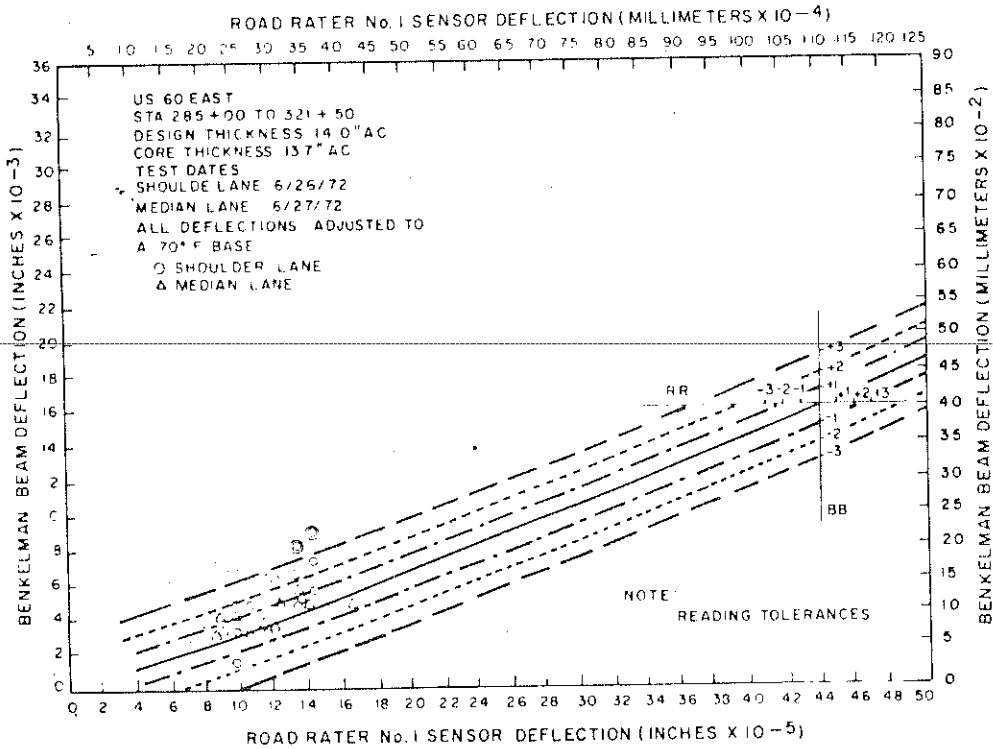


Figure 6. Plot of Road Rater No. 1 Deflection versus Benkelman Beam Deflections for 356 mm (14 inches) of Full-Depth Asphaltic Concrete.

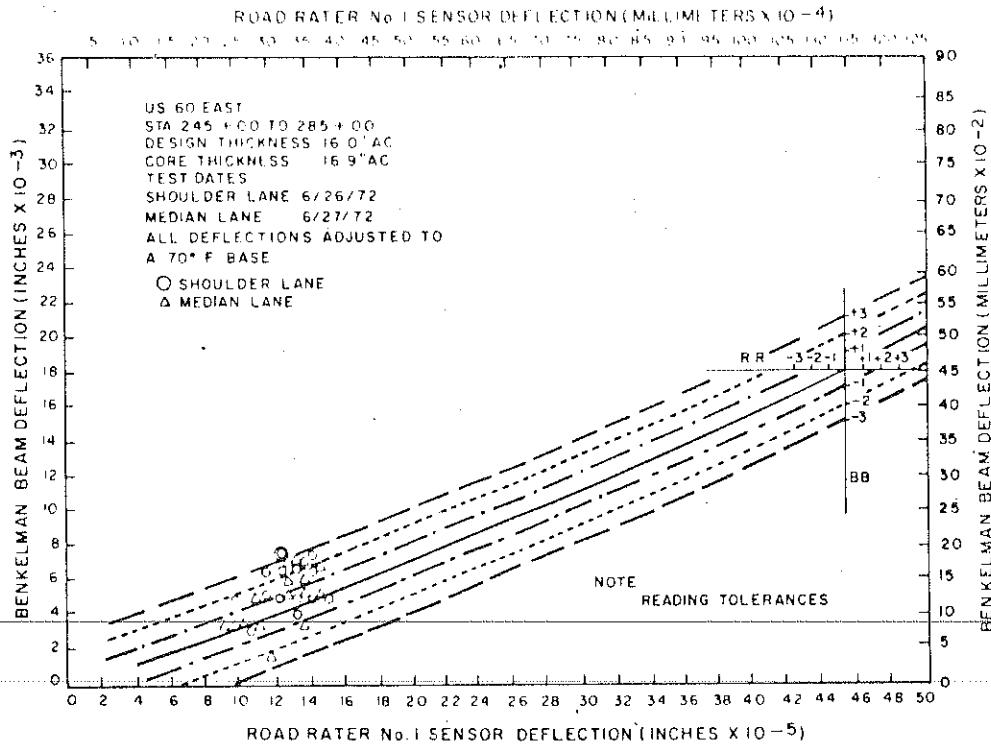


Figure 7. Plot of Road Rater No. 1 Deflection versus Benkelman Beam Deflections for 406 mm (16 inches) of Full-Depth Asphaltic Concrete.

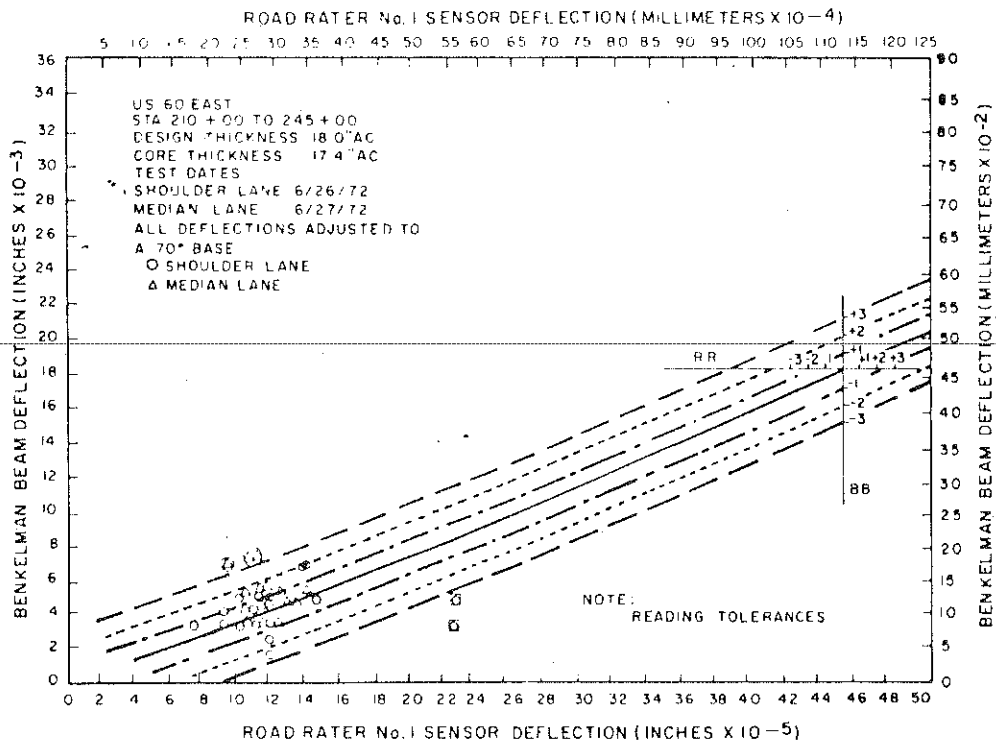


Figure 8. Plot of Road Rater No. 1 Deflection versus Benkelman Beam Deflections for 457 mm (18 inches) of Full-Depth Asphaltic Concrete.

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