Technical Report Documentation Page

1. Report No. TX-98/3923-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PALS 2.0 USER'S GUIDE		5. Report Date October 1997
		6. Performing Organization Code
7. Author(s) Emmanuel G. Fernando		8. Performing Organization Report No. Research Report 3923-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Study No. 7-3923
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Research: September 1996 - August 1997
		14. Sponsoring Agency Code

15. Supplementary Notes

Research Performed in cooperation with the Texas Department of Transportation.
Research Study Title: Continued Development of the TxDOT Superheavy Load Analysis Procedure (PALS)

16. Abstract

PALS is an acronym for **P**rogram to **A**nalyze **L**oads **S**uperheavy. Gross vehicle weights associated with superheavy load moves range from 1112 kN to more than 8896 kN and include loads like dragline components, off-shore pipe laying equipment, oil pressure vessels, and electric transformers. The number of superheavy load permit applications has increased over the years. Before a permit can be issued, TxDOT needs to determine whether the proposed route is structurally adequate to sustain the superheavy load. PALS is a tool for conducting this assessment. It incorporates 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. PALS Version 2.0 is a major revision of the original program developed in Project 0-1335, "Movement of Superheavy Loads Over the State Highway System." Significant enhancements include the development of 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. Instructions in the operation of PALS 2.0 are provided in this guide. The program is now implemented in TxDOT for permitting superheavy load moves.

17. Key Words Superheavy Loads, Pavement Evaluation, Pavement Response Modeling, Nonlinear Material Behavior, Mohr-Coulomb Yield Criterion		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 82	22. Price

PALS 2.0 USER'S GUIDE

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Research Report 3923-1
Research Study Number 7-3923
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Superheavy Load Analysis Procedure (PALS)

Sponsored by the
Texas Department of Transportation

October 1997

TEXAS TRANSPORTATION INSTITUTE
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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. 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 the application of PALS on actual superheavy load moves. To evaluate the potential for edge shear failure, PALS 2.0 incorporates 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 2.0 also allows 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.

ACKNOWLEDGMENTS

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. Finally, Mr. Amit Govil wrote the user-interface program for the version of PALS presented herein.

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SUMMARY

PALS is an analysis tool for evaluating the structural adequacy of superheavy load routes. This analysis is concerned with the potential for rapid, load-induced failure rather than long-term failure from repeated load applications. PALS incorporates 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.

Version 2.0 of the analysis program incorporates new options added during the present study. TTI researchers developed a procedure to evaluate the potential for edge shear failure for moves on routes with no paved shoulders where the wheel loads will track close to the pavement edge. In this procedure, an equivalent surface is evaluated for the given pavement based on the ratio of edge to interior displacements. Specifically, the modulus of the surface material is reduced to account for the increased displacement at the edge. In addition, the surface cohesion is adjusted based on the reduction in the layer modulus. An analysis is then conducted assuming a pavement with this equivalent surface to establish the potential for edge shear failure during the superheavy load move.

PALS 2.0 also includes an option to evaluate the failure wheel load for a given pavement. Previously, this required a manual trial and error procedure in which multiple runs of the program were made with varying surface wheel loads. This analysis is now automated. The pavement engineer can use this feature to establish the need for additional axles or trailer units to reduce the surface wheel loads to a magnitude that the given pavement can sustain.

Finally, researchers revised the user-interface in the original program and recompiled the computer code to implement the analysis software in the Windows environment. This user's guide gives instructions in the operation of the computer program. Although the illustrations provided are specific to the Windows 95 operating system, the instructions on program use are general and also apply to the Windows NT version of the analysis software.

CHAPTER I

EVALUATING SUPERHEAVY LOAD ROUTES

INTRODUCTION

In 1992, the Texas Department of Transportation (TxDOT) funded a research project 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. However, the total load on a single axle is often close to or more than 500 kN.

The analysis of damage potential under superheavy loads differs from routine pavement design methods. To prevent structural failure under normal loading conditions, the designer is primarily concerned with preventing long-term accumulated strains and fatigue, which manifest themselves in the form of rutting and cracking. However, in the analysis of pavements under superheavy loads, the concern is with the magnitude of the wheel loads rather than with the number of load repetitions. 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. 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 1 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 1. 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
Nonlinear, stress-dependent material parameters, K_1, K_2, and K_3	●Resilient Modulus Test (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 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.

METHODOLOGY FOR ANALYZING SUPERHEAVY LOAD ROUTES

Figure 1 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 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.

PALS is an acronym for Program to Analyze Loads Superheavy. 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 reader is referred to this report for a detailed presentation of the theory and the rational that underpin the PALS application. This background material is beyond the scope of this report, which is intended primarily as a user's guide to the program.

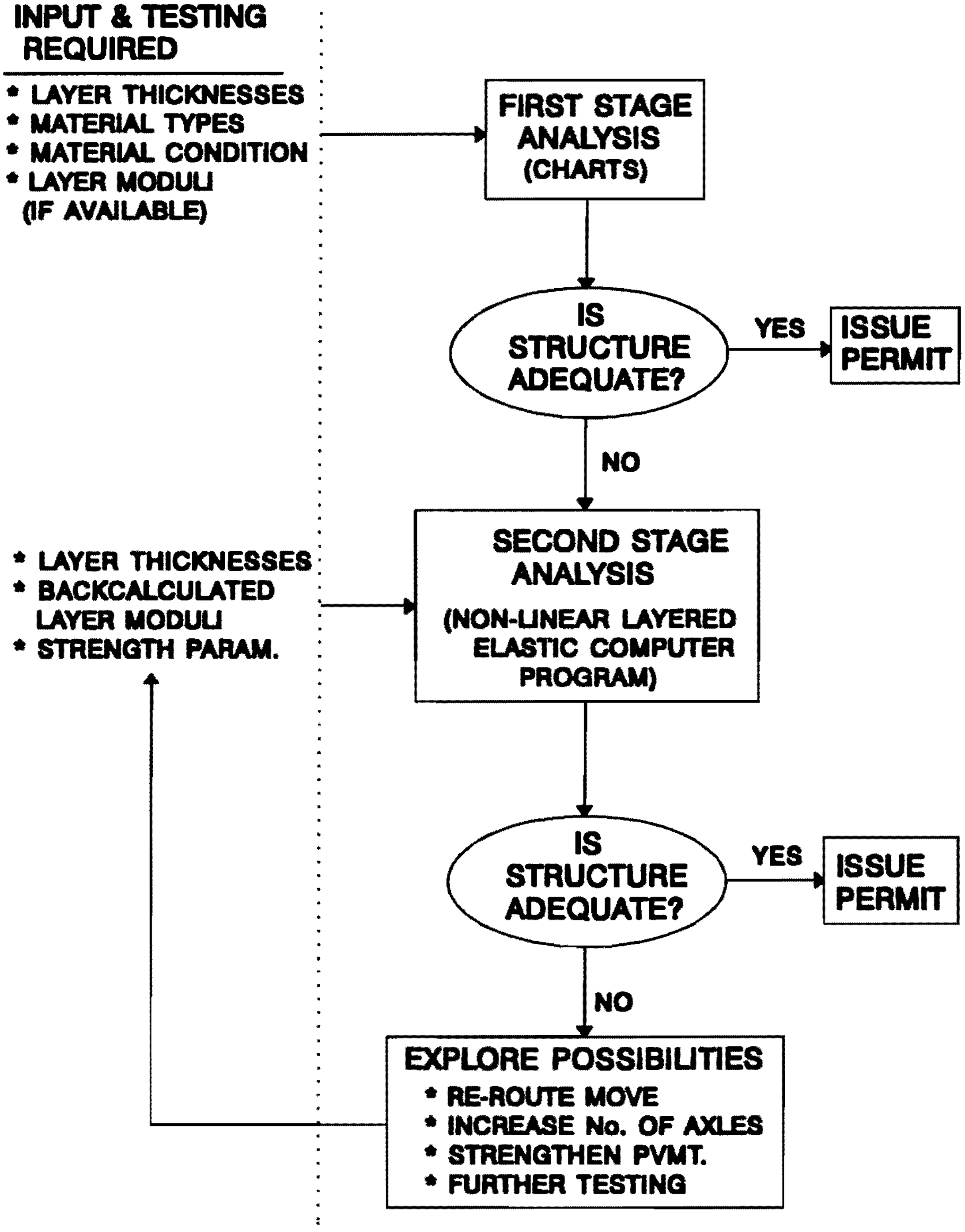


Figure 1. Schematic Representation of Superheavy Load Analysis Procedure (Jooste and Fernando).

Because of the minimal requirement for testing, most of the material parameters assumed in the development of the charts included in the first stage analysis 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 2 summarizes the material parameters used to generate the charts. More detailed information about the development of the charts are provided by Jooste and Fernando (1995). These charts, shown in Figures 2 to 5, 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.

Table 2. 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°

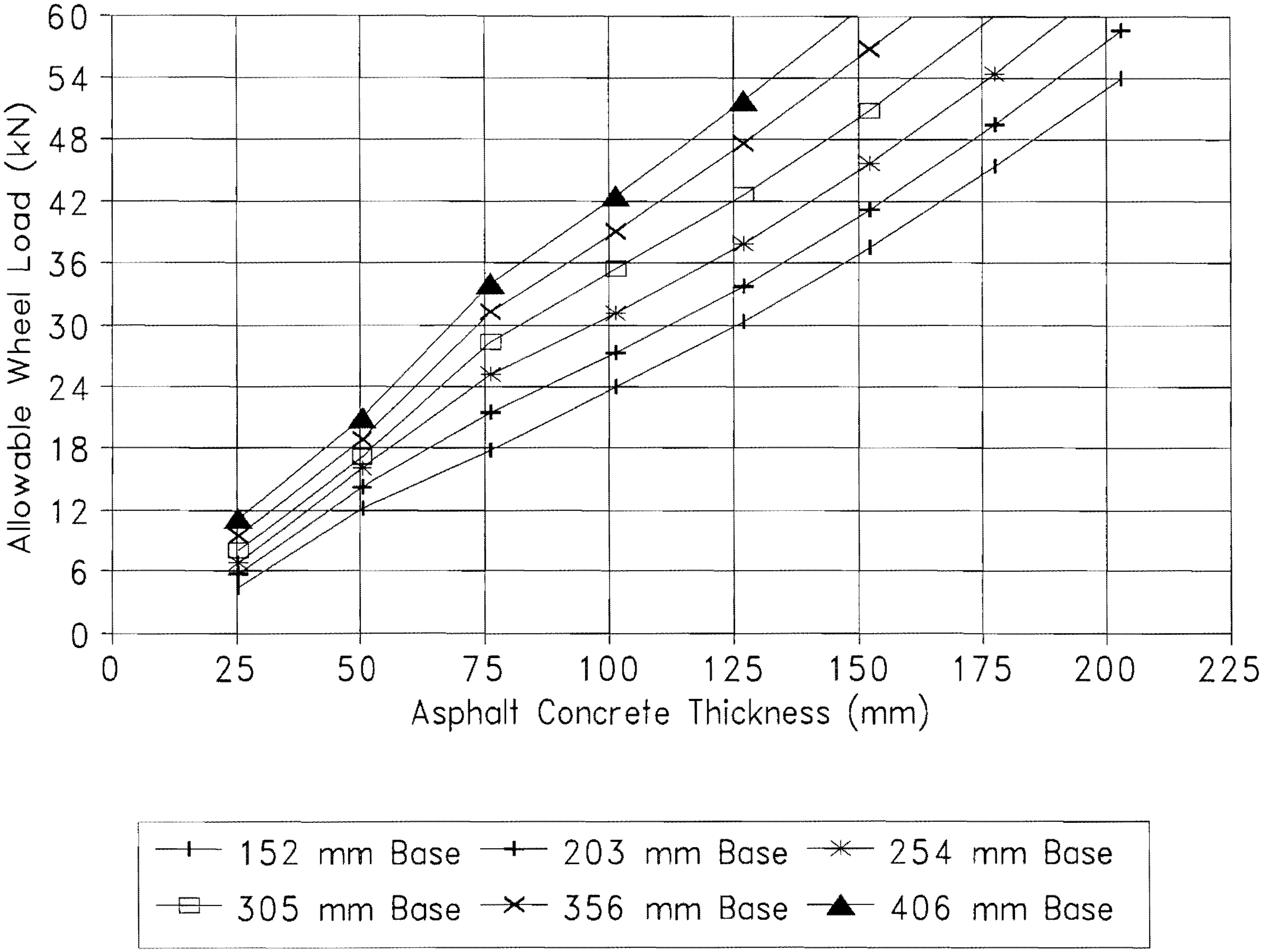


Figure 2. Allowable Wheel Load for Weak Subgrade, Weak Base Condition (Jooste and Fernando).

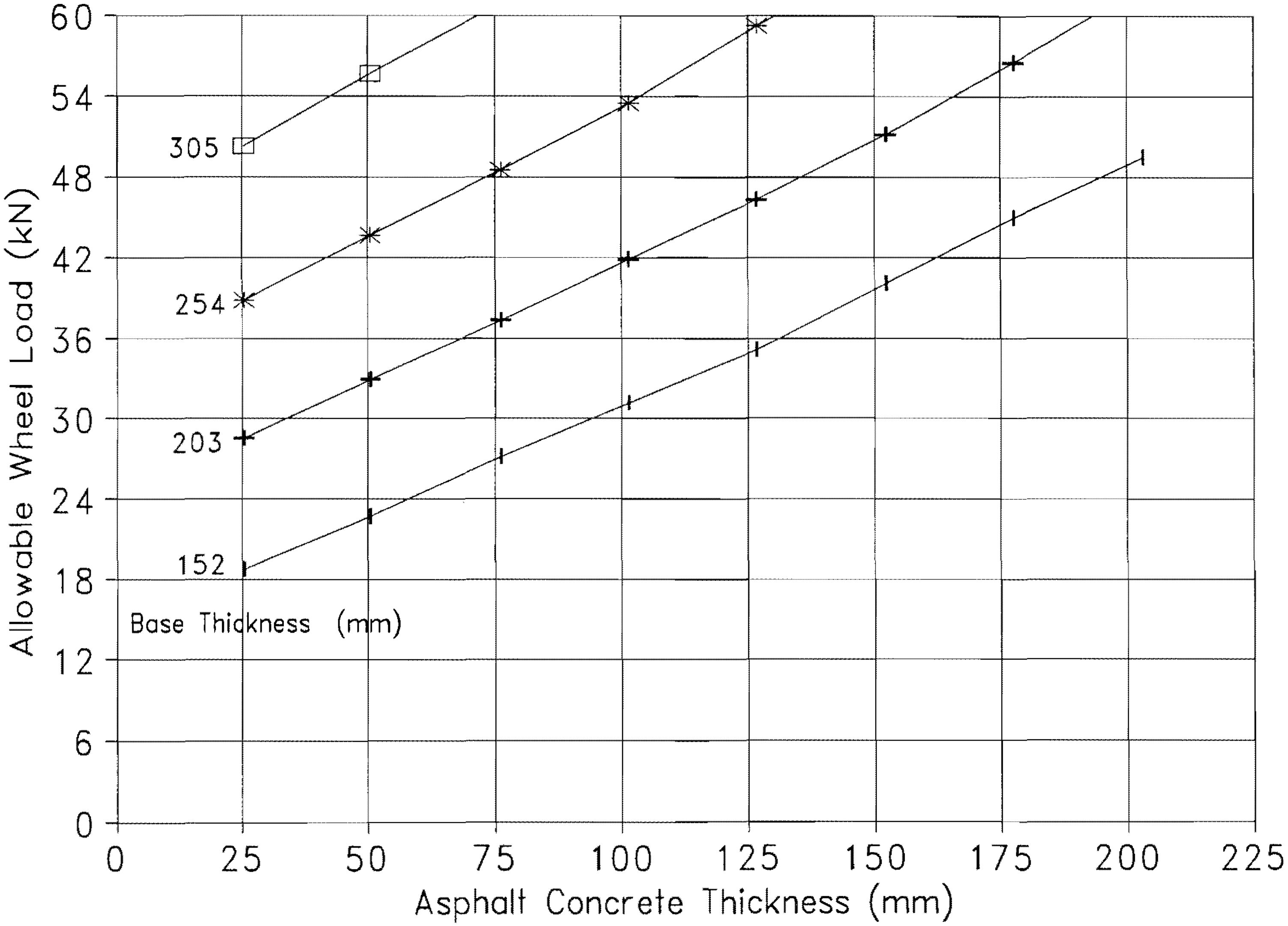


Figure 3. Allowable Wheel Load for Weak Subgrade, Stabilized Base Condition (Jooste and Fernando).

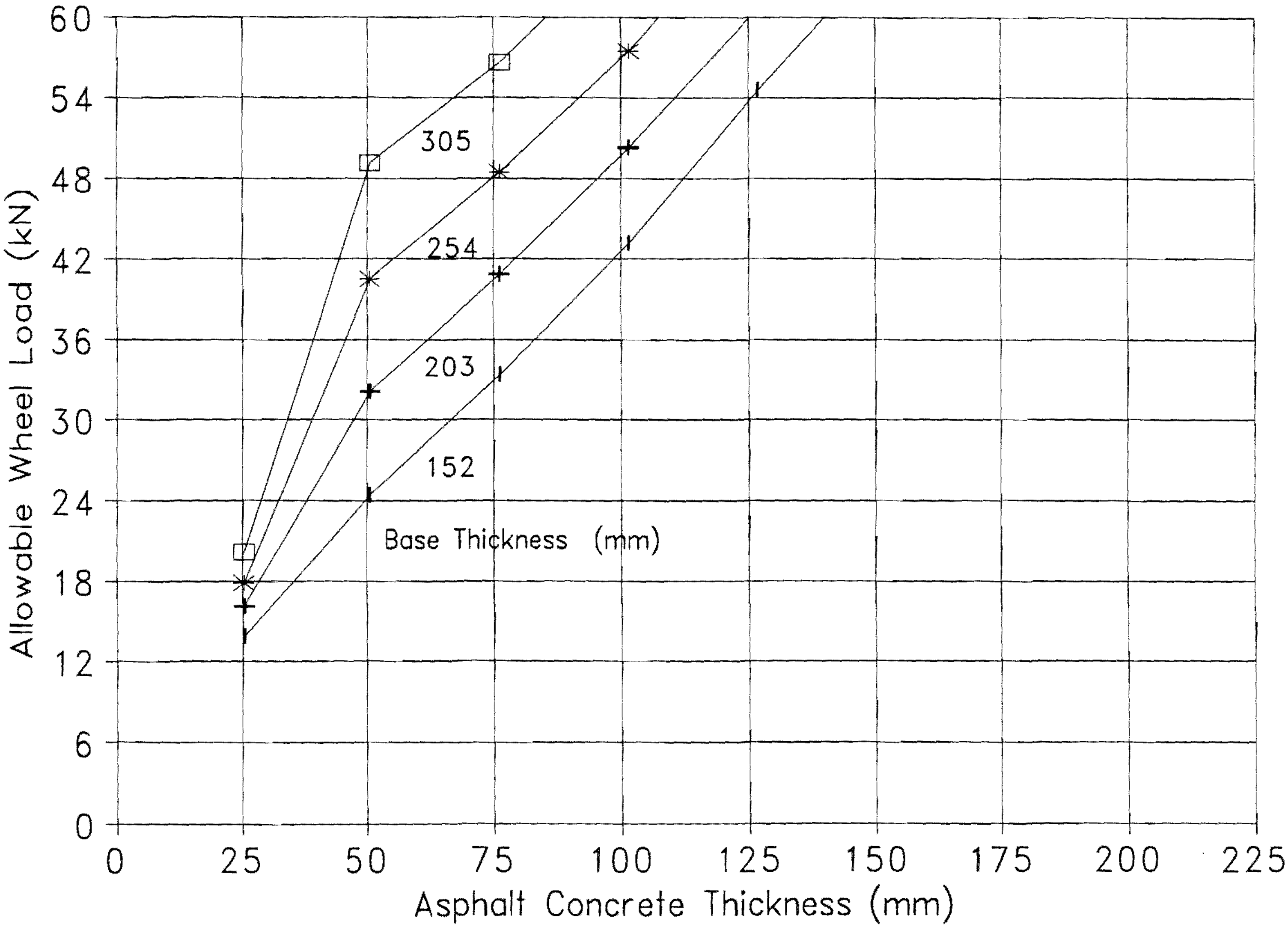


Figure 4. Allowable Wheel Load for Stiff Subgrade, Weak Base Condition (Jooste and Fernando).

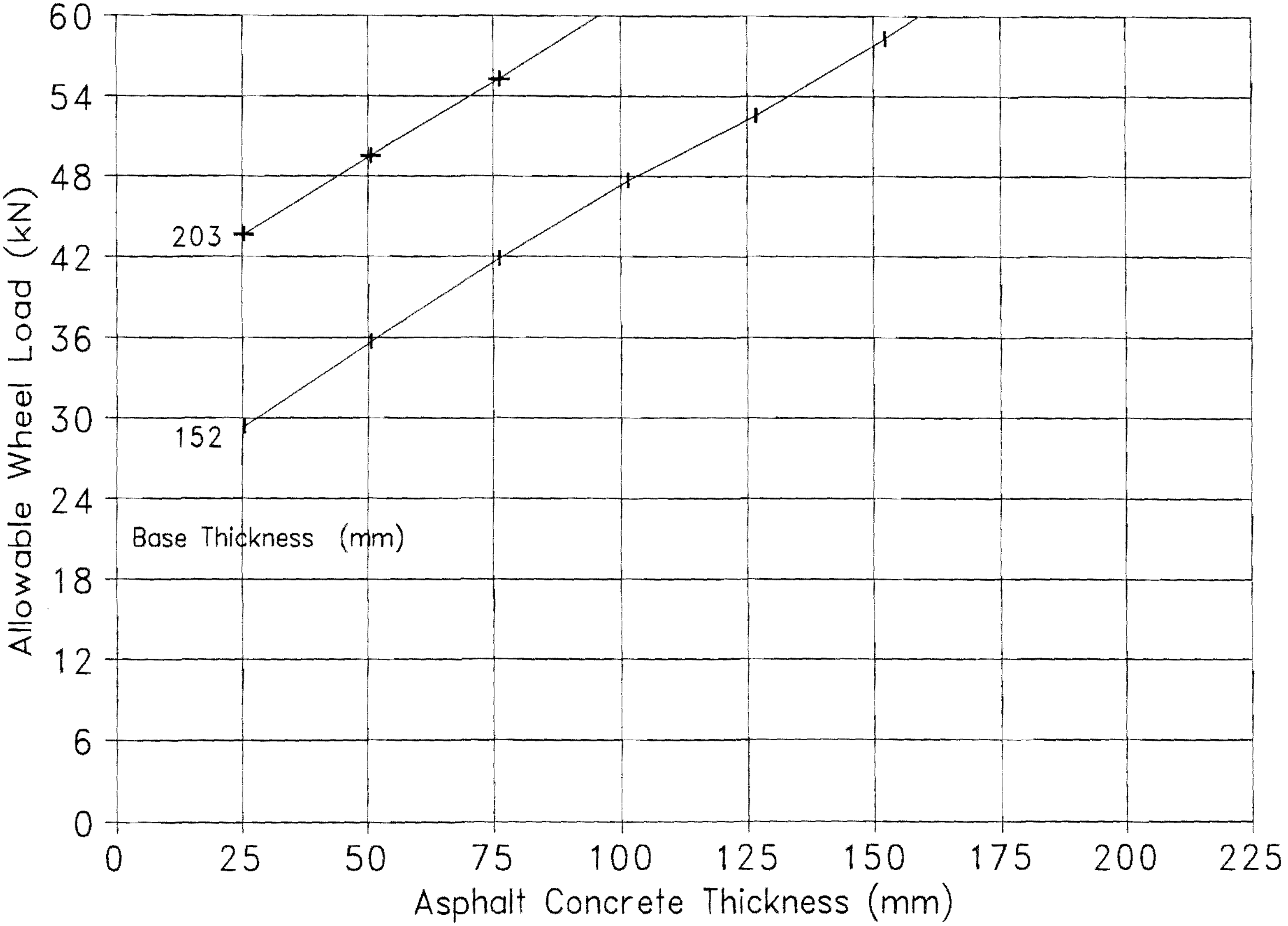


Figure 5. Allowable Wheel Load for Stiff Subgrade, Stabilized Base Condition (Jooste and Fernando).

The non-linear material constants, K_1, K_2 and K_3, in Table 2 are the parameters of the model proposed by Uzan (1985) to characterize the stress-dependency of the resilient modulus, E_r, of pavement materials. This model is given by the equation:

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

where, I_1 = first stress invariant,

τ_{oct} = octahedral shear stress, and

Atm = the atmospheric pressure = 100 kPa.

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 2, a subgrade with a backcalculated modulus in excess of 90 MPa may be classified as a stiff subgrade.

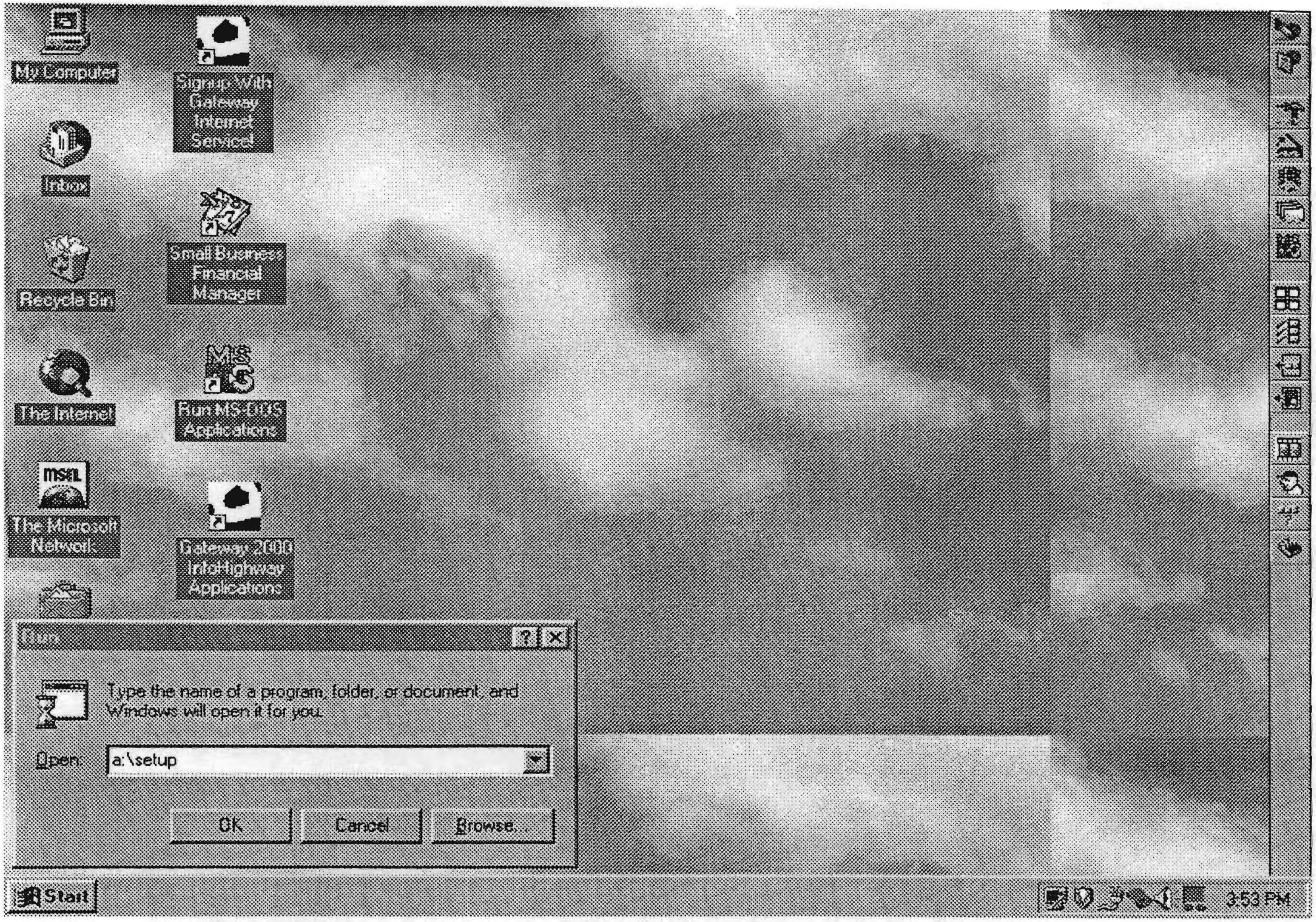
The analysis is also sensitive to layer thickness which influences the results in two ways. First, it affects the backcalculation of layer moduli from FWD data. Second, the predicted pavement response under surface wheel loads is sensitive to the layer thicknesses. Thus, the importance of getting accurate layer thickness information in evaluating superheavy load routes is emphasized.

If the charts used in the first stage analysis indicate that the potential for pavement damage exists, a more detailed investigation is warranted. Additional data collection and analysis to improve the accuracy of the pavement characterization are recommended. This may include FWD testing and backcalculation; GPR measurements coupled with coring or DCP testing to establish layer thicknesses on segments of the route identified as weak in the first-stage analysis; and laboratory testing on soil samples taken from the proposed route to establish material parameters, e.g., cohesion and angle of friction values. The data obtained are then used in the PALS program to evaluate the failure potential within analysis segments of the proposed superheavy load route.

SYSTEM REQUIREMENTS AND PROGRAM INSTALLATION

PALS 2.0 requires a microcomputer operating under Windows 95 or NT. Researchers recommend a Pentium microprocessor or its equivalent and a minimum of 16 Mb of memory. Program installation requires a 3.5-inch floppy drive. The files are stored in two diskettes in compressed format. During installation, these files are expanded and will occupy about 3.5 Mb of hard disk space when installed.

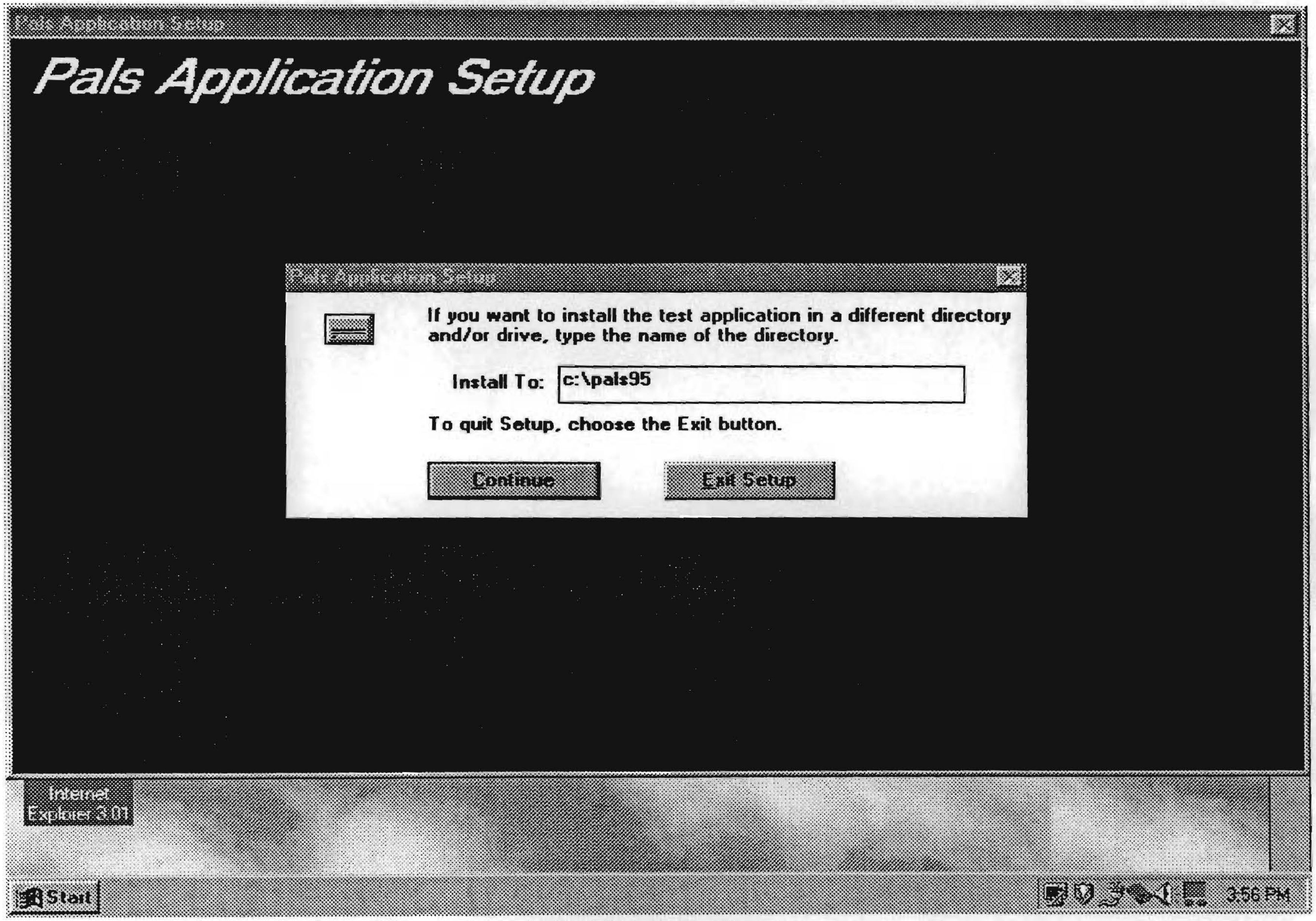
To install the analysis program, insert Disk 1 into the computer's floppy drive (usually the ***A: drive***). Click on the ***Start*** button in Windows 95, and select ***Run***. The dialog box illustrated in Figure 6 is displayed. In the ***Open*** field of this dialog box, type, ***a:\setup***, where it is assumed that the floppy drive has a designation of, ***a:***. If this is not the case, simply use the correct designation with the setup program, e.g., ***b:\setup***. Then, click on ***OK***. This will begin the setup process. Simply follow the instructions that appear on screen. You will be prompted for a subdirectory or folder in which to store the program files on your computer's hard drive. Enter a folder name, e.g., ***C:\PALS95***, as illustrated in Figure 7. The program files are then copied into this folder. When the installation is complete, the PALS program box is displayed, as illustrated in Figure 8. Double-click on the PALS icon to start the analysis program. At any time after installation, you may also execute PALS 2.0 through your ***Programs*** list. Simply click on the ***Start*** button, move the pointer to ***Programs***, then to ***PALS V2.0***. The PALS icon will be displayed. Double-click on the icon to load the program. The remainder of this user's guide provides instructions in the use of PALS 2.0.



Type the name of a program, folder, or document, and Windows will open it for you.

Open: a:\setup

Figure 6. Running the SETUP Program to Install PALS.



If you want to install the test application in a different directory and/or drive, type the name of the directory.

Install To: c:\pals95

To quit Setup, choose the Exit button.

Figure 7. Specifying a Folder in Which to Store the PALS Program Files.

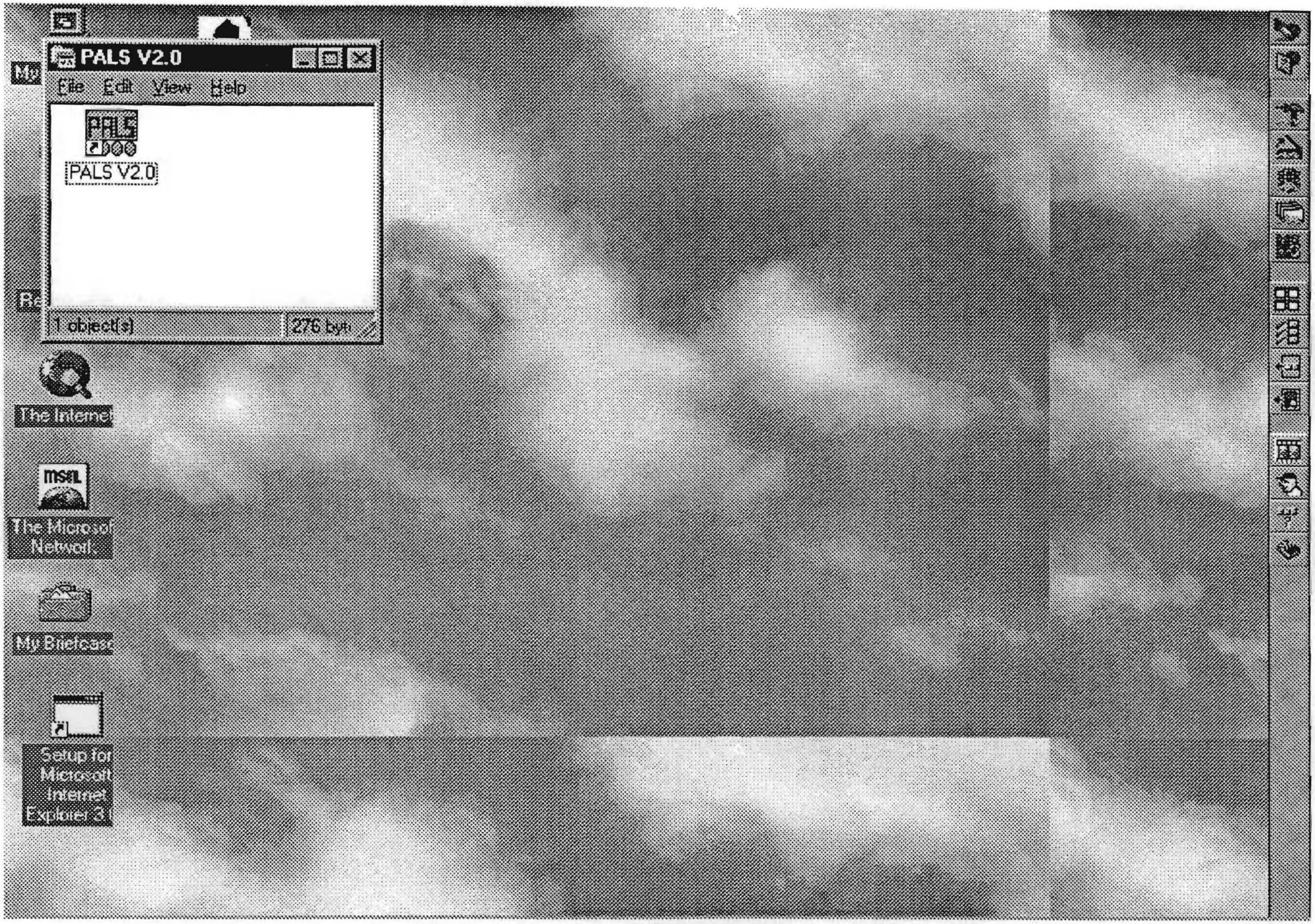


Figure 8. PALS Program Group Box Displayed After Installation.

CHAPTER II

ENTERING INPUT DATA INTO THE PALS ANALYSIS PROGRAM

User-interface screens in PALS facilitate the entry of input data to perform a given analysis. Specifying input parameters is the first activity after loading the computer program. This is done by manually entering the required parameters using the interface screens, or by retrieving an existing input file and editing the data accordingly within the PALS program. Before going further, here are a few simple guidelines to remember when navigating through the different menus of PALS:

1. To select a particular option, move the pointer to it, and then click on the option with the left mouse button. Alternatively, you may also activate an option by:
    a. Pressing the ***ALT*** key, holding it, and then pressing the underlined letter associated with the label of the option; or by
    b. Pressing the ***TAB*** key repeatedly until you get to the selected option, and then hitting the carriage return <*CR*> key. When you get to the option you want, the label of the button corresponding to that option is enclosed within a dotted box. This is the way to recognize that the option is current.
2. To enter data for a particular parameter, move the cursor to its field or cell. Then, type in the required data. You position the cursor to an input field by:
    a. Moving the pointer to the field and clicking on it; or by
    b. Pressing the ***TAB*** key repeatedly until you get the cursor to the selected field.
3. You may click on the ***Clear Data*** button in a data entry menu to clear all entries in that menu and position the cursor in the first input field. The ***Modify Data*** button brings the cursor to the first input field of a given menu.

To load the analysis program, double-click on its icon as explained previously. The Main Menu, shown in Figure 9, is then displayed on the monitor. For input data entry, click on the ***Input Data*** option. You will then go through a series of menus to specify input parameters for a given problem.

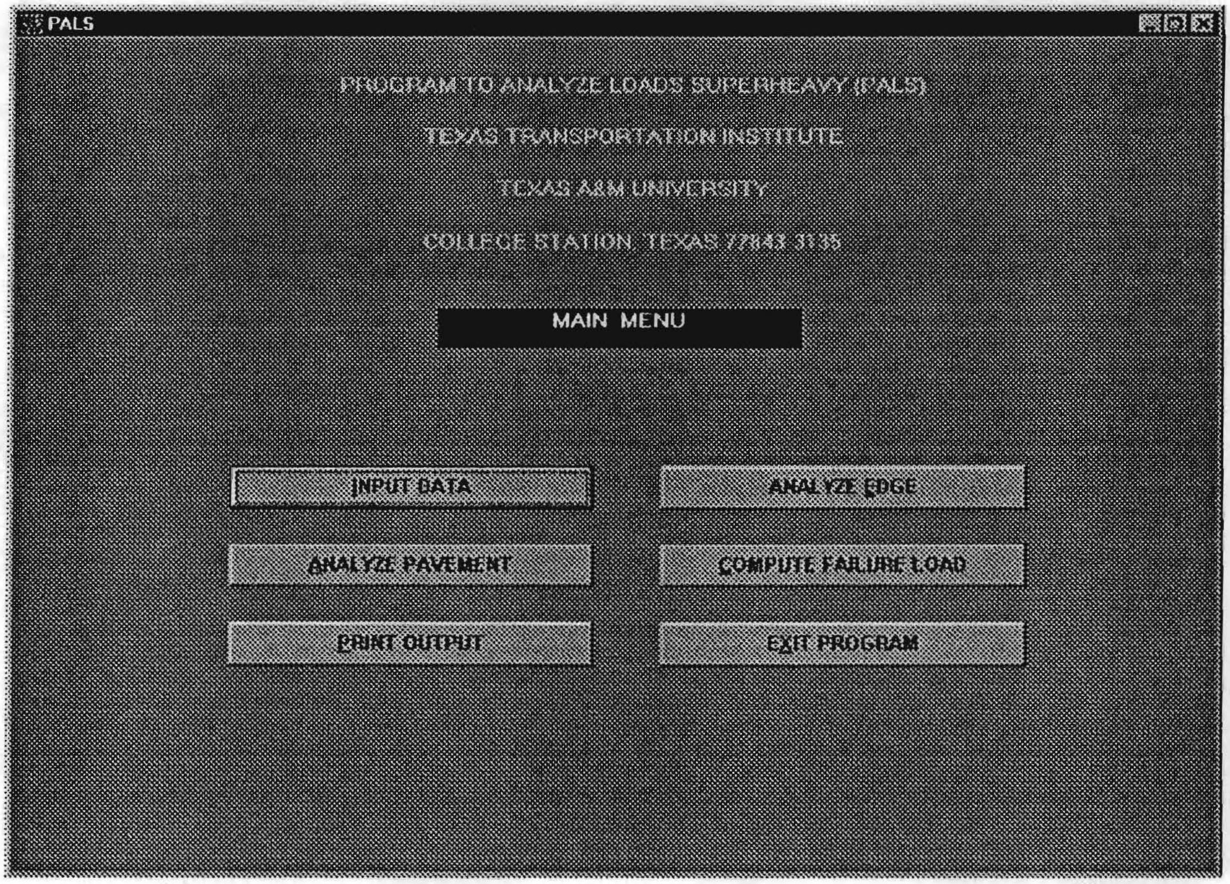


Figure 9. Main Menu of PALS.

Six options are available in the Main Menu illustrated in Figure 9. Before any analysis can be made, you must first specify the input parameters for a given problem. Click on the ***Input Data*** option to do this. After the required data are specified, you may then proceed with the analysis. You have three choices:

1. Choose ***Analyze Pavement*** to establish the potential for pavement damage when edge loading is not a concern; or
2. Select ***Analyze Edge*** if the wheels of the transport vehicle are expected to track close to the pavement edge and the shoulder is unpaved; or
3. Click on ***Compute Failure Load*** to determine the wheel load at which over stressing of the given pavement is predicted.

Chapter III discusses the analysis options. To view or print the results of a given analysis, click on ***Print Output***. When you are done, click on ***Exit Program***. Next, the data entry menus in PALS are discussed.

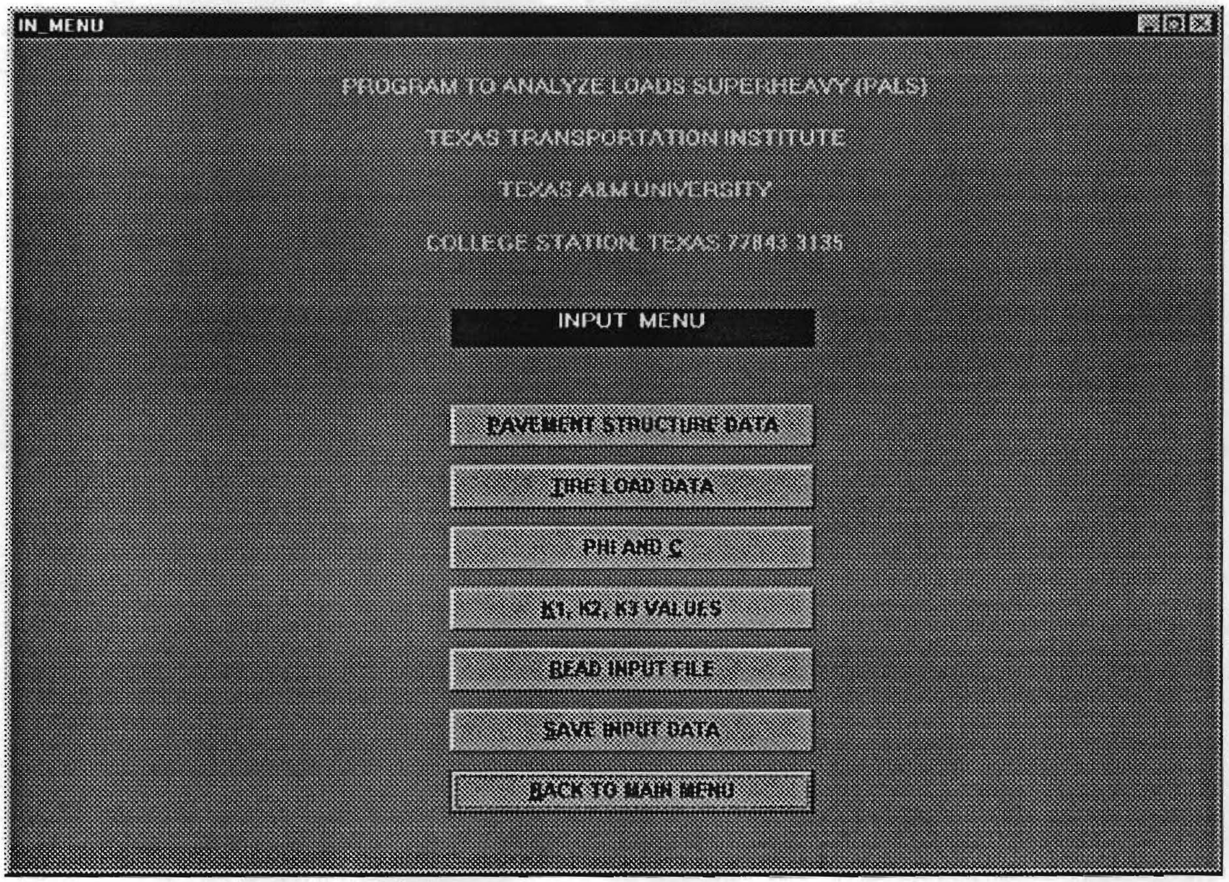

PROGRAM TO ANALYZE LOADS SUPERHEAVY (PALS)
TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY
COLLEGE STATION, TEXAS 77843-3135

Figure 10. Main Input Menu of PALS.

If you selected ***Input Data*** from the main program menu, the above screen is displayed. The following actions can be taken:

1. You can specify pavement layer thicknesses for a given highway segment by selecting the ***Pavement Structure*** option. You must select this option first to define the pavement to be analyzed. Alternatively, you may retrieve and edit an existing data file.
2. You can enter the tire loads imposed by the superheavy transport vehicle through the ***Tire Load Data*** option.
3. You can specify the Mohr-Coulomb failure parameters, ϕ and c, of the different pavement materials by selecting the third option of the input menu.
4. You can specify the nonlinear, stress-dependent material parameters, K_1, K_2, and K_3, of pavement materials along the superheavy load route by selecting option 4.
5. You can retrieve data stored in an existing file through the ***Read Input File*** option.
6. You can save data entered to a file through the ***Save Input Data*** option.
7. You can go back to the main menu by selecting the last option.

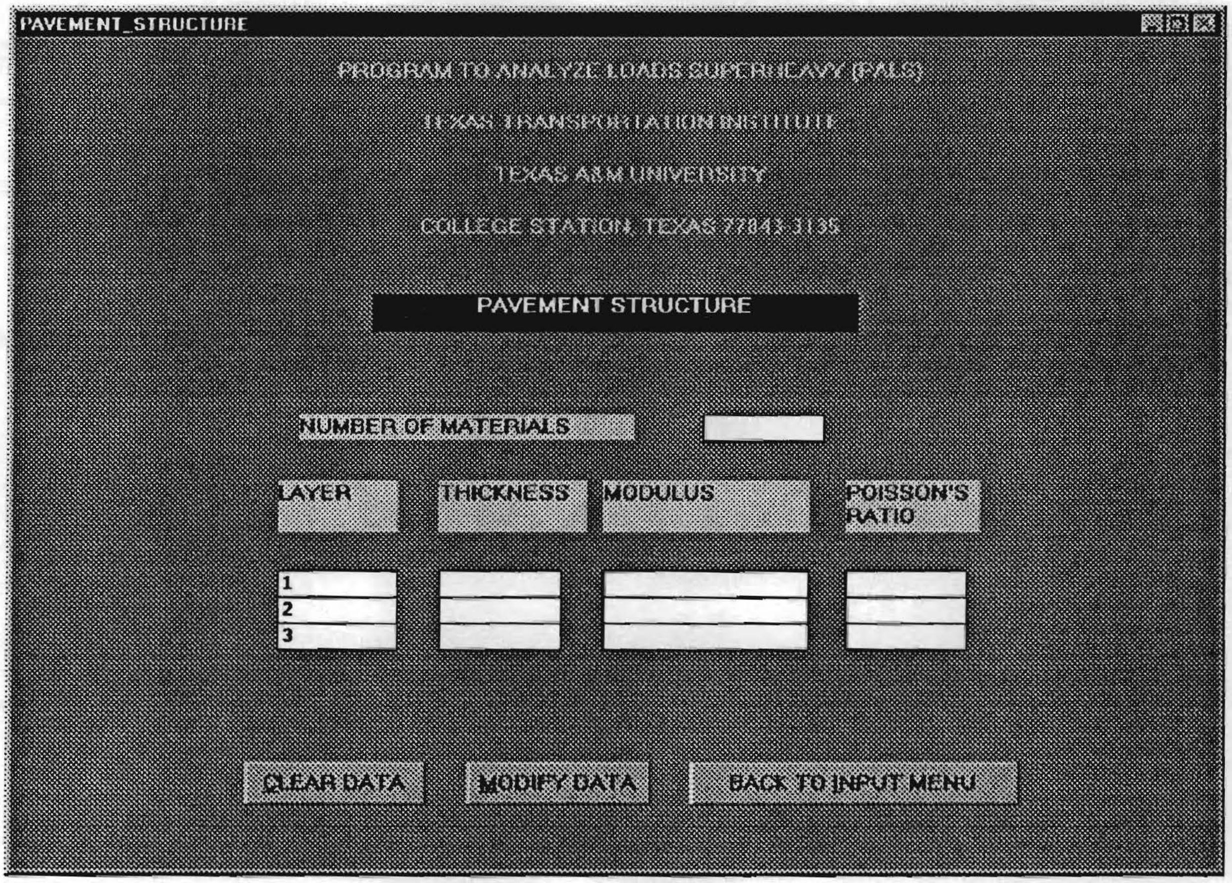


Figure 11. Menu to Enter Data on Pavement Structure.

If you clicked on the ***Pavement Structure*** option in the input menu (Figure 10), the first item you will specify is the number of materials or layers that comprise the pavement to be analyzed. In the analysis, the pavement is represented as a layered system (see Figure 12). Each layer is of finite thickness, characterized by a modulus or stiffness, and a Poisson's ratio. The bottom layer is assumed to be rigid and of infinite depth. This layer is referred to as the rigid bottom. Up to four distinct layers above the rigid bottom can be specified. The layer immediately above the rigid bottom is the subgrade. The modulus and Poisson's ratio of each pavement layer above the rigid bottom may be modeled as constants (independent of stress) or as stress-dependent. For the latter case, the modulus and Poisson's ratio entered in the above menu are used as starting values in an iterative scheme to get stress-compatible modulus and Poisson's ratio for a given layer or pavement material.

When you are done entering the required data, click on ***Back to Input Menu***. You are then asked to confirm your entries. Click on ***Yes*** to get back to the input menu and specify other parameters for the analysis. Otherwise, click on ***No*** to edit the data entered.

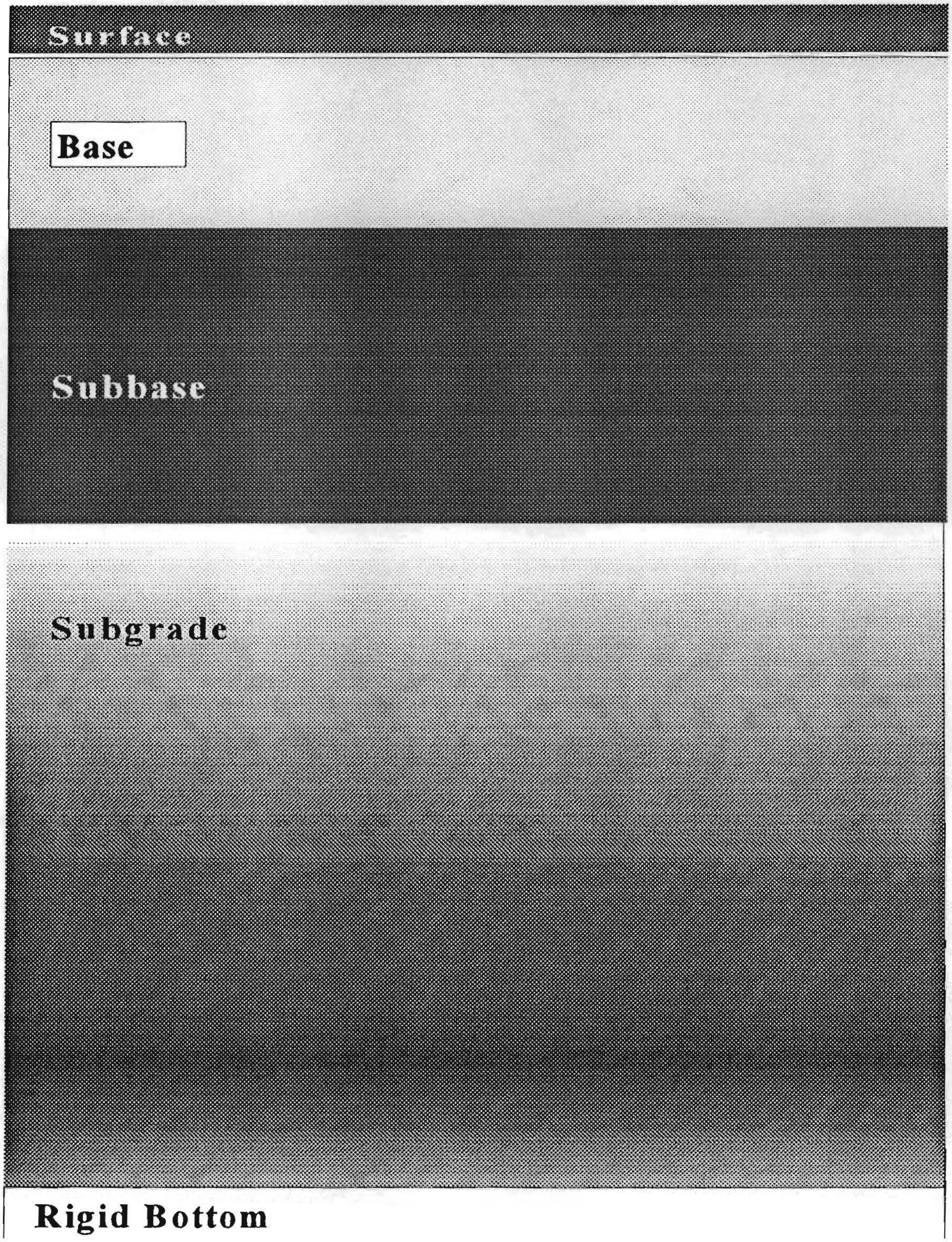


Figure 12. Representation of Pavement as a Layered System.

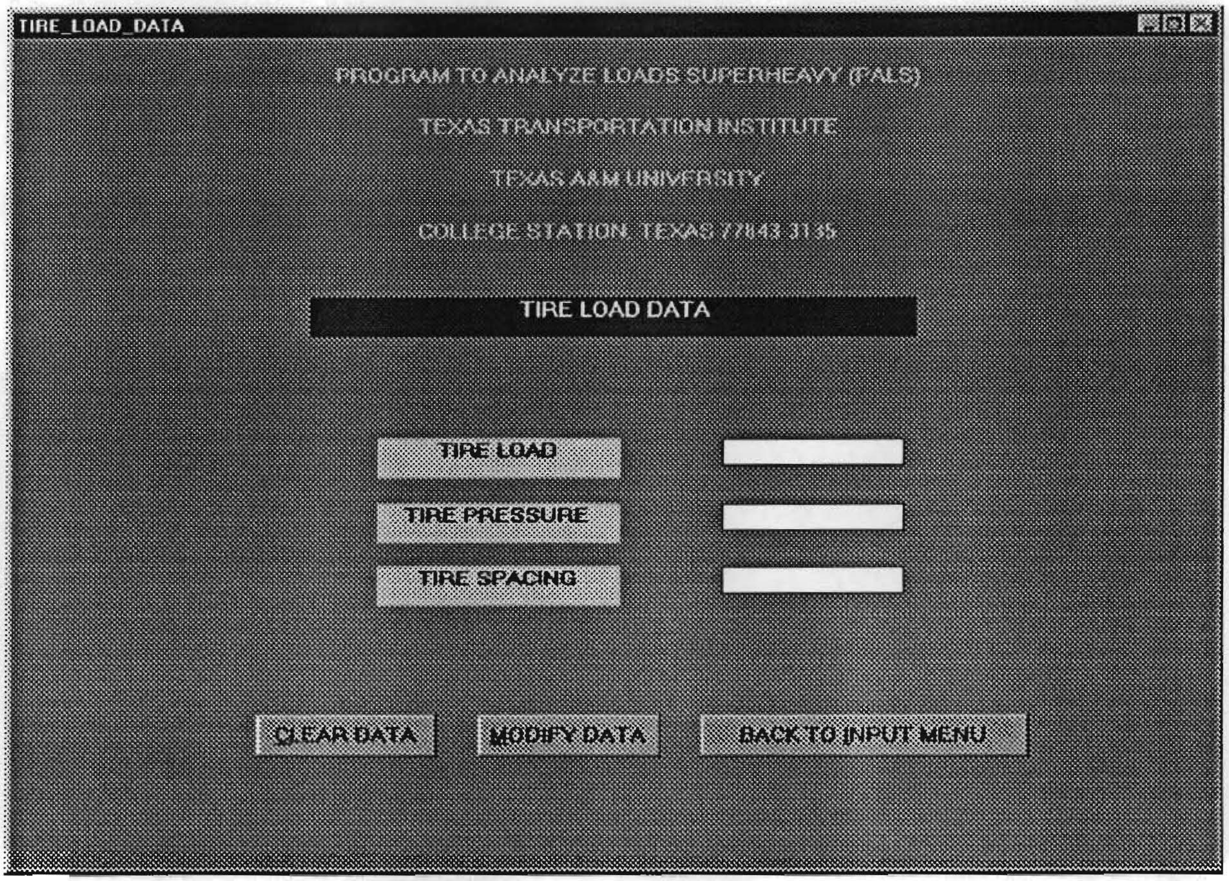


Figure 13. Menu to Enter Tire Load Data.

If you clicked on the ***Tire Load Data*** button in the input menu, the above screen is displayed. Enter the tire loads of the superheavy transport vehicle that you want to analyze. Dual tire loads are modeled in the computer program with the spacing that you specify. The use of dual wheel loads to predict pavement response under the superheavy load is based on an evaluation of different load configurations by Jooste and Fernando (1995). To model a single wheel load, specify a large spacing between tires to minimize the interaction between the dual wheels.

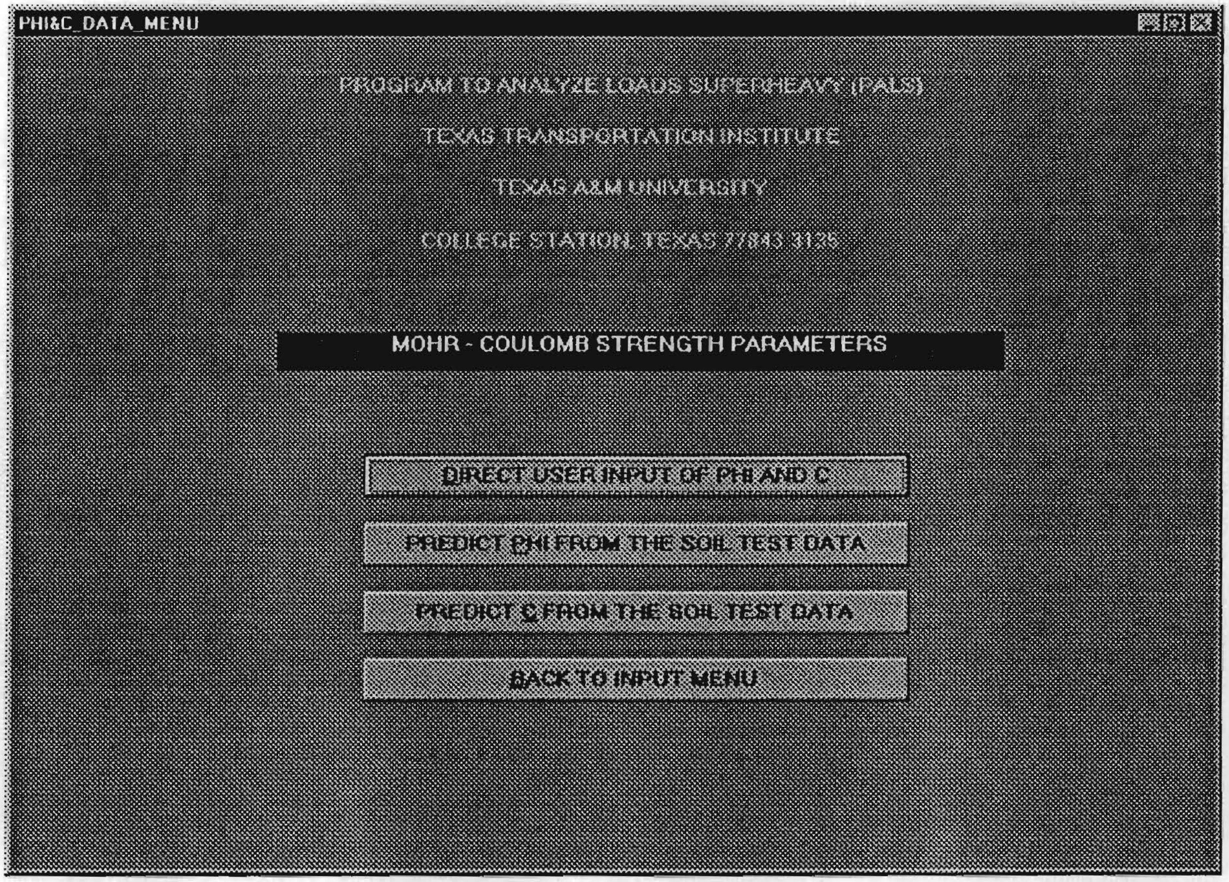


Figure 14. Menu to Enter Mohr-Coulomb Strength Parameters.

To specify the Mohr-Coulomb strength parameters, click on the ***Phi and C*** button in the input menu. The above screen is then displayed. For each pavement material, the friction angle, ϕ, and cohesion, c, must be specified to predict if yielding will occur under the superheavy load based on the Mohr-Coulomb yield criterion. These parameters are obtained from triaxial tests or may be estimated from results of simple soil tests using correlations developed by Glover and Fernando (1995). The cohesion and friction angle values for each pavement layer may be specified using Option 1 of the above menu if the parameters are known from previous testing. Tables 3 and 4 show representative values of the Mohr-Coulomb strength parameters for a variety of base and subgrade materials, respectively. Alternatively, the strength parameters may be estimated using data from simple soil tests using Options 2 and 3. Table 5 shows the soil test data needed to estimate the cohesion and friction angle values from regression equations developed through laboratory testing by Glover and Fernando (1995). These regression equations are coded into the PALS computer program.

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

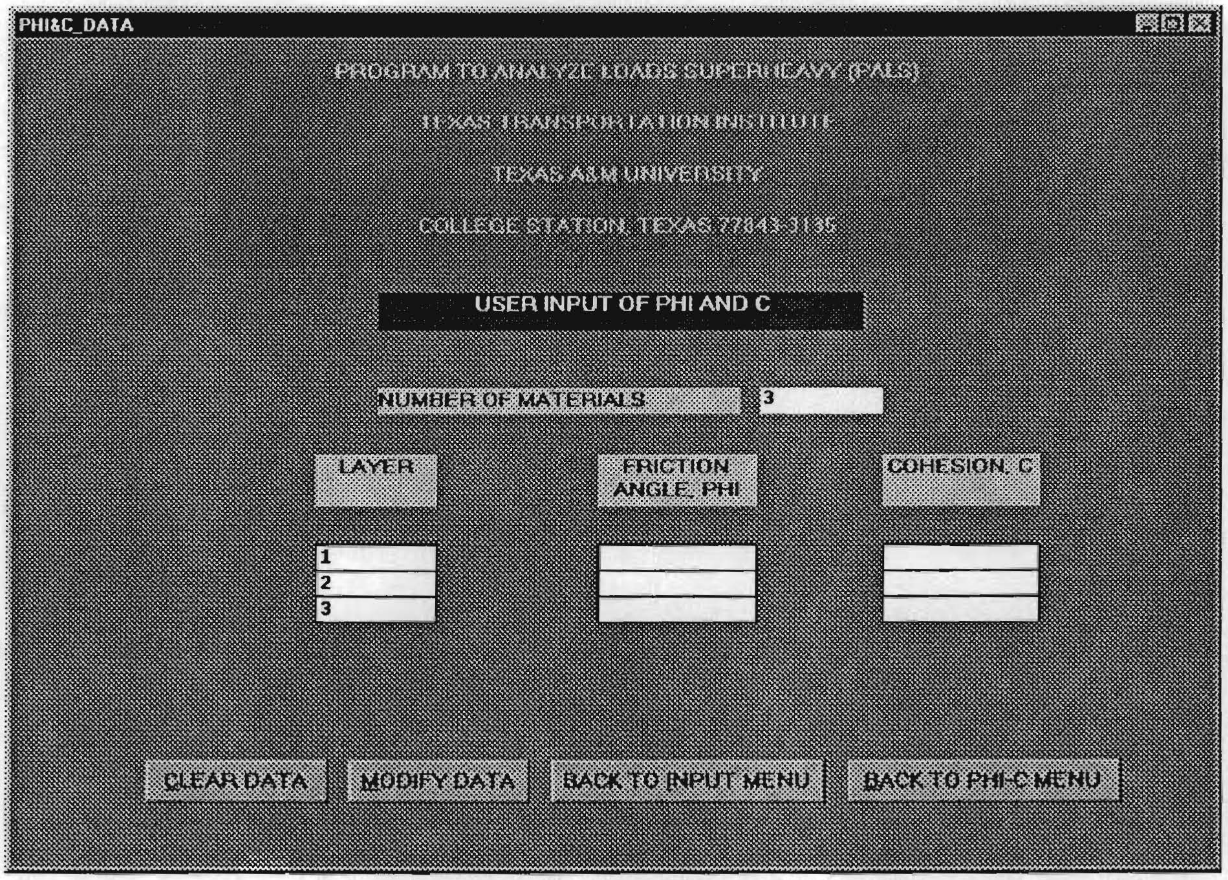
Table 4. Measured Cohesion and Angle of Friction Values for Subgrade Materials (Glover and Fernando, 1995).

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

Table 5. Soil Properties Used to Estimate Strength and Nonlinear 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.



NUMBER OF MATERIALS 3

Figure 15. Menu to Enter ϕ and *c* Values Directly for Each Pavement Layer.

If you clicked on the first option of the *Mohr-Coulomb Strength Parameters* menu (Figure 14), the above screen is displayed allowing you to enter the angle of friction and cohesion values for the different materials comprising the pavement. The cohesion and angle of friction values for soils may be determined from triaxial tests (TEX-117-E) conducted at various confining pressures. Conducting the tests at a moisture content representative of in-situ conditions during the time of the superheavy load move is recommended. From the test data, the failure envelope for a given material is determined. This is the line tangent to the Mohr's circles corresponding to the different confining pressures, as illustrated in Figure 16. The intercept of this line on the ordinate axis is the cohesion, and the slope of the line is the friction angle.

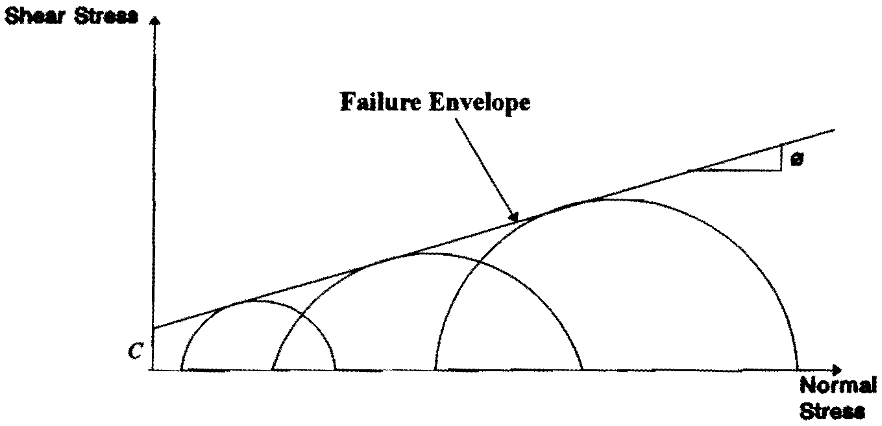
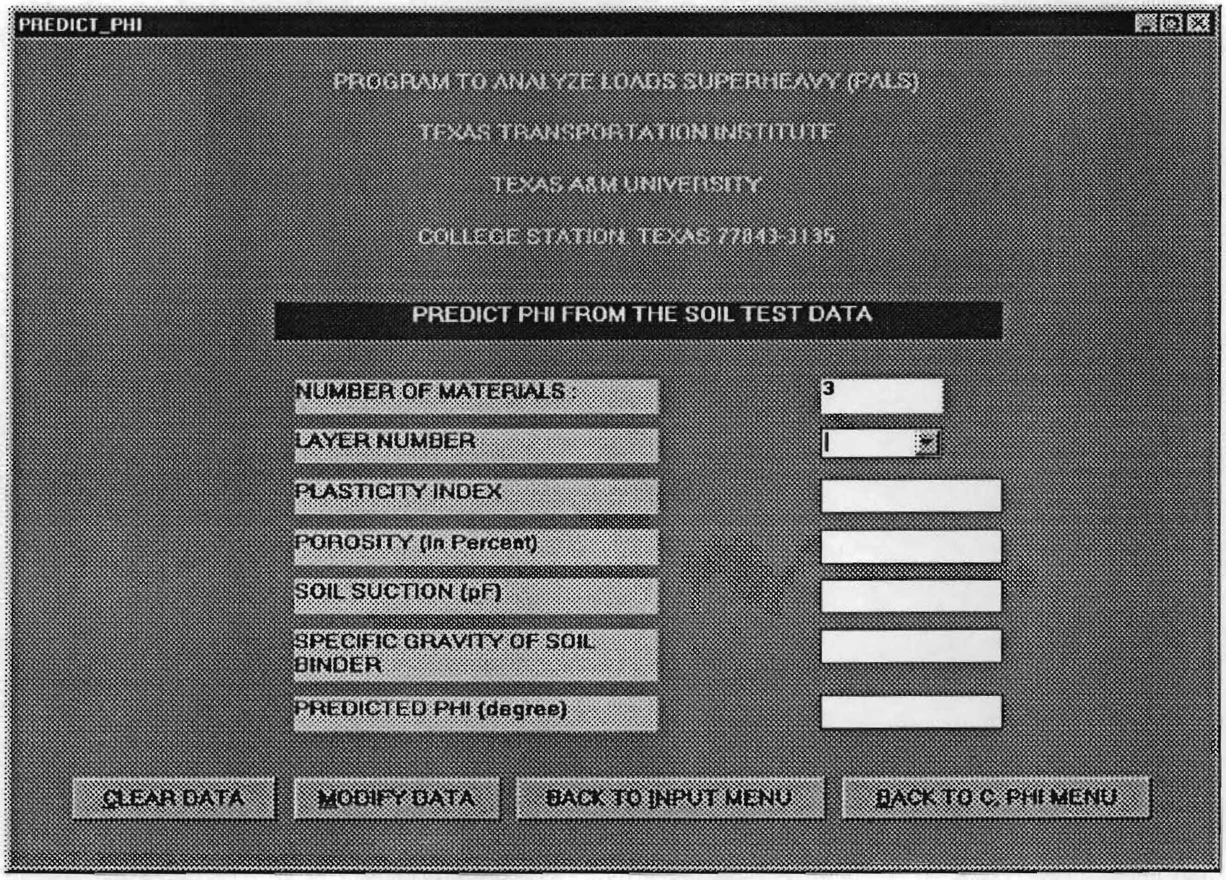


Figure 16. Mohr-Coulomb Failure Envelope.



PROGRAM TO ANALYZE LOADS SUPERHEAVY (PALS)

TEXAS TRANSPORTATION INSTITUTE

TEXAS A&M UNIVERSITY

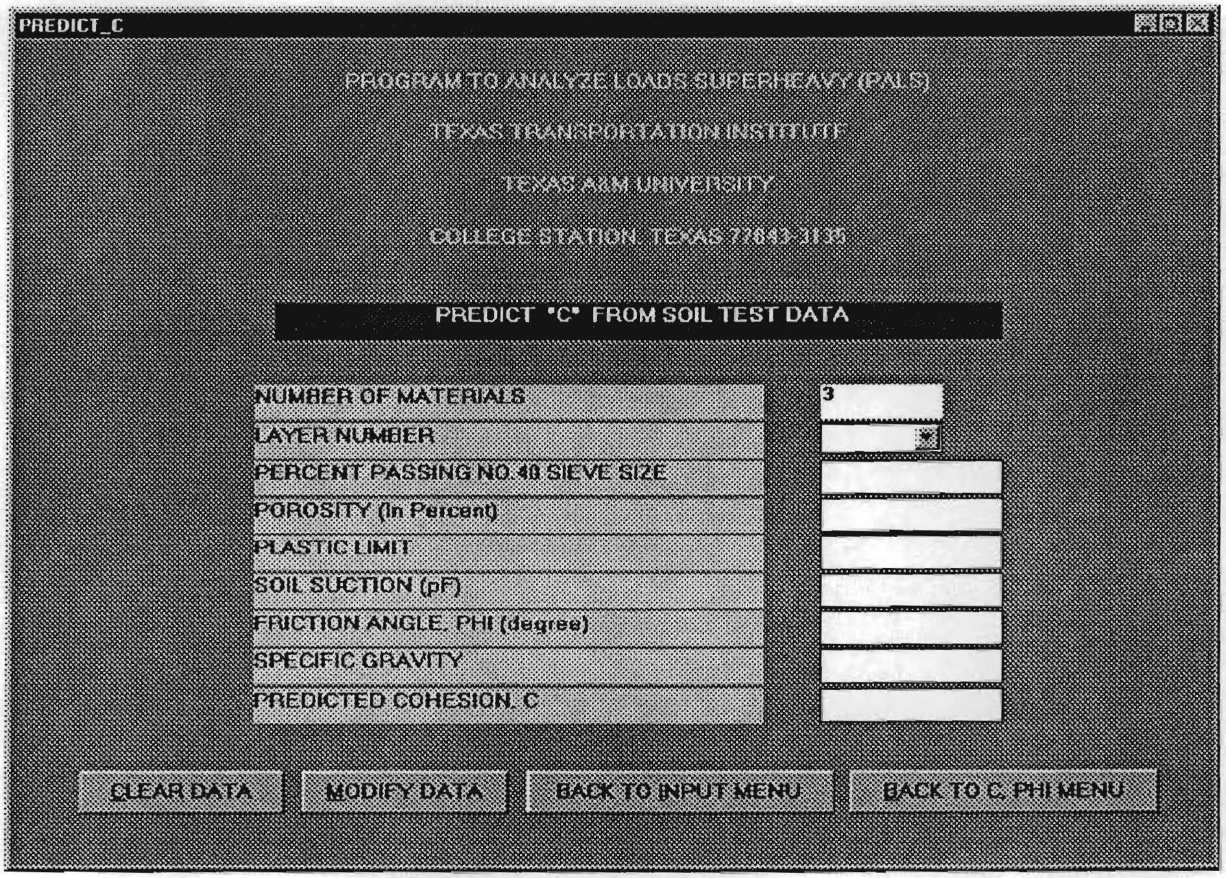
COLLEGE STATION, TEXAS 77843-3135

PREDICT PHI FROM THE SOIL TEST DATA

NUMBER OF MATERIALS : 3
LAYER NUMBER: 1
PLASTICITY INDEX
POROSITY (In Percent)
SOIL SUCTION (pF)
SPECIFIC GRAVITY OF SOIL BINDER
PREDICTED PHI (degree)

Figure 17. Menu to Estimate Friction Angle From Soil Test Data.

The friction angles for the different pavement layers may also be estimated from results of soil tests shown in Table 5. If data from these tests are available, enter the required data to estimate the friction angle, ϕ, in the above menu. This screen is displayed when the second option of the *Mohr-Coulomb Strength Parameters* menu (Figure 14) is selected.



NUMBER OF MATERIALS 3
LAYER NUMBER
PERCENT PASSING NO.40 SIEVE SIZE
POROSITY (In Percent)
PLASTIC LIMIT
SOIL SUCTION (pF)
FRICTION ANGLE, PHI (degree)
SPECIFIC GRAVITY
PREDICTED COHESION, C

Figure 18. Menu to Estimate Cohesion From Soil Test Data.

The cohesion values for the different pavement layers may also be estimated from results of soil tests shown in Table 5. If these results are available, enter the required information to estimate cohesion in the above menu. This screen is displayed when the third option is selected in the *Mohr-Coulomb Strength Parameters* menu shown in Figure 14. Note that the friction angle for a given pavement layer must already be known to estimate the cohesion for that layer in this menu.

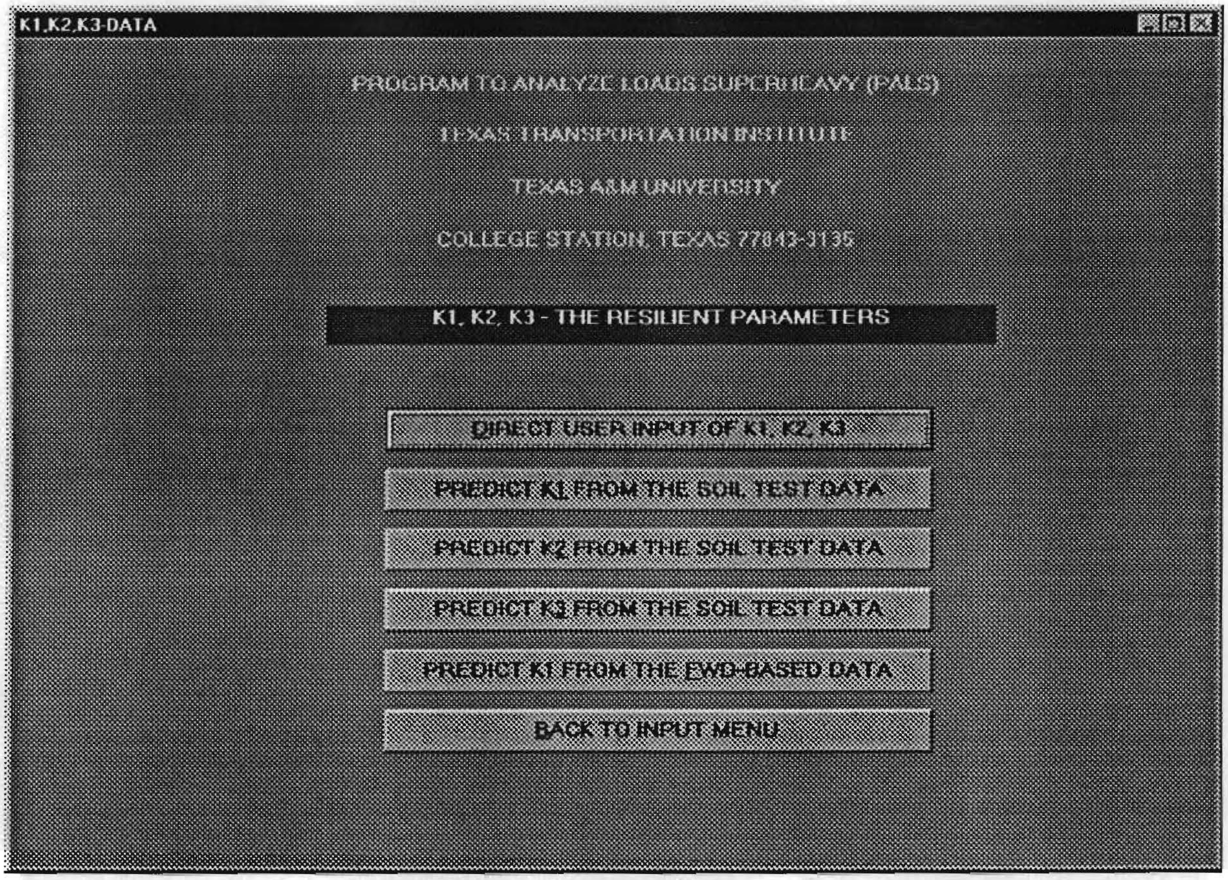


Figure 19. Menu to Specify Non-Linear, Stress-Dependent Material Parameters.

To model the stress-dependency of the resilient modulus, E_r, of pavement materials, the parameters, K_1, K_2, and K_3 of the following model must be specified for each pavement layer:

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

where, I_1 = first stress invariant,
τ_{oct} = octahedral shear stress, and
Atm = the atmospheric pressure = 100 kPa.

Typical K_1 to K_3 values for base and subgrade materials are shown in Tables 6 and 7, respectively. These material parameters are also used to model the stress-dependency of the Poisson's ratio in the PALS program. The above screen is displayed when you click on the

Table 6. 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

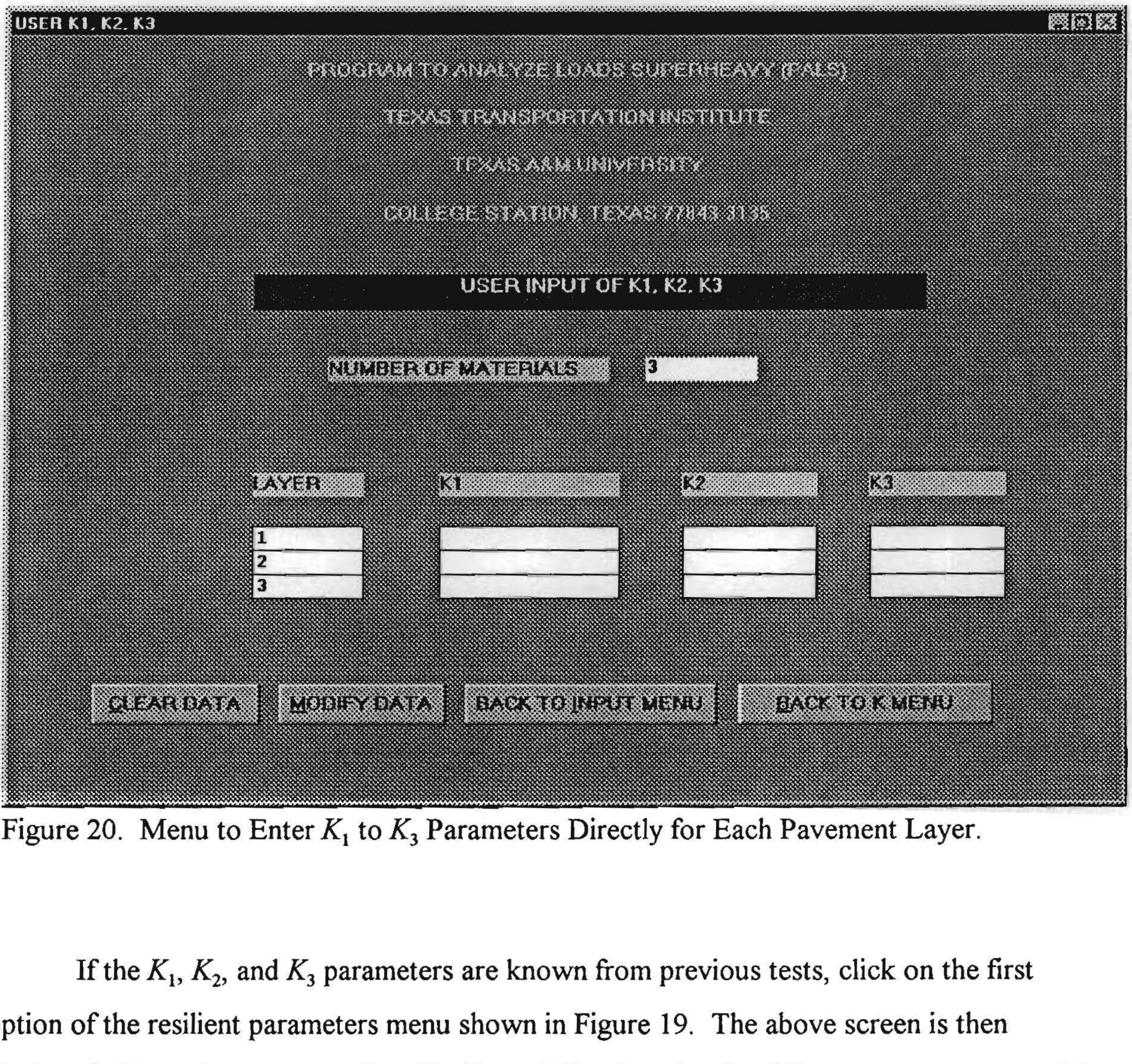
[1] From tests run at moisture contents below optimum.

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

K_1, K_2, K_3 Values option of the input menu in Figure 10. Using the menu in Figure 19, you can specify the stress-dependent material parameters directly, if these are available (Option 1); estimate K_1, K_2, and K_3 from soil test data (Options 2, 3, and 4 respectively); or estimate K_1 from Falling Weight Deflectometer (FWD) data taken on the proposed superheavy load route (Option 5). For this latter option, the K_2 and K_3 values for the pavement layers must be known. The various options for specifying the non-linear, stress-dependent material parameters are presented in the following.

Table 7. Typical K_1 to K_3 Values for Subgrade Materials (Glover and Fernando, 1995).

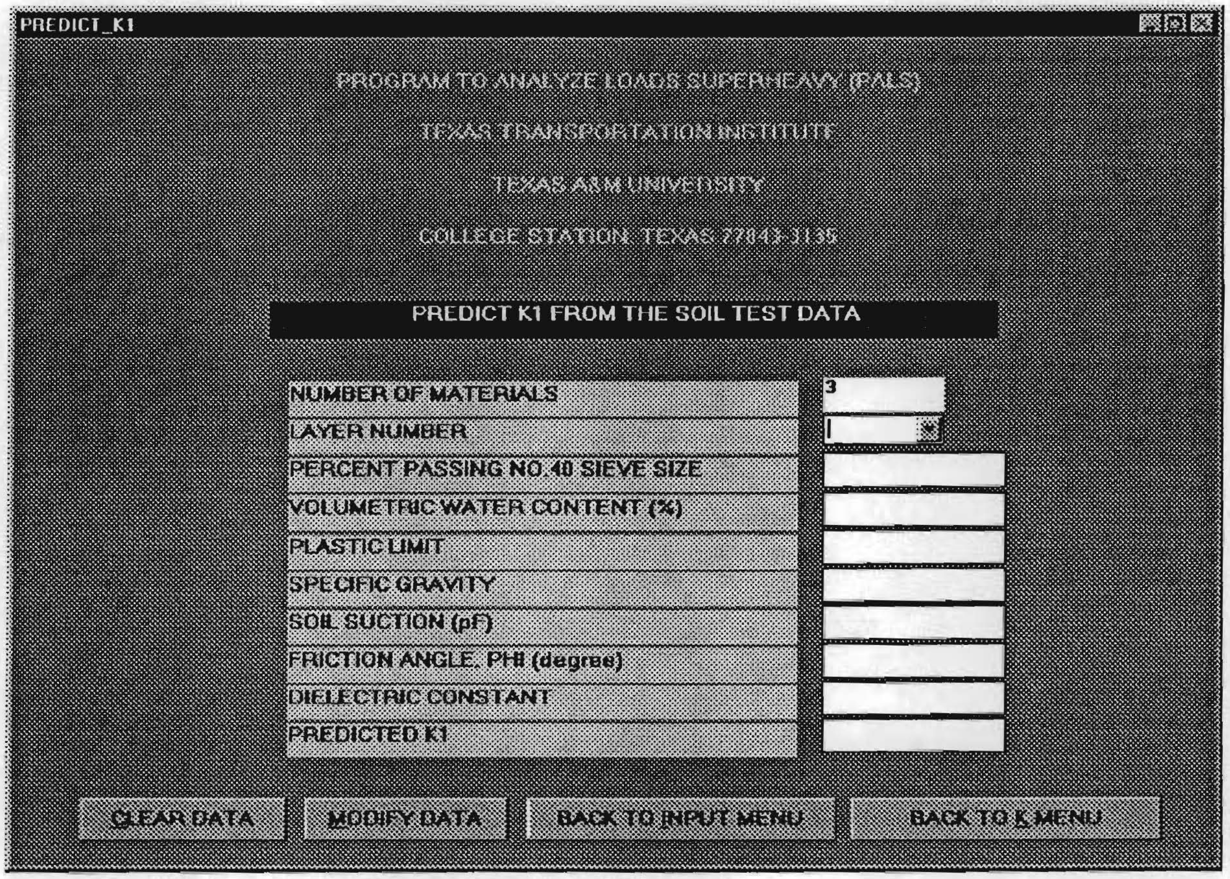
Material Type	K_1			K_2			K_3		
	- opt.	at opt.	+ opt.	- opt.	at opt.	+ opt.	- opt.	at opt.	+ opt.
Sand	3118	6434	6319	0.44	0.51	0.40	0.00	0.00	-0.03
Sandy Gravel	11,288	1574	-	0.63	0.67	-	-0.10	-0.28	-
Lean Clay	4096	105	776	0.00	0.32	0.10	-0.27	0.10	-0.55
Fat Clay	200	263	440	0.66	1.25	0.66	-1.47	-0.50	-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



NUMBER OF MATERIALS: 3

Figure 20. Menu to Enter K_1 to K_3 Parameters Directly for Each Pavement Layer.

If the K_1, K_2, and K_3 parameters are known from previous tests, click on the first option of the resilient parameters menu shown in Figure 19. The above screen is then displayed. Enter the corresponding K_1, K_2, and K_3 values for the different pavement materials. These parameters may be determined from resilient modulus testing following the procedure in AASHTO T-292-91 (AASHTO, 1997) or from compressive creep and recovery tests as conducted by Glover and Fernando (1995).



PROGRAM TO ANALYZE LOADS SUPERHEAVY (PALS)
TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY
COLLEGE STATION, TEXAS 77843-3135

PREDICT K1 FROM THE SOIL TEST DATA

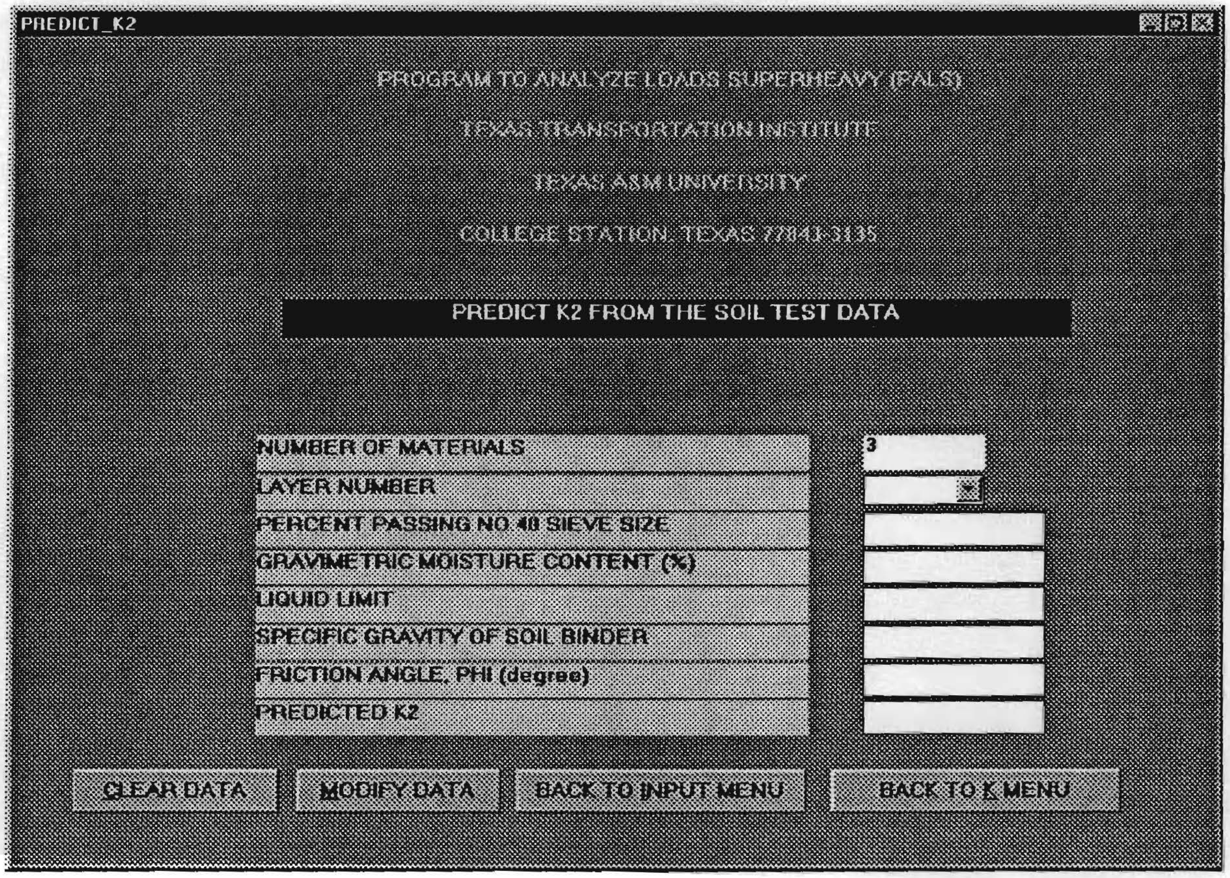
NUMBER OF MATERIALS	3
LAYER NUMBER	1
PERCENT PASSING NO.40 SIEVE SIZE	
VOLUMETRIC WATER CONTENT (%)	
PLASTIC LIMIT	
SPECIFIC GRAVITY	
SOIL SUCTION (pF)	
FRICTION ANGLE, PHI (degree)	
DIELECTRIC CONSTANT	
PREDICTED K1	

Figure 21. Menu to Estimate K_1 From Soil Test Data.

If data from the soil tests shown in Table 5 are available to estimate K_1, enter the corresponding data for each pavement layer in this menu. The above screen is accessed by selecting Option 2 of the resilient parameters menu shown in Figure 19. Note that the friction angle for each layer must be known to estimate K_1 as well as the dielectric constant. Typical values of the dielectric constants of various materials are shown in Table 8. This soil property may be determined from dielectric probe measurements conducted on laboratory molded samples or from a Ground Penetrating Radar (GPR) survey of the proposed superheavy load route. For assistance with GPR or dielectric probe measurements, call the Materials and Pavements Division of the Texas Transportation Institute at (409) 845-8212. In addition, the Pavements Section of TxDOT's Design Division has a fully operational GPR van which may be available for in-situ determination of layer thicknesses and dielectric constants on the proposed superheavy load route. Contact the Pavements Section at (512) 465-3686 for inquiries about the use of TxDOT's GPR van.

Table 8. 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



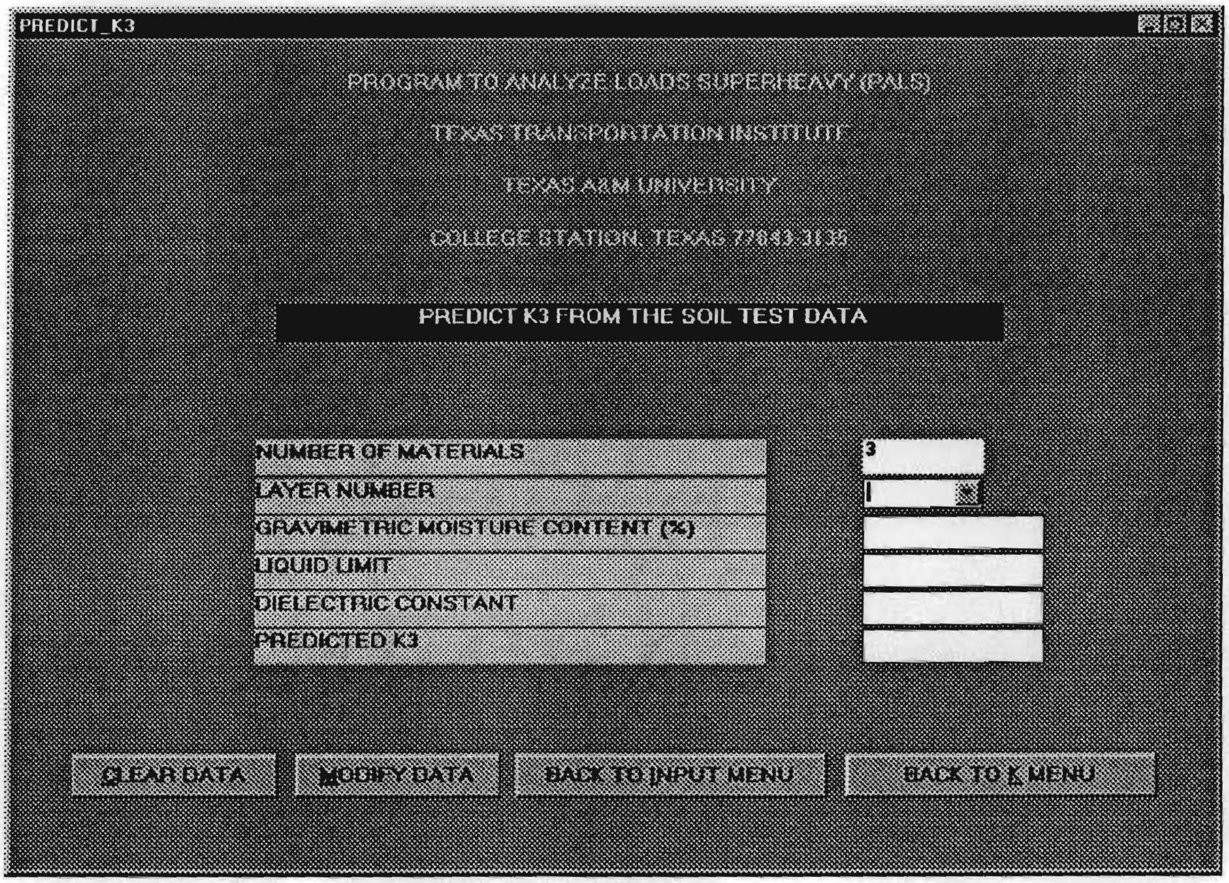
PROGRAM TO ANALYZE LOADS SUPERHEAVY (PALS)
TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY
COLLEGE STATION, TEXAS 77843-3135

PREDICT K2 FROM THE SOIL TEST DATA

NUMBER OF MATERIALS	3
LAYER NUMBER	
PERCENT PASSING NO 40 SIEVE SIZE	
GRAVIMETRIC MOISTURE CONTENT (%)	
LIQUID LIMIT	
SPECIFIC GRAVITY OF SOIL BINDER	
FRICTION ANGLE, PHI (degree)	
PREDICTED K2	

Figure 22. Menu to Estimate K_2 From Soil Test Data.

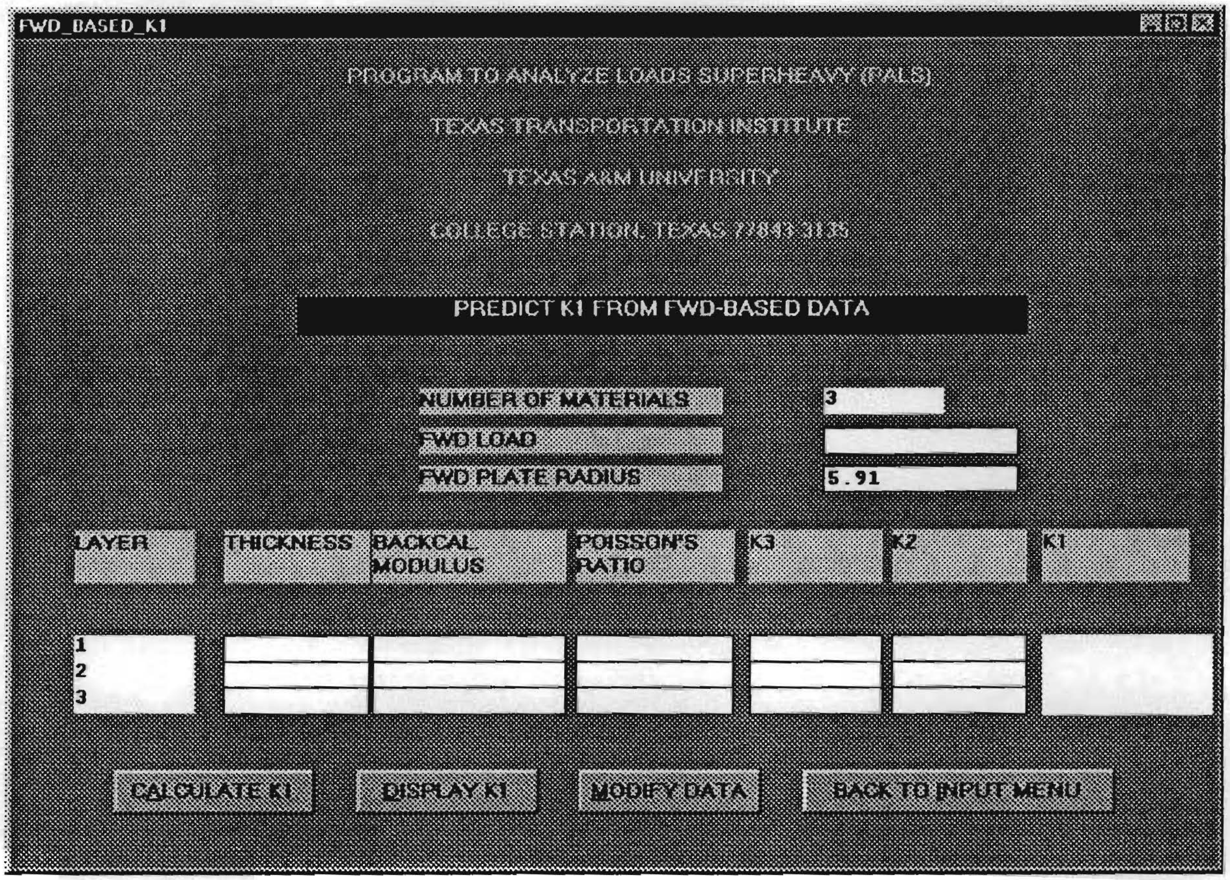
If results from the soil tests shown in Table 5 are available to estimate K_2, enter the corresponding data for each pavement material in this menu. This screen is displayed when Option 3 is selected from the resilient parameters menu shown in Figure 19. Note that the friction angle for a given material must be known to estimate K_2.



NUMBER OF MATERIALS 3
LAYER NUMBER 1

Figure 23. Menu to Estimate K_3 From Soil Test Data.

If results from the soil tests shown in Table 5 are available to estimate K_3, enter the corresponding data for each pavement material in this menu. This screen is displayed when Option 4 is selected from the resilient parameters menu shown in Figure 19.



NUMBER OF MATERIALS: 3
FWD LOAD:
FWD PLATE RADIUS: 5.91

LAYER	THICKNESS	BACKCAL MODULUS	POISSON'S RATIO	K3	K2	K1
1						
2						
3						

Figure 24. Menu to Estimate K_1 From Falling Weight Deflectometer (FWD) Data.

This screen is displayed when Option 5 is selected from the resilient parameters menu shown in Figure 19. It is used to estimate K_1 using the results of backcalculations done on FWD data collected along the proposed superheavy load route. For a given analysis segment of the route, enter the layer thicknesses, backcalculated layer moduli, and Poisson's ratios considered to be representative of the given segment. In addition, enter the FWD load and plate radius used in the deflection measurements. Representative K_2 and K_3 values for the pavement materials found within the segment to analyze are also needed to estimate K_1.

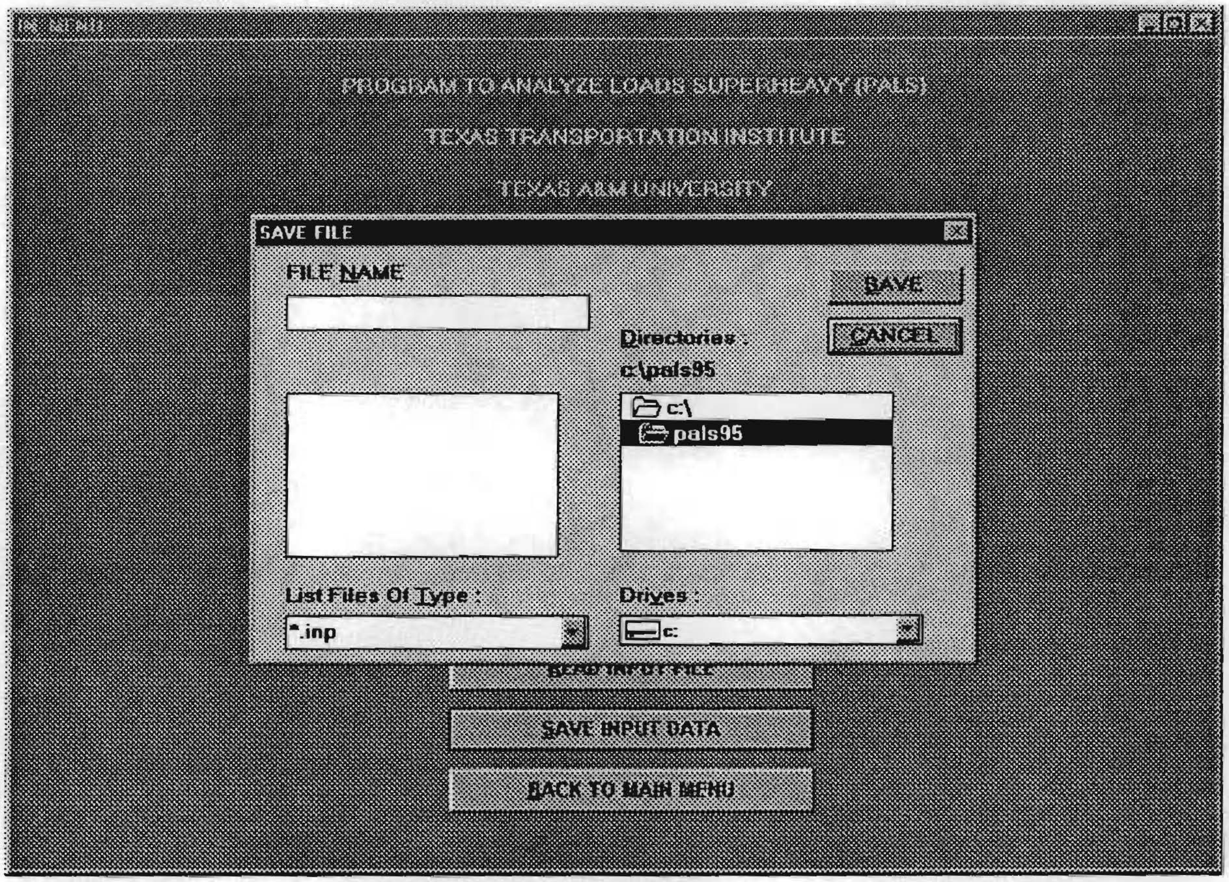
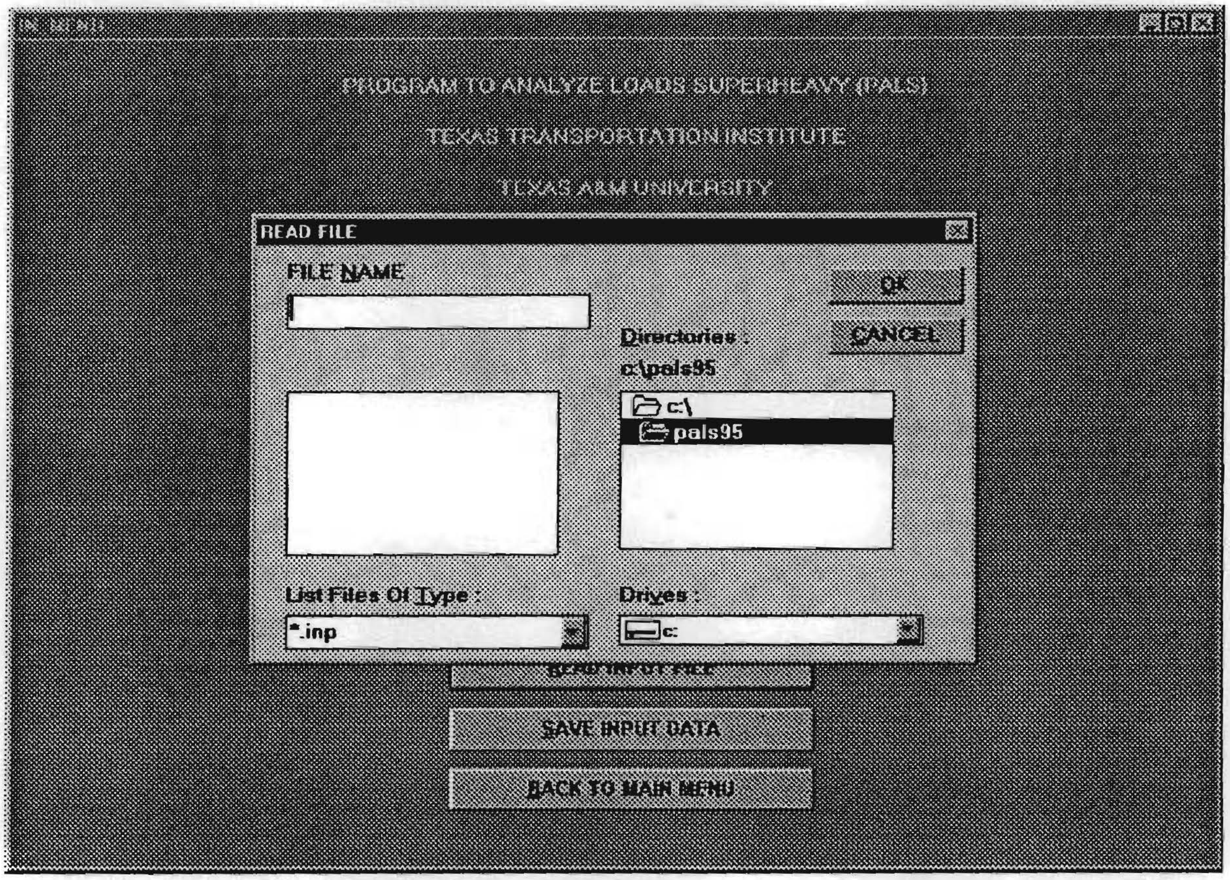


Figure 25. Menu to Save Input Data Into a Disk File.

When you have finished entering data for a particular pavement to analyze, you may save the data to a disk file by clicking on the ***Save Input Data*** option in the input menu. This will allow you to retrieve the data for later use. You will be prompted for the name of the file to save the data to. In the above menu, position the cursor in the ***File Name*** field, and type the name of the file to write the data to. You may also specify the drive and subdirectory in which the file will be saved. To specify the drive, click on the ***Drives*** field. You will then be shown a list of available drives. Choose one by clicking on it. To specify which subdirectory in the selected drive to save the file to, double-click on the drive letter in the ***Directories*** field. The list of subdirectories in the current drive is then displayed. Open a folder or subdirectory by double-clicking on its name. The input file will then be saved in this folder. Click on the ***Save*** button to save the input data to the specified file. The format of this file is documented in the appendix. If you changed your mind and decided against saving the input data, click on the ***Cancel*** button of the ***Save File*** window illustrated above. The input menu shown in Figure 10 is again displayed.



Directories : c:\pals95

c:\
pals95

List Files Of Type : *.inp

Drives : c:

Figure 26. Menu to Retrieve an Existing Input File.

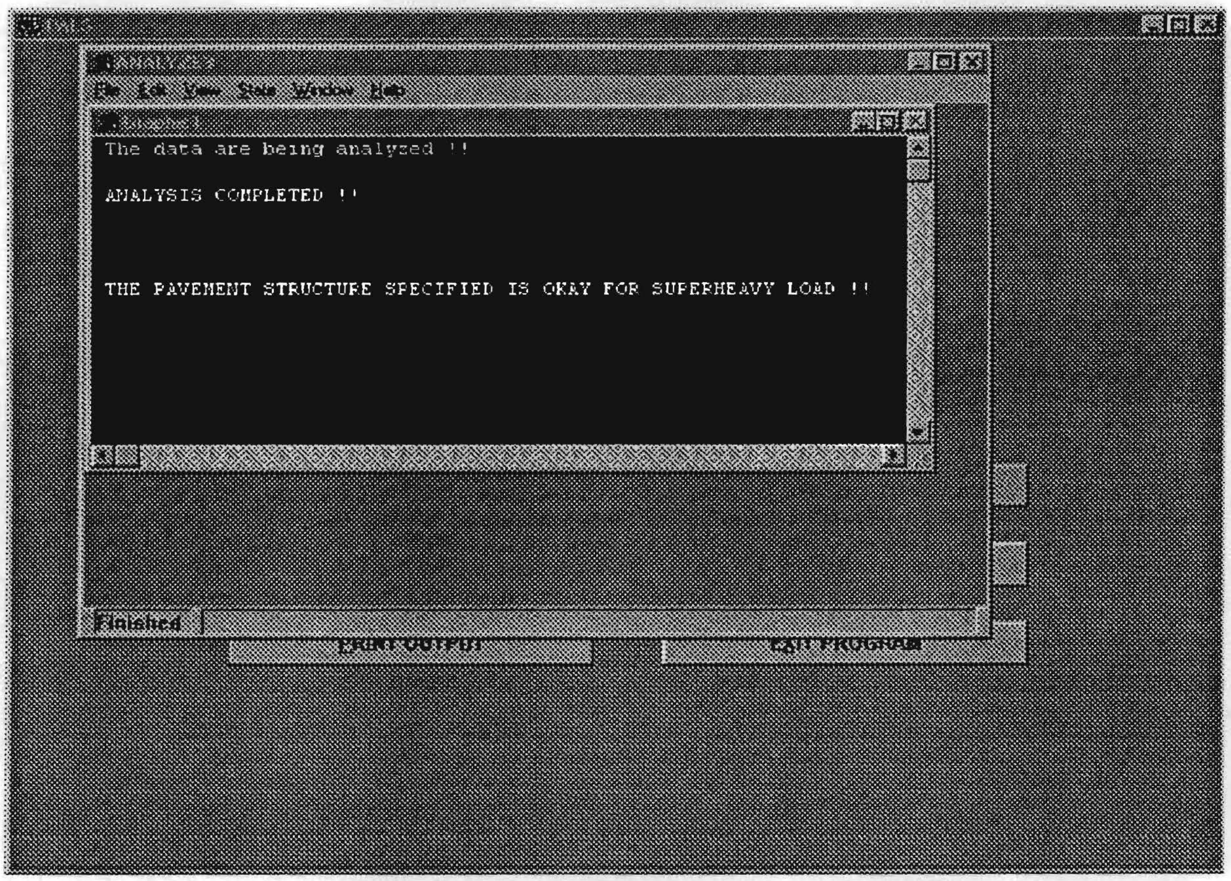
Input data previously saved to a disk file using the PALS program may be retrieved for subsequent modification and analysis using the ***Read Input File*** option of the input menu. If you click on this option, the ***Read File*** window illustrated above is displayed. Position the cursor in the ***File Name*** field, and type in the name of the file to retrieve. If this file resides in a different drive and/or subdirectory, change the current drive and/or subdirectory in the ***Read File*** window. Do this following the instructions given previously for saving input data. To retrieve the specified file, click on the ***OK*** button. Otherwise, you may click on ***Cancel*** in the ***Read File*** window to get back to the input menu shown in Figure 10.

CHAPTER III

USING THE ANALYSIS OPTIONS IN PALS

When you are done entering input data for a given pavement, you may conduct an evaluation using the analysis options in the PALS main menu (Figure 9). The option(s) to run depends on the particular problem at hand. To analyze a pavement where edge loading is not a concern, choose the ***Analyze Pavement*** option. There are many situations where this option is applicable. 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 may be necessary to evaluate the potential for edge shear failure. This can be accomplished using the ***Analyze Edge*** option in the PALS main menu.

The likelihood of pavement damage is evaluated based on the Mohr-Coulomb yield criterion. If this analysis predicts over stressing in one or more pavement layers under the superheavy load, measures must be taken to minimize or prevent this from occurring during the move. One effective method is through the use of laminated plywood mats. This option is applicable when the length of pavement to be protected spans a short distance. Another is through the use of additional axles to reduce the wheel loads to a magnitude that the given pavement can sustain without yielding. To identify alternative trailer configurations to reduce the wheel loads to a safe level, the ***Compute Failure Load*** option can be used. This option determines the wheel load at which yielding of the given pavement is predicted. Consideration may then be given to configuring the trailer so that individual wheel loads are less than the predicted load at yield. The menus associated with the analysis options are presented in the following.



```
The data are being analyzed !!

ANALYSIS COMPLETED !!


THE PAVEMENT STRUCTURE SPECIFIED IS OKAY FOR SUPERHEAVY LOAD !!
```

Figure 27. Screen Displayed After Running the Analyze Pavement Option.

To investigate a problem where edge loading is not a concern, choose the ***Analyze Pavement*** option in the PALS main menu (Figure 9). During program execution, messages are displayed in the output window illustrated above. When the analysis is complete, the program displays a message indicating whether the pavement analyzed can carry the superheavy load without developing some damage. The potential for pavement damage is evaluated using the Mohr-Coulomb yield criterion. For this analysis, the yield criterion is evaluated at a number of locations beneath the superheavy wheel loads as shown in Figure 28. If the predicted stress states at all evaluation points are within the corresponding Mohr-Coulomb failure envelopes of the pavement materials, the pavement is deemed adequate to carry the superheavy load without sustaining damage. Otherwise, if one or more points within the pavement are predicted to be at yield, pavement damage may occur.

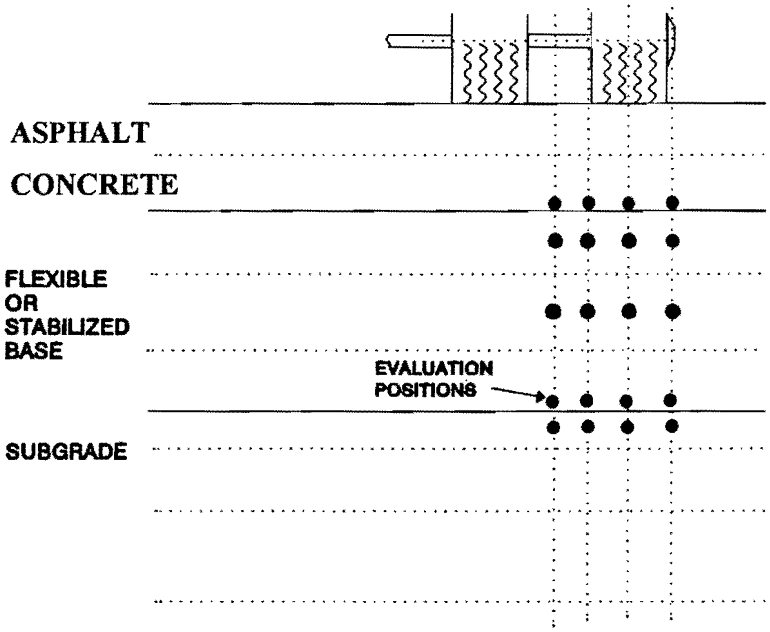
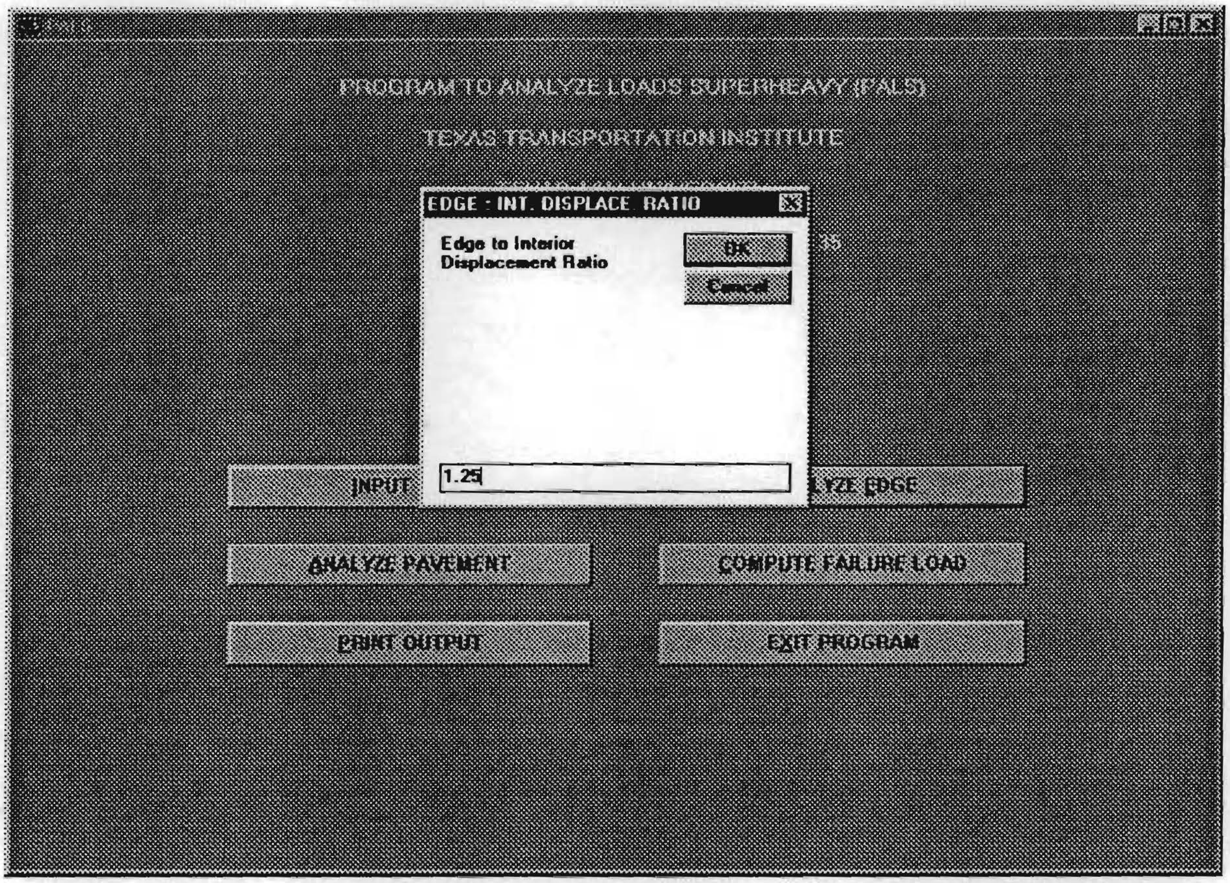


Figure 28. Locations Within Pavement Where Mohr-Coulomb Yield Function is Evaluated.



Edge to Interior Displacement Ratio
1.25

Figure 29. Specifying the Edge to Interior Displacement Ratio in the Analyze Edge Option.

If you click on the ***Analyze Edge*** option in the PALS main menu, you will be asked to specify an edge to interior displacement ratio, as illustrated in the above figure. This 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 30 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 beneath the travel lane are assumed to extend to the unpaved shoulder. Also, the layer thicknesses are unchanged.

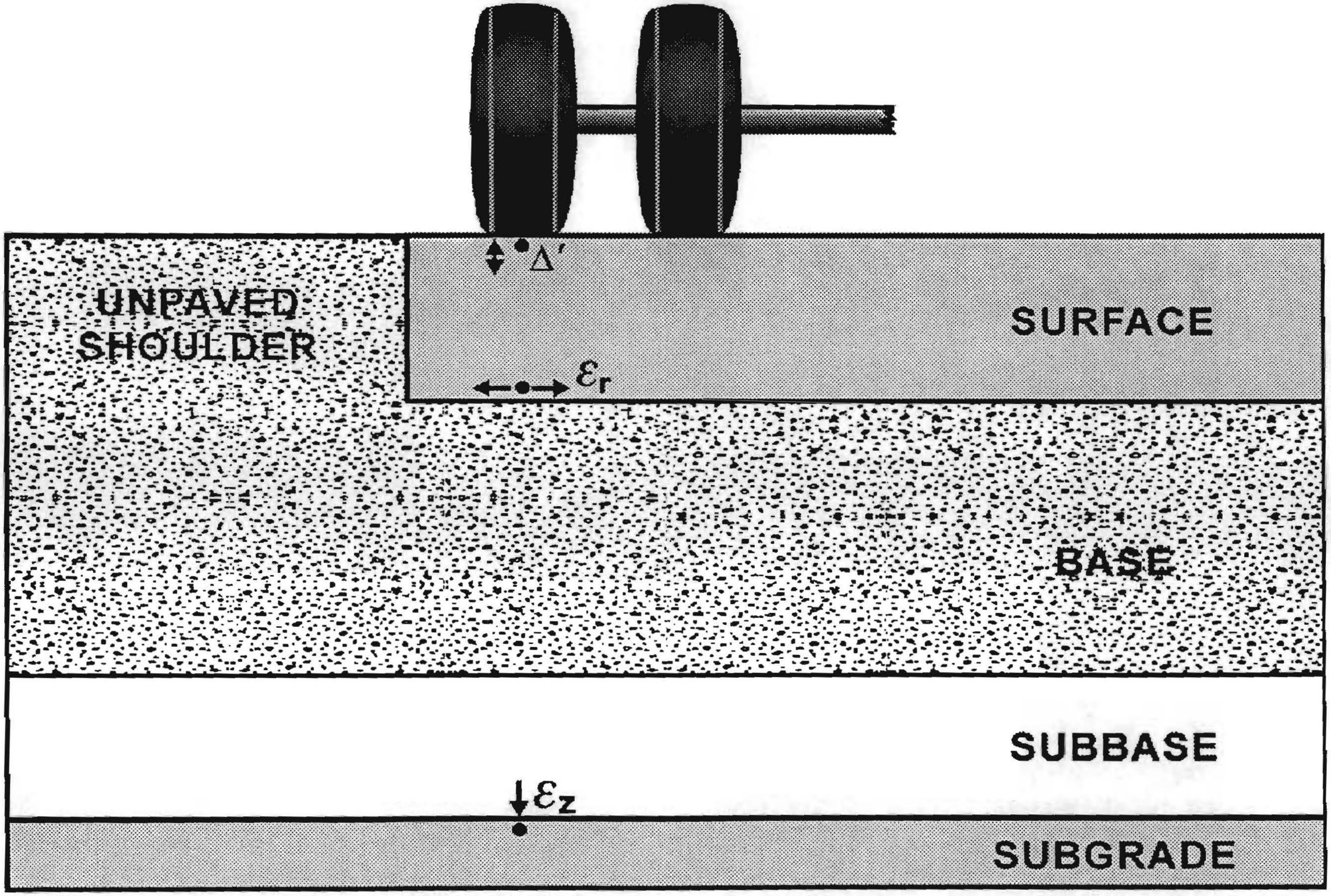
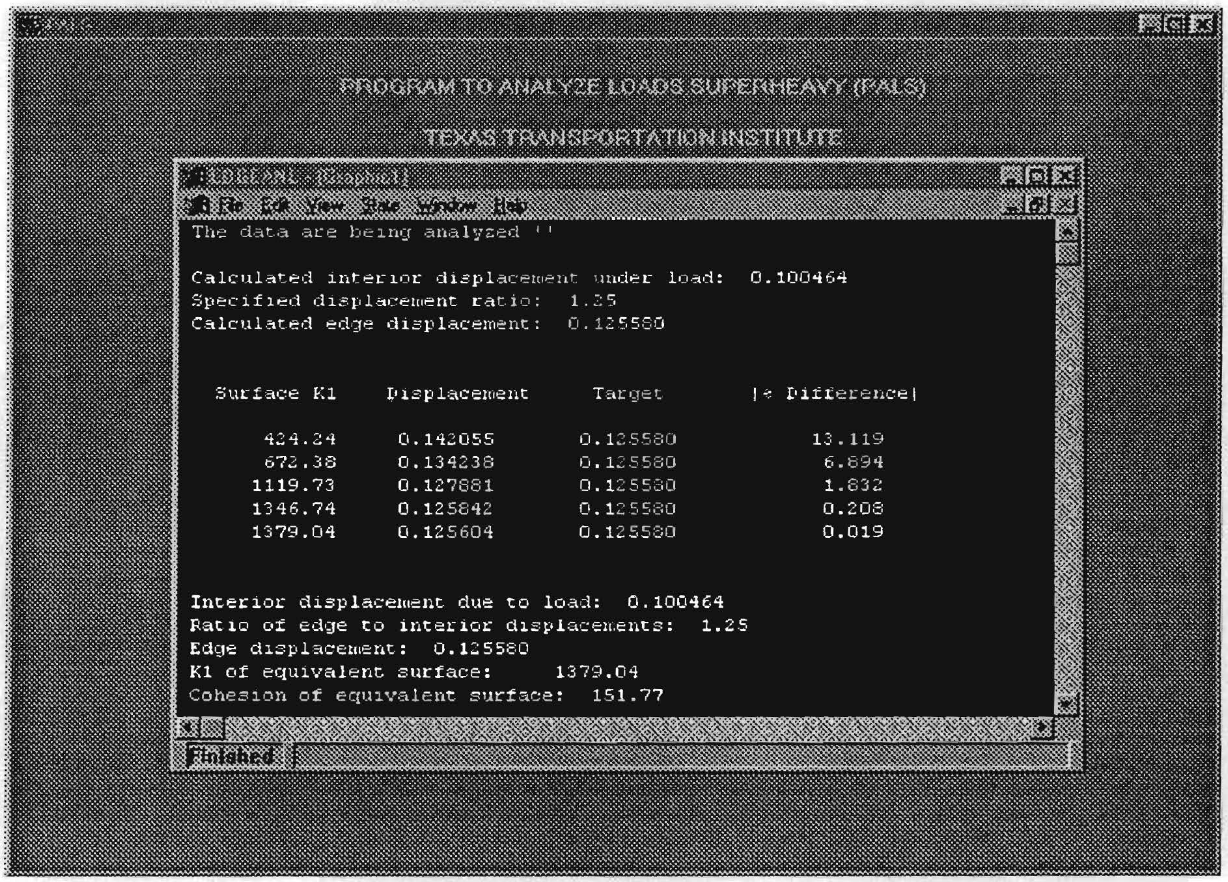


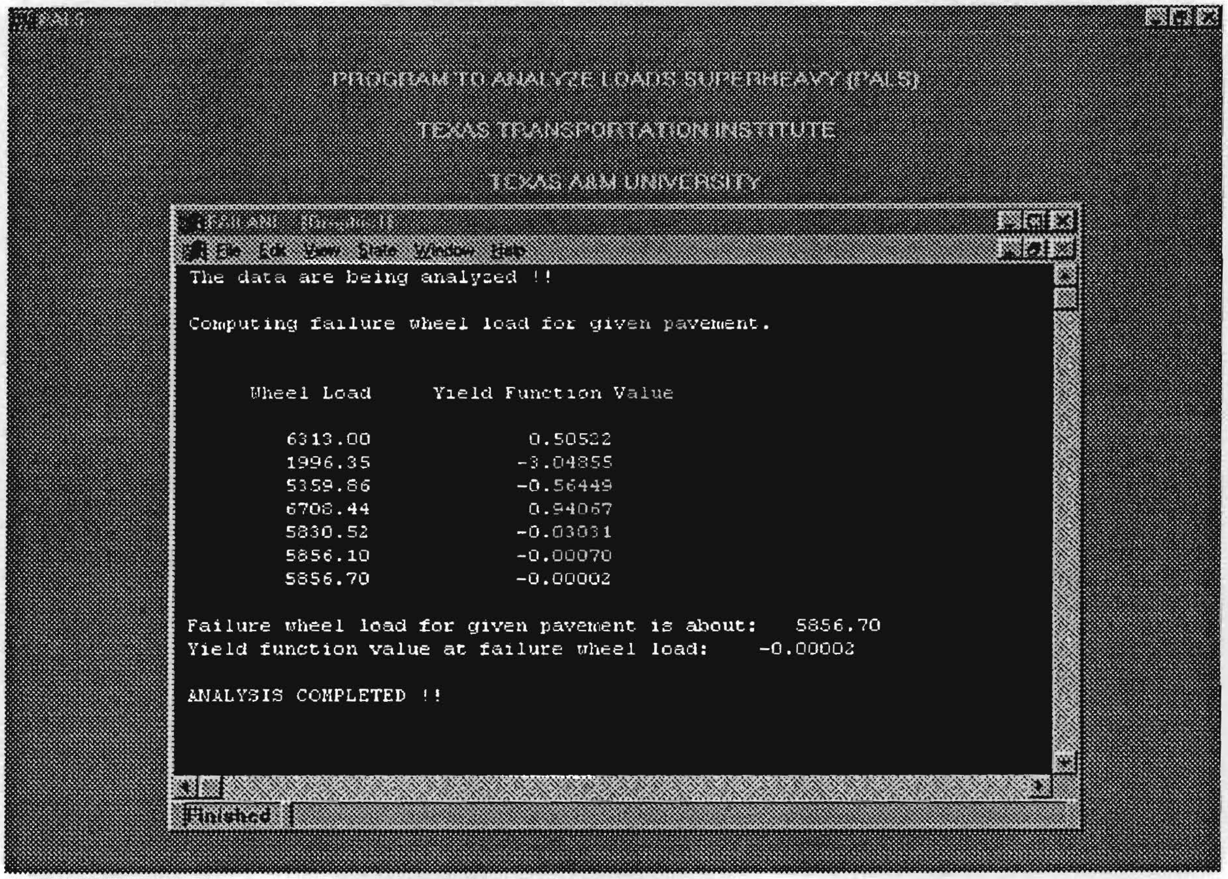
Figure 30. Illustration of Edge Load Condition.



```
The data are being analyzed ''

Calculated interior displacement under load:  0.100464
Specified displacement ratio:  1.25
Calculated edge displacement:  0.125580


  Surface K1     Displacement      Target        |% Difference|

      424.24      0.142055       0.125580            13.119
      672.38      0.134238       0.125580             6.894
     1119.73      0.127881       0.125580             1.832
     1346.74      0.125842       0.125580             0.208
     1379.04      0.125604       0.125580             0.019


Interior displacement due to load:  0.100464
Ratio of edge to interior displacements:  1.25
Edge displacement:  0.125580
K1 of equivalent surface:      1379.04
Cohesion of equivalent surface:  151.77
```

Figure 31. Determining an Equivalent Surface Layer for the Edge Load Analysis.

During execution of the edge load analysis, the program opens an output window (Figure 31), which displays the results from iterations made to determine an equivalent surface. This is done by adjusting the parameter, K_1, such that the predicted displacement is greater than the computed displacement for the original pavement by a factor equal to the specified displacement ratio. Iterations continue until the computed displacement under load matches the predicted edge displacement to within a prescribed tolerance. In addition, the cohesion of the surface is adjusted to reflect the change in K_1, assuming that cohesion is proportional to $\log(K_1)$. The response of this equivalent pavement is then evaluated to determine the potential for edge shear failure during the superheavy load move.



```
The data are being analyzed !!

Computing failure wheel load for given pavement.


     Wheel Load      Yield Function Value

        6313.00             0.50522
        1996.35            -3.04855
        5359.86            -0.56449
        6708.44             0.94067
        5830.52            -0.03031
        5856.10            -0.00070
        5856.70            -0.00002

Failure wheel load for given pavement is about:    5856.70
Yield function value at failure wheel load:    -0.00002

ANALYSIS COMPLETED !!
```

Figure 32. Evaluating the Failure Wheel Load.

If the pavement is predicted to experience yielding under the superheavy load, measures must be taken to reduce the induced stresses to allowable levels based on the strength of the materials that comprise the given pavement. One consideration is to modify the vehicle configuration by adding more axles, or another trailer unit to reduce the surface wheel loads. The ***Compute Failure Load*** option in the PALS main menu determines the wheel load at which yielding of the given pavement is predicted. This is done through an iterative scheme in which the wheel loads are varied until the computed yield function value is near zero. During execution, results of the iterations are displayed in an output window, illustrated in Figure 32. 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. If this is not a viable option, other measures must be considered to prevent pavement damage. One alternative is to use a different route. Another is to protect the weak areas using laminated plywood mats that are placed on top of the pavement surface. These are made up of layers of plywood that are nailed or screwed together to form a rigid unit. Figure 33 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 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.

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 34 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. Observe that the reduction in pavement deflections with matting is significant. Also, 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 35 and 36 show the development of residual strains with and without matting for the same pavement section. Observe 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.

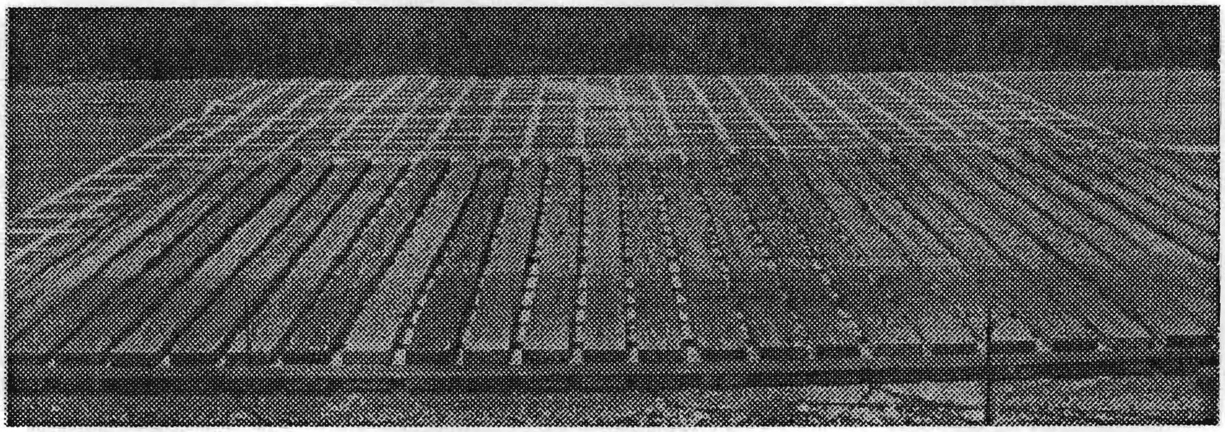


Figure 33. Laminated Plywood Mat.

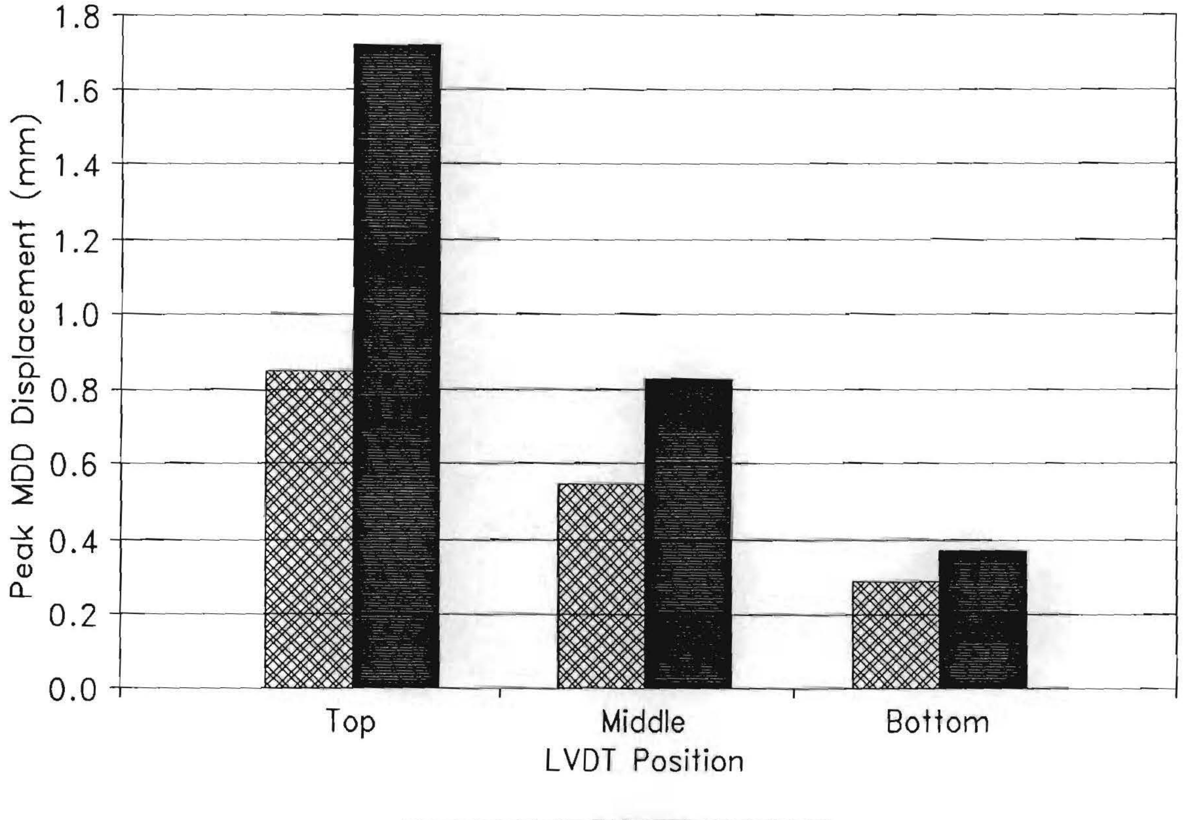


Figure 34. Peak MDD Displacements Measured With and Without Mat on a Test Section With a 254 mm Crushed Limestone Base Overlying Clay Subgrade.

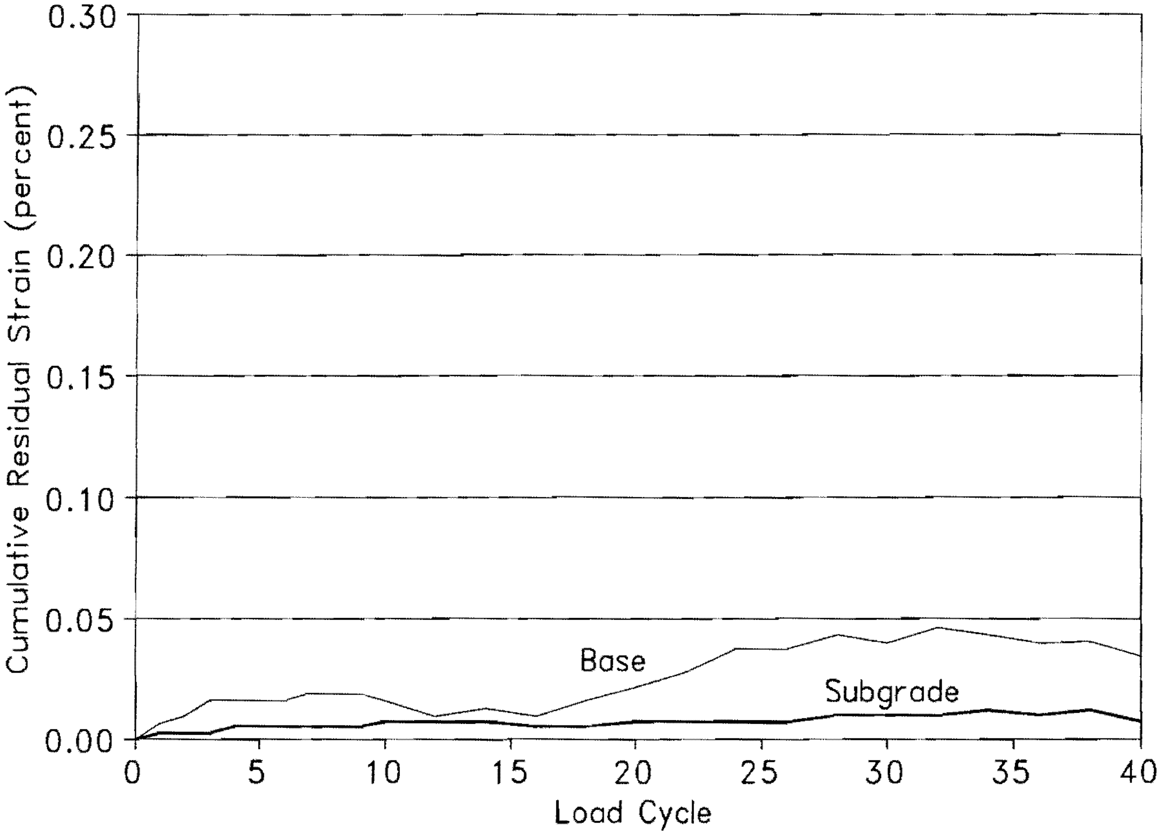


Figure 35. Development of Residual Compressive Strain With Repeated Load Applications Near Edge of Matted Test Section Having a 254 mm Crushed Limestone Base Overlying Clay Subgrade.

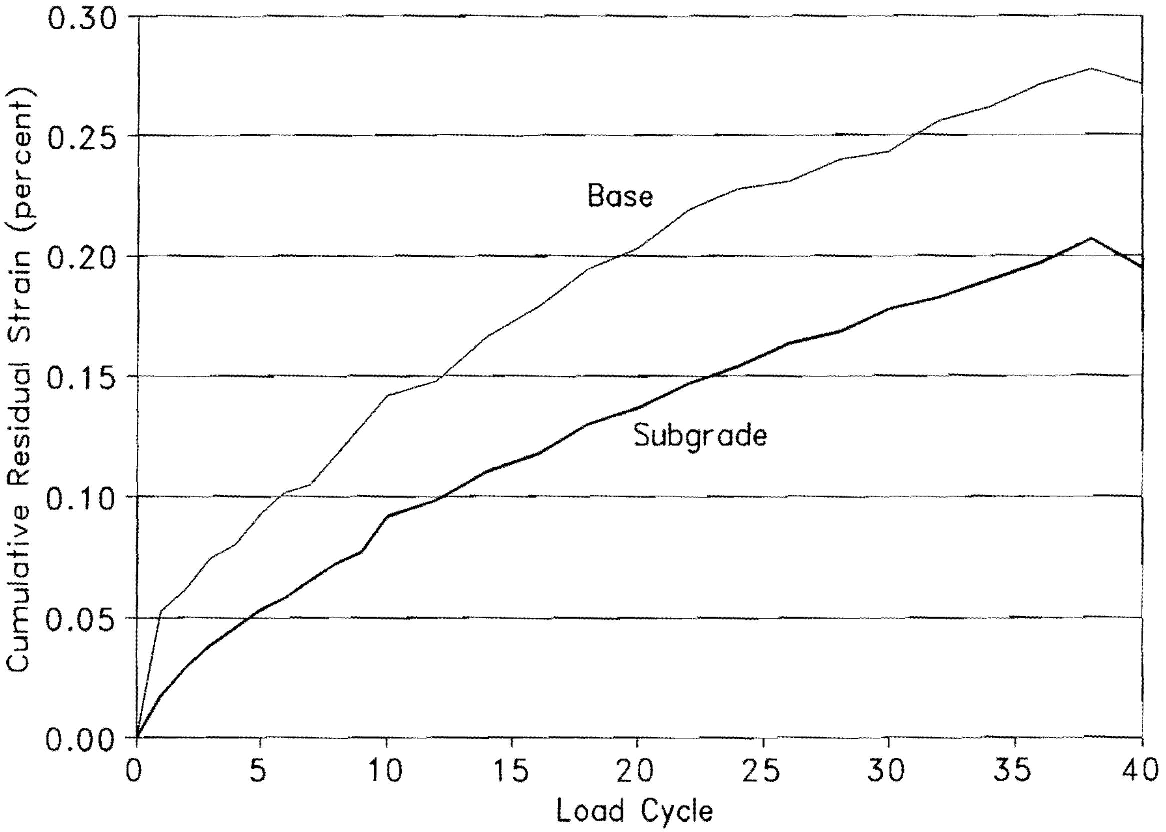


Figure 36. Development of Residual Compressive Strain With Repeated Load Applications Near Edge of Un-Matted Test Section Having a 254 mm Crushed Limestone Base Overlying Clay Subgrade.

CHAPTER IV

VIEWING PROGRAM OUTPUT IN PALS

After analyzing a given segment, you may view and/or print the results by selecting the ***Print Output*** option in the PALS main menu (Figure 9). After clicking on this option, the output menu shown in Figure 37 is displayed. You should first view the results on-screen using the ***View Output*** option. If you are satisfied with the results, you may then get a hard copy by clicking on ***Print Output*** in the menu. Additionally, you may save the results to a disk file using the ***Save Output*** option.

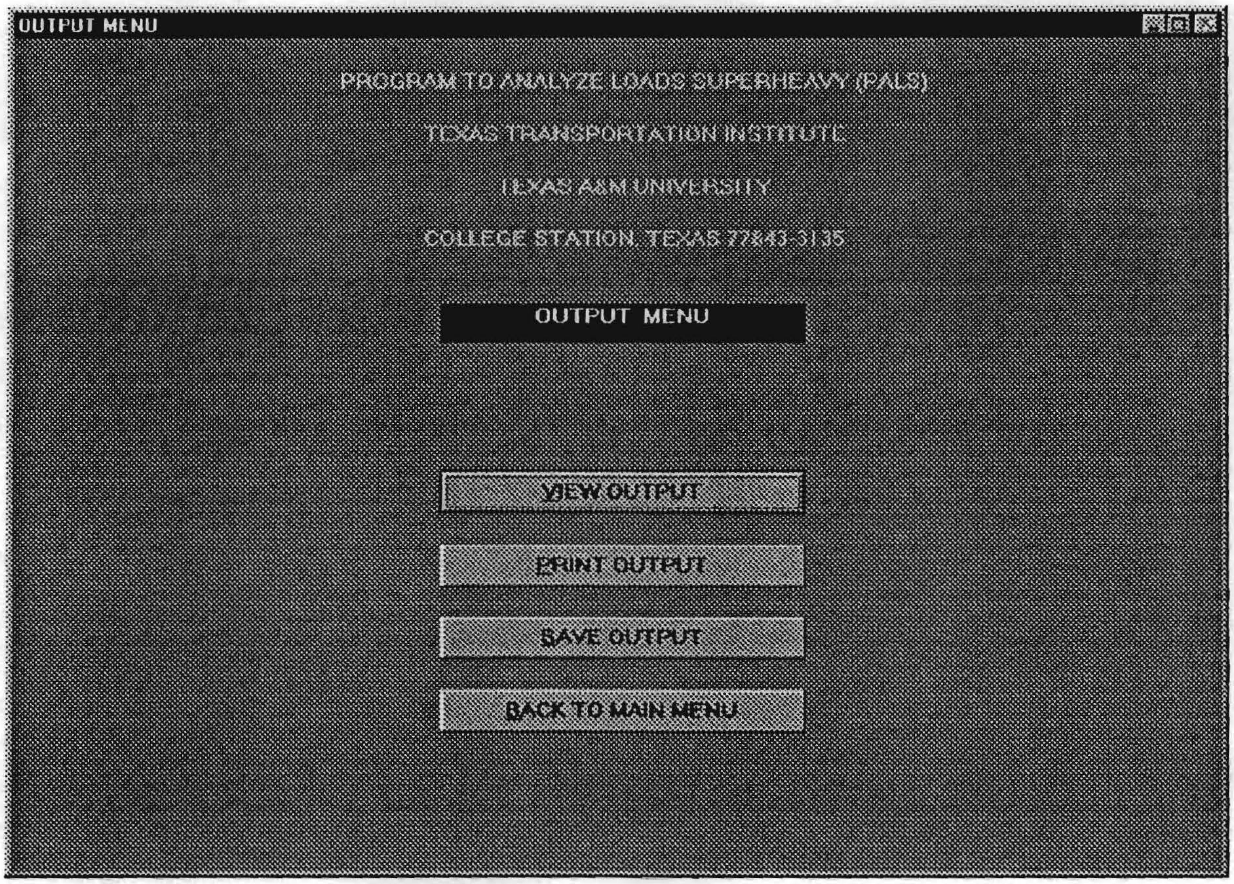
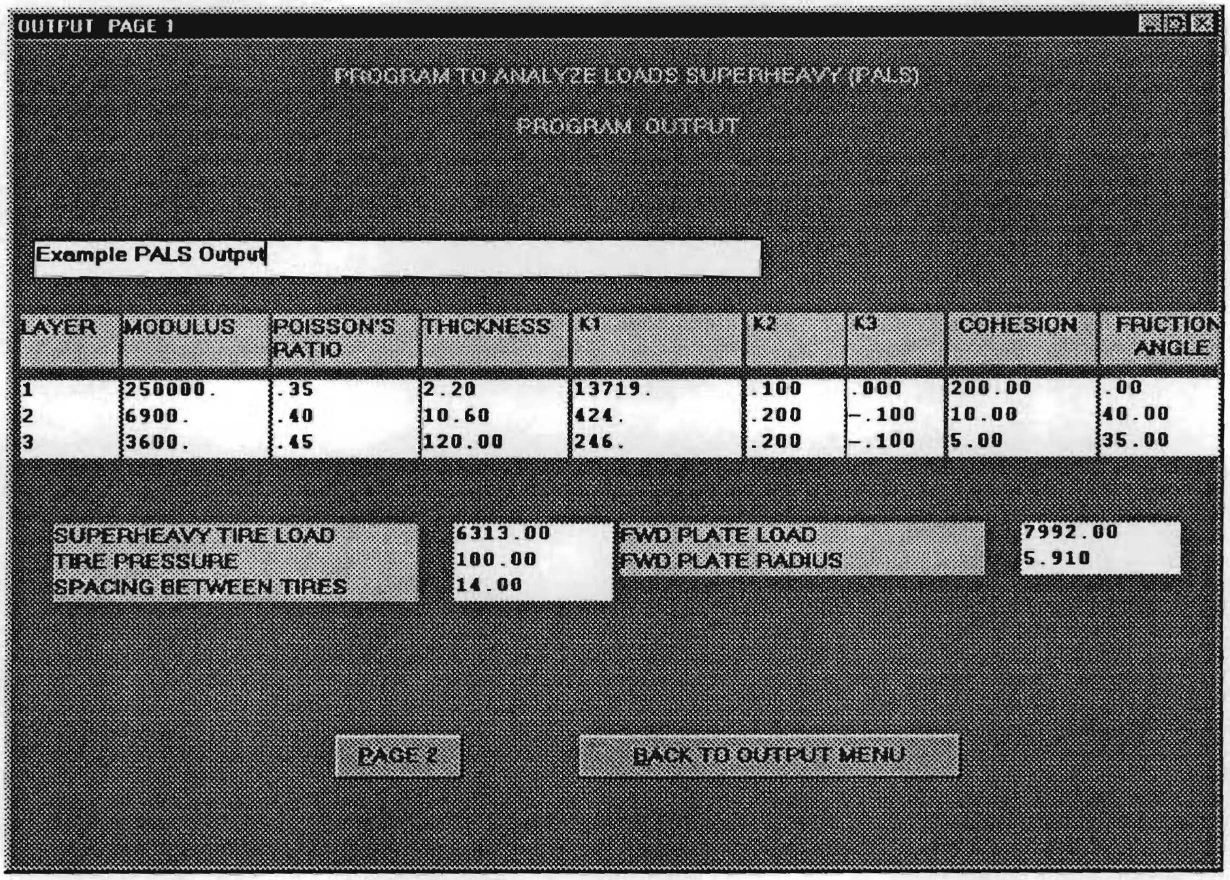


Figure 37. Output Menu of PALS Program.



Example PALS Output

LAYER	MODULUS	POISSON'S RATIO	THICKNESS	K1	K2	K3	COHESION	FRICTION ANGLE
1	250000.	.35	2.20	13719.	.100	.000	200.00	.00
2	6900.	.40	10.60	424.	.200	–.100	10.00	40.00
3	3600.	.45	120.00	246.	.200	–.100	5.00	35.00

SUPERHEAVY TIRE LOAD	6313.00	FWD PLATE LOAD	7992.00
TIRE PRESSURE	100.00	FWD PLATE RADIUS	5.910
SPACING BETWEEN TIRES	14.00		

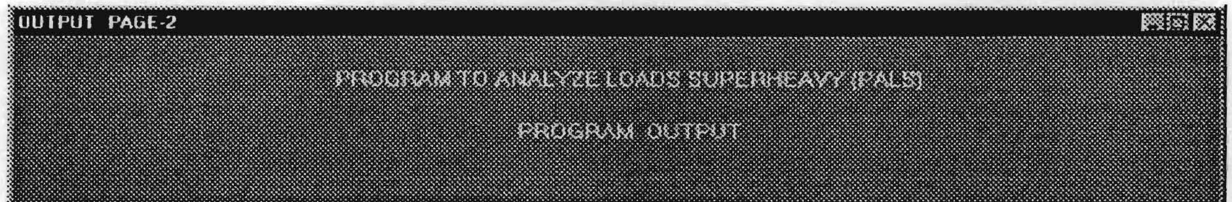
Figure 38. View Output Screen #1.

When you select the ***View Output*** option, the above screen is initially displayed. The first output line on this screen allows you to enter header information appropriate for the given run. In Figure 38, the header, *Example PALS Output*, has been entered in the first output line. When the screen is first displayed, the cursor is positioned at the first output line. You may then type information to identify the given run, followed by a *<CR>*. Input data for the given run are then displayed that include:

1. The modulus and Poisson's ratio of each pavement layer above the rigid bottom. If these material parameters are assumed to be stress-dependent, the quantities displayed are the starting values for determining the stress-compatible modulus and Poisson's ratio. If the modulus and Poisson's ratio are assumed to be independent of stress, the corresponding K_2 and K_3 values for the layer are zero. In this case, the modulus equals the product of the parameter, K_1, and the atmospheric pressure, *Atm*.
2. The nonlinear, stress-dependent parameters, K_1, K_2, and K_3.

3. The Mohr-Coulomb strength parameters for each pavement layer.
4. The superheavy tire load, tire pressure, and tire spacing.
5. The FWD load and plate radius if FWD data were used to estimate K_1 for each pavement layer.

Note that the output displayed are the results from the most recent analysis made. If this was to evaluate the potential for edge shear failure, the output page displays the cohesion and K_1 values for the equivalent surface in lieu of the original surface. To view the next screen of output, click on ***Page 2*** at the bottom of the page. The screen shown in Figure 39 is then displayed. This output screen displays soil test data used to estimate the Mohr-Coulomb strength parameters, and the K_1, K_2, and K_3 stress-dependent material parameters. If soil test data were not used to estimate these variables, each field will show the value assigned to missing data, e.g., -99 as illustrated in Figure 39.



Example PALS Output

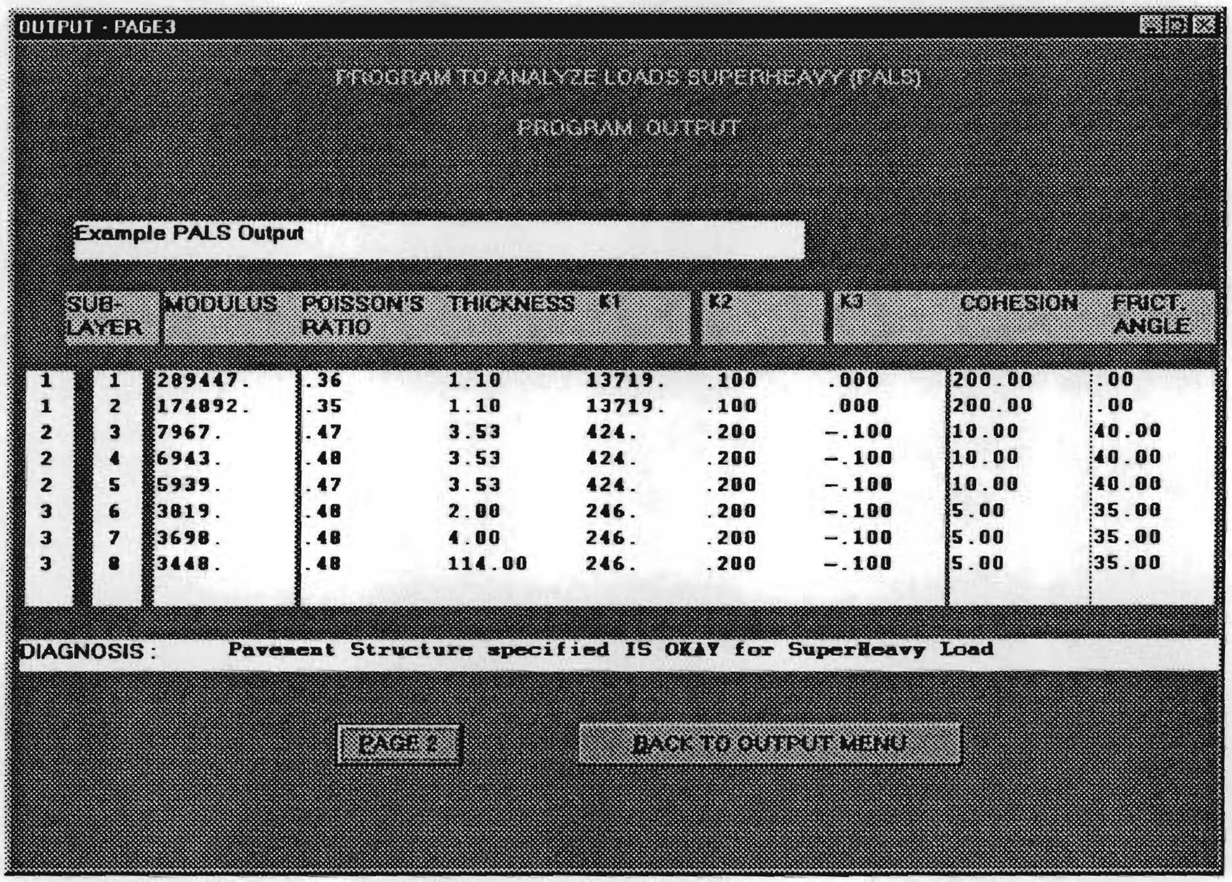
	SOIL PROPERTY	LAYER 1	LAYER 2	LAYER 3
1.	PLASTICITY INDEX	-99.000	-99.000	-99.000
2.	POROSITY (In Percent)	-99.000	-99.000	-99.000
3.	SOIL SUCTION (pF)	-99.000	-99.000	-99.000
4.	SPECIFIC GRAVITY OF SOIL BINDER	-99.000	-99.000	-99.000
5.	PERCENT PASSING No. 40 SIEVE SIZE	-99.000	-99.000	-99.000
6.	PLASTIC LIMIT	-99.000	-99.000	-99.000
7.	SPECIFIC GRAVITY	-99.000	-99.000	-99.000
8.	VOLUMETRIC WATER CONTENT (%)	-99.000	-99.000	-99.000
9.	GRAVIMETRIC MOISTURE CONTENT (%)	-99.000	-99.000	-99.000
10.	DIELECTRIC CONSTANT	-99.000	-99.000	-99.000
11.	LIQUID LIMIT	-99.000	-99.000	-99.000

Figure 39. View Output Screen #2.

To view another page of output, click on ***Page 1*** or ***Page 3*** at the bottom of the screen. Clicking on ***Page 3*** displays the next page illustrated in Figure 40. This output screen shows how the pavement was subdivided to model the stress-dependency of the different pavement layers. The stress-compatible modulus and Poisson's ratio of each sublayer are shown. A limit of 0.48 is imposed on the Poisson's ratio based on research conducted by Jooste and Fernando (1995). This means that the procedure models the stress-dependency of the Poisson's ratio, but only for values equal to or less than 0.48. When the stress-dependent Poisson's ratio is calculated to be above 0.48, the value is set at 0.48. In addition, the output screen displays the thickness of each sublayer, the K_1, K_2, and K_3 parameters, and the cohesion and friction angles used in the analysis of the given segment of the proposed superheavy load route. Note that the cohesion and friction angle for the surface layer are adjusted if an edge analysis was conducted.

A message is also displayed regarding the structural adequacy of the pavement to carry the superheavy load without developing damage. If the possibility of damage is predicted, a message is displayed which shows the sublayer where the critical yield function was evaluated. To leave this page, click on one of the two options below the page. Clicking on ***Back to Output Menu*** allows you to print and/or save the results. To print the results of the last analysis, simply click on ***Print Output*** in the menu. Figure 41 shows a sample printout from the computer program.

To save the output from PALS, click on the third option of the output menu illustrated in Figure 37. The Save Output window in Figure 42 will be displayed. Click on the ***File Name*** field, and type the name of the file to write the data to. You may also specify the drive and subdirectory where the output file will be saved.



PROGRAM TO ANALYZE LOADS SUPERHEAVY (PALS)

PROGRAM OUTPUT

Example PALS Output

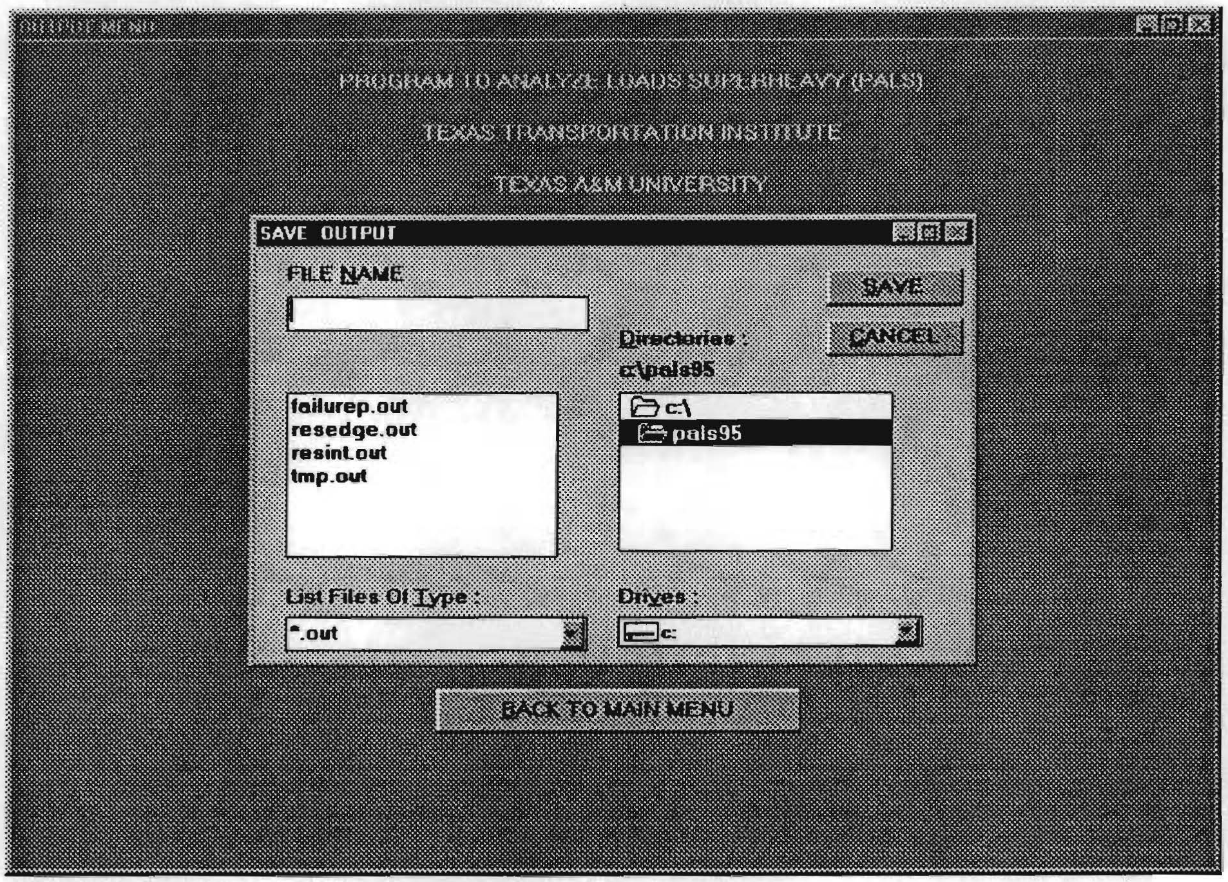
	SUB-LAYER	MODULUS	POISSON'S RATIO	THICKNESS	K1	K2	K3	COHESION	FRICT. ANGLE
1	1	289447.	.36	1.10	13719.	.100	.000	200.00	.00
1	2	174892.	.35	1.10	13719.	.100	.000	200.00	.00
2	3	7967.	.47	3.53	424.	.200	-.100	10.00	40.00
2	4	6943.	.48	3.53	424.	.200	-.100	10.00	40.00
2	5	5939.	.47	3.53	424.	.200	-.100	10.00	40.00
3	6	3819.	.48	2.00	246.	.200	-.100	5.00	35.00
3	7	3698.	.48	4.00	246.	.200	-.100	5.00	35.00
3	8	3448.	.48	114.00	246.	.200	-.100	5.00	35.00

DIAGNOSIS : Pavement Structure specified IS OKAY for SuperHeavy Load

Figure 40. View Output Screen #3.

```
                     Program to Analyze Loads Superheavy (PALS)
                                  Program Output

  Example PALS Output

   Layer  Modulus  Poisson's  Thick.    K1       K2       K3     Cohesion Frict.
                     Ratio                                                 Angle


     1    250000.     .35      2.20    13719.    .100     .000  200.00      .00
     2      6900.     .40     10.60      424.    .200    -.100   10.00    40.00
     3      3600.     .45    120.00      246.    .200    -.100    5.00    35.00

   Superheavy Tire Load ......... 6313.00   FWD Plate Load ........ 7992.00
   Tire Pressure .................. 100.00   FWD Plate Radius ........ 5.910
   Spacing Between Tires .......... 14.00


         Soil Property                        Layer 1  Layer 2  Layer 3  Layer 4

     1.  Plasticity index                     -99.000  -99.000  -99.000  -99.000
     2.  Porosity (in percent)                -99.000  -99.000  -99.000  -99.000
     3.  Suction (pF)                         -99.000  -99.000  -99.000  -99.000
     4.  Specific gravity of soil binder      -99.000  -99.000  -99.000  -99.000
     5.  Percent passing No. 40 sieve         -99.000  -99.000  -99.000  -99.000
     6.  Plastic limit                        -99.000  -99.000  -99.000  -99.000
     7.  Specific gravity of aggregate        -99.000  -99.000  -99.000  -99.000
     8.  Volumetric water content (%)         -99.000  -99.000  -99.000  -99.000
     9.  Gravimetric water content (%)        -99.000  -99.000  -99.000  -99.000
    10.  Dielectric constant                  -99.000  -99.000  -99.000  -99.000
    11.  Liquid limit                         -99.000  -99.000  -99.000  -99.000


    Sub-  Modulus  Poisson's  Thick.    K1       K2       K3     Cohesion Frict.
   layer             Ratio                                                 Angle

  1  1    289447.     .36      1.10    13719.    .100     .000  200.00      .00
  1  2    174892.     .35      1.10    13719.    .100     .000  200.00      .00
  2  3      7967.     .47      3.53      424.    .200    -.100   10.00    40.00
  2  4      6943.     .48      3.53      424.    .200    -.100   10.00    40.00
  2  5      5939.     .47      3.53      424.    .200    -.100   10.00    40.00
  3  6      3819.     .48      2.00      246.    .200    -.100    5.00    35.00
  3  7      3698.     .48      4.00      246.    .200    -.100    5.00    35.00
  3  8      3448.     .48    114.00      246.    .200    -.100    5.00    35.00

  DIAGNOSIS:  Pavement structure specified is OKAY for superheavy load.
```

Figure 41. Example Printout From PALS Program.



Directories : c:\pals95

c:\
pals95

failurep.out
resedge.out
resint.out
tmp.out

List Files Of Type : *.out

Drives : c:

Figure 42. Menu to Save Output From PALS Program.

COMPUTED YIELD FUNCTION VALUES

As discussed in Chapter III, the potential for pavement damage is based on evaluating the onset of yielding at the locations shown in Figure 28. At each location, the induced stresses under loading are predicted, and a determination is made on whether or not yielding of the material is expected under the given stress state. This determination is based on the Mohr-Coulomb yield function (Chen and Baladi, 1985):

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

where,

I_1 = first stress invariant

J_2 = second deviatoric stress invariant

c = cohesion

ϕ = friction angle

θ = Lode angle

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 is calculated from the equation:

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

where, J_3, is the third deviatoric stress invariant. From mechanics, the onset of yield or inelastic deformation is predicted when the value of the yield function is zero. When this condition is plotted for the Mohr-Coulomb yield function, the yield surface illustrated in Figure 43 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 28, 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 computed yield function values are written in program work files generated from a given analysis. These work files are in ASCII or text format and can be viewed with any editor or word processor. If you would like to know the yield function values, open the work file from a given analysis. For the ***Analyze Pavement*** option, the file is called, **RESINT.OUT**. For the ***Analyze Edge*** option, it is called, **RESEDGE.OUT**.

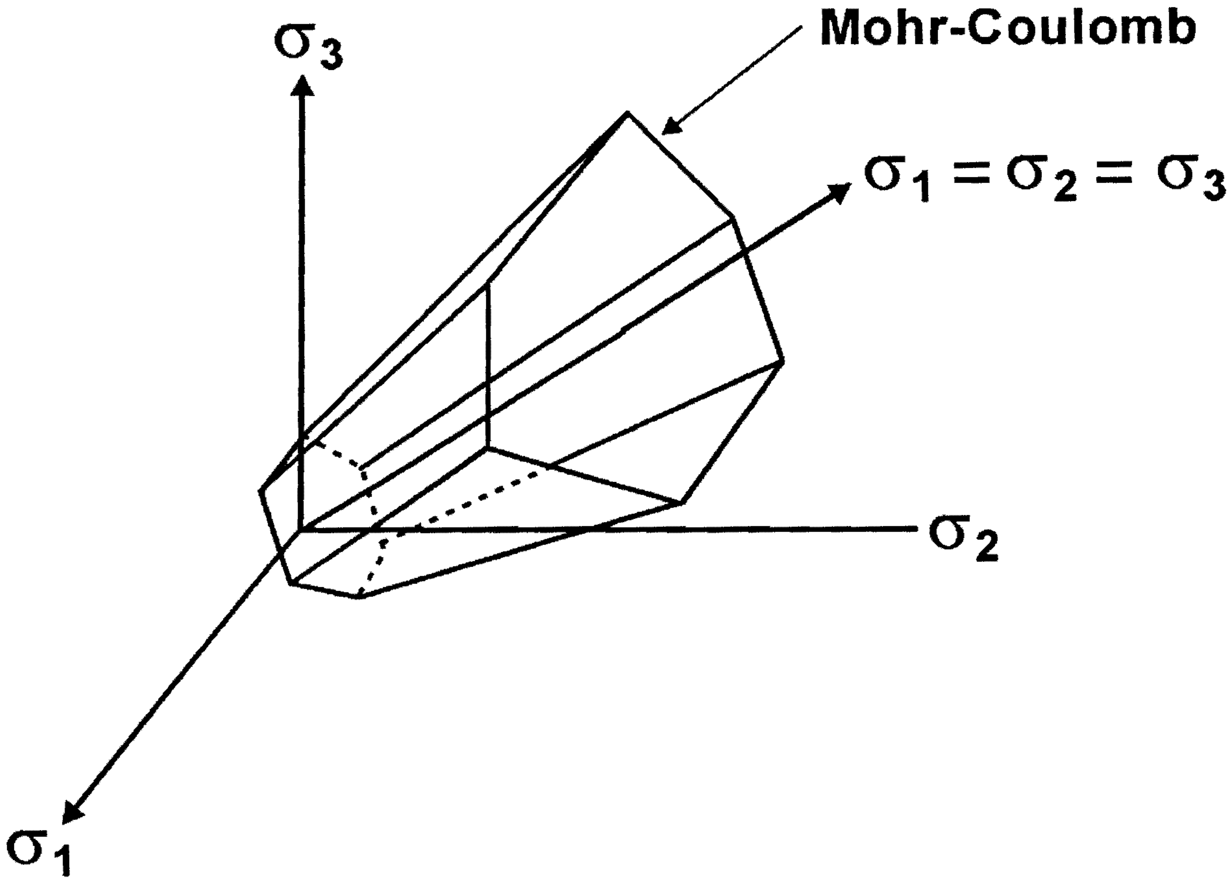
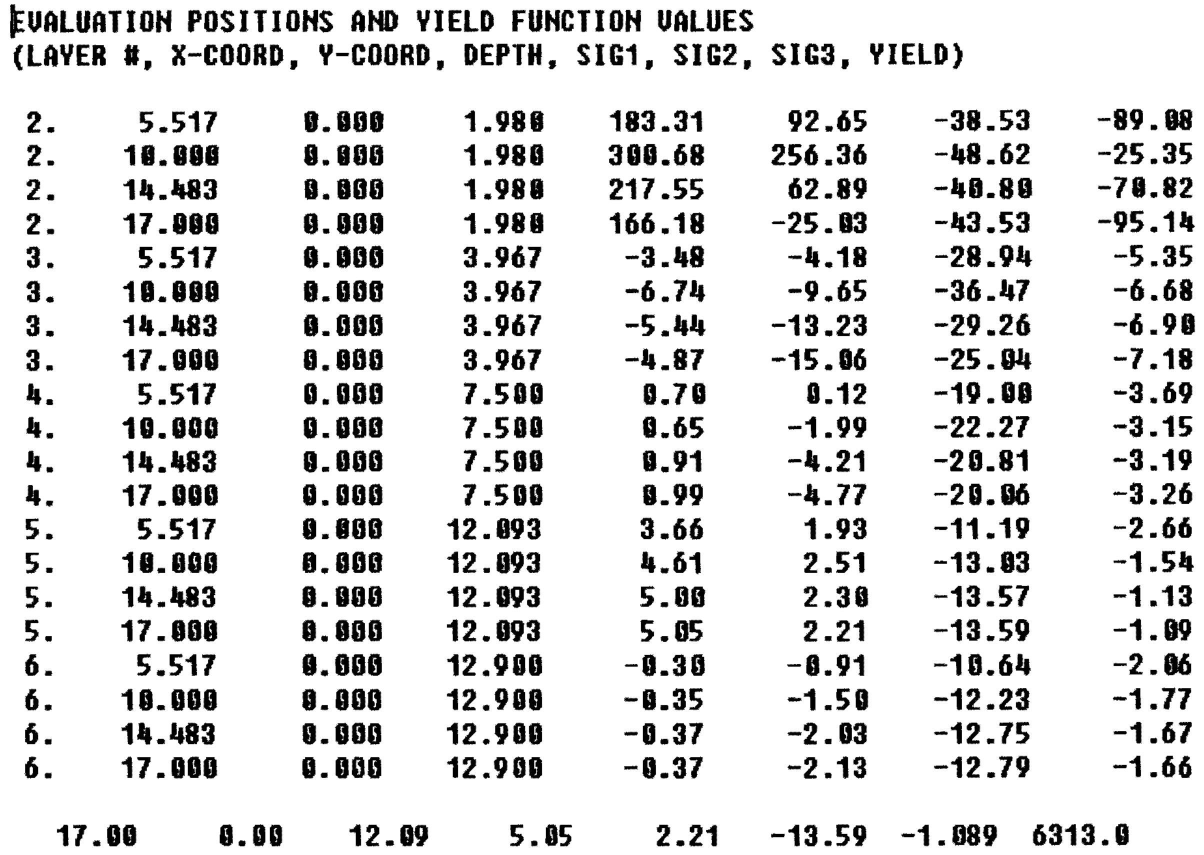


Figure 43. Graphical Illustration of Mohr-Coulomb Yield Criterion.

You may open these files when you exit the PALS program. Figure 44 shows the computed yield function values from a given analysis. When you open a particular file, search for the string, *YIELD,* using your editor or word processor. This brings into view the line with the header, *EVALUATION POSITIONS AND YIELD FUNCTION VALUES*, followed by another line with the header, *(LAYER #, X-COORD, Y-COORD, DEPTH, SIG1, SIG2, SIG3, YIELD)*. Scroll past this second line to see the yield function values calculated at various locations within the pavement. As may be inferred from the second header, the following information are presented for each evaluation point: 1) the sublayer where the given point is found; 2) the *x*, *y*, and *z* coordinates of the evaluation point; 3) the principal stresses predicted at the given point; and 4) the computed yield function value. Immediately following the last evaluation point, the location with the highest yield function value is identified. In the example given in Figure 44, this location has a computed yield function of -1.089.



```
EVALUATION POSITIONS AND YIELD FUNCTION VALUES
(LAYER #, X-COORD, Y-COORD, DEPTH, SIG1, SIG2, SIG3, YIELD)

 2.      5.517     0.000     1.980    183.31     92.65    -38.53    -89.08
 2.     10.000     0.000     1.980    300.68    256.36    -48.62    -25.35
 2.     14.483     0.000     1.980    217.55     62.89    -40.80    -70.82
 2.     17.000     0.000     1.980    166.18    -25.03    -43.53    -95.14
 3.      5.517     0.000     3.967     -3.48     -4.18    -28.94     -5.35
 3.     10.000     0.000     3.967     -6.74     -9.65    -36.47     -6.68
 3.     14.483     0.000     3.967     -5.44    -13.23    -29.26     -6.90
 3.     17.000     0.000     3.967     -4.87    -15.06    -25.04     -7.18
 4.      5.517     0.000     7.500      0.70      0.12    -19.00     -3.69
 4.     10.000     0.000     7.500      0.65     -1.99    -22.27     -3.15
 4.     14.483     0.000     7.500      0.91     -4.21    -20.81     -3.19
 4.     17.000     0.000     7.500      0.99     -4.77    -20.06     -3.26
 5.      5.517     0.000    12.093      3.66      1.93    -11.19     -2.66
 5.     10.000     0.000    12.093      4.61      2.51    -13.03     -1.54
 5.     14.483     0.000    12.093      5.00      2.30    -13.57     -1.13
 5.     17.000     0.000    12.093      5.05      2.21    -13.59     -1.09
 6.      5.517     0.000    12.900     -0.30     -0.91    -10.64     -2.06
 6.     10.000     0.000    12.900     -0.35     -1.50    -12.23     -1.77
 6.     14.483     0.000    12.900     -0.37     -2.03    -12.75     -1.67
 6.     17.000     0.000    12.900     -0.37     -2.13    -12.79     -1.66

   17.00      0.00     12.09      5.05      2.21    -13.59  -1.089  6313.0
```

Figure 44. Computed Yield Function Values From PALS.

When an analysis indicates that the pavement is weak for the superheavy load, it is good to view the work file associated with the analysis to identify the points within the pavement where yielding is predicted. The more points predicted to be at yield, the greater the potential for pavement damage from the superheavy load move. Alternatively, there may only be one location where yielding is predicted. In this case, check the value of the yield function. If this value is at zero or close to zero, a small change in the input parameters may swing the yield function the other way, i.e., toward the negative side. Consequently, the effect of inaccuracies in the input data will be more pronounced when the computed yield function value is zero or just slightly above zero. In this case, it is advisable to re-assess the input parameters, particularly those which have a significant influence on the Mohr-Coulomb yield function. Based on the study by Jooste and Fernando (1995) and on field experience, these are the layer thickness, cohesion, and the K_1 value of a given material. After re-evaluating the input data, re-run the analysis of the given pavement as appropriate.

REFERENCES

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2. Chen, Dar-Hao, E. G. Fernando, and M. Murphy. *Application of Falling Weight Deflectometer Data for Analysis of Superheavy Loads.* Transportation Research Record 1540, Transportation Research Board, Washington, D. C., 1996, pp. 83 - 90.

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5. Glover, L. T. and E. G. Fernando. *Evaluation of Pavement Base and Subgrade Material Properties and Test Procedures.* Research Report 1335-2, Texas Transportation Institute, Texas A&M University, College Station, TX., 1995.

6. Jooste, F. J. and E. G. Fernando. *Development of a Procedure for the Structural Evaluation of Superheavy Load Routes.* Research Report 1335-3F, Texas Transportation Institute, Texas A&M University, College Station, TX., 1995.

7. Uzan, J. *Granular Material Characterization.* Transportation Research Record 1022, Transportation Research Board, Washington, D. C., 1985, pp. 52 - 59.

APPENDIX

FORMAT OF PALS INPUT FILE

RECORD 1

NUMLAY - number of layers or material types above the rigid bottom. This variable ranges from 1 to 4.

NEXT (NUMLAY + 1) x 8 RECORDS

For each pavement layer (including the rigid bottom), the following data are written, one record per item:

1. Layer modulus
2. Poisson's ratio
3. Layer thickness
4. Nonlinear, stress-dependent parameter, K_1
5. Nonlinear, stress-dependent parameter, K_2
6. Nonlinear, stress-dependent parameter, K_3
7. Cohesion
8. Friction angle

NEXT RECORD

After the material properties and thicknesses of the pavement layers are specified, the FWD load and plate radius for determining K_1 are written on the next record if the option to backcalculate K_1 from FWD data is used. Otherwise, a zero is written for each variable indicating that the option was not used. The data are written in free-format, with a comma separating the input variables.

NEXT RECORD

The superheavy wheel load, tire pressure, and wheel spacing are written in free-format with a comma separating each entry.

NEXT (NUMLAY + 1) x 11 RECORDS

For each layer, the following soil test data are written to the file, one record per item. If no soil test data were specified, zeros are written.

1. Plasticity Index
2. Porosity (percent)
3. Soil suction (pF)
4. Specific gravity of soil binder
5. Percent passing the #40 sieve size
6. Plastic Limit
7. Bulk specific gravity
8. Volumetric water content (percent)
9. Gravimetric moisture content (percent)
10. Relative dielectric constant
11. Liquid Limit