Strategic Highway Research Program Falling Weight Deflectometer Quality Assurance Software

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Nondestructive deflection testing using falling weight deflectometers (FWDs) is one element of the monitoring effort currently under way by the Strategic Highway Research Program (SHRP) for the Long-Term Pavement Performance (LTPP) study. Because accurate data are key to the success of the LTPP study, SHRP has implemented a number of measures to ensure the quality of deflection data. They include equipment comparison and calibration, standardized field testing procedures and field data checks, and quality assurance software. SHRP FWD quality assurance software is the focus—specifically the FWDSCAN and FWDCHECK computer programs. Program FWDSCAN has been developed to verify the integrity and completeness of the FWD deflection data after they have been delivered to the SHRP regional offices. Program FWDCHECK has been developed to analyze deflection data for test section homogeneity, the degree to which test pit data are representative of the section, the presence of data outliers within the section, and overall reasonableness from a structural capacity viewpoint.

The Long-Term Pavement Performance (LTPP) study of the Strategic Highway Research Program (SHRP) involves intensive monitoring of numerous pavement sections located throughout North America. One aspect of the LTPP data collection is deflection testing, which provides information on structural capacity and material properties. Four falling weight deflectometers (FWDs) manufactured by Dynatest are used in the SHRP deflection testing.

Because accurate data are the key to the success of the LTPP study, SHRP has implemented a number of measures to ensure the quality of deflection data. They include equipment comparison and calibration, standardized field testing procedures and field data checks, and quality assurance software. This paper focuses on the quality assurance software.

Equipment calibration and field data checks built into the FWD data acquisition software are the first line of defense against invalid deflection data. The second line of defense is a computer program, called FWDSCAN, which verifies the integrity, completeness, and compliance with the established test pattern of the field data after they are delivered to the SHRP regional office (*1*). For the final stage in the quality assurance process, a computer program called FWDCHECK has been developed to analyze deflection data for test section homogeneity, the degree to which test pit data are representative of the section, the presence of data outliers within the section, and overall reasonableness from a structural capacity viewpoint (*2*). As a rule, the checks embodied in FWDCHECK will not eliminate data, but instead will flag potential problems.

The remainder of this paper provides a brief overview of SHRP's deflection testing program (to facilitate the understanding of the software), followed by detailed descriptions of the FWDSCAN and FWDCHECK computer programs. Typical analysis results are also presented and discussed.

SHRP DEFLECTION TESTING PROGRAM

SHRP is conducting two basic types of deflection tests: basin tests, which are conducted on all pavement types, and load transfer tests, which are conducted only on portland cement concrete (PCC) pavements. Pertinent details of the testing program are as follows. The full testing program is described in the SHRP field manual for FWD testing (*3*).

A single sensor configuration is used for all deflection basin tests, regardless of pavement type, to minimize the probability of sensor location errors. The sensors are located at radii of r = 0, 8, 12, 18, 24, 36, and 60 in. from the loading plate center. A similar sensor configuration is used for all load transfer tests, except that the sensor at r = 8 in. is moved to the rear of the loading plate 12 in. from the center of the loading plate.

A uniform drop sequence is used at all test points within a test section. This drop sequence begins with a series of three drops at a load of 12,000 to 14,000 lbf for seating purposes, followed by four repeat drops at each drop height (load level) used. For flexible [i.e., asphalt concrete (AC)] pavements, four drop heights are used, producing nominal loads of 6,000, 9,000, 12,000, and 16,000 lb. On rigid (jointed and continuously reinforced concrete) pavements, only three drop heights are employed, producing nominal loads of 9,000, 12,000, and 16,000 lb.

Testing within the section is completed in two or three passes at various lateral (transverse) locations in the lane: midlane, defined as 6.0 ± 0.05 ft from the pavement edge; outer wheel path, defined as 2.5 ± 0.25 ft from the pavement edge; and pavement edge, where the load plate is located within 3 in. of the pavement edge. All testing in a given lateral

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location is completed in a single pass over the section for reasons of ease, efficiency, and error reduction. The midlane locations are tested first, followed by the edge locations where applicable, and the outer wheel path locations.

Deflection basin tests at two test pit locations, approximately 50 ft outside the section boundaries, are also conducted for all pavement types. The function of these tests is to provide a basis for "linking" test pit information (i.e., laboratory characterization) with the overall section response. Test pit locations are tested first (i.e., before the within-section testing) so that drilling operations can commence.

All testing uses station 0+00 of the test section as the reference point for the FWD distance measuring instrument to ensure that test locations can be accurately located in the future. The specific test pattern used on the test sections varies with pavement type and is summarized in Table 1. The approximate longitudinal test point spacing for all pavement types is 25 ft, resulting in a minimum of 20 test points per pass per section.

Air and pavement surface temperatures are also monitored by sensors mounted on the FWD trailer; these data are recorded with the deflection data for each test point. Additional temperature data are obtained by manual monitoring of temperatures at three depths (bottom, middle, and surface) in the pavement surface layer at two locations, one at each end of the test section, just beyond the section boundaries. These manual measurements are obtained at the start of testing, at the end of testing, and at hourly intervals during testing.

Because of large file size and the need for back-up copies, data are backed up in the field using commercial back-up software, then restored to the original form on arrival at the SHRP regional office.

PROGRAM FWDSCAN

All deflection data collected in the field and received by SHRP are checked to ensure that they have been restored to their original form, that all data are present, complete and in a readable form, and that they comply with the established test pattern. This is accomplished by means of the FWDSCAN program.

Each FWD data file can be thought of as being composed of two primary parts. The first part consists of 36 lines of header information. The second part of the data file, known as the data block, consists of the loads, deflections, temperatures, and stations collected during a given pass.

Verifying the contents of the header information consists of two distinct parts. The first part involves the comparison of the data items in the file to either lists of possible values or specified values—for example, that the load plate radius is the correct value. The second part of the verification procedure consists of checking that the remaining items contain reasonable values for what they represent—for example, that calibration factors are between 0.98 and 1.02 for all deflectors.

The data block of the FWD data file consists of a repeating series of lines defining the testing at each station. For each station, the following data should be present: a line containing station identification, lane specification, and other information that occurs once at each station; 12 or 16 lines (depending on the pavement type) of load and deflection data; operator comments (optional); and 151 or 301 line blocks containing load and deflection time history data for a single drop height at this station, repeated up to three or four times at each station, depending on the pavement type being tested.

Accordingly, verification of the data block contents consists of scanning each line of the remainder of the FWD data file to ensure its readability and completeness. In addition, to ensure the reasonableness of the data, the verification procedure also entails a comparison of the data with valid data ranges; that is, lane specification codes must be from the list specified in the SHRP FWD manual, deflection values must range from 0.1 to 80.0 mils, loads must range from 500 to 32,000 lbf, and air and surface temperatures must range from 0°F to 160°F.

TABLE 1 FWD Test Plan Summary

Pavement Type	Transverse Location (Pass)	Longitudinal Location	Interval	Test Type	Number of Points
Flexible	Mid-Lane Wheel Path**	- -	25 feet 25 feet	Basin Basin	23* 21
Rigid -Jointed Plain or Reinforced Concrete	Mid-Lane Edge Edge Wheel Path**	Mid-Panel Corner Mid-Panel Joint	Each Panel Each Panel Each Panel Each Panel	Basin Basin Basin Load Transfer	22* 20 20 40
Rigid - Continuously Reinforced Concrete	Mid-Lane Edge Edge Wheel Path**	Mid-Panel Center/Crack Mid-Panel Crack	± 25 feet ± 25 feet ± 25 feet ± 25 feet	Basin Basin Basin Load Transfer	22* 20 20 40

* Includes 2 test pit locations ± 50 feet from section limits.

** Wheel path testing is in the outer (rightmost) wheel path.

A list of the specific data items that are checked during the scanning process follows:

1. Miscellaneous checks: report scan start time and date, verify line length for each line, report number of skipped records, report total number of records processed, and report scan end time and date.
2. Checks of header information: determine units for data collection, report total expected number of records, determine data collection date, verify use of edition 10 of Dynatest software, determine number of active deflectors, determine deflector range, determine FWD serial number, determine deflection filtering mode, determine load cell gain, determine deflector gains, and determine operator's name.
3. Checks at each station: determine peak data block, verify use of a valid lane, determine specification, verify that stations are increasing, verify that stations are within the 500-ft limits of the test section, determine number of peak records recorded, verify that temperatures are within acceptable range, verify that deflections are within deflector limits, verify that deflections decrease at increasing distance from the load plate, verify that load is within the acceptable range, check for comments, check for unidentifiable data, check for new subsection identification, check for an unexpected end to the file.
4. History data block: determine number of history records recorded, verify that deflections are within deflector limits, verify that load is within acceptable range, check for comments, check for unidentifiable data, check for new subsection identification, check for an unexpected end to the file.

Some checks are for the presence of specific data items, other checks are for data within an acceptable range of numbers, and other checks simply report what was present in the data file.

The results of these scanning procedures are written to an output file as a permanent record of this process having been performed. Erroneous or inconsistent data items are noted by lines beginning with an asterisk or exclamation mark. These lines fully describe which data element is incorrect or inconsistent. Some errors in the data file generate more than one warning message, and sometimes they affect whether subsequent data are interpreted correctly. Table 2, an excerpt from one of these files, contains two warnings, only the first of which is truly an error. In this case, the unrecognized lane specification at station 219 causes the lane specification at station 231 to appear to be out of the normal sequence of testing.

Depending on the results of the verification procedure, a number of scenarios are possible. For all scenarios in which the file is corrupted, the first two remedial steps are the same. The first consists of redoing the restore procedure and repeating the verification, because the original data restoration may have been the cause of the data corruption, and repeating it may eliminate the problem. If this step fails to remedy the problem, the second step is to request that the FWD operator transmit another copy of the data to SHRP and repeat the verification process. If this step also fails, then additional steps are taken, depending on the exact nature of the problem with the data. When errors are not from corruption in the data file but are from erroneously recorded data, the FWD data file may be edited to correct these errors.

TABLE 2 Excerpt of FWDSCAN Output File Containing Errors

150 history records successfully read in block 2 at station 207
150 history records successfully read in block 3 at station 207
* Undefined lane specification (J3]) at station 219
12 peak records successfully read at station 219
150 history records successfully read in block 1 at station 219
150 history records successfully read in block 2 at station 219
150 history records successfully read in block 3 at station 219
* Test sequence locations not in expected order at station 231
Testing J2 (RIGID) at station 231
12 peak records successfully read at station 231
150 history records successfully read in block 1 at station 231
150 history records successfully read in block 2 at station 231
150 history records successfully read in block 3 at station 231
Testing J3 (RIGID) at station 238
12 peak records successfully read at station 238
150 history records successfully read in block 1 at station 238

PROGRAM FWDCHECK

Program FWDCHECK has been developed to analyze deflection data for test section homogeneity, the degree to which test pit data are representative of the section, the presence of data outliers with the section, and overall reasonableness from a structural capacity viewpoint. The objective of these checks is to flag potential problems and areas in which reality may deviate from assumptions. FWDCHECK is intended for the analysis of midslab deflection basin test data (not load transfer) for rigid pavements and outer-wheel path deflection data for flexible pavements.

For purposes of describing this program, this section has been subdivided into four subsections: preliminary data analysis, section homogeneity analysis, nonrepresentative data analysis, and structural capacity analysis. The order in which these subsections are presented corresponds with the FWDCHECK analysis sequence.

Preliminary Data Analysis

Before any checks are performed, the deflection data in question is normalized to provide a uniform basis for comparison. Various normalized deflection statistics—mean, standard deviation, and coefficient of variation for each geophone number and drop height combination—are also calculated for the pavement section in question.

Uncorrected normalized deflections are calculated by means of the following relation:

$$\hat{\delta}_u = \frac{\sum_{i=1}^{n}\left(\frac{\delta_{mi}}{P_i}\right)}{n} \quad (1)$$

where

$\hat{\delta}_u$ = uncorrected normalized mean deflection (mils/lb),
i = repeat drop in question,

n = number of repeat drops used,
δ_{mi} = measured deflection for ith repeat drop, and
P_i = applied load (lb).

For flexible pavements, temperature-corrected normalized deflections are also computed in the manner described above, except that the measured deflections are first corrected to a standard temperature of 68°F (*2*). These corrections are applicable only to the maximum deflections (i.e., under load center) and are made on the basis of temperature-depth data measured in the field.

Section Homogeneity Analysis

Because pavements are inherently variable, the nondestructive evaluation of any pavement test section will yield variable deflection data. The first data check in the FWDCHECK program is aimed at evaluating the homogeneity of the test section (i.e., determine whether one or more pavement subsections are present based on a comparison of means and standard deviations).

This particular data check is subjective because, on the basis of a visual assessment of the deflection profile, the user selects the boundaries, if any, delimiting pavement subsections. To aid the user in the definition of these boundaries, tabular summaries of the uncorrected and temperature-corrected normalized deflection statistics and deflection plots versus station are generated by the program. Figure 1 is an example of a deflection versus station plot.

If two or more subsections are identified, the program computes the mean normalized deflection (temperature corrected for AC pavements) and standard deviation of Geophone 1 for each subsection. The section uniformity analysis is based only on the analysis of the (nominal) 9,000-lb load data, which closely simulate the "standard" 18-kip single axle load often used in pavement analyses. FWDCHECK then performs a statistical comparison of the means and variances for each pair of adjacent subsections to determine whether they are statistically different. The statistical test of the means assumes that the normalized deflections for each subsection follow a Student's t distribution and that the true standard deviations are unknown and unequal. Furthermore, the test for equal means uses a 95 percent level of probability (two-tailed). An F-test is used for the comparison of the variances for each pair of adjacent subsections. The subsections are considered different if either (or both) the means or the variances are statistically different.

Figure 2 is an example of an SHRP section where subsections may exist. As shown, this section can be divided into three subsections at Stations 130 and 290. Subsection 1 (Stations 0 to 130) has a relatively low maximum deflection. Subsection 2 (Stations 130 to 290) has much higher deflections than Subsection 1, with its overall average about 50 percent higher than that for Subsection 1. Subsection 3 (Station 290 to 500) has a more uniform maximum deflection than Subsection 2, with its overall average similar to that of Subsection 1. Although not shown, the hypothesis tests for these subsections indicated that the means are statistically different, but that the variances are not. Thus, subsections are indeed present within the overall section according to the established criteria.

Depending on the outcome of the analysis, one or more messages are sent to the screen and to the program output file; for example, a message indicating that a pair of adjacent subsections have equal means but unequal variances. If two or more subsections are found to be equal by both means and variances, the subsection boundaries are redefined before proceeding with the program.

Nonrepresentative Data Analysis

The LTPP testing program relies on the assumption that materials from the area adjacent to the monitored section are representative of those within a test section. Deflection data obtained at the time of materials sampling provides an opportunity to evaluate this assumption.

This evaluation, and a check for "outliers" within the section, are accomplished through comparison of normalized de-

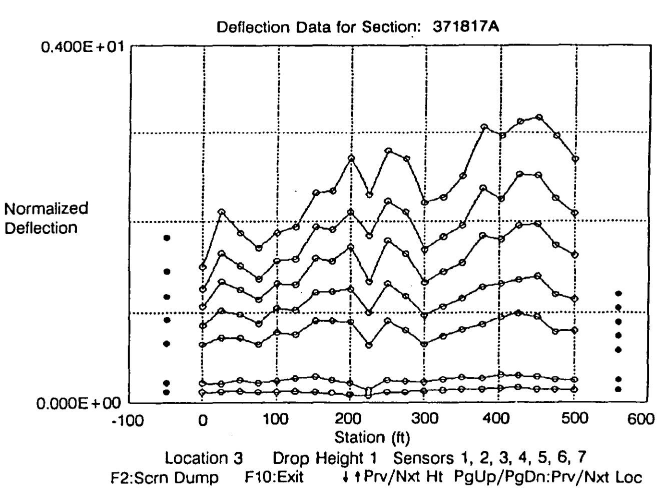

FIGURE 1 Uncorrected normalized deflection versus station plot.

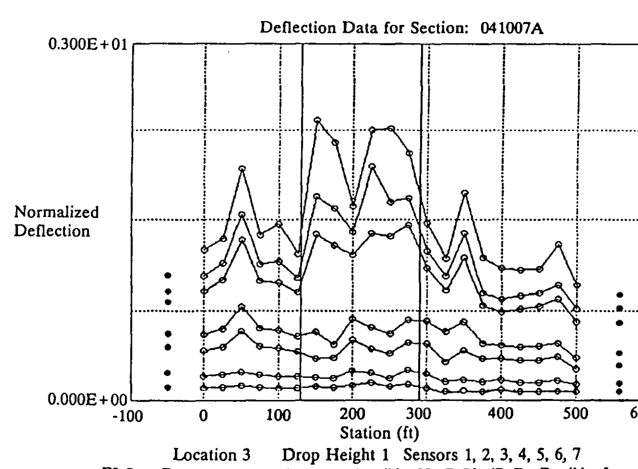

FIGURE 2 Sample subsection delineation: Section 041007A.

flection statistics for all geophone and drop height combinations. For the test pit location, normalized deflection data are first compared with the corresponding section means. In those cases in which two or more subsections have been identified, the test pit data are compared with the means for the adjacent subsection. In either case, warnings are automatically generated by the program when the test pit data differ from the section or subsection means by more than two standard deviations.

As in the test pit analysis, the check for data outliers within a section entails the comparison of the normalized deflections for each geophone and drop height combination at each station to the section or corresponding subsection mean. Warning messages are generated by the program when the difference from the section or subsection mean is more than two standard deviations; a tabular summary of the nonrepresentative data found within a section is sent to the output file that includes, for each data point, the station, drop height, geophone number, and number of standard deviations away from the section or subsection mean.

The program also generates normalized deflection-versus-station plots for each combination of geophone and drop height. An example of these plots is given in Figure 3. As shown, a series of lines indicating the mean, mean ± 1 standard deviation, mean ± 2 standard deviations, and so on are superimposed on these plots. Based on these plots, the user can, if desired, include additional messages in the output file in the form of running comments.

Structural Capacity Analysis

The last set of FWDCHECK data checks deals with the overall reasonableness of the deflection data from a structural capacity viewpoint. It involves the computation of pavement structural capacity and the comparison of the results to what one might expect on the basis of layer thicknesses and material properties.

Because the main objective of this last set of data checks is to verify the general reasonableness of the data, a direct structural capacity approach was selected for implementation in the program. The particular analysis procedure used is dependent on the pavement type, as described next.

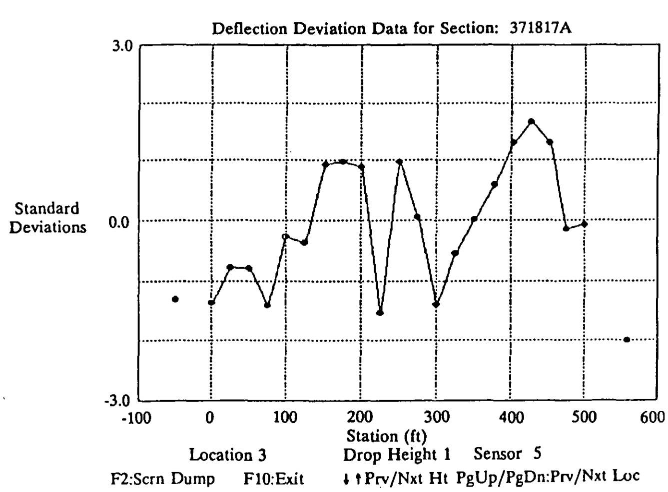

FIGURE 3 Sample deflection deviation versus station plot for nonrepresentative data analysis.

Rigid Pavement Analysis

Structural capacity estimates for rigid pavements are derived on the basis of a modified Westergaard solution for interior deflections. The analysis is predicated on the assumption that the slab is "relaxed" (i.e., no curling). The specific model used in this analysis is given by Ioannides et al. (*4*):

$$\delta = \frac{P}{8K\ell^2}\left[1 + \left(\frac{1}{2\pi}\right)\left(\log_e\left(\frac{a}{2\ell}\right) + \gamma - 1.25\right)\left(\frac{a}{\ell}\right)^2\right] \qquad (2)$$

with

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1 - \mu^2)K}}$$

where

- δ = maximum deflection (i.e., under load center);
- a = radius of loaded area;
- P = total applied load;
- K = composite modulus of subgrade reaction;
- γ = 0.57721566490, Euler's constant;
- ℓ = radius of relative stiffness;
- E = elastic modulus of portland cement concrete;
- h = slab thickness; and
- μ = Poisson's ratio of portland cement concrete.

Assuming an elastic modulus of E = 5,000,000 lb/in.² and a Poisson's ratio of μ = 0.15 for portland cement concrete, Westergaard's solution is used in an iterative mode to calculate the effective thickness (h) of the slab at the time of testing. Because the maximum deflection, applied load, and radius of loaded area are all known, the only unknown parameter is the composite modulus of subgrade reaction or K.

The K value is determined from the applied load and the volume of the deflection basin. This approach assumes that the slab is incompressible and, as a consequence, the volume of soil or other materials, or both, displaced by the load is equal to the volume of the deflection basin. Accordingly, the K value is calculated as follows:

$$K = \frac{P}{V} \qquad (3)$$

where P is the applied load and V is the effective volume of deflection basin. The effective volume of the deflection basin is limited to approximately the dimension of half of the lane width (72 in.) and is determined by rotating the deflection basin area through 360 degrees.

Composite modulus of subgrade reaction and effective slab thickness values are determined for all possible location, station, and drop height combinations. The resulting thickness data are then compared with the expected range of thickness to assess the reasonableness of the deflection data. The expected range is defined as 0.65 (to allow for deterioration of the slab) to 1.15 (to allow for hardening of the concrete) times the actual slab thickness. Warnings are generated by the program and sent to the output file when the estimated effective thickness falls outside the expected range.

The program also generates the following information: (a) plot of equivalent thickness versus station (with the expected thickness range superimposed) for each drop height; (b) plot of composite modulus of subgrade reaction versus station for each drop height; (c) plots of composite modulus (i.e., single value representation of the overall pavement stiffness) versus radial distance for all drop heights at any given station; and (d) tabular summaries of K and thickness values as well as corresponding statistics at each drop height for the pavement section or subsections. An example of the thickness-versus-station plot is given in Figure 4. On the basis of this and other information, the user can, if desired, include additional warning messages in the output file in the form of running comments.

Flexible Pavement Analysis

The structural capacity analysis of flexible pavements follows the AASHTO direct structural number procedure, which is based on the premise that the overall pavement structural capacity is the result of the combined stiffness influence of each layer (*5*). Accordingly, the maximum deflection may be viewed as being composed of two separate components: (a) pavement structural capacity and (b) subgrade support.

The procedure implemented in FWDCHECK uses outer deflection basin data to estimate the subgrade modulus and then uses this parameter, along with the maximum deflection, to directly estimate the effective structural number (*SN*) of the pavement system. The specific evaluation technique used involves the following major steps.

1. An estimate of the radius of influence (a_{3e}) at the pavement-subgrade interface is made on the basis of composite modulus at each geophone location; deflections obtained beyond this value are assumed to be caused by subgrade deformations only. Composite moduli are calculated in the program as follows:

$$E_c = \frac{2 * (1 - \mu_{sg}^2) * p_c * a_c}{\delta} \qquad \text{if } r \le 0.25a_c \tag{4a}$$

or

$$E_c = \frac{(1 - \mu_{sg}^2) * p_c * a_c^2}{\delta * r} * C \qquad \text{if } r > 0.25a_c \tag{4b}$$

where

E_c = composite modulus,
r = radial distance,
p_c = contact pressure applied by NDT device,
a_c = radius of contact of NDT device,
μ_{sg} = Poisson's ratio of the subgrade,
δ = measured deflection at given radial distance, and
C = the lower of $1.1 * \log(r/a_c) + 1.15$ and $0.5 * \mu_{sg} + 0.875$.

2. If a stiff layer is present beneath the pavement structure, it will have a major influence on the measured deflections and hence structural capacity analysis. To overcome this, a number of assumptions are first made: (a) the deflections measured at distances beyond the radius of influence (a_{3e}) are solely a function of the subgrade and stiff layers; (b) the stiff layer has an elastic modulus of E = 1,000,000 lb/in.^{2} and a Poisson's ratio of μ = 0.35; and (c) a typical layer modulus and Poisson's ratio is assigned to each layer in the pavement structure (exclusive of subgrade) on the basis of material type, as shown in Table 3.

The assumed layer moduli and Poisson's ratios, along with the known layer thicknesses and depth to stiff layer, are then input into CHEVRON *N*-layer code (*6*) to predict surface deflections at all geophone locations beyond the radius of influence, for subgrade modulus values of 5,000, 15,000 and 30,000 lb/in.^{2}. In turn, these results are used to develop log-log regression equations of surface deflection versus subgrade modulus for each geophone location beyond a_{3e}. Finally, the surface deflection versus subgrade modulus correlations are used to determine the subgrade modulus that yields a surface deflection equal to that measured in the field for each geophone location beyond a_{3e}. Although only an estimate, the resulting values represent the subgrade moduli at each geophone location, independent of the stiff layer.

3. If the subgrade soil is perfectly elastic, the subgrade moduli derived from the stiff layer analysis for distances beyond the radius of influence will be the same. If nonlinear, however, there will be some degree of stress softening; that is, as the stresses increase, the subgrade modulus decreases. Because the structural analysis is based on the AASHTO structural number as calculated from the maximum measured deflection and the subgrade modulus, it is critical that the best possible estimate of the subgrade modulus underneath the load center be made.

Accordingly, the layer modulus and Poisson's ratio assumed for each layer in the pavement structure, along with the known layer thicknesses and subgrade moduli predicted from the stiff layer analysis, are first input into the CHEVRON *N*-layer code to predict deviator stresses at the pavement-subgrade

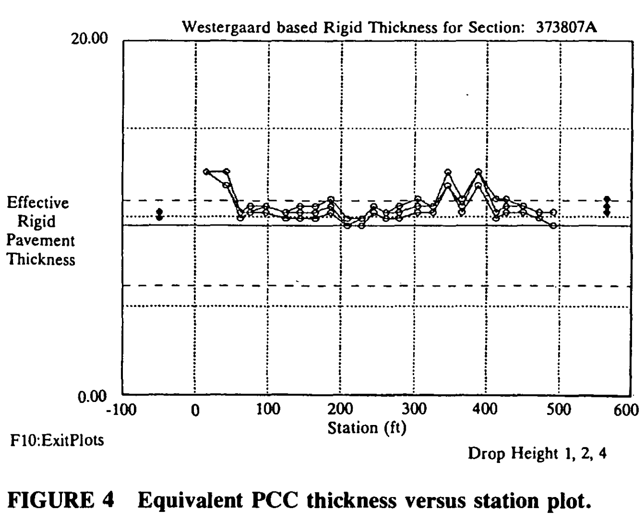

FIGURE 4 Equivalent PCC thickness versus station plot.

TABLE 3 Typical Modulus, Poisson's Ratio, and Layer Coefficient Values Used in FWDCHECK

Material Type	Elastic Modulus (ksi)	Poisson's Ratio	Layer Coefficient	
			Minimum	Maximum
Uncrushed Gravel	20.0	0.40	0.07	0.17
Crushed Stone	45.0	0.40	0.11	0.21
Crushed Gravel	30.0	0.40	0.09	0.18
Crushed Slag	50.0	0.40	0.12	0.22
Sand	10.0	0.40	0.05	0.15
Fine Soil-Agg. Mixture	15.0	0.40	0.06	0.16
Coarse Soil-Agg. Mixture	20.0	0.40	0.07	0.17
Sand Asphalt	200.0	0.40	0.10	0.30
Asphalt Treated Mixture	300.0	0.35	0.15	0.35
Cement Aggregate Mixture	750.0	0.30	0.25	0.45
Econocrete	1,500.0	0.25	0.40	0.60
Cement Treated Soil	100.0	0.35	0.10	0.25
Lean Concrete	1,500.0	0.25	0.40	0.60
Sand-Shell Mixture	75.0	0.40	0.15	0.25
Limerock, Caliche	200.0	0.35	0.15	0.30
Lime Treated Soil	75.0	0.35	0.10	0.25
Soil Cement	200.0	0.35	0.15	0.30
Pozzolanic-Agg. Mixture	500.0	0.35	0.20	0.40
Cracked & Seated PCC	1,000.0	0.25	0.35	0.45
Asphaltic Concrete	450.0	0.35	0.35	0.45
Portland Cement Concrete	5,000.0	0.15	0.60	0.80

interface at all geophone locations beyond a_{3e} and directly under the load center. The deviator stresses predicted for distances beyond a_{3e} and the subgrade moduli computed in the stiff layer analysis are then used to develop a log-log regression equation of subgrade modulus versus deviator stress. Finally, the predicted deviator stress at a radial distance of zero is input into the subgrade modulus-deviator stress correlation to determine the subgrade modulus directly under the load center.

4. Once the subgrade modulus under the load center has been established, the effective structural number of the pavement is determined through an iterative process. Assuming that the pavement structure can be represented by a one-layer system resting on the subgrade and that crushed stone (a_s = 0.14, E_s = 30,000 lb/in.^{2}, and μ_s = 0.35) is the standard material, the equivalent modulus of the one-layer system (for a given *SN* value) and hence the theoretical maximum deflection can be derived using Equations 5 through 9 (*5*):

$$E_e = \left(\frac{SN}{0.0043h_T}\right)^3 (1 - \mu_e^2) \quad (5)$$

where

E_e = elasticity modulus of equivalent one-layer system,
SN = pavement structural number,
μ_e = Poisson's ratio of equivalent one-layer system, and
h_T = total pavement thickness;

$$\delta_0 = \frac{2p_c a_c(1 - \mu_{sg}^2)}{E_{sg}} \quad (6)$$

where δ_0 is the maximum measured deflection and E_{sg} is the elastic modulus of subgrade;

$$F_w = \frac{E_{sg}(1 - \mu_e^2)}{E_e(1 - \mu_{sg}^2)} + F_b\left[1 - \left(\frac{E_{sg}}{E_e}\right)\right] \quad (7)$$

where F_w is Burmeister's two-layer deflection factor;

$$F_b = \left[\sqrt{\left(1 + \frac{h_e^2}{a_c}\right)} - \frac{h_e}{a_c}\right] \times \left[1 + \frac{\frac{h_e}{a_c}}{2(1 - \mu_{sg})\sqrt{\left(1 + \frac{h_e^2}{a_c}\right)}}\right] \quad (8)$$

where F_b is Boussinesq's one-layer deflection factor; and

$$h_e = 0.9h_T\sqrt[3]{\frac{E_e(1 - \mu_{sg}^2)}{E_{sg}(1 - \mu_e^2)}} \quad (9)$$

where h_e is transformed thickness of pavement in terms of the subgrade modulus.

Therefore, by iterating on the *SN* value, the structural number that results in a predicted deflection equal to the measured value adjusted to a standard temperature of 68°F is determined. The resulting *SN* data are then compared with those in the expected range to assess the reasonableness of the deflection data. The expected range is defined for each pavement section on the basis of the combination of material types and layer thicknesses as follows:

$$SN = \sum_{i=1}^{n} (a_i * h_i) \qquad (10)$$

where

n = number of layers in the pavement (exclusive of subgrade);
i = pavement layer in question;
a_i = structural layer coefficient of the ith layer; and
h_i = thickness of the ith layer.

Minimum and maximum material layer coefficients used to generate the expected *SN* range are summarized in Table 2.

As with the rigid pavement structural analysis, warnings are generated by the program and sent to the output file when the predicted structural number falls outside the expected range. The program also generates the following information: (a) plot of structural number versus station (with the expected *SN* range superimposed) for each drop height; (b) plot of subgrade modulus (under the load plate) versus station for each drop height; (c) plots of composite modulus versus radial distance for all drop heights at any given station; and (d) tabular summaries of subgrade modulus and *SN* values as well as corresponding statistics at each drop height for the pavement section or subsections. An example of the structural number versus station plot is given in Figure 5. On the basis of this and other similar information, the user can, if desired, include additional warning messages in the output file in the form of running comments.

FWDCHECK Messages

The FWDCHECK program provides both tabular and graphical data displays for the four major factors evaluated. Examples of these displays have been shown throughout the paper. In addition, the program generates an output file containing a detailed summary of the analysis results. Included at the end of this file are summary remarks that will be stored in the SHRP data base and that will be of significant benefit to users of the SHRP data base. These remarks will be provided automatically to those who request SHRP deflection data. Table 4 provides an example of the summary remarks generated by FWDCHECK for a rigid pavement section.

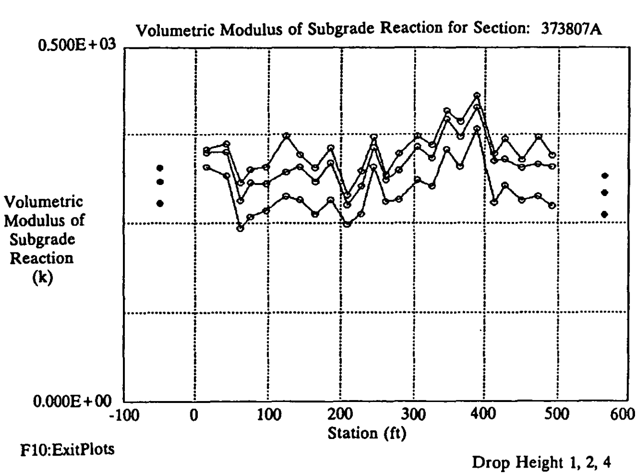

FIGURE 5 Structural number versus station plot.

TABLE 4 Excerpt of FWDCHECK Output File—Summary Remarks

Section uniformity:
Subsections were identified within the section.
Subsection 1 boundaries occur at 0 ft. and 320 ft.
Subsection 2 boundaries occur at 320 ft. and 410 ft.
Subsection 3 boundaries occur at 410 ft. and 500 ft.

Comparing subsections:
Subsections 1 and 2: UNEQUAL means and EQUAL variances.
Subsections 2 and 3: UNEQUAL means and EQUAL variances.

Outliers - Test pits: 21 combinations at each test pit.
All TP 1 data appears representative of section data.
6 height/sensor combinations at TP 2 DO NOT appear representative of section data.

Outliers - Section data: 546 total combinations within the section.
14 height/sensor/station combinations are data outliers in subsection 1.
There are NO data outliers within subsection 2.
There are NO data outliers within subsection 3.

Structural capacity - Test pits: 3 combinations at each test pit
All results for TP 1 are within the range of expected values.
1 height(s) for TP 2 are NOT within the range of expected values.

Structural capacity - Section data: 78 total combinations within the section.
17 height/station combinations are NOT within the range of expected values.

SUMMARY AND CONCLUSIONS

SHRP has established standard nondestructive deflection test procedures for monitoring pavement structural properties and has invested significant effort to ensure the quality of the data obtained using these procedures. Measures implemented by SHRP to ensure the quality of the deflection data include equipment comparison and calibration, standard testing procedures and field data checks, and quality assurance software.

This paper focused on the SHRP FWD quality assurance software developed for use with the SHRP LTPP deflection data. The program FWDSCAN is used to verify the integrity, completeness, and compliance with the established test pattern of the field data after being delivered to the SHRP regional offices, whereas the FWDCHECK program performs more detailed analyses to check the deflection data for section homogeneity, nonrepresentative data (from either the destructive sampling area or within the section), and general reasonableness (or agreement with expectations) from a structural capacity point of view.

These programs, used in conjunction with solid equipment calibration and field data collection procedures, will help to ensure the integrity of the deflection data entered into the SHRP LTPP data base and provide future users of those data with valuable flags regarding section uniformity, structural capacity, and the relationship between deflection data and data obtained from materials testing.

Although specifically developed to meet SHRP needs, these programs could also be of value to state highway agencies and other organizations involved in deflection testing of pavements. Because of the large quantity of data collected within a single set of guidelines, a program such as FWDSCAN is highly valuable. In any other testing environment in which test conditions are likely to vary from site to site, such a program is much less valuable. FWDCHECK, on the other hand, could be greatly useful to other agencies, after some features specific to SHRP are removed. For example, removing the 500-ft test section assumption, lane specification requirements, and test pit comparisons would greatly enhance the usefulness of FWDCHECK.

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