Modeling of Pavement Response Under Superheavy Loads

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An analysis of pavement response under multiple-axle, superheavy-load vehicles is presented. Pavement displacements under superheavy loads were measured using multidepth deflectometers. A procedure for data acquisition and modeling of the pavement structure and multiple-axle wheel loads is described. Pavement response is calculated using multilayer elastic theory, and the measured and calculated results are compared. It was found that layered elastic theory can provide a fairly accurate estimate of pavement displacements under expected superheavy loads, provided that the wheel load magnitudes are known.

The Texas Department of Transportation (TxDOT) has been issuing permits for the movement of superheavy loads on an ever-increasing basis. TxDOT defines gross vehicle weights in excess of 1114 kN (250 kips) as superheavy loads. Superheavy loads in excess of 8909 kN (2,000 kips) have been moved. The effects of superheavy loads on pavements are not well established. To address that problem, TxDOT funded a research project to study the movement of superheavy loads over the state's highway system. The objective of the study was to develop a procedure to evaluate the potential for pavement damage on a proposed superheavy-load route and to determine the need for temporary strenthening measures to minimize or prevent pavement damage.

In this paper the methodology for pavement structural capacity evaluation and modeling of pavement response under superheavy loads is described. The methodology includes field data acquisition for evaluation of pavement structural capacity, as well as modeling of pavements and superheavy loads to analyze stresses and strains and determine the potential for pavement damage. The methodology described is meant to serve as a first-stage procedure only; it is likely to be improved upon as research progresses. Application of the methodology and the results obtained with it are illustrated with a case study.

DATA ACQUISITION AND PAVEMENT MODELING

One of the aims of the research project is to formulate a procedure for the routine evaluation of pavement structural capacity to be implemented on routes on which superheavy-load movements are planned. The modeling of the pavement response under a simulated load plays an important part in this process. The procedure that is being developed for the purposes of this study uses the most modern nondestructive testing methods available to TxDOT. This procedure is expected to have a tiered structure with varying levels of complexity depending on the magnitude of the superheavy load and the importance of the superheavy-load route. A proposed scheme for the route evaluation is presented in the following.

The nondestructive testing procedure is based on falling-weight deflectometer (FWD) measurements. For flexible pavements, FWD measurements are analyzed using backcalculation of pavement properties (*1,2*). The MODULUS backcalculation program (*3*) is used for routine backcalculation purposes. It is recognized that the nonlinear load response of unbound pavement materials has to be accounted for in any pavement model. Therefore, FWD measurements are taken at load levels that are comparable with the wheel loads expected to be applied by the superheavy-load vehicles.

Extensive use is made of ground-penetrating radar (GPR) to provide for the nondestructive determination of layer thicknesses and to identify weak or wet spots within a given route (*4,5*). A video log is taken of the roadway in conjunction with GPR measurements to assist in the interpretation of the radar data and to document roadway features such as curves and turns, as well as potential obstructions such as traffic signs and signals. GPR measurements are verified by taking cores as needed. Dynamic cone penetrometer (DCP) measurements are used to assist in the determination of pavement layer properties (*6*).

The frequency of GPR and FWD measurements is generally dictated by the length of the pavement being evaluated. Typically, GPR measurements are taken at 3-m (10-ft) intervals, whereas FWD measurements are taken at 800-m (0.5-mi) intervals. Pavement analysis consists of two phases. First, subsections having similar construction types and layer thicknesses are identified. The subsectioning is done using a computerized procedure that is based on the GPR predicted layer thicknesses (*7*). The second part of the analysis consists of modeling the pavement structure in order to calculate stresses and strains under the expected loading conditions. Backcalculated layer properties are verified as needed by further testing the cores as well as considering DCP measurements.

In addition to measurements for structural evaluation purposes, a condition survey is done using TxDOT's automatic road analyzer (ARAN) unit (*8*), which provides measurements of rut depth and present serviceability along the proposed superheavy-load route. Also, the presence of surface cracking is established by viewing the video of the pavement surface taken with the ARAN. The condition survey is done before and after the superheavy-load moves.

CASE STUDY

Two superheavy-load moves took place in Victoria, Texas, during December 1992 that were monitored by the Texas Transportation

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Institute. Both loads were structural components of an offshore pipe layer. The heavier of the two loads, the "tower," was transported on a self-propelled multiple-axle trailer that consisted of three units, each having six lines. As used by superheavy-load haulers, a line denotes a row of two axles on the trailer unit, with each axle having two tires. The second, lighter load, the "base support," was transported by means of a tractor-trailer combination. Gross vehicle weights of the tower and the base support were 2380 kN (534.3 kips) and 1131 kN (254 kips), respectively.

The route along which the loads were moved consisted of three sections. The total length of the route was 19.8 km (12.4 mi). Figure 1 presents typical results of the GPR layer thickness predictions together with a comparison of measured core thicknesses. FWD measurements were taken at 800-m intervals. A number of cores were taken on each pavement section, and DCP measurements were taken inside selected core holes.

MODELING OF LOAD AND PAVEMENT RESPONSE

One of the most important instruments used for modeling pavement response under multiaxle loads is the multidepth deflectometer (MDD). The MDD uses linear variable differential transducers to measure in situ pavement displacements (*9,10*). An MDD was installed along one of the sections of the superheavy-load route. The site of the MDD installation was that which FWD and GPR measurements determined to be the weakest part of the route. MDD sensors were installed at three different depths, that is, 95, 340, and 635 mm (3.7, 13.3 and 25 in.). The arrangement allowed displacements to be measured in each of the three layers of the pavement system. Figure 2 presents a schematic representation of the MDD installation. MDD measurements allowed pavement response to be measured under various loads, including the two superheavy loads. The principal reason for using MDD measurements was to help establish a model for predicting pavement response. By comparing the measured displacements with the predicted displacements from theory, a verification of the pavement model could be made before an evaluation of stresses and strains for damage assessment was undertaken.

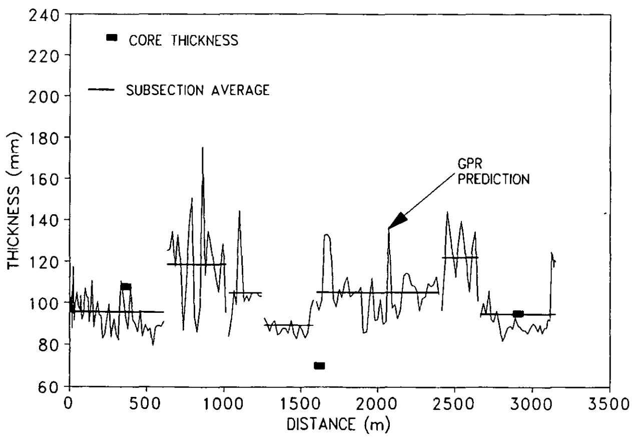

FIGURE 1 GPR measurements on FM 1432, Victoria, Texas (1 mm = 0.04 in., 1 m = 3.29 ft).

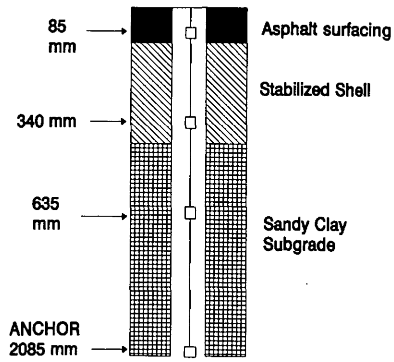

FIGURE 2 MDD installation on FM 1432, Victoria, Texas (1 in. = 25.4 mm).

During the superheavy load moves in Victoria, Texas, FWD measurements were taken at a 229-mm (9-in) offset from the MDD installation point, to allow for measurement of the MDD anchor movement. The movement of the rod was monitored by coupling the MDD anchor rod to the seventh sensor of the FWD. Backcalculations that were subsequently made using the FWD measurements provided estimates of the pavement layer stiffnesses in the area of the MDD installation. The backcalculated-pavement structure is summarized in Table 1. The pavement structure shown in Table 1 was used in all subsequent modeling of the pavement response under simulated loading conditions.

FWD measurements were made close to the time the superheavy load would move. In practice, there is a time window within which a route evaluation must be completed so that a permit will be issued within a reasonable time before the scheduled date of the superheavy-load move. Thus, differences in environmental conditions existing at the time of testing and the projected conditions at the time of the move must be considered in the evaluation.

MDD displacements measured under the FWD load are indicated in Figure 3. The applied FWD load was used as input in the WESLEA program (*11*) to simulate the pavement response under FWD loading. A comparison of the measured and calculated displacements is presented in Figure 4, showing an acceptable correlation between the measured and calculated displacements for the uppermost sensors. In the case of the third (lowest) sensor, however, calculated and measured displacements reflect poor agreement. Note that the low displacement measured on the bottom sensor is somewhat unusual. Typically, third sensor readings are much closer to the top and second sensor readings, as was seen earlier (*10*). There are two possible explanations for the present observation:

1. The third sensor may be founded on a stiff subgrade, whereas there may be a soft interlayer between the third sensor and the two sensors closer to the surface.
2. The low displacement may be the result of an electrical or mechanical problem, such as slipping.

The first of these possibilities was tested by trying to recalculate the layer moduli with the inclusion of a soft interlayer in the pavement system. However, no feasible solution could be obtained with this arrangement. This observation was supported by the

TABLE 1 Backcalculated Pavement Structure Used in Load and Pavement Modeling

Layer Description	Thickness (mm)	Backcalculated Moduli (MPa)
Asphalt Surfacing	107	2,645
Stab. Shell Base	305	69.0
Subgrade	1054	23.4
Stiff Layer	semi-infinite	69,000

(Note: 1 mm = 0.04 in, 1 MPa = 0.14 ksi)

DCP measurements, which indicated that the subgrade was soft, with no apparent sublayering. On the basis of these results, it was concluded that the third sensor was suspect and was subsequently not used in the modeling of pavement response.

The modeling of multiaxle superheavy-load vehicles consisted of two phases. First, a sensitivity analysis was conducted in order to establish how the multiple wheels of the superheavy-load vehicle should be modeled. Second, the actual modeling of the superheavy loads was done, and a comparison of the calculated and measured displacements was made. A sensitivity analysis was conducted through repeated runs of the BISAR linear-elastic layered computer program (*12*). As part of a sensitivity analysis, stresses, strains, and displacements were calculated at various offsets from the applied load, thereby establishing the zone of influence of the load for different pavement structures. Results of the sensitivity analysis are published elsewhere (*13*) and are not detailed here. The sensitivity analysis showed that only about 5 percent of the maximum displacement is calculated at distances greater than 2.74 m (9 ft) from the load. That would seem to indicate that, for the purposes of modeling multiple wheel loads, all loads falling within a radius of approximately 2.74 to 3.05 m (9 to 10 ft) from the point where stresses and strains are to be evaluated should be included in the analysis.

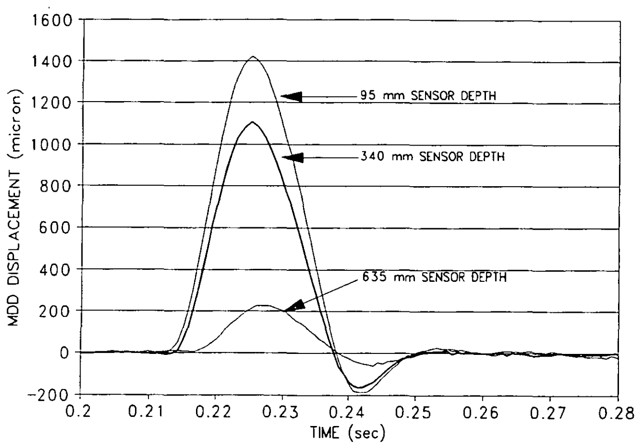

FIGURE 3 MDD response under FWD loading (1 μm = 0.04 mil).

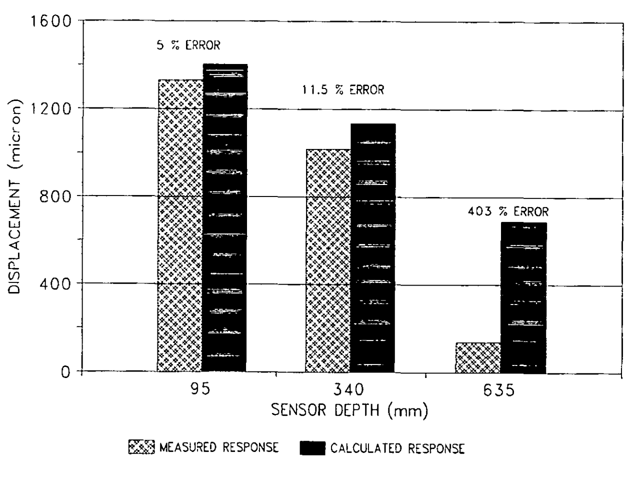

FIGURE 4 Measured versus calculated MDD response (1 μm = 0.04 mil).

MODELING OF PAVEMENT RESPONSE UNDER TOWER

The MDD response measured under the tower is illustrated in Figure 5. The positions of the peaks and troughs of the waveform represent the displacements measured under and between the axles, respectively. It should be noted that the movement of the anchor could not be measured under the superheavy load and was not taken into account in this figure. However, the error from this is expected to be relatively small, because the anchor movement measured under the dynamic FWD loading was only 6 percent of the peak MDD displacement (i.e., that of the MDD sensor).

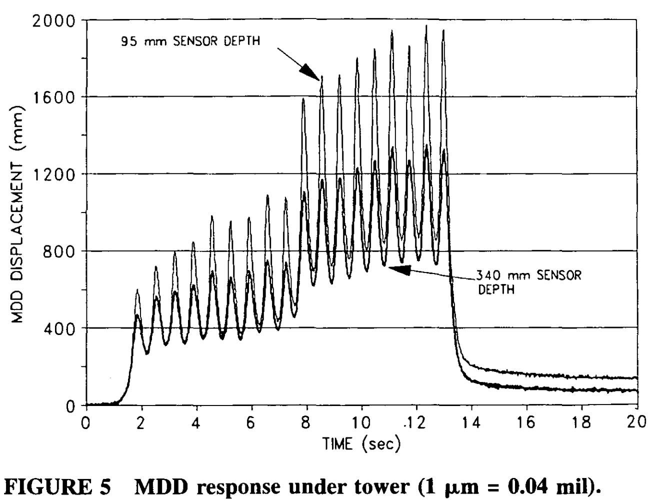

FIGURE 5 MDD response under tower (1 μm = 0.04 mil).

Figure 5 clearly indicates that there are two distinct phases in the pavement response. Displacements measured under the first nine lines are substantially lower than those measured under the last nine lines. A possible explanation for this observation may be an uneven distribution of the load. As a first attempt at modeling this load, the gross vehicle weight was divided by the total number of wheels to obtain the average load per wheel. The load model was set up to resemble the line and wheel spacing of the transport vehicle. By varying the position at which the pavement response was calculated, the effect of a moving load could be simulated. A video taken during the move showed that for the first five lines of the transport vehicle, the outer wheels were slightly offset from the MDD sensor. In modeling the load, this initial offset was simulated by calculating the displacements at a similar offset from the vehicle tires. Displacements that were calculated in this way are represented in Figure 6.

Several interesting observations follow from Figure 5. Differences between the displacements calculated for the top and middle sensors are similar to those of the measured responses. Also, the tendency of the measured top and middle displacements to fall together between the axles is reflected in the calculated response. Note that the calculated response (see Figure 6) falls approximately halfway between the higher and lower portions of the measured response (as in Figure 5). This last observation seems to support the suspicion that the load was not evenly distributed across all vehicle axles.

In order to test the hypothesis of an uneven load distribution, it was necessary to first establish whether an MDD response accurately reflects the magnitude of the load under which the displacements are being measured. It also had to be determined whether displacements calculated by means of the assumed mechanistic model can reflect accurately a change in the applied load. Verification involved considering the MDD response measured under a dump truck for which the exact axle weights were known.

Figure 7 shows the MDD response measured under the dump truck. Also reported is the calculated response. Clearly, there is good agreement between the measured and calculated responses. It is significant that the ratio of 0.48 between the lower and higher displacements is very close to the ratio of 0.41 between the front and rear axle weights. This indicates that for the pavement under consideration, pavement response closely resembles linear elastic behavior.

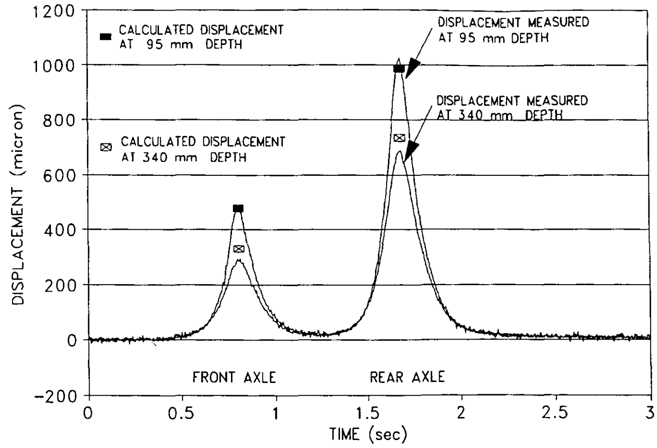

FIGURE 7 Measured and calculated responses under dump truck (1 μm = 0.04 mil).

The superheavy-load simulation was redone following this observation. However, the measured response was divided into two phases: the first consisted of displacements measured under the first nine lines, the second of measurements under the last nine lines. For each of the two phases, the average maximum displacement under each line was calculated. Gross vehicle weight was then distributed between the first and last nine lines according to the ratio of these averages to each other. The arrangement resulted in the modeling of the last nine lines with a load that was 30 percent higher than the theoretical average load per line. Conversely, the first nine lines were modeled with a load that was 30 percent lower than the theoretical average load.

Figures 8 and 9 plot the measured MDD response together with the calculated response for the first and second sensors. The measured response is represented only by sampled points (such as the peaks and troughs) of the total measured response indicated in Figure 5. It is clear that the redistribution of the load resulted in

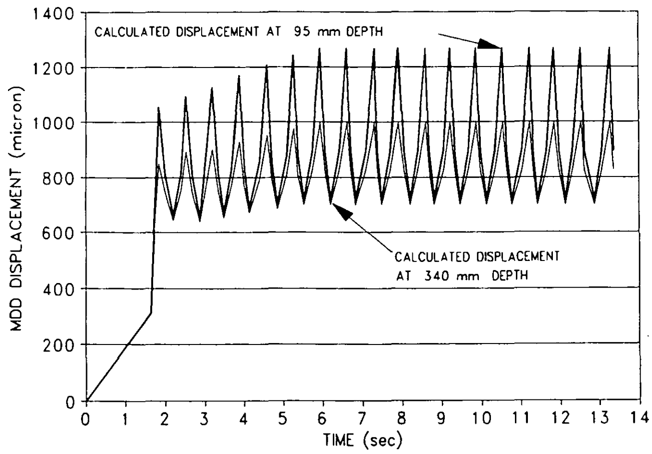

FIGURE 6 Calculated MDD response under tower (1 μm = 0.04 mil).

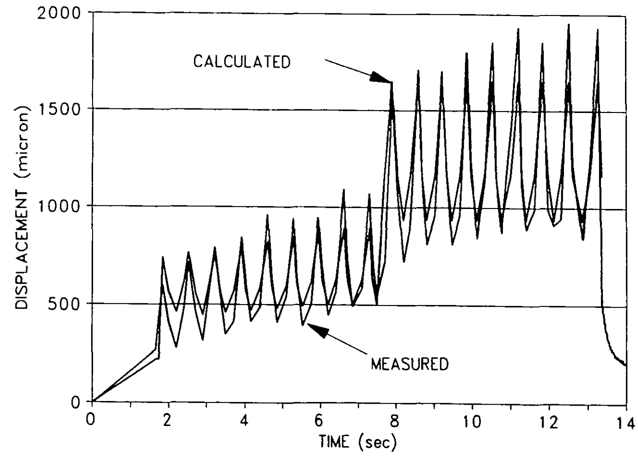

FIGURE 8 Measured and calculated responses under tower at 95-mm depth (1 mm = 0.04 in.).

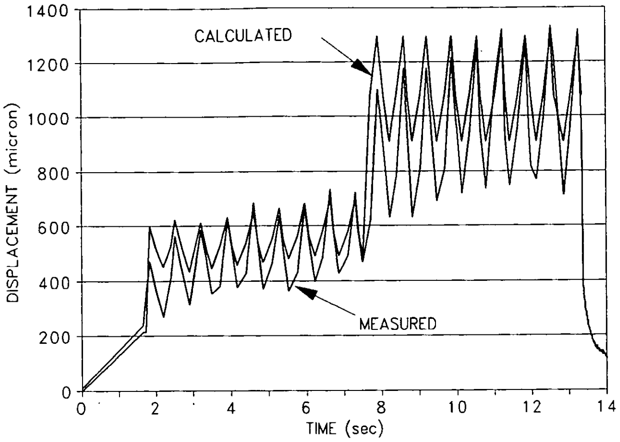

FIGURE 9 Measured and calculated responses under tower at 340-mm depth (1 mm = 0.04 in.).

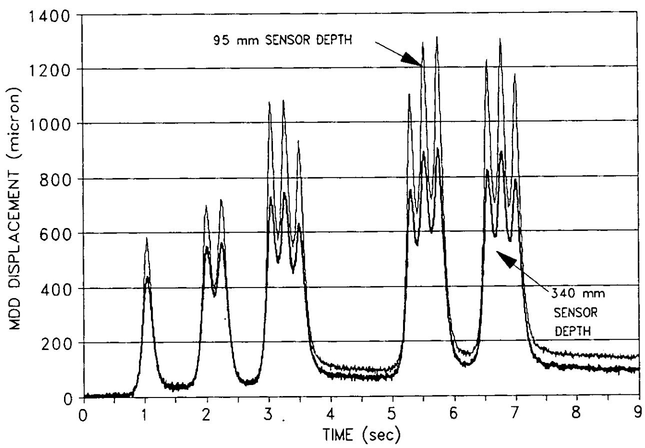

FIGURE 10 Measured and calculated responses under base support (1 mm = 0.04 in.).

a much-improved agreement between the measured and calculated responses.

Preferably, wheel loads could be measured before a superheavy-load move. However, this is difficult to do in practice because route assessment needs to be made and a permit issued well in advance of the superheavy-load move. The problem was addressed in the development and implementation of a route assessment procedure for this study.

MODELING OF PAVEMENT RESPONSE UNDER BASE SUPPORT

The MDD response measured under the 1131-kN (254-kip) load is shown in Figure 10. Peak-displacements under each of the load groups are clearly visible. In the modeling of this load, the gross vehicle weight was distributed between axle groups in a way similar to that described for the tower load. For each axle group, the average maximum measured displacement was calculated. The gross vehicle weight was then assigned to each axle group according to the average. Displacements were then calculated as before. Figures 11 and 12 show the measured and calculated responses. As was the case with the tower load, measured and calculated responses show good agreement.

APPLICATION OF LOAD AND PAVEMENT MODELING

The ultimate aim of load and pavement modeling is to predict the possibility of subgrade failure under expected loading conditions. Such a prediction can only be made after considering stresses and strains, together with an engineering estimate of the pavement's resistance to deformation or shear failure. For the load and pavement case discussed here, a detailed analysis of stresses and strains was undertaken and is published elsewhere (*13*).

In this analysis, the potential for immediate failure of the subgrade was evaluated by calculating the ratio of the octahedral shear stresses to the octahedral shear strength of the subgrade material under expected loading conditions. Damage assessment based on rutting of the subgrade or asphalt fatigue cracking was

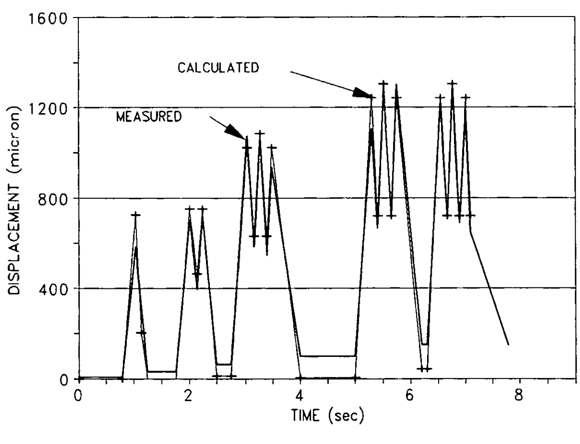

FIGURE 11 Measured and calculated responses under base support at 340-mm depth (1 mm = 0.04 in.).

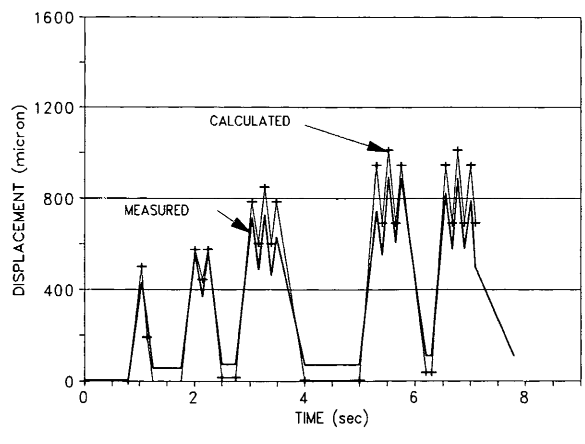

FIGURE 12 Measured and calculated responses under base support at 340-mm depth (1 mm = 0.04 in.).

also evaluated. Analysis methods described above are not necessarily the most accurate, and use of other types of failure criteria may be justified. However, once it has been established that the load and pavement model can simulate accurately the actual response of the pavement under the applied load, any further analysis of stresses and strains can be undertaken with relative ease simply by altering the positions where stresses and strains need to be calculated in order to suit that particular method of analysis.

SUMMARY AND CONCLUSIONS

A procedure for modeling pavement response under superheavy loads was presented. To date, results obtained with the procedure have led to the following conclusions and suggestions for further work:

1. Measured MDD data can be of considerable use in validating any assumption made in the modeling pavement structures and multiaxle wheel loads. Although the use of MDD data on a regular basis would not be feasible, its application in the development of load and pavement modeling procedures is recommended.
2. For the pavement section discussed in this paper, results obtained in simulating pavement response by using layered elastic theory are encouraging. The results reported indicate that layered elastic theory can provide a reasonable estimate of pavement response under multiaxle superheavy loads, as long as the wheel load magnitudes are known. A route assessment scheme using elastic layered theory can function as a Level 1 procedure within the multilevel framework established for evaluating proposed superheavy load routes.
3. The manner in which the load is distributed over the axles of the transport vehicle is of extreme importance. Movers and owners of superheavy loads should be made aware of the importance of achieving the projected wheel loads that they provide to the highway department in the process of requesting a permit. Some transport vehicles are equipped with gauges that measure the pressures inside the hydraulic lines of the vehicle axles. These gauges can be used to monitor vehicle loads. Consideration should be given to encouraging their use, and it is important to discuss the matter with the highway department and movers of superheavy loads.

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