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16. Abstract

Superheavy loads are defined as loads that have gross vehicle weights in excess of 1112 kN. In the past, loads in excess of 8900 kN have been moved. Before a permit can be issued for a superheavy load move, TxDOT needs to determine whether the proposed route is structurally adequate to sustain the superheavy load. The analysis of damage potential under superheavy loads concerns the likelihood of a rapid, load-induced shear failure as opposed to the long-term accumulation of permanent deformation and fatigue due to repeated load applications. A methodology for evaluating superheavy load routes was developed in Project 0-1335, "Movement of Superheavy Loads Over the State Highway System." This methodology is now implemented in TxDOT for permitting superheavy load moves. It is based on an incremental, non-linear layered elastic pavement model for predicting the induced pavement response under surface wheel loads. Predicted stresses under a superheavy load are used with the Mohr-Coulomb yield criterion to evaluate the potential for pavement damage prior to the superheavy load move. Since the initial development, a follow-up study led to enhancements in the analysis procedure. Researchers developed routines to evaluate the edge load condition and to determine the failure wheel load for a given pavement structure. The former modification is used to evaluate the potential for edge shear failure on moves where the wheel loads will travel close to the edge of a given pavement with unpaved shoulders. The latter modification is used in identifying alternative trailer configurations to prevent pavement damage during superheavy load moves. This project summary report provides guidelines in the application of the methodology to evaluate superheavy load routes.

17. Key Words
Superheavy Loads, Pavement Evaluation, Pavement Response Modeling, Non-linear Material Behavior, Mohr-Coulomb Yield Criterion

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GUIDELINES FOR EVALUATING SUPERHEAVY LOAD ROUTES

by

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Research Report 3923-S
Research Study Number 7-3923
Research Study Title: Continued Development of the TxDOT Superheavy Load Analysis Procedure (PALS)

Sponsored by the
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October 1997

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IMPLEMENTATION STATEMENT

The Texas Department of Transportation (TxDOT) is implementing the PALS computer program to evaluate the structural adequacy of proposed superheavy load routes. **PALS** is an acronym for Program to Analyze Loads Superheavy. During this study, TTI assisted in the implementation effort by conducting a training session on the operation of the PALS analysis program and by providing guidance in its application on actual superheavy load moves. To evaluate the potential for edge shear failure, the computer program was revised to incorporate a structural analysis routine that determines an equivalent surface layer based on a given ratio of edge to interior displacements. An analysis is then conducted assuming a pavement with this equivalent surface to establish the potential for edge shear failure on a given move. This option was specifically developed for cases where the superheavy wheel loads will track close to the edge of a particular roadway with unpaved shoulders.

PALS was also modified to enable the user to determine the failure wheel load for a given pavement. This option is particularly useful in identifying alternative trailer configurations to minimize or prevent pavement damage during superheavy load moves. Based on experience from actual field applications, the importance of accurate pavement layer thicknesses was made evident. Layer thickness affects the analysis in two ways. First, it influences the backcalculation of layer moduli from Falling Weight Deflectometer (FWD) data. Second, the induced pavement response under surface wheel loads is sensitive to the layer thicknesses. Consequently, data collection to conduct a superheavy load analysis should include measurements of layer thicknesses by coring, Dynamic Cone Penetrometer testing, Ground Penetrating Radar, or a combination of these test methods. The determination of layer thicknesses should precede the FWD data collection on the given route. In this way, the locations of FWD measurements may be better established and tied to the thickness data.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the project was Dr. Emmanuel G. Fernando, P.E. # 69614.

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The work reported herein was conducted as part of a research study sponsored by the Texas Department of Transportation. The support and guidance of the Project Director, Mr. Michael Murphy, are gratefully acknowledged. A sincere note of appreciation is also extended to the Pavement Design Engineers in the following Districts who participated in the training session on the PALS analysis program: Beaumont, Corpus Christi, Fort Worth, Houston, Waco, and Yoakum Districts.

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SUMMARY

The analysis of damage potential under superheavy loads is concerned with the likelihood of a rapid, load-induced failure in one or more pavement layers resulting from a shear stress that exceeds the shear strength afforded by the material's internal frictional resistance and cohesion. To evaluate the structural adequacy of superheavy load routes, researchers developed a methodology that is based on an incremental, non-linear layered elastic pavement model for predicting induced stresses under surface wheel loads. The predicted stress state is used in conjunction with the Mohr-Coulomb failure criterion to establish the potential for pavement damage under superheavy loads. This evaluation is conducted using a computer program called, PALS, which is now used by TxDOT in permitting superheavy load moves. As part of implementing the methodology to evaluate superheavy load routes, a training class on the operation of the PALS analysis program was conducted in the present study. To address needs identified from the initial implementation, two new options were added to the computer program. First, TTI researchers developed a procedure to evaluate the potential for edge shear failure on routes with no paved shoulders where the wheel loads will track close to the pavement edge. Second, the program was modified to include an option to evaluate the failure wheel load for a given pavement. A user's guide to the revised version of PALS (Release 2.0) was prepared. This new version is implemented in the Windows 95 or NT environment.

In the analysis of edge loading, an equivalent surface is evaluated for the given pavement, with a reduced modulus to reflect the increase in surface displacement at the edge. In addition, the surface cohesion is adjusted based on the reduction in layer modulus. The analysis is then conducted assuming a pavement with this equivalent surface to establish the potential for edge shear failure during the superheavy load move.

To assist in the implementation effort, this research report provides guidelines in the application of the methodology to evaluate superheavy load routes. This methodology was initially developed in Project 0-1335 and updated in the present study (Project 7-3923). The guidelines presented are based on the findings from these studies and on actual field experience in the implementation of the analysis procedure.

CHAPTER I

INTRODUCTION

In 1992, the Texas Department of Transportation (TxDOT) funded a research study (Project 0-1335) with the Texas Transportation Institute (TTI) to develop a procedure for evaluating the structural adequacy of superheavy load routes. By definition, superheavy loads have gross vehicle weights in excess of 1112 kN. In the past, loads in excess of 8900 kN have been moved. Most superheavy load transport vehicles are equipped with multiple axles to increase load distribution. Figures 1 to 3 illustrate vehicle configurations that are typically used to move superheavy loads, such as oil pressure vessels, electric transformers, dragline components, and off-shore pipe-laying equipment. Based on data collected from previous superheavy load moves, the total load on a single axle of a transport vehicle is often close to or more than 500 kN.

Project 0-1335 led to the development of a methodology to evaluate the structural adequacy of proposed superheavy load routes. In contrast to routine pavement design, the analysis of pavements under superheavy loads is concerned with the likelihood of a rapid load-induced shear failure in one or more pavement layers, as opposed to the long-term accumulation of permanent deformation and development of fatigue cracking due to repeated load applications. Load repetitions, in the case of superheavy load vehicles, are not likely to exceed 30 or 40, even when two vehicles are moved in short succession. Thus, the expected mode of failure is a rapid load-induced failure resulting from a shear stress which exceeds the shear strength afforded by the material's internal friction and cohesion.

Implementation of the methodology to evaluate superheavy load routes began in 1995. This methodology is based on an incremental, non-linear layered elastic pavement model for predicting the induced stresses under surface wheel loads. The predicted stresses are then used with the Mohr-Coulomb failure criterion to evaluate the potential for pavement damage prior to the superheavy load move. It is noted that the objective in the permitting process is to prevent pavement damage. In those cases where the structural assessment indicates

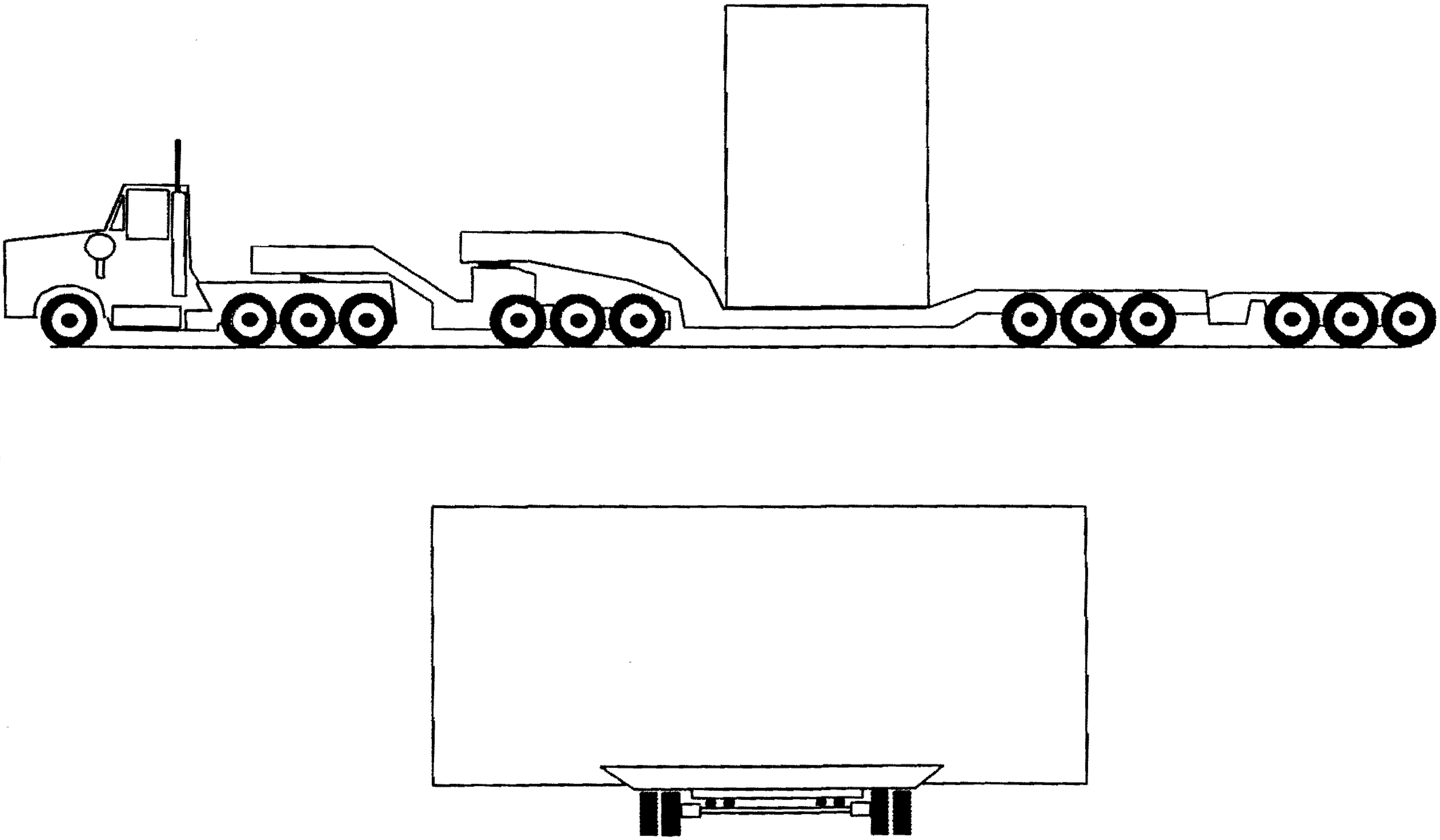

Figure 1. Example of a Conventional Truck and Trailer Combination (Jooste and Fernando, 1995).

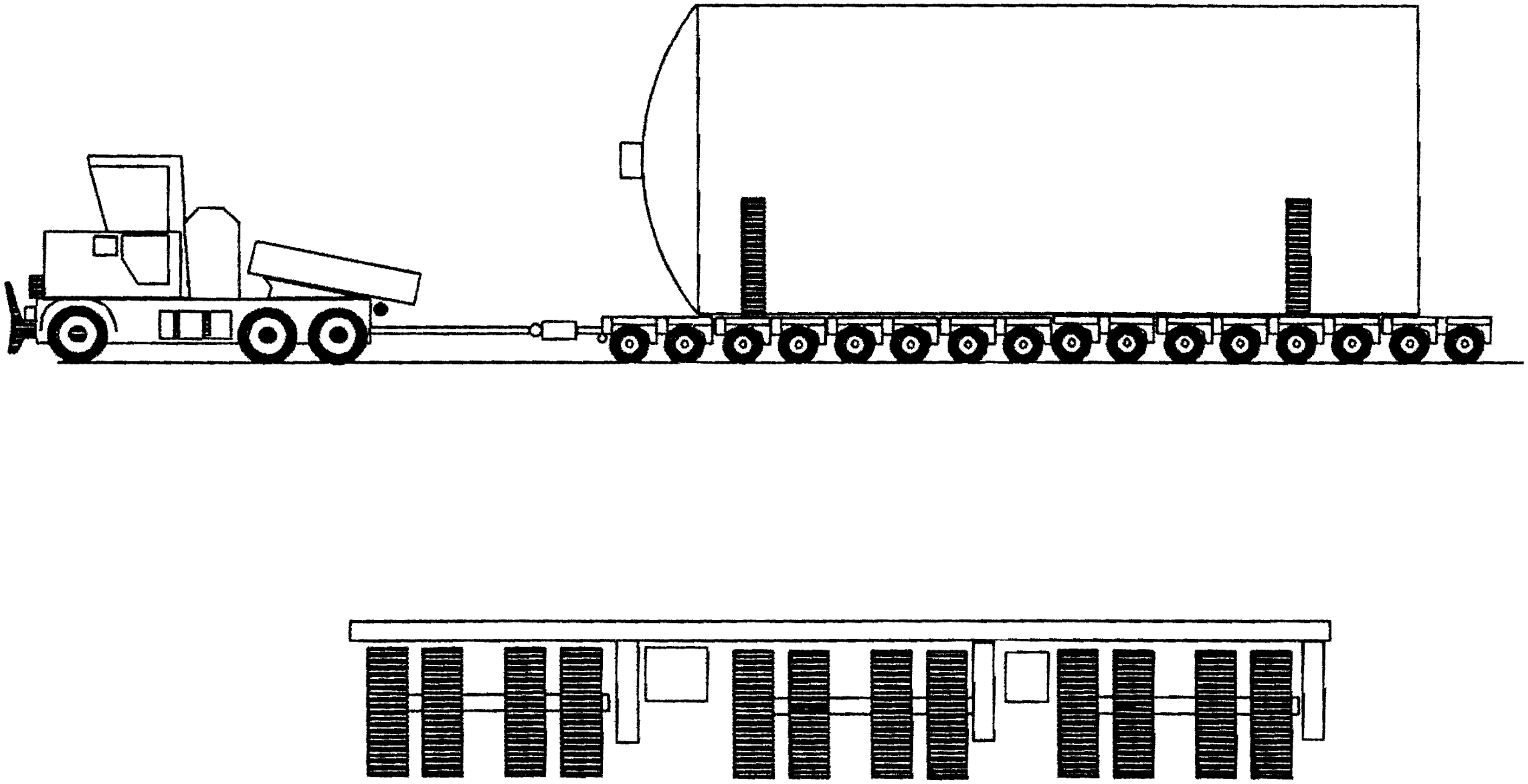

Figure 2. Example of a Specialized Tractor-Trailer Combination (Jooste and Fernando, 1995).

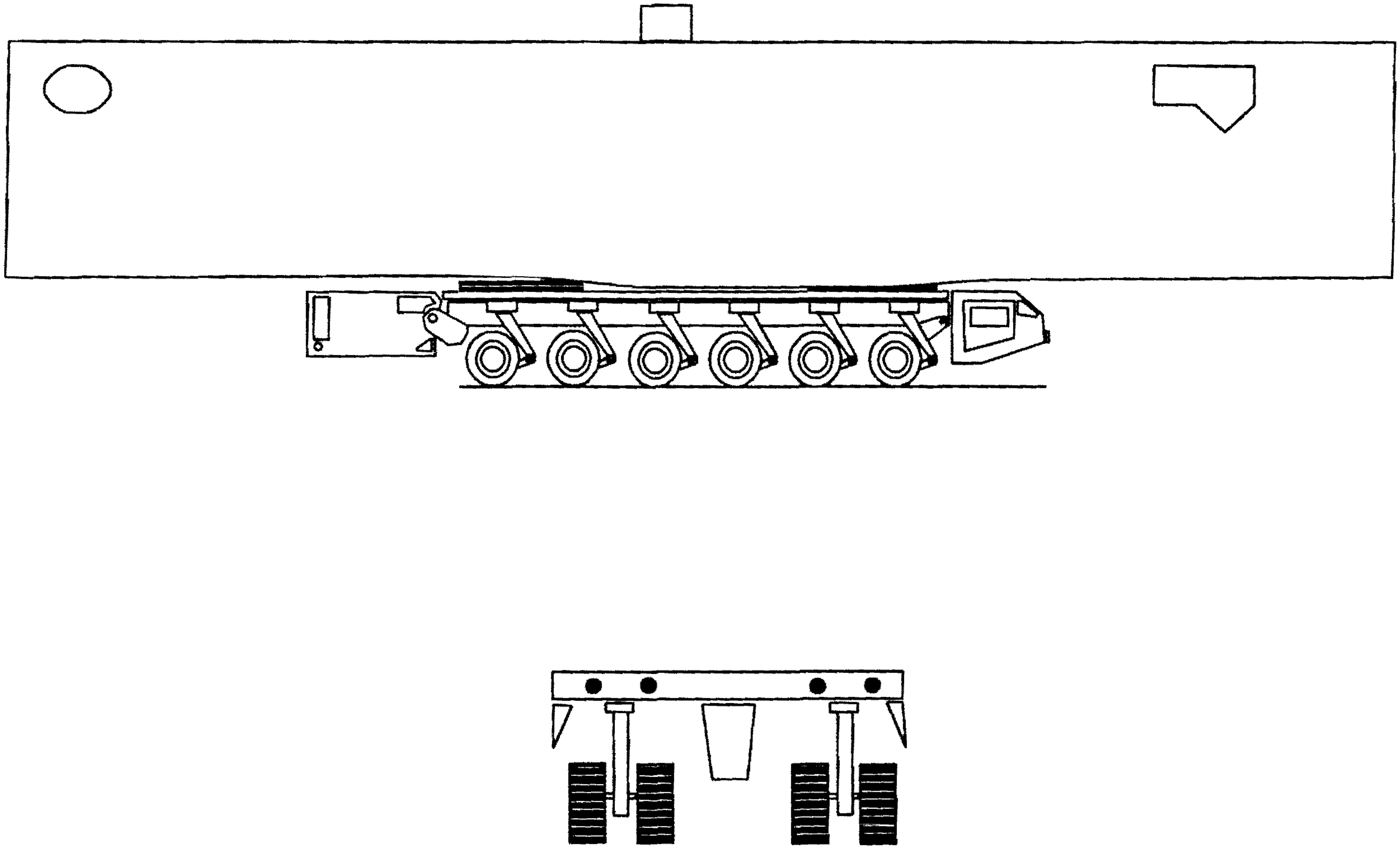

Figure 3. Example of a Self-Propelled Multiple Axle Trailer (Jooste and Fernando, 1995).

potential pavement damage under a specified superheavy load, alternative routes should be investigated, the vehicle configuration modified, or temporary strengthening measures applied on the weak portions of the proposed superheavy load route.

From the initial implementation, a number of needs were identified that led to a follow-up study (Project 7-3923) with the following objectives:

1. Develop a procedure to determine the potential for pavement damage due to edge loads;
2. Identify effective methods for reducing the potential for pavement damage;
3. Establish guidelines to evaluate long superheavy load routes;
4. Provide ad hoc support in analyzing superheavy load routes; and
5. Provide training on the methodology developed to establish the potential for pavement damage from a superheavy load move.

This summary report describes the analysis procedure developed from research sponsored by TxDOT to study the effects of superheavy loads on state-maintained highways. Although the document is primarily intended to explain how the procedure is applied in practice, the underlying principles are briefly explained in Chapter II to provide a basic understanding of the theory behind the methodology and to introduce the material parameters that are important to model the pavement response under superheavy loads. To facilitate implementation, emphasis is placed on providing guidelines in the field application of the superheavy load analysis procedure. Specifically, Chapter III explains the framework for analyzing superheavy load routes; identifies the site-specific data required to perform a structural evaluation, including test methods to determine the required input parameters; presents methods to reduce or eliminate the potential for pavement damage on a given route; and provides guidelines in the evaluation of long superheavy load routes that cross District boundaries. The guidelines presented are based on findings from Projects 0-1335 and 7-3923, and on actual field experience from application of the methodology to evaluate superheavy load routes. Finally, Chapter IV offers recommendations for future work in this area.

CHAPTER II

PRINCIPLES OF SUPERHEAVY LOAD ANALYSIS

The analysis of superheavy loads requires the determination of the induced pavement stresses under surface wheel loads coupled with an evaluation of the structural adequacy of the pavement to sustain the imposed stresses without developing damage. To predict the stresses that develop during loading, an incremental, non-linear layered elastic pavement model is used wherein the pavement is represented as a layered system (Figure 4), comprised of a surface, base, subbase, and subgrade layers. Each layer is of finite thickness, characterized by a modulus or stiffness, and a Poisson's ratio, both of which may be modeled as constants (independent of stress) or as stress-dependent. Jooste and Fernando (1995) document in detail the development and evaluation of the pavement response model for superheavy load analysis. The reader is referred to this reference for an in-depth presentation of the pavement response model. Only a brief overview is provided in this chapter.

MODELING OF PAVEMENT RESPONSE

In the analysis of the response of pavement materials to loading, the concept of resilient modulus is usually encountered. This property is typically obtained from repeated load tests of laboratory molded specimens of a given material. When a cylindrical sample of a pavement material is tested under repeated loading, the total deformation at a given number of load applications is observed to consist of a resilient or recoverable component, and a non-recoverable component (see Figure 5). From the test data, the resilient modulus is calculated as the ratio of the repeated deviatoric stress to the recoverable axial strain (Huang, 1993). Since the stiffness of most pavement materials is dependent on the rate of loading and applied stress, laboratory tests are usually conducted at a range of frequencies and deviatoric stresses that correspond to the expected traffic loadings in the field. In the procedure developed to analyze superheavy load routes, the stress-dependency is defined by three material parameters,

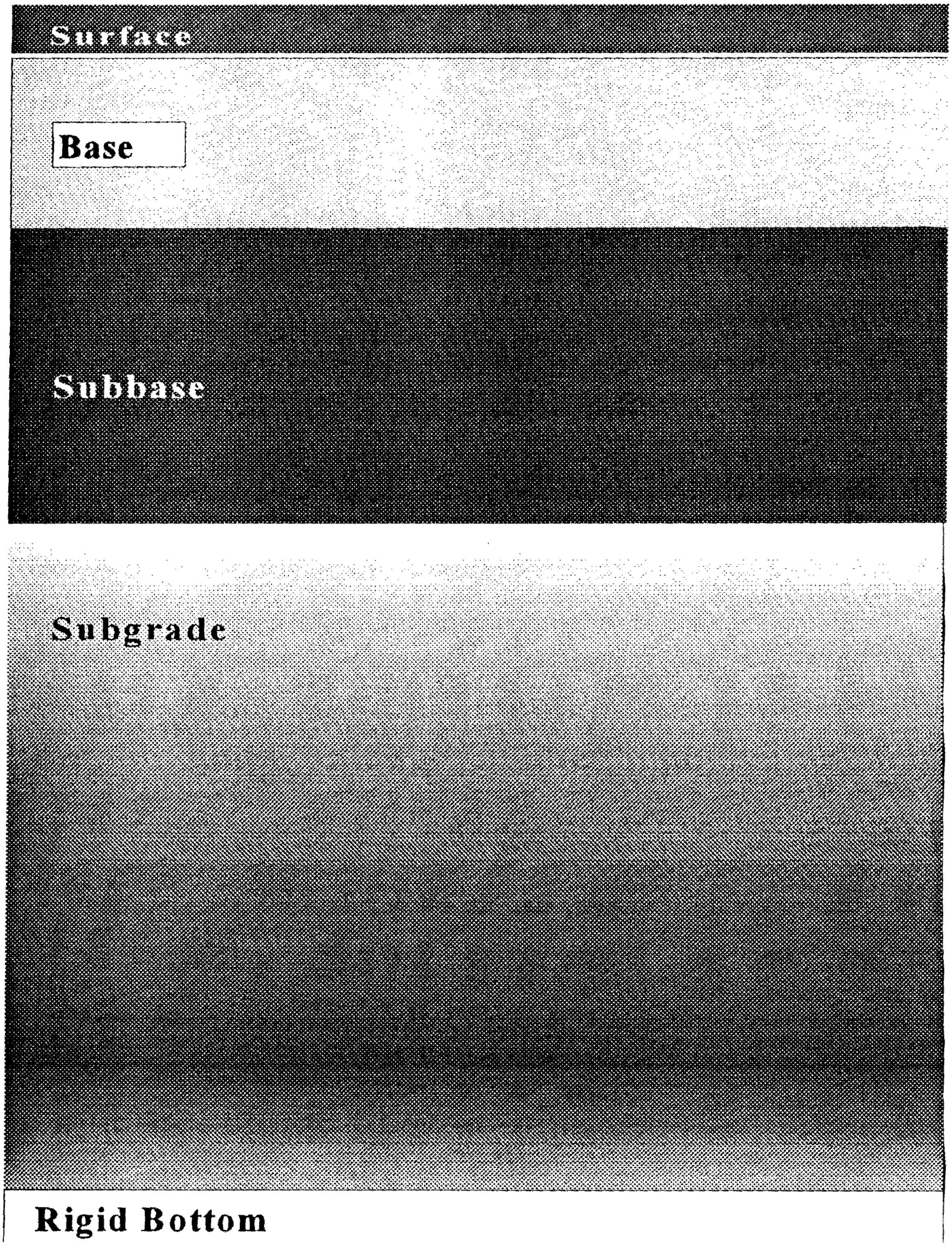

Figure 4. Representation of Pavement as a Layered System.

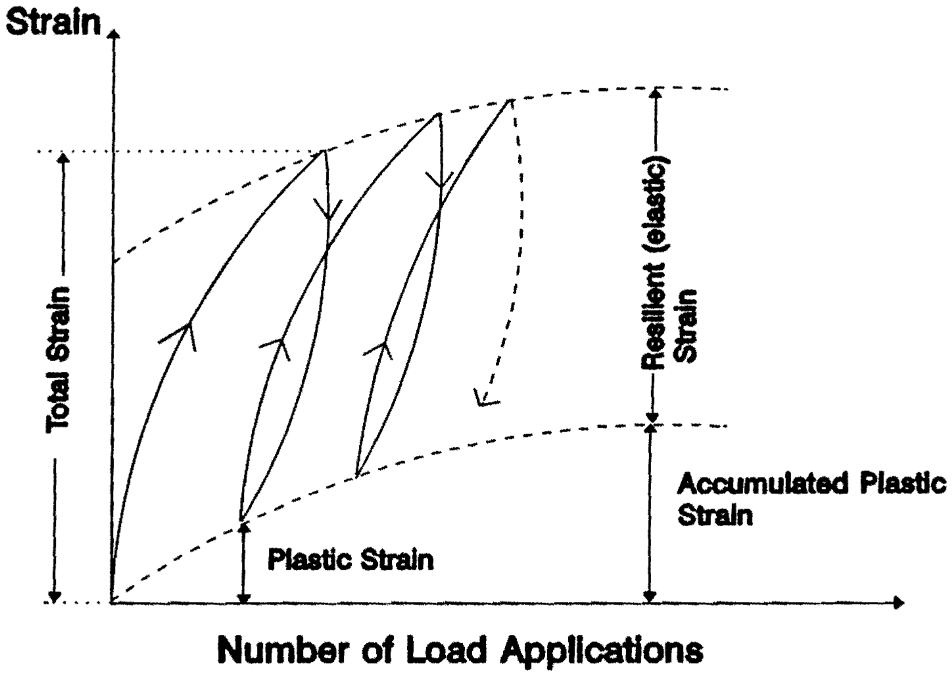

Figure 5. Typical Strains Resulting from a Repeated Load Test (Jooste and Fernando, 1995).

K_1, K_2, and K_3, that are characterized for each pavement layer. Specifically, the relation between the resilient modulus, E_r, and the predicted stress state is defined by (Uzan, 1985):

$$E_r = K_1 \, Atm \left(\frac{I_1}{Atm} \right)^{K_2} \left(\frac{\tau_{oct}}{Atm} \right)^{K_3} \tag{1}$$

where,

I_1 = first stress invariant = $\sigma_1 + \sigma_2 + \sigma_3$ (2)

τ_{oct} = octahedral shear stress

$$= \frac{1}{3} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{\frac{1}{2}} \tag{3}$$

Atm = the atmospheric pressure = 100 kPa,

$\sigma_1, \sigma_2, \sigma_3$ = predicted principal stresses under loading

Measured values of K_1, K_2, and K_3 from laboratory tests on base and subgrade materials are shown in Tables 1 and 2, respectively. From results of sensitivity analyses conducted by Jooste and Fernando (1995), the coefficient, K_1, was found to have the most influence on the predicted resilient modulus. In general, the higher the K_1, the higher the predicted resilient modulus. This is illustrated in Figure 6 which shows predicted resilient moduli for a granular base material at three different values of K_1. The data shown were calculated assuming a pavement with a 100 mm thick asphalt concrete surface layer and a 200 mm thick granular base layer. Values of 0.6 and -0.3 were assumed for the parameters, K_2 and K_3, respectively, for the base layer. For a given curve, it is observed that the resilient modulus increases with increasing wheel load, illustrating the hardening effect of increasing confinement on the predicted resilient modulus. This hardening effect is associated with the K_2 term in Eq. (1) which is a function of the first stress invariant, I_1:

$$K_2 \ term = \left(\frac{I_1}{Atm} \right)^{K_2} \tag{4}$$

As the wheel load increases, the confining pressures also increase, resulting in higher predicted values for the resilient modulus. It is noted that the octahedral shear stress also increases with increasing wheel load, which will tend to decrease the resilient modulus. However, for the pavement and range of wheel loads considered in Figure 6, the increase in confinement with higher wheel loads more than compensates for the softening effect of the octahedral shear stress, although at the higher wheel loads, the rate of increase in modulus is less. Thus, the resilient modulus is predicted to increase with higher wheel loads in the figure shown. However, the opposite trend may be obtained for other pavements (such as thin pavements), where the softening effect of the octahedral shear stress may be more pronounced. The hardening effect of higher confinement and the softening effect of higher octahedral shear stress can be discerned from Figure 7. The K_3 term in the figure is associated with the octahedral shear stress, τ_{oct}:

Table 1. Typical K_1 to K_3 Values for Base Materials (Glover and Fernando, 1995).

Material Type	K_1			K_2			K_3		
	- opt.[1]	at opt.	+ opt.[2]	- opt.	at opt.	+ opt.	- opt.	at opt.	+ opt.
Caliche	1443	888	477	1.18	0.83	0.19	0.00	0.00	0.00
Iron Ore Gravel	2816	3271	211	0.60	0.49	0.56	0.00	0.00	0.00
Shell Base	827	815	753	1.10	0.60	0.78	0.00	0.00	0.00
Crushed Limestone	1498	1657	-	0.90	0.90	-	-0.33	-0.33	-
Average	1646	1658	480	0.95	0.71	0.51	-0.33	-0.33	0.00
Std. Dev.	725	988	221	0.22	0.17	0.24	0.00	0.00	0.00

[1] From tests run at moisture contents below optimum.

[2] From tests conducted at moisture contents above optimum.

Table 2. Typical K_1 to K_3 Values for Subgrade Materials (Glover and Fernando, 1995).

Material Type	K_1			K_2			K_3		
	- opt.	at opt.	+ opt.	- opt.	at opt.	+ opt.	- opt.	at opt.	+ opt.
Sand	3118	6434	6319	0.44	0.51	0.40	0.00	0.00	-0.03
Sandy Gravel	11,288	1574	-	0.63	0.67	-	-0.10	-0.28	-
Lean Clay	4096	105	776	0.00	0.32	0.10	-0.27	0.10	-0.55
Fat Clay	200	263	440	0.66	1.25	0.66	-1.47	-0.50	-0.17
Silt	824	1172	998	1.19	0.52	0.50	-0.11	-0.20	-0.10
Averages for Sandy Materials	7203	4004	6319	0.53	0.59	0.40	-0.05	-0.14	-0.03
Standard Deviation for Sandy Materials	4085	2430	0	0.09	0.08	0.00	0.05	0.14	0.00
Averages for Clayey Materials	1707	513	738	0.62	0.70	0.42	-0.62	-0.20	-0.27
Standard Deviation for Clayey Materials	1709	470	229	0.49	0.40	0.24	0.61	0.24	0.20

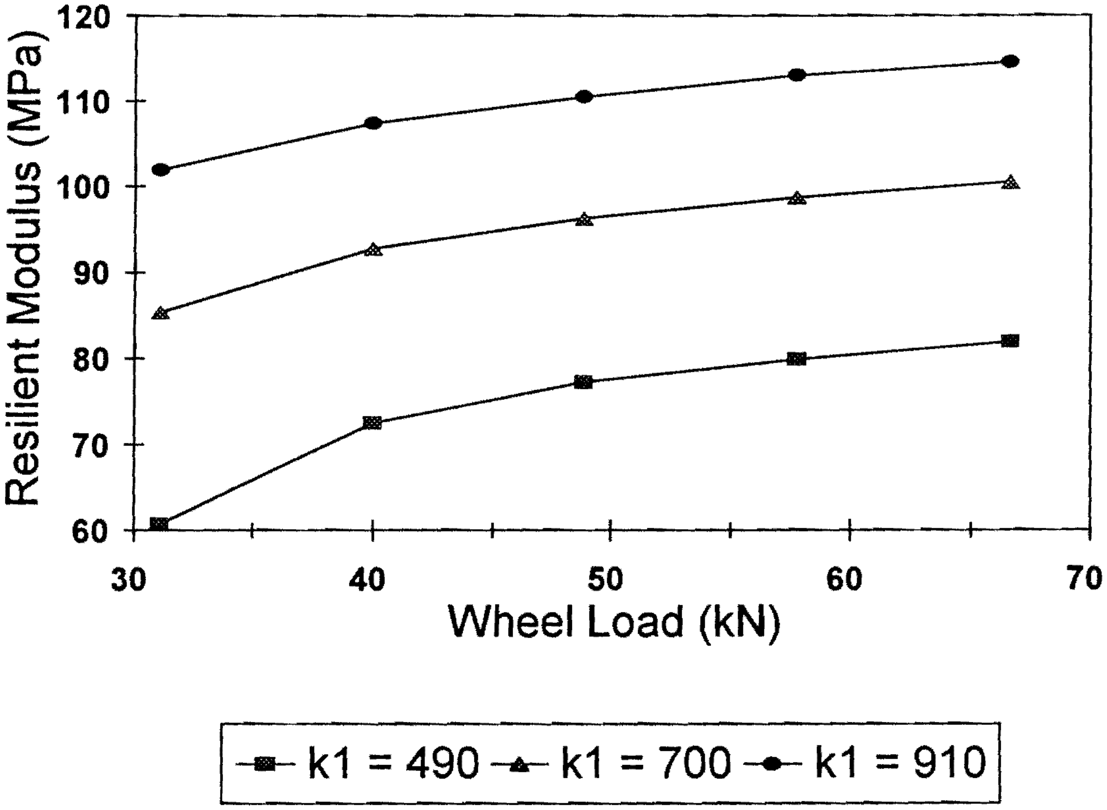

Figure 6. Variation in Resilient Modulus with Parameter, K_1 (Jooste and Fernando, 1995).

$$K_3\ term = \left(\frac{\tau_{oct}}{Atm}\right)^{K_3} \tag{5}$$

Note that, as the wheel load increases, the K_2 term increases because of higher confinement. However, the octahedral shear stress also increases so that the K_3 term diminishes with higher wheel loads. Consequently, while the effect of higher K_1 is generally to increase the predicted resilient modulus, the effects of K_2 and K_3 depend on the interactions between these coefficients, the applied loads, and the pavement geometry. The tendency of a material to stiffen with increasing confinement (I_1) is related to K_2. However, this tendency is

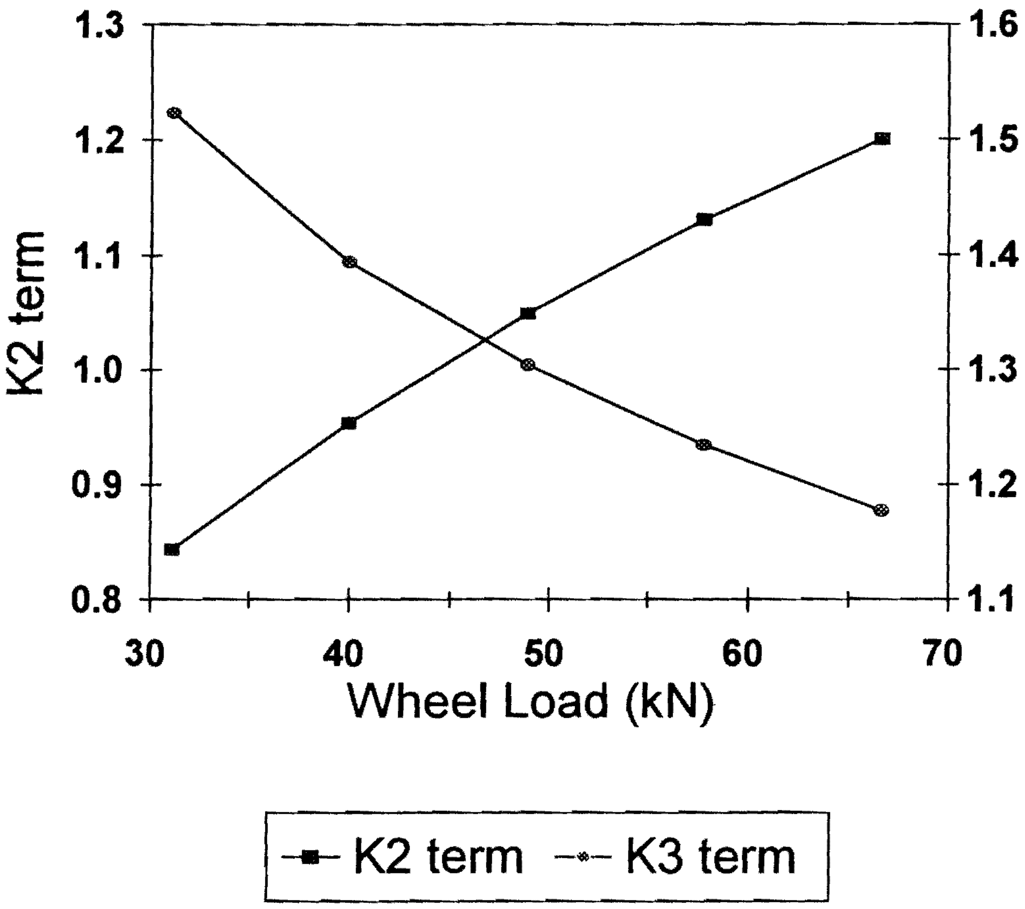

Figure 7. Illustration of the Hardening Effect Due to I_1 and the Softening Effect Due to τ_{oct} (Jooste and Fernando, 1995).

counteracted by the softening effect under increasing shear, as controlled by the coefficient, K_3. The greater the tendency of a material to stiffen under increasing confinement, the higher the effect of K_2. Similarly, the greater the tendency of a material to soften under shear, the higher the effect of K_3. The effects of these coefficients on the resilient modulus are also influenced by the applied loads and pavement geometry due to the effects of these latter factors on the induced stresses. The coefficients, K_1, K_2, and K_3, are also used in evaluating the stress-dependency of the Poisson's ratio in the analysis procedure based on the relationship developed by Uzan (1992).

EVALUATION OF PAVEMENT DAMAGE POTENTIAL

Researchers followed a pro-active approach in the development of the superheavy load analysis procedure. In view of the specialized nature of these moves, the timing and routing of the moves are relatively easier to control compared to the permitting of other oversized and overweight vehicles with axle and gross vehicle weights that exceed the legal load limits but do not classify as superheavy loads. Consequently, if the analysis of a proposed route indicates that pavement damage may occur during a move, alternative routes are investigated, the vehicle configuration is modified, or temporary strengthening measures are applied on weak segments of the proposed route to reduce or eliminate the potential for pavement damage. Rather than pursuing the recovery of costs to repair pavement damage from a superheavy load move, TxDOT engineers believe that the evaluation of pavement damage potential and the prevention of pavement damage should guide the permitting process. Consistent with this guideline, the evaluation of pavement damage potential is achieved by predicting the occurrence of first yield, i.e., the stress level at which plastic deformations will take place. This simplifies the modeling of pavement response under surface wheel loads since the post-yield behavior is not of interest. Consequently, if yielding in one or more layers is predicted under the stresses induced by the superheavy load, pavement damage is deemed to be likely. Under this situation, the pavement engineer must consider ways of minimizing or eliminating the potential for pavement damage, such as those noted previously. Chapter III explores this subject in more detail. The present discussion examines the application of the Mohr-Coulomb yield criterion to determine the occurrence of yield due to the action of stresses induced by superheavy loads. In this analysis, the onset of yield is evaluated at a number of locations beneath the superheavy wheel loads as shown in Figure 8. Specifically, the predicted stresses at each location are used with the Mohr-Coulomb yield function to determine whether or not yielding of the material will take place under the induced stresses. This yield function, f, is given by the relation (Chen and Baladi, 1985):

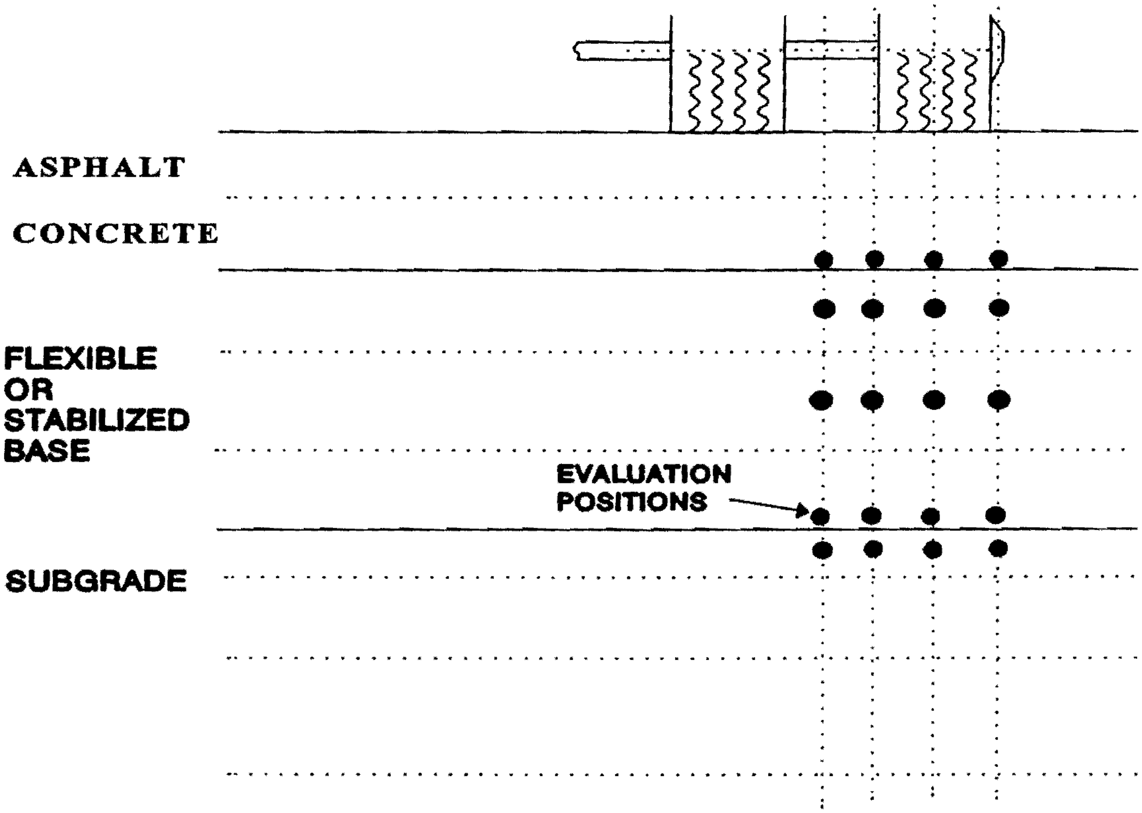

Figure 8. Locations Within Pavement Where Mohr-Coulomb Yield Function Is Evaluated.

$$f = \frac{I_1}{3}\sin(\phi) + \sqrt{J_2}\sin\left(\theta + \frac{\pi}{3}\right) + \frac{\sqrt{J_2}}{\sqrt{3}}\cos\left(\theta + \frac{\pi}{3}\right)\sin(\phi) - c\cos(\phi) \qquad (6)$$

where,

I_1 = the first stress invariant

J_2 = the second deviatoric stress invariant = $\frac{3}{2}\tau_{oct}^2$ (7)

c = cohesion of the material

ϕ = friction angle

θ = Lode angle

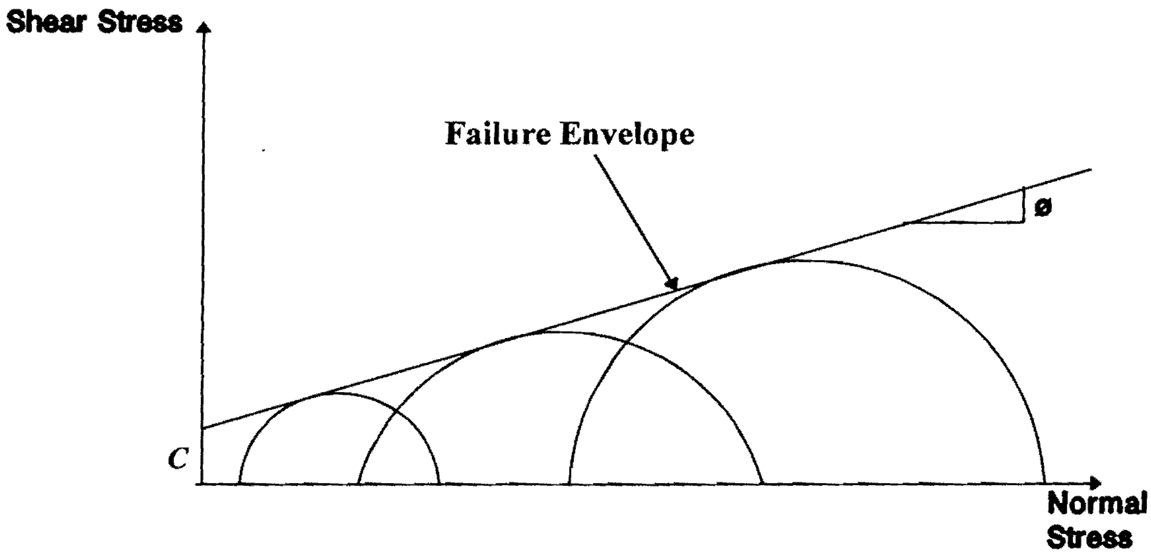

Figure 9. Determining the Mohr-Coulomb Strength Parameters from Triaxial Test Data.

Figure 9 illustrates the cohesion, *c*, and friction angle, ϕ, referred to herein as the Mohr-Coulomb strength parameters. These parameters may be determined by conducting triaxial tests on a given material. From the test data, the failure envelope for the given material is determined. This is the line tangent to the Mohr's circles corresponding to the different confining pressures used during testing (see Figure 9). The intercept of this line on the ordinate axis is the cohesion, and the slope of the line is the friction angle. Tables 3 and 4 show representative values of the Mohr-Coulomb strength parameters for a variety of base and subgrade materials, respectively.

Physically, the first stress invariant is associated with volume change in a material under loading, while the second deviatoric stress invariant is associated with distortion of the material. The Lode angle in the yield function is calculated from the equation:

$$\theta = \frac{1}{3} \cos^{-1} \left[\frac{3\sqrt{3}}{2} \frac{J_3}{J_2^{3/2}} \right] \qquad (8)$$

Table 3. Measured Cohesion and Angle of Friction Values for Base Materials (Glover and Fernando, 1995).

Material Type	Cohesion at moisture content (kPa)			Angle of Friction (Degrees)		
	below opt.	at opt.	above opt.	below opt.	at opt.	above opt.
Caliche	91	77	47	43	48	49
Iron Ore Gravel	68	73	59	47	48	48
Shell Base	74	68	60	51	51	53
Limestone	30	49	54	55	53	52
Average	66	67	55	49.0	50.0	50.5
Std. Dev.	26	13	6	5.2	2.4	2.4

Table 4. Measured Cohesion and Angle of Friction Values for Subgrade Materials (Glover and Fernando, 1995).

Material Type	Cohesion at moisture content (kPa)			Angle of Friction at moisture content (Degrees)		
	below opt.	at opt.	above opt.	below opt.	at opt.	above opt.
Sand	8	10	5	42	40	41
Sandy Gravel	25	16	21	29	48	39
Lean Clay	109	113	52	44	38	38
Fat Clay	137	120	43	18	0	0
Silt	32	33	29	43	42	43
Averages for Sandy Materials	17	13	13	36	44	40
Standard Deviation for Sandy Materials	12	4	12	9.9	5.7	1.41
Averages for Clayey Materials	93	89	41	35	27	27
Standard Deviation for Clayey Materials	54	48	12	14.7	23.2	23.5

where, J_3, is the third deviatoric stress invariant. From mechanics, J_3 is determined from the principal stresses through the relation:

$$J_3 = \left(\sigma_1 - \frac{I_1}{3}\right)\left(\sigma_2 - \frac{I_1}{3}\right)\left(\sigma_3 - \frac{I_1}{3}\right) \tag{9}$$

The onset of yield or inelastic deformation is predicted when the value of the yield function is zero, i.e., $f = 0$ in Eq. (6). When this condition is plotted for the Mohr-Coulomb yield function, the yield surface illustrated in Figure 10 is obtained. Stress states falling inside the yield surface correspond to a condition of elastic behavior, i.e., below yield. Mathematically, this is equivalent to a computed yield function value less than zero, i.e., $f < 0$, for the given cohesion and friction angle, and induced stress state. It is observed that the cross-sectional area of the Mohr-Coulomb yield surface increases as the hydrostatic stress component, represented by the mean stress, $I_1/3$, in the Mohr-Coulomb yield function is increased. Physically, this means that a material subjected to higher confinement will sustain a higher stress level before reaching the yield point.

The computed yield function values are used in determining whether a given pavement will sustain a superheavy load without developing distress. When the computed yield function values from the analysis are negative for all evaluation points shown in Figure 8, pavement damage from the superheavy load move is deemed to be unlikely. However, when one or more points are predicted to be at yield, then, pavement damage may occur during the move. The more points predicted to be at yield, the greater the potential for pavement damage from the superheavy load move.

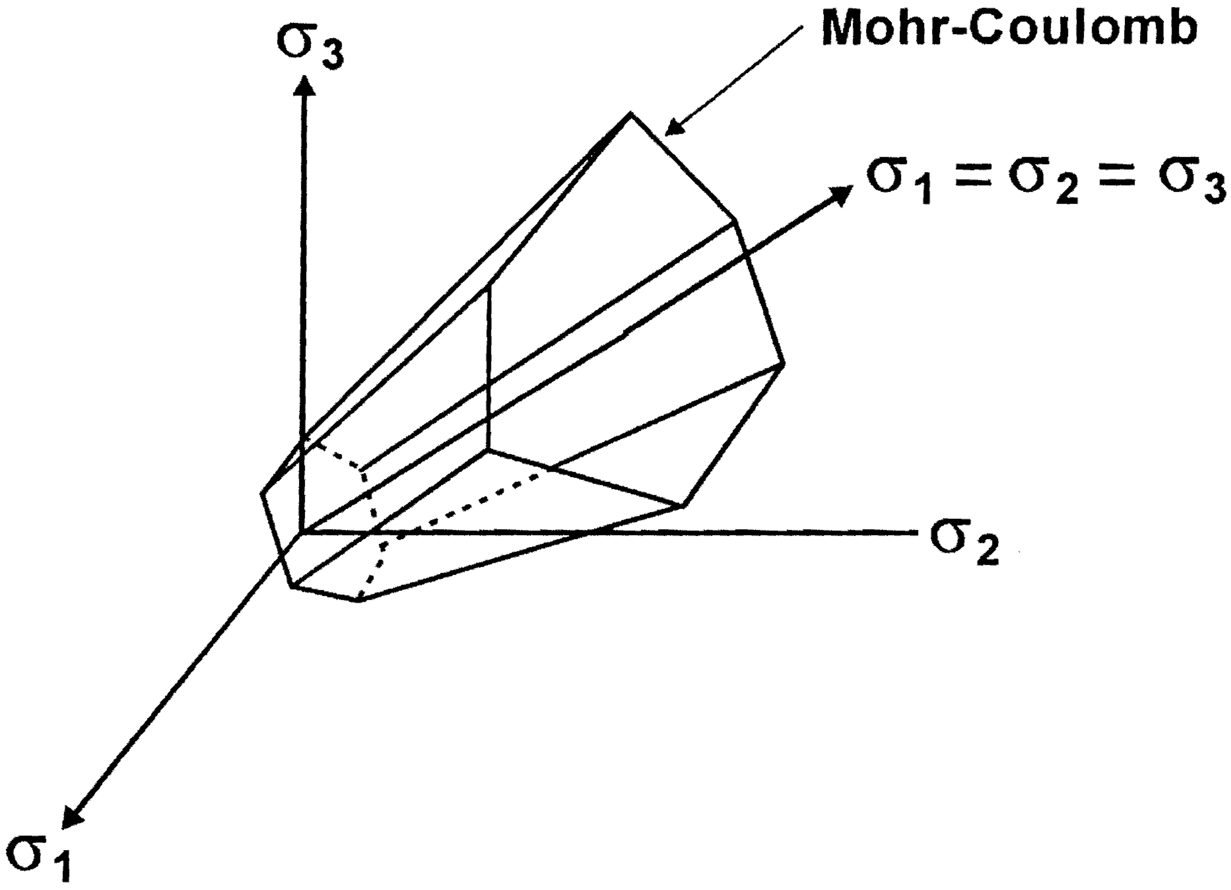

Figure 10. Graphical Illustration of Mohr-Coulomb Yield Criterion.

CHAPTER III

EVALUATING SUPERHEAVY LOAD ROUTES

The analysis procedure presented in Chapter II was incorporated into a framework for evaluating superheavy load routes. A product of the development efforts is a computer program called PALS, for conducting the analysis presented in Chapter II. **PALS** is an acronym for **P**rogram to **A**nalyze **L**oads **S**uperheavy. It is an incremental, non-linear layered elastic program that uses the Mohr-Coulomb yield criterion to determine if material yielding will occur under the stresses induced by the superheavy load. PALS is based on the BISAR structural analysis program (De Jong, et al., 1973) with modifications made by TTI researchers to model the stress-dependency of the resilient modulus and Poisson's ratio of pavement materials. The development of the analysis program is documented by Jooste and Fernando (1995). The present study (Project 7-3923) updated the program to include analysis routines to evaluate the edge load condition and to compute the failure wheel load for a given pavement. A User's Guide to the latest version of PALS (Release 2.0) is available (Fernando, 1997), and the reader is referred to this document for specific information regarding program use. This chapter presents guidelines on the application of the methodology to evaluate superheavy load routes.

METHODOLOGY FOR ANALYZING SUPERHEAVY LOAD ROUTES

The structural evaluation of superheavy load routes involves the following steps:

1. The expected superheavy wheel loads and the load geometry are established.
2. The proposed superheavy load route is characterized to determine the layer thicknesses along the route; the strength parameters of the different pavement layers; and the parameters that define the stress-dependency of the pavement materials found along the route. Table 5 summarizes the data necessary to evaluate the structural adequacy of a proposed superheavy load route. A visual survey is also conducted to establish the base line condition of the route and to identify potentially weak areas,

Table 5. Input Data Required to Characterize a Superheavy Load Route.

Data Requirements	Methods of Getting Data
Layer thicknesses	•Coring •Dynamic Cone Penetrometer (DCP) •Ground Penetrating Radar (GPR)
Mohr-Coulomb strength parameters: cohesion, *c*, and angle of friction, ϕ	•Triaxial test (TEX-117-E) •Correlations with physical soil properties
Non-linear, stress-dependent material parameters, K_1, K_2, and K_3	•Resilient Modulus Test (e.g., AASHTO T-292-91) •Compressive Creep and Recovery Test •Falling Weight Deflectometer (FWD) •Correlations with physical soil properties
Superheavy wheel loads, vehicle load geometry	•Supplied by superheavy load mover
Pavement surface condition	•Visual survey •ARAN •PMIS (consider timeliness of data)

such as those where cracks have developed and where moisture infiltration may have potentially weakened the underlying material.

3. The route is divided into analysis segments based on the data collected such that the pavement characteristics within a segment are more or less uniform.
4. The structural adequacy of each analysis segment is evaluated. In this analysis, the stresses induced under loading are predicted, and a determination is made to verify if material yielding will occur due to the induced stresses. This determination is based on the Mohr-Coulomb yield criterion.
5. Portions of the proposed route where damage is likely are identified, and recommendations are made to minimize or prevent damage from taking place. Measures that may be taken include placing laminated plywood mats on the weak areas, specifying additional axles on the vehicle to reduce the wheel loads, and re-

> routing the superheavy load move. Collecting additional data, particularly on the weak segments, is recommended. The analysis results depend on the accuracy of the pavement characterizations made. Collecting additional data that will yield more accurate geometric and material characteristics should be considered to verify the results obtained.

The pavement engineer should initially go over the proposed route to identify potentially weak areas and to gather information useful in planning subsequent data collection efforts and tests. Observations should be made on the types of truck traffic that travel on the proposed route. From these observations, it may be possible to estimate the truck wheel loads that the proposed route is presently subjected to, and to consider this information in determining whether or not the proposed route will sustain the superheavy load without developing damage. Additionally, information on prior superheavy load moves made on the route should be considered in this determination. It is noted that the analysis procedure presented herein is only a tool to assist the pavement engineer in his or her evaluation. Ultimately, the decision regarding the move is the responsibility of the engineer. Getting accurate and relevant site-specific information on which to base this decision is crucial.

Figure 11 illustrates the two-stage analysis procedure for structural assessment of superheavy load routes. In the first stage, the structural adequacy of the proposed route is evaluated by means of charts. The first stage requires a minimal amount of testing and is intended as a screening procedure to establish where additional data collection and analysis may be warranted. The charts are applicable in cases where edge loading is not a concern. However, there are situations when the move may have to pass routes that are only two-lanes wide with no paved shoulders. For these cases, edge loading may be a concern, particularly when the size of the load will dictate that the wheels track close to the pavement edge. The computer program, PALS, will have to be used in these instances to analyze the potential for edge shear failure. However, for segments of the route where edge loading is not a concern, the charts may be used to perform a preliminary analysis. Should the charts indicate that the

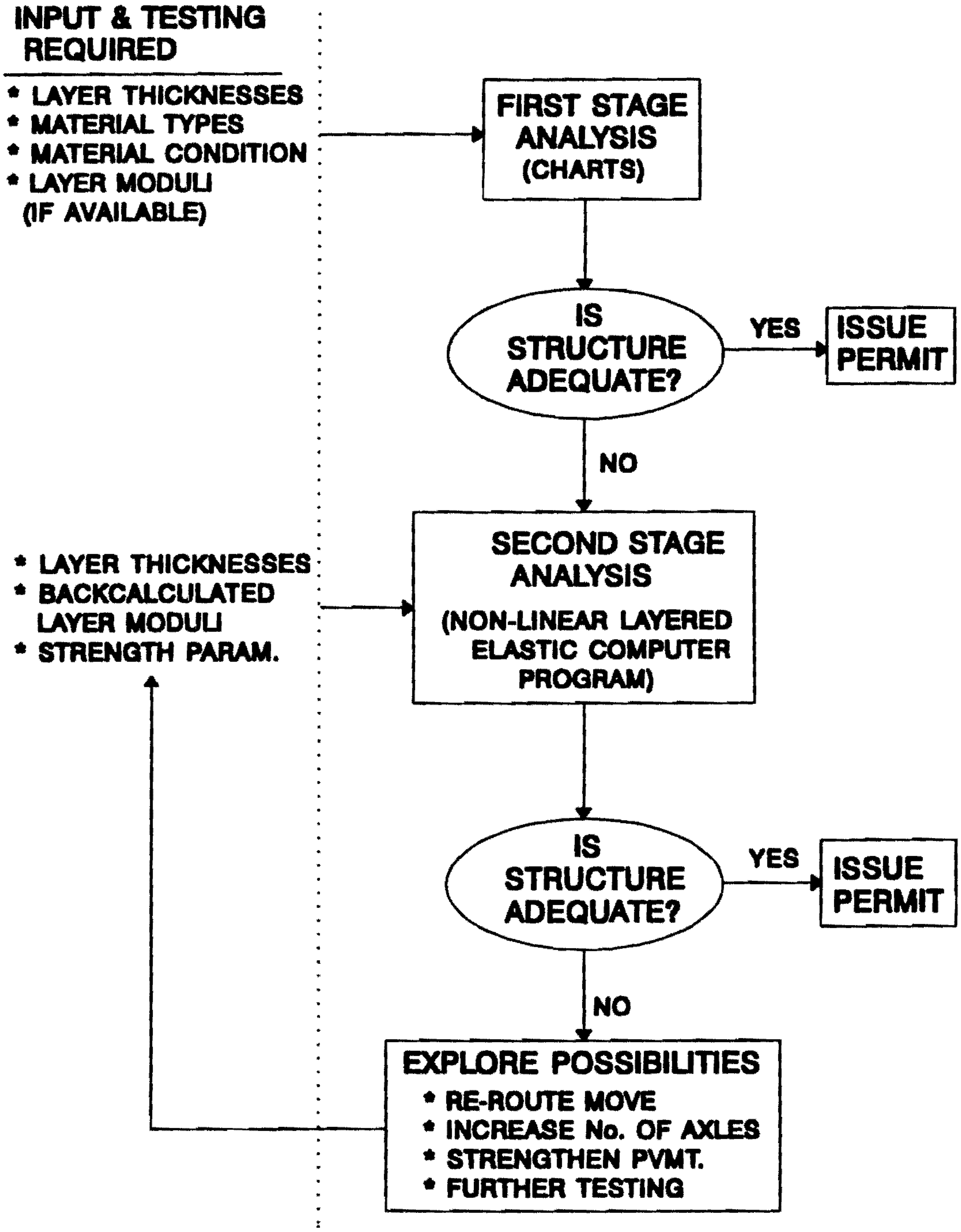

Figure 11. Schematic Representation of Superheavy Load Analysis Procedure (Jooste and Fernando, 1995).

pavement structure is adequate for the expected superheavy load, no further analysis on that segment is needed. Otherwise, a more detailed investigation involving additional data collection, testing, and analysis, is warranted. This is done in the second stage which also involves using the computer program, PALS, to assess the damage potential under the superheavy load.

Because of the minimal requirement for testing, most of the material parameters assumed in the development of the charts are conservative. These charts were generated through repetitive runs of the PALS program. In order to accommodate as large a range of pavement situations as possible, different material types and combinations were assumed in developing the charts. However, no distinction was made between material types. Instead, reference is made to the moduli and strength characteristics of each layer. The nomenclature used to distinguish between material types, therefore, consist of generic terms such as stiff, weak, or stabilized. Table 6 summarizes the material parameters used to generate the charts. More detailed information about the development of the charts is provided by Jooste and Fernando (1995). These charts, shown in Figures 12 to 15, may be used to determine the allowable wheel load for a given subgrade support (i.e., weak or stiff), base thickness, and asphalt concrete thickness. If the allowable wheel load from the charts is more than the maximum wheel load on the transport vehicle, then the pavement is considered to be adequate for the superheavy load. Otherwise, the pavement may be weak and not be able to sustain the superheavy load without developing damage.

The stress-dependent nature of pavement materials was considered in developing the charts. Consequently, the modulus of each layer varied with load magnitude and the position at which the stress-dependent modulus was evaluated within the layer. Table 6 shows the K_1, K_2, and K_3 parameters assumed in developing the charts and the resulting range in layer moduli obtained. Table 7 briefly describes the material types included in the charts.

Table 6. Material Parameters Used to Derive Charts (Jooste and Fernando, 1995).

Layer Description	Non-linear Material Constants			Resulting Range of Moduli (MPa)	Cohesion (kPa)	Angle of Friction
	K_1	K_2	K_3			
Asphalt Surface	10000 to 15000	0.1	0.0	790 to 2070	938.0	0.0°
Weak Base	1000	0.6	-0.3	62 to 235	49.0	50.0°
Stabilized Base	20000 to 25000	0.1	0.0	1500 to 3200	621.0	40°
Weak Subgrade	300	0.0	-0.3	48 to 62	41.0	30°
Stiff Subgrade	900	0.0	-0.3	90 to 138	103.0	30°

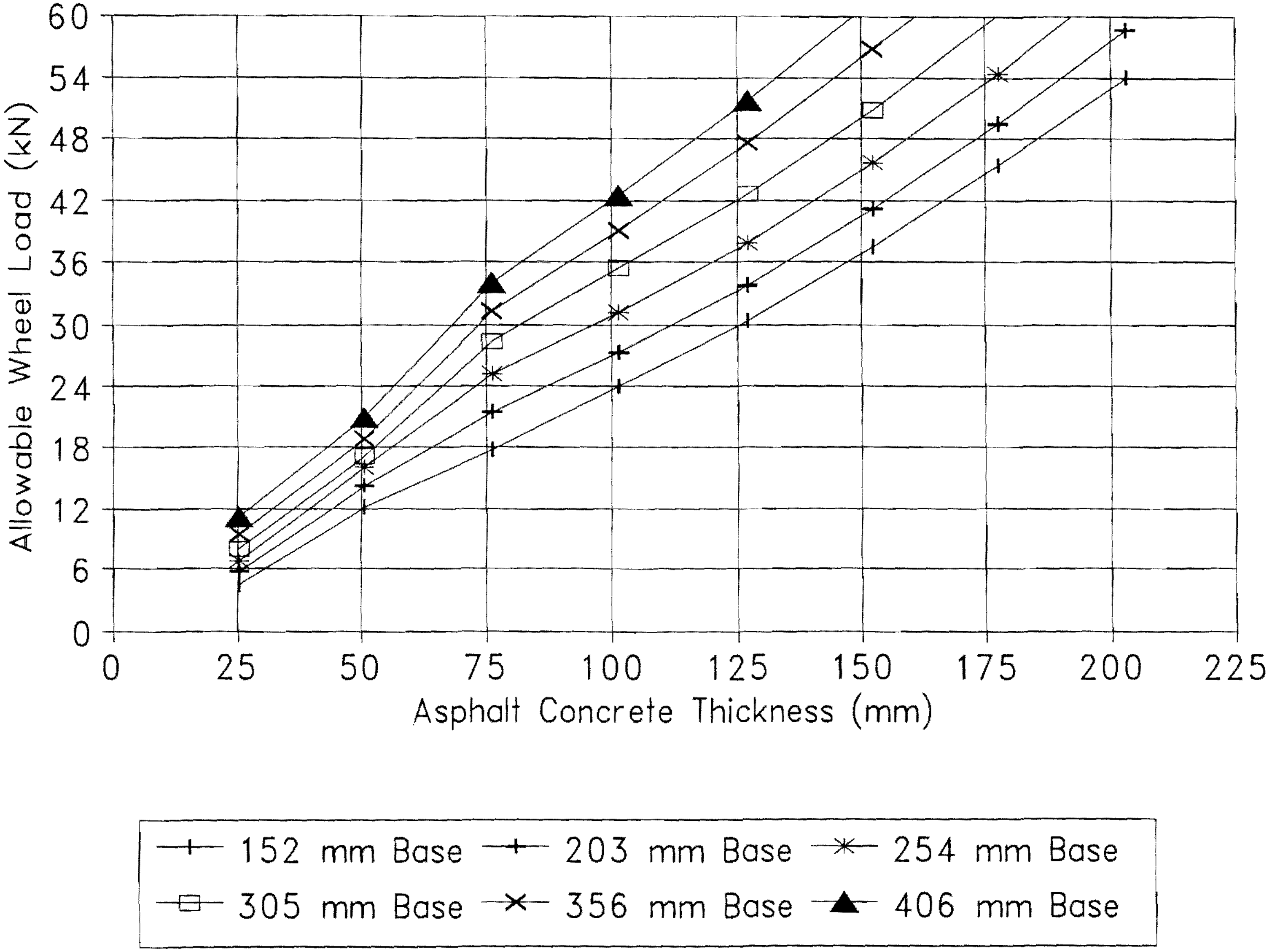

Figure 12. Allowable Wheel Load for Weak Subgrade, Weak Base Condition (Jooste and Fernando, 1995).

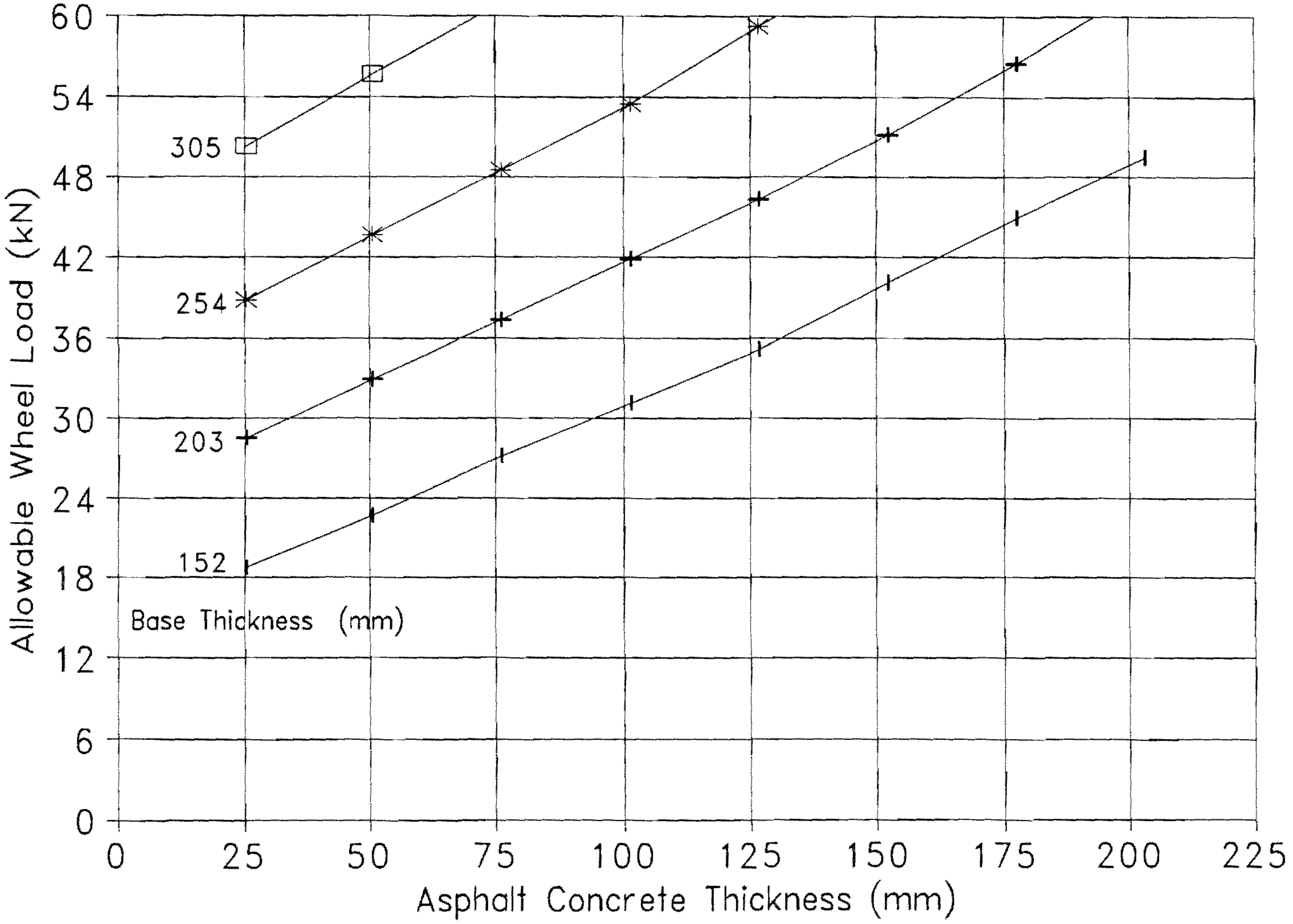

Figure 13. Allowable Wheel Load for Weak Subgrade, Stabilized Base Condition (Jooste and Fernando, 1995).

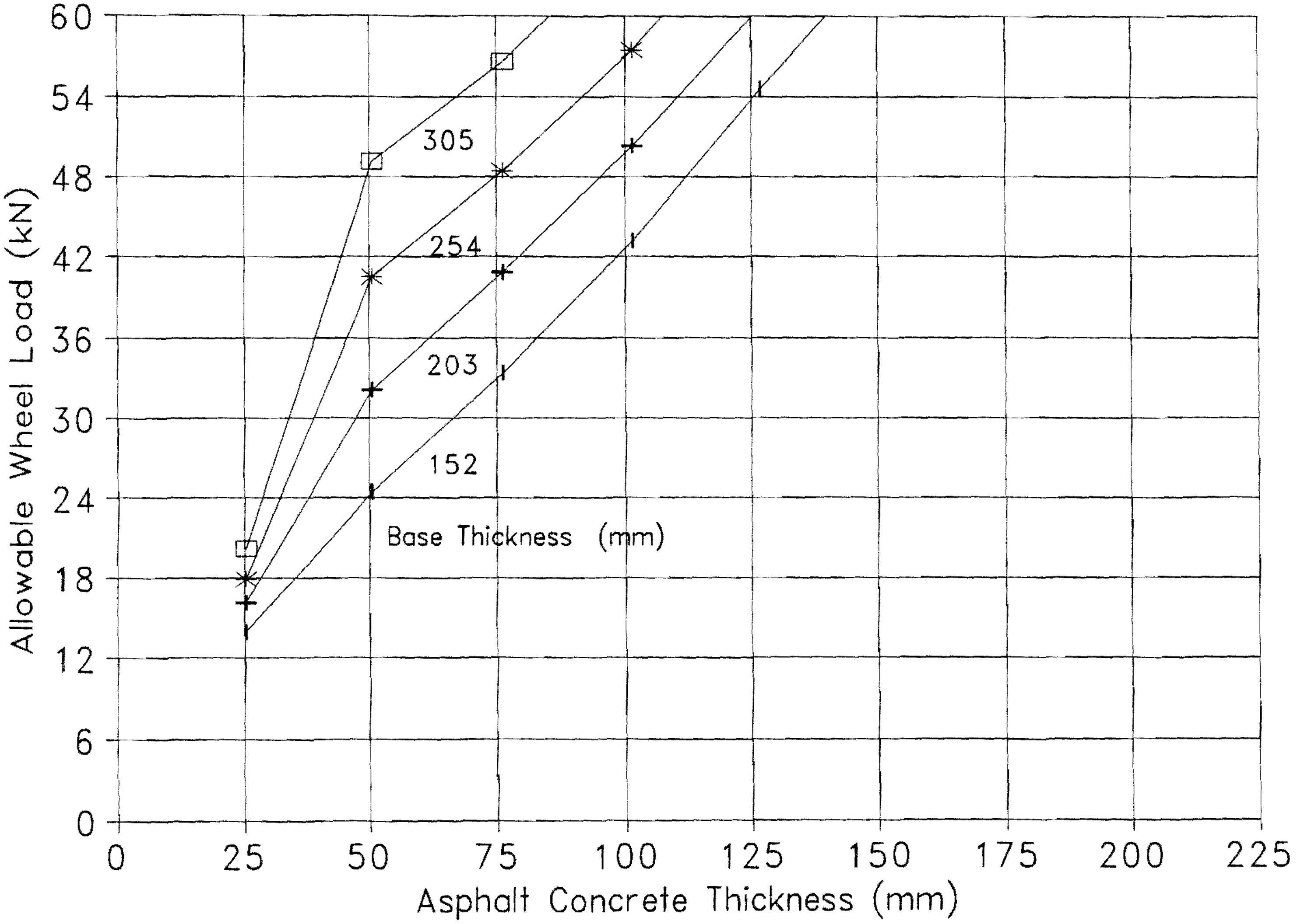

Figure 14. Allowable Wheel Load for Stiff Subgrade, Weak Base Condition (Jooste and Fernando, 1995).

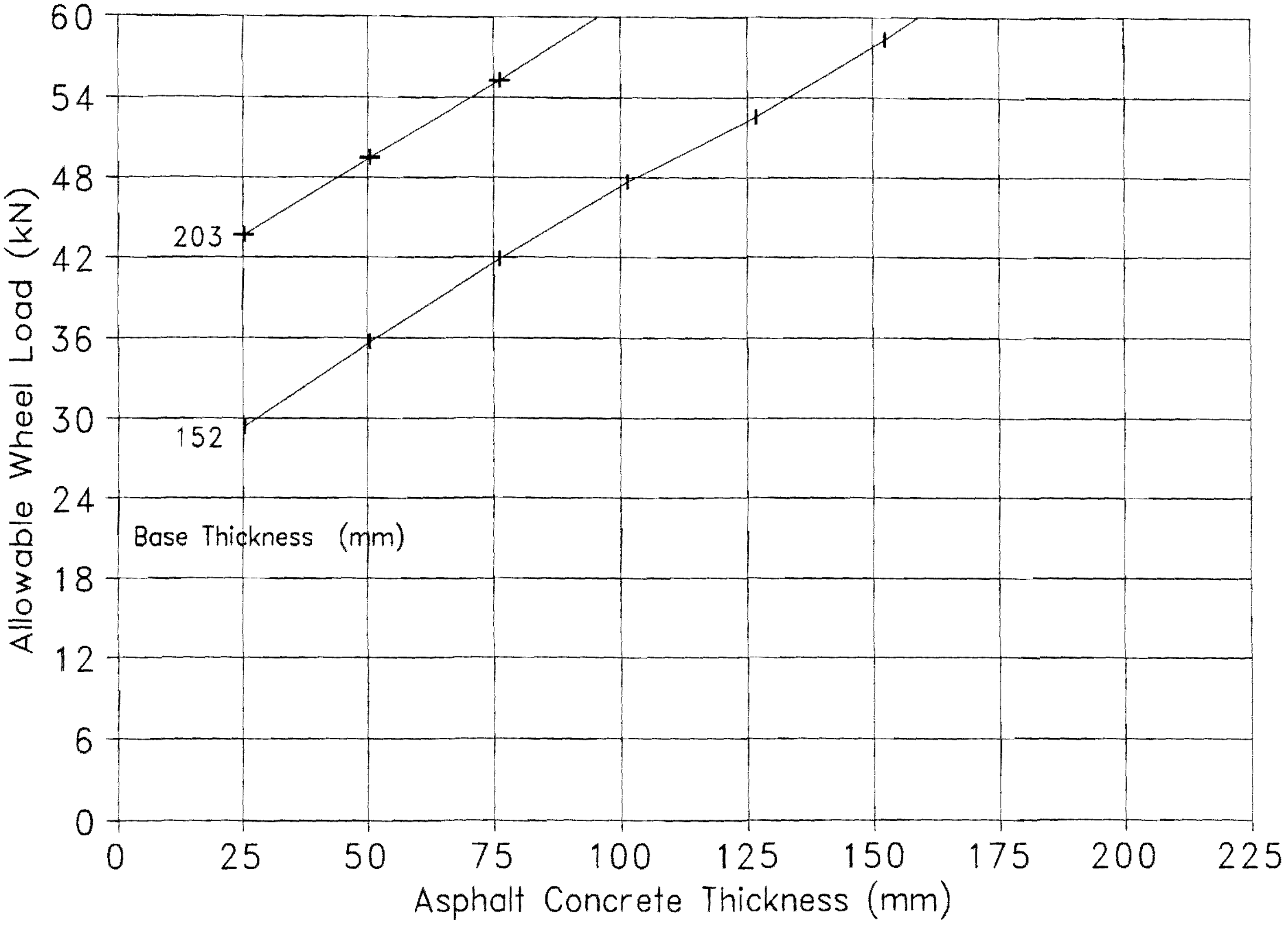

Figure 15. Allowable Wheel Load for Stiff Subgrade, Stabilized Base Condition (Jooste and Fernando, 1995).

Table 7. Descriptions of Material Types Included in Charts.

Material Type	Description
Asphalt Concrete	Soft with low cohesion having a modulus between 800 to 2100 MPa.
Weak Base	Unstabilized granular base at a moisture content that is wetter than optimum, with an approximate Texas Triaxial Class of 3.5 to 4.0, and a California Bearing Ratio (CBR) of between 60 and 15.
Stabilized Base	Base material stabilized with lime or cement with a modulus between 1500 to 3200 MPa and unconfined compressive strength of about 2800 kPa representing a material that has undergone some degradation due to traffic and environmental effects.
Weak Subgrade	Soft material having a modulus between 48 and 62 MPa with a moisture content wetter than optimum.
Stiff Subgrade	Fairly stiff material having a modulus between 90 and 138 MPa. May represent a lightly stabilized poor quality material or dry clay.

The stiffness of the subgrade has a significant effect on the predicted allowable wheel load. Since the stiffness of the subgrade is one of the easier parameters to determine in backcalculation procedures, a significant benefit can be derived from FWD data with respect to estimating the subgrade modulus. With this information, the pavement engineer can ascertain which charts to use in the first stage analysis. Based on the assumed moduli values shown in Table 6, a subgrade with a backcalculated modulus in excess of 90 MPa may be classified as a stiff subgrade.

The analysis is also sensitive to layer thickness which influences the results in two ways. First, it affects the backcalculation of layer moduli from FWD data. Second, the predicted pavement response under surface wheel loads is sensitive to the layer thicknesses. Thus, the importance of getting accurate layer thickness information in evaluating superheavy load routes is emphasized. While records may be available that contain the layer thicknesses on a particular route, the timeliness of the data must be considered. Often, thickness information on design plans or straight line diagrams are outdated and do not reflect prior maintenance or resurfacing work done since the time these plans or diagrams were drawn or updated. Thus, if there is doubt about the accuracy of available thickness information, thickness measurements on the route should be made by coring, DCP testing, GPR, or a combination of these test methods.

If the charts used in the first stage analysis indicate that the potential for pavement damage exists, a more detailed investigation is warranted on segments of the route which were analyzed as weak for the superheavy load. Additional data collection and analysis to improve the accuracy of the pavement characterization should be made as warranted. In particular, the analysis is most sensitive to the layer thickness, the parameter K_1, and the cohesion of each pavement layer, so that accurate characterization of these variables is important. Further investigations in the second stage should consider the following.

FWD Testing

The backcalculated layer moduli from FWD data may be used in PALS to estimate the parameter, K_1, for each layer, given that the corresponding K_2 and K_3 values are known. This option in the analysis program is described in the User's Guide (Fernando, 1997).

Layer Thickness Measurements

GPR measurements coupled with coring or DCP testing are recommended to establish layer thicknesses. These measurements should precede any planned FWD data collection on the proposed route. In this way, the locations of FWD measurements may be better established and tied to the thickness data. It is noted that TxDOT has a fully operational GPR van. For assistance in radar thickness measurements or DCP testing, contact the Pavements Section of the Design Division at (512) 465-3686.

Soil Sampling and Laboratory Testing

As appropriate, laboratory testing on soil samples taken from the proposed route should be conducted to establish material parameters, e.g., cohesion and angle of friction values. From Table 5, the Mohr-Coulomb strength parameters may be determined from triaxial tests following TEX-117-E, while the K_1, K_2, and K_3 parameters may be determined from resilient modulus testing such as described in AASHTO T-292-91 (AASHTO, 1997). When conducting triaxial tests using TEX-117-E, consideration must be given to testing specimens at a moisture content representative of field conditions, in lieu of applying capillary saturation as prescribed in the test procedure. Although capillary saturation will lead to conservative values for the Mohr-Coulomb strength parameters, the test results may not be representative of the subsurface conditions in the proposed route. Consequently, the results from the analysis may not be realistic.

As an alternative to direct material characterizations, estimates of the required material parameters may be obtained using correlations developed from laboratory test data by Glover and Fernando (1995). The use of these correlations is applicable when equipment and/or personnel required to run the triaxial and resilient modulus tests are not available. Table 8 summarizes the data necessary to use the regression equations to estimate c, ϕ, K_1, K_2, and K_3, and the test methods for determining the required data. It is noted that these tests require simpler equipment to run. The dielectric constant that is required to estimate the K_1 and K_3 parameters of a given material may be determined from data collected on a GPR survey of the route or from a dielectric probe. Typical values of the dielectric constants of various materials are given in Table 9. For assistance in dielectric probe measurements, call the Materials and Pavements Division of the Texas Transportation Institute at (409) 845-8212. The regression equations have been coded into the computer program, PALS, as options in specifying the parameters c, ϕ, K_1, K_2, and K_3 for a given pavement. Glover and Fernando (1995) document the development of the regression equations.

Table 8. Soil Properties Used to Estimate Strength and Non-Linear Material Parameters[1].

Soil Property	Applicable Test Methods	ϕ	c	K_1	K_2	K_3
Plasticity Index	TEX-104-E, TEX-105-E, TEX-106-E	▨				
Plastic Limit	TEX-105-E		▨	▨		
Liquid Limit	TEX-104-E				▨	▨
Specific Gravity	TEX-108-E	▨	▨	▨	▨	
Gravimetric Moisture Content	TEX-103-E				▨	▨
Volumetric Moisture Content	TEX-103-E, TEX-113-E, TEX-114-E			▨		
Percent Passing #40 Sieve Size	TEX-110-E		▨	▨	▨	
Porosity	TEX-103-E, TEX-113-E, TEX-114-E	▨	▨			
Soil Suction	ASTM D5298-94 (Filter Paper Method) Pressure Plate Method AASHTO T273-86 (Thermal Psychrometer)	▨	▨	▨		
Dielectric Constant	Dielectric Probe Ground Penetrating Radar (GPR)			▨		▨

[1] Shaded cell indicates property is required to predict the given material parameter.

Table 9. Typical Relative Dielectric Constants.

Material	Relative Dielectric Constant
Air	1
Water	81
Asphalt Concrete	3 - 6
Portland Cement Concrete	6 - 11
Crushed Limestone	10 - 23
Dry Sand	3 - 5
Clays	5 - 40

The data from the tests discussed in the preceding section are used in the PALS program to re-evaluate the failure potential for those segments identified as weak from the first stage. If the results from the second stage analysis confirm the existence of weak segments in the proposed route, measures must be taken to reduce or eliminate the likelihood of pavement damage from the superheavy load move. Alternatives to be considered in this regard are discussed in the next section.

REDUCING THE POTENTIAL FOR PAVEMENT DAMAGE

If the second stage analysis indicates that a potential for damage exists, a number of options are available to reduce or eliminate the likelihood of pavement damage from the move. The first option to consider is to re-route the load over a stronger pavement which would require that a second analysis be undertaken on the new route. However, re-routing is often not possible because of geometric restrictions, e.g., vertical clearances beneath overhead structures or the presence of posted bridges on alternative routes. Consequently, other options must be considered. One alternative is to modify the proposed trailer configuration to reduce the wheel loads to a safe level. In this regard, the computer program, PALS, provides the option to determine the wheel load at which yielding of a given pavement is predicted.

This is accomplished through an iterative scheme in which the wheel load magnitudes are varied until the maximum computed yield function value at the evaluation positions shown in Figure 8 is near zero. Knowing the load at yield, the requirements for additional axles may be established so that the wheel loads are reduced to a level that does not exceed the strength of the pavement materials. Discussions should then be made with the mover to ascertain the feasibility of modifying the trailer configuration for the particular move.

Another effective method of reducing or eliminating the potential for damage is to use laminated plywood mats on the weak segments of the route. These are made up of layers of plywood that are nailed or screwed together to form a rigid unit. Figure 16 shows an example of a laminated plywood mat that is typically used during superheavy load moves. This option is particularly applicable when the length of pavement to be protected spans a short distance. In practice, mats have been used by movers to protect weak areas that span a distance of up to 5.6 km. The mats are usually laid out in short segments at a time. As the transport vehicle moves, the mats at the rear are picked up with forklifts and then moved up station. This operation continues until the vehicle has passed over the weak areas.

Figure 16. Laminated Plywood Mat.

Tests conducted by TTI researchers have demonstrated the effectiveness of using plywood mats to reduce the potential for pavement damage during superheavy load moves. Figure 17 illustrates the reduction in pavement deflection that may be realized from using plywood mats. Vertical deflections were measured using a Multi-Depth Deflectometer (MDD) with three linear variable differential transducers (LVDTs) positioned at different depths. The MDD was installed near the edge of the test section. Deflections were measured at three different depths corresponding to the top of a crushed limestone base, the bottom of the base, and 305 mm into a clay subgrade. These positions correspond, respectively, to the top, middle, and bottom LVDT positions noted in the figure. It is observed that the reduction in pavement deflections with matting is significant. It is also noted that the differences between measured deflections at different depths with the plywood mat are significantly less than the differences between deflections measured without the mat. This observation indicates that the mat has high rigidity such that the wheel loads are distributed over a wide area similar to a concrete slab. Figures 18 and 19 show the development of residual strains with and without matting for the same pavement section. It is observed that the residual compressive strains measured during repeated load applications are significantly less with the mat than without it. This further demonstrates the effectiveness of matting in minimizing or preventing pavement damage during superheavy load moves.

ANALYSIS OF EDGE LOADING

Since moves are usually made with traffic control, it is often possible to have the driver of the transport vehicle steer away from the pavement edge, particularly on four-lane undivided highways, or when the trailer fits within a lane. When possible, it is good practice to have the vehicle track away from the edge, particularly if the shoulder is unpaved and there is less lateral support. However, this is not always possible. There will be moves that must pass on narrow, two-lane highways with unpaved shoulders, where the trailer is about as wide as the roadway. In these cases, it will be necessary to evaluate the potential for edge shear failure. This may be accomplished using the PALS program.

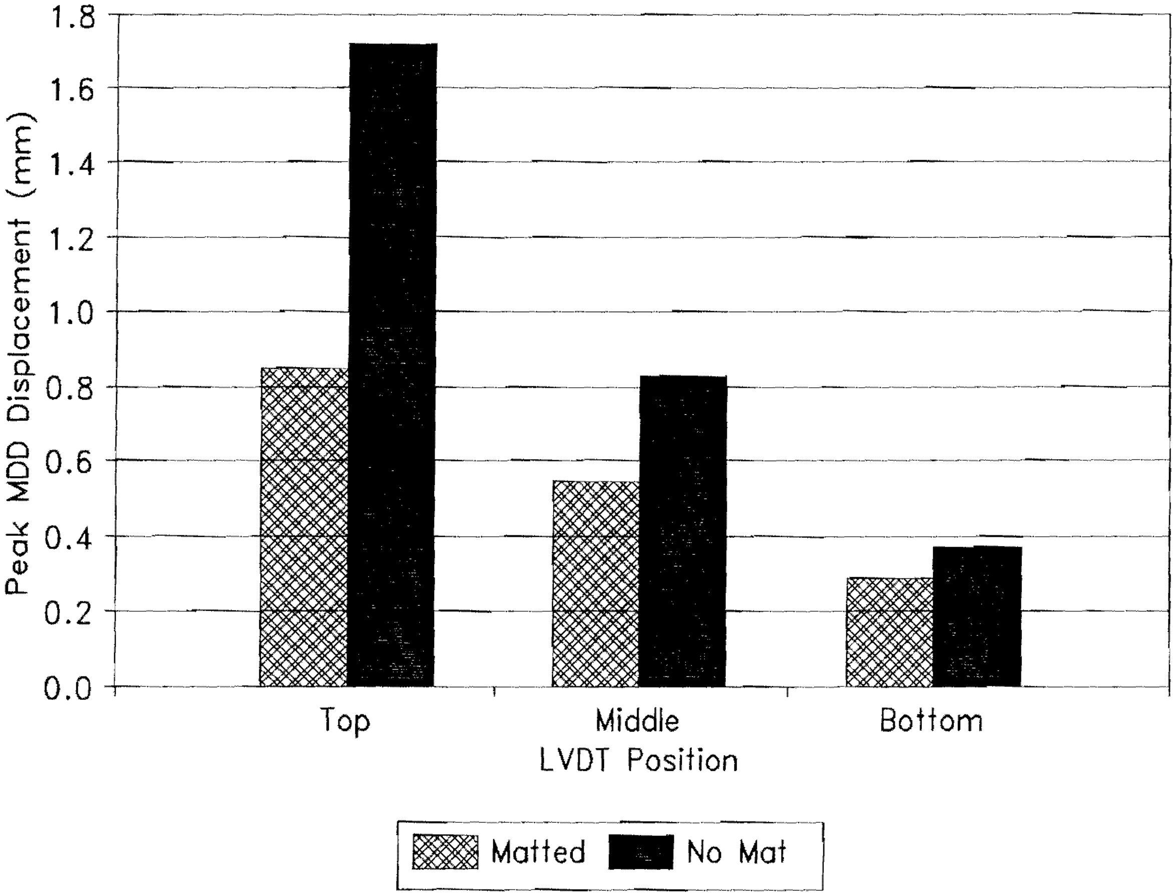

Figure 17. Peak MDD Displacements Measured with and Without Mat on a Test Section with a 254 mm Crushed Limestone Base Overlying Clay Subgrade.

Figure 18. Development of Residual Compressive Strain with Repeated Load Applications near Edge of Matted Test Section Having a 254 mm Crushed Limestone Base Overlying Clay Subgrade.

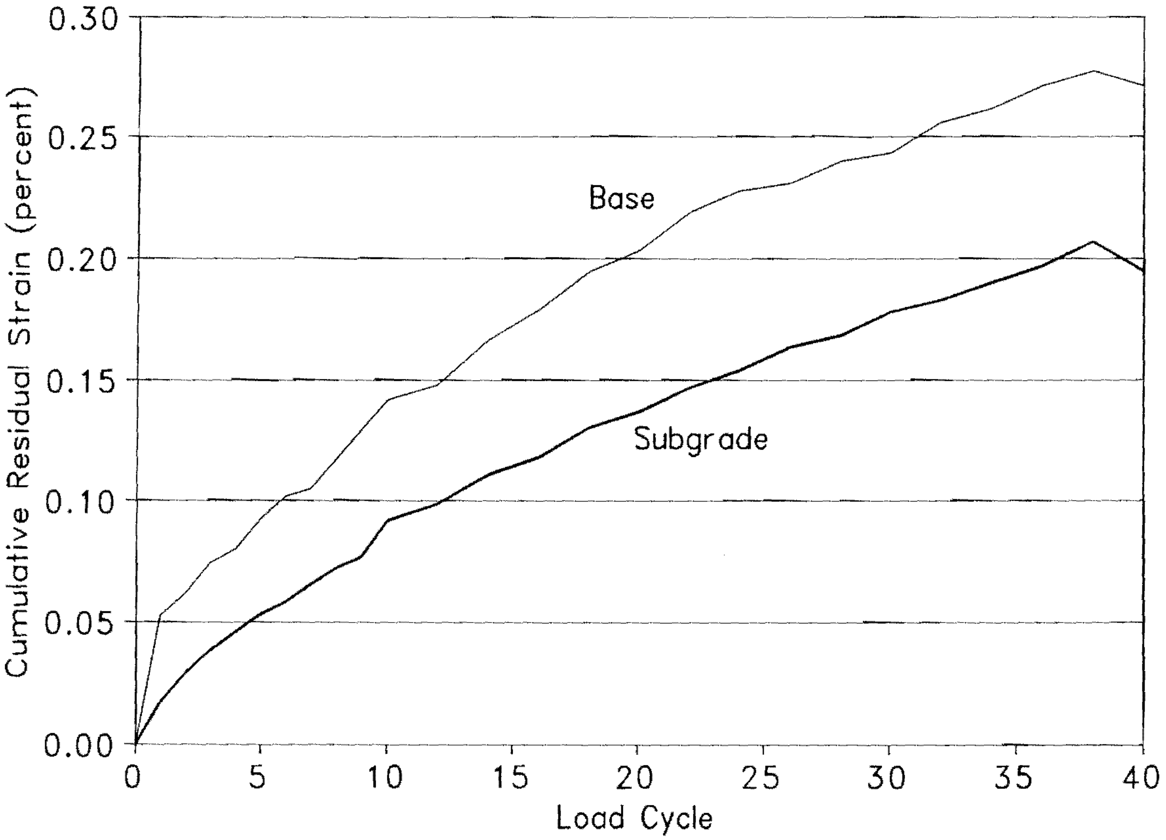

Figure 19. Development of Residual Compressive Strain with Repeated Load Applications near Edge of Un-Matted Test Section Having a 254 mm Crushed Limestone Base Overlying Clay Subgrade.

To perform the edge analysis on a given pavement, it is necessary to quantify the difference in pavement response under edge and interior loading. This is done by specifying an edge to interior displacement ratio which is simply the ratio of the displacement under a surface load positioned at or near the pavement edge, to the displacement under the same load positioned away from the edge or in the interior of the pavement. Because of the diminished lateral support at the edge, particularly for pavements with unpaved shoulders, the effect of edge loading needs to be considered. Chen et al. (1996) collected FWD data at different lateral positions from the edge and reported that the surface displacement under the FWD load increases as the distance of the load from the edge diminishes. The increase in surface displacement varied from 20 to 100 percent, with the effect of load placement being more pronounced for thin pavements than for thick pavements.

For the edge analysis in PALS, it is recommended that the displacement ratio be determined from FWD measurements taken from the pavement under consideration. Specifically, on segments of the route where edge loading is a concern, FWD data should be taken at two or three locations near the edge where the outside wheels of the transport vehicle are expected to track. Deflection data should be collected at a load level comparable to the superheavy wheel loads. Based on the FWD sensor 1 displacements taken near the edge and the corresponding displacements taken at the outer wheelpath, the edge to interior displacement ratio for the analysis may be established. This ratio is used in PALS to determine an equivalent surface layer that yields a predicted displacement under load, greater than the computed surface displacement for interior loading, by a factor equal to the specified displacement ratio.

Figure 20 illustrates the edge load condition. In the analysis, the parameter, K_1, of the surface layer is adjusted to match the predicted displacement due to edge loading, denoted as, Δ', in the figure. In addition, the cohesion of the surface layer is adjusted to reflect the decrease in K_1 associated with the higher edge displacement. The response of this equivalent pavement under the superheavy load is then evaluated to establish the potential for edge shear failure. It is noted that only the surface layer is transformed. The base and subgrade materials

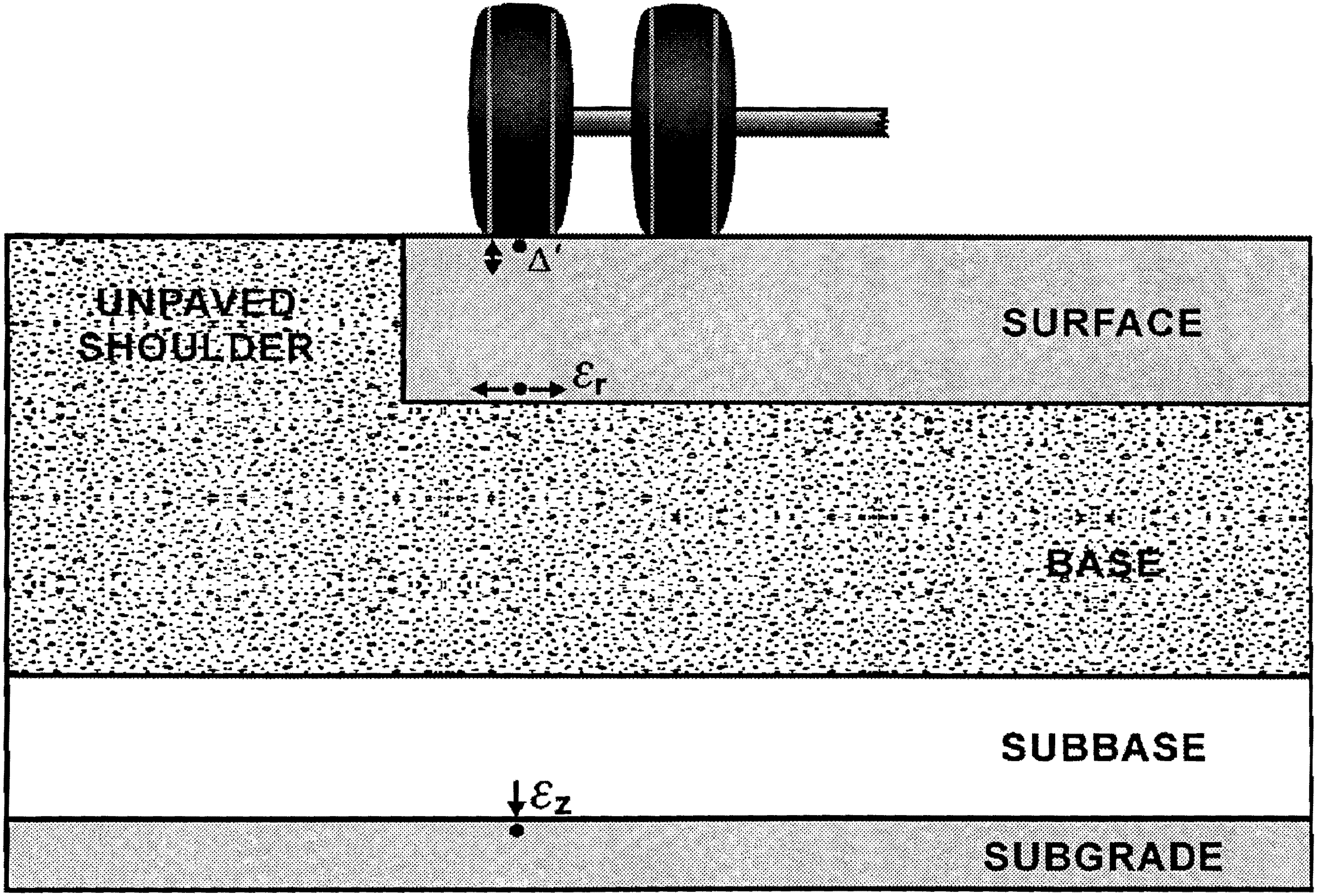

Figure 20. Illustration of Edge Load Condition.

beneath the travel lane are assumed to extend to the unpaved shoulder. Also, the layer thicknesses are unchanged.

EVALUATING LONG SUPERHEAVY LOAD ROUTES

According to the Motor Carriers Division of TxDOT, superheavy loads up to 3556 kN GVW have been moved on routes that crossed District boundaries and spanned distances exceeding 161 km. These moves are generally made using the vehicle configuration illustrated in Figure 1. Loads are typically mounted on tractor-pulled trailers having trunion axles.

In the analysis of long superheavy load routes, the guidelines presented previously are still applicable. However, because of the length that must be evaluated, it is even more important to perform an initial screening wherein potentially weak segments of the route are identified. This will help in defining the scope of the investigation to within manageable limits. Figure 21 shows the proposed procedure for evaluating long superheavy load routes. The procedure consists of two levels. In the first level, weak portions of the route are identified from available data and from a radar/video survey of the route. Possible problem areas that may require additional testing are:

1. load-zoned pavements along the route;
2. segments that show significant distress based on the visual survey or from the Pavement Management Information System (PMIS) database;
3. two-lane highways identified from a TxDOT roadway map that have unpaved shoulders based on communications with the Districts; and
4. thin pavements with indications of high moisture in the base or subgrade from evaluation of radar data collected along the route.

The primary purpose of the first level is as a screening procedure, to identify areas where more detailed field and/or laboratory testing is needed for evaluating pavement structural adequacy. In this first level, the allowable wheel load charts in Figures 12 to 15 are used to separate the strong segments of the route from the weak areas where the potential for pavement damage is a concern. A more detailed evaluation is then conducted during the second stage on the weak segments of the route. For the weak areas, additional field tests

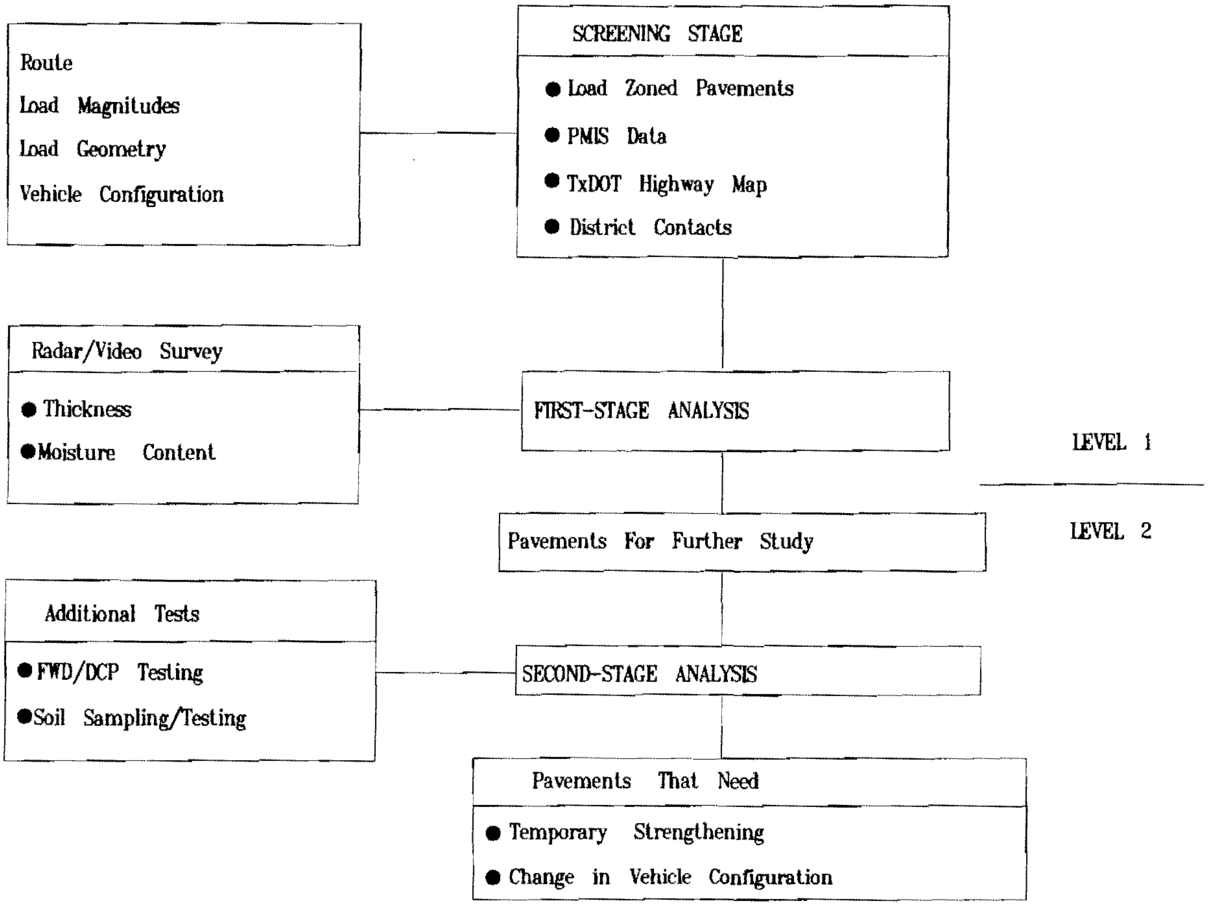

Figure 21. Procedure for Evaluating Long Superheavy Load Routes.

with the FWD and DCP are recommended. The locations of the FWD testing may be established by subdividing the radar data into homogeneous segments based on the predicted layer thicknesses using the cumulative difference method (AASHTO, 1993; Fernando and Chua, 1994). DCP measurements should supplement the radar data, particularly in areas where the base/subgrade interface was not detected. Coring may also be planned for these areas. However, the DCP provides estimates of CBR in addition to layer thicknesses, and estimating thicknesses with the DCP may be easier to do than coring.

The FWD data are used with the MODULUS program (Michalak and Scullion, 1995) in the second stage to estimate the insitu layer stiffnesses on the weak segments of the route. The backcalculated layer moduli are subsequently used with the PALS program to evaluate the pavement structural adequacy for the planned superheavy load move. The results from this analysis may show portions of the route which will require temporary strengthening, such as through plywood matting, or indicate the need to modify the vehicle configuration proposed by the mover. This latter option will be more applicable in cases where the weak areas of the route span a long distance, e.g., more than 5 km.

CHAPTER IV

SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

The methodology presented herein for evaluating superheavy load routes was initially developed in Project 0-1335. Based on experience with the implementation efforts that began in 1995, TxDOT sponsored a follow-up study (Project 7-3923) that led to enhancements in the analysis procedure. These include routines to evaluate the edge load condition and the failure wheel load for a given pavement, as well as the implementation of the computer program, PALS, in the Windows 95 or NT environment. To further support the implementation efforts, the following tasks were accomplished during the present study:

1. A training session on the analysis of superheavy load routes was conducted;
2. Assistance was provided to TxDOT engineers in their analysis of actual superheavy load moves; and
3. This summary document was prepared, providing guidelines in the application of the procedure, particularly in the collection of site-specific data related to a given move; in reducing or eliminating the likelihood of pavement damage; and in evaluating long superheavy load routes.

While much has been accomplished since the initial development to understand the effects of superheavy loads on state-maintained highways, the experience from the field implementation has identified a number of areas where additional work is needed. Recommendations for future work are given in the following.

COMPILE DATA ON SUPERHEAVY LOAD ROUTES

The implementation of the analysis procedure will benefit from the creation and maintenance of a database on superheavy load routes. As a minimum, this database should identify routes on which superheavy load moves have been made, the date of last resurfacing, and the maximum superheavy load that passed a given route since the last resurfacing. Beyond this requirement, the following are offered for further consideration:

1. The database described in the preceding may show areas of concentration of superheavy load moves. It is advisable to collect data on routes within those areas and to include the information into the proposed database. For example, layer thicknesses on the routes may be determined and samples of materials collected for characterization of strength and stress-dependent properties. Additionally, TxDOT should weigh the benefits and costs of upgrading routes on which a lot of superheavy load moves are made.
2. Data collected as part of a superheavy load analysis should also be included in the proposed database. Already, there have been numerous routes evaluated since implementation of the analysis procedure on which FWD and layer thickness measurements have been made. The data collected from previous analyses could prove useful in future investigations, not only of superheavy load routes, but for purposes related to design, resurfacing, construction, and pavement management activities.

DEVELOP A PERMANENT DEFORMATION MODEL

The analysis procedure is presently limited to predicting the point of initial yield. If the induced stresses under loading exceed the yield point, measures are taken to reduce the stresses to within allowable levels consistent with the objective of preventing damage from the superheavy load. Future development work should include the modeling of the post-yield behavior with the objective of developing a method to predict permanent deformation. In this way, the consequence of overstressing weak segments under a given superheavy load can be quantified in terms of the expected permanent deformation due to stresses exceeding the strength of pavement materials. This model can be incorporated as another level in the analysis procedure developed for superheavy loads.

LABORATORY TESTING OF PAVEMENT MATERIALS

A database of strength and stress-dependent material parameters for unstabilized materials was initially developed in Project 0-1335. This database should be expanded to include asphalt concrete, Portland cement concrete, and stabilized base and subgrade materials. This study should also evaluate the relationship between the parameter, K_1, and the cohesion of a given material. The former parameter is directly related to the material stiffness which is typically estimated from FWD measurements. Data from laboratory tests conducted at TTI indicate a positive relationship between cohesion and K_1, with cohesion increasing as K_1 increases. This relationship needs to be further studied to provide a firm basis for estimating cohesion changes with changes in layer moduli. This is an important task since the prediction of initial yield is significantly influenced by cohesion and K_1.

MODIFY THE PALS SOFTWARE

The PALS program will be updated to include the permanent deformation model and the relationship developed between cohesion and K_1. The proposed laboratory tests may also provide additional relationships for estimating the strength and stress-dependent parameters of stabilized materials. Consideration will be given to incorporating these new relationships into the analysis software and to compile the materials data into a "look-up" table within the computer program. Additionally, the following software changes are recommended based on feedback received from the implementation efforts:

1. Allow the analysis of multiple test locations included in the FWD data;
2. Display the computed yield function values in a tabular or graphical format; and
3. Modify the program so that the primary option for specifying K_1 is by backcalculation from FWD data.

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