STATE OF FLORIDA

A PRACTICAL APPROACH TO PREDICTING FLEXIBLE PAVEMENT EMBANKMENT MODULI USING FALLING WEIGHT DEFLECTOMETER (FWD) DATA

Research Report
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EXECUTIVE SUMMARY

The present investigation was initiated to assess the feasibility of using the Falling Weight Deflectometer (FWD) deflection results in the Florida Department of Transportation (FDOT) current procedure for predicting the in-place modulus of a pavement embankment. The intent is to recommend a practical approach for using FWD deflections that would also ensure the compatibility of the latter data with those collected with the Dynaflect device for pavement design purposes. Deflection measurements were collected using both FWD and Dynaflect devices on more than three hundred pavement sections throughout the State.

The findings indicated that, when using FWD deflection data, a simple power law equation was appropriate for determining the embankment moduli for pavement design purposes. This prediction equation appears to result in a higher level of agreement between the FWD and the current Dynaflect-based method for the determination of embankment moduli.

BACKGROUND

Because of the speed and ease of operation, deflection-based techniques are being widely used in the evaluation of the structural integrity and the estimation of the elastic moduli of in-place pavement systems. Deflections can be non-destructively induced and measured using different commercially available devices. The more commonly used devices are generally categorized into two types depending on how the load is applied to the pavement system. Vibratory devices, such as Dynaflect, apply a steady-state sinusoidal load, while those known as impact or falling weight devices apply an impulse load to the pavement. Currently, Florida uses a Dynaflect device on flexible pavement structures to predict the in-situ resilient moduli or soil support values for pavement design purposes. This practice is a result of comprehensive and empirical correlations between the Dynaflect and the 12-inch plate bearing field test data developed in an earlier study *(1)*.

In recent years, the FWD device is gaining more acceptance among highway agencies because of its versatility, reliability, and ease of use. It is also believed that FWD loading better simulates the effects of traffic on pavement structures. Therefore, FDOT is presently considering implementing the use of FWDs to estimate the in-situ resilient moduli of pavement embankments. The purpose of this study is to recommend a practical approach for such an implementation.

OBJECTIVE

The present study was initiated with the primary objective of assessing the feasibility of using FWD-induced deflections in the Department's present procedure for predicting the embankment moduli of in-service flexible pavements. The intent is to recommend a practical approach for using FWD deflections that would also ensure the compatibility of the latter data with those collected with the Dynaflect device.

EXPERIMENTAL PROGRAM AND DATA COLLECTION

Testing Equipment

Falling Weight Deflectometer (FWD)

The Falling Weight Deflectometer, or FWD, consists of a trailer mounted with a falling weight system capable of loading a pavement in a manner that simulates, in both magnitude and duration, actual wheel loads. An impulse load is generated by dropping a weight mass from a specified height. The mass is raised hydraulically, then released by an electrical signal and dropped with a buffer system on a 12-inch (300-mm) diameter rigid steel plate. A thin, hard rubber pad rests between the plate and the pavement surface to allow for an even load distribution. The resulting pavement deformations are picked up through a series of sensors located along the centerline of the trailer. The deflection measurements are recorded by the data acquisition system located in the tow vehicle. For the purpose of this investigation, a nine-kip (4082 kg) load level was adopted. In addition, the resulting deflections were monitored using a 7-sensor setup spaced to conform to the Strategic Highway Research Program (SHRP) recommendation for flexible pavement testing. Figure 1 gives a schematic illustration of such a testing setup.

Dynaflect

Dynaflect consists of a relatively lightweight (2,000 lbs./907 kg) two-wheel trailer equipped with an automated data acquisition and control system. The dynamic loading of a pavement surface is done using two counter-rotating eccentric steel weights. These steel weights, rotating at a constant frequency of eight cycles per second (8 Hz), generate dynamic loads of approximately ± 500 pounds (227 kg) in magnitude. The total load applied to a pavement system is a combination of the static weight of the trailer and the dynamic loads generated by the rotating weights. The resulting deflections of the pavement system are measured with geophones. The geophones are electromechanical devices that use a magnetic field to produce an electrical impulse. The Dynaflect equipment used for the purpose of the present study has five geophones suspended from the tongue of the trailer placed at one-foot intervals, as shown in Figure 2.

Data collection

Deflection measurements were obtained using both FWD and Dynaflect devices on more than three hundred 1-mile (1.6-km) long roadway test sites throughout the State. All the test sites were essentially surface-on-grade flexible pavement sections. Fourteen test locations were randomly selected within each section along the outer wheel path. At each location, the testing was completed concurrently (using both FWD and Dynaflect devices) to limit the effects of temperature on the deflection measurements. When testing with the FWD, three load drops were used. However, only the deflection data resulting from the last two loadings were considered for further analysis to ensure adequate characterization of the pavement system. It is generally believed that the deflection data produced under the first impact load may not be always representative of the true pavement reaction *(2)*. Therefore, the first load was mainly used for the loading plate "seating" purposes.

As stated earlier, both FWD and Dynaflect devices are equipped with data acquisition systems to provide for automatic data collection and processing. In both cases, data from the sensors and the load cell are passed through their respective system processor to the on-board personal computer, which controls and monitors the entire testing operation. All the deflection data were obtained using the sensor configurations shown in Figures 1 and 2. Also, each test was conducted in accordance with the recommendations of the manufacturer of each of the devices, including full calibration of the equipment before the onset of the testing.

Prediction of In-Place Moduli of Embankment Material

The current FDOT procedure for predicting the in-place strength of the embankment material of a pavement system was based on the use of Dynaflect-induced deflections. In this procedure, the embankment modulus is estimated using the following prediction equation:

$$\log E_r = 4.0419 - 0.5523 \cdot \log d_4 \qquad (1)$$

Where:

E_r = Embankment modulus, in psi; and

d_4 = Deflection measured at 36 inches away from the load, in mils.

As state earlier, this practice is a result of an empirical correlation developed between Dynaflect and a 12-inch (300-mm) plate bearing field tests.

In addition, the procedure described in the *AASHTO Guide for Design of Pavements Structures* was used for backcalulating the embankment moduli when FWD data were considered *(3)*. This method of estimating pavement embankment modulus was proposed by Ullidtz *(4)*, and is based on Boussinesq's theory on a concentrated load applied on an elastic half-space *(5)*. In this procedure, the modulus of a subgrade material is estimated as follows:

$$E_r = 0.24P / d_r \cdot r \qquad (2)$$

Where:

E_r = Subgrade modulus, in psi;

P = Applied load, in pounds;

d_r = Deflection measured at a radial distance r, in inches; and

r = Radial distance at which the deflection is measured, in inches.

For practical purpose, the *AASHTO Design Guide* suggests the deflection used in the above equation be measured as close as possible to the loading plate and yet be sufficiently far from the load. This is suggested to satisfy the assumption that, at points sufficiently distant from the load, the deflections measured at the pavement surface are mainly due to the embankment deformation, and are also independent of the load plate size. Florida's previous experience with non-destructive deflection testing has shown that the pavement deflections measured at 36 inches away from the load are appropriate for the determination of the embankment moduli. Other studies elsewhere had resulted in algorithms for estimating the embankment resilient moduli from pavement surface deflections also at 36 inches from the point of loading *(6, 7)*. Therefore, for the purpose of this study, only the pavement deflections measured at 36 inches away from the load were considered.

DATA ANALYSIS

If the FWD data are to be considered for pavement design purposes in Florida, it is essential to assess their level of correlation with those collected with the Dynaflect-based method presently in use. Thus, the primary objective of this study was to compare FWD testing resulting embankment moduli with those of Dynaflect. The deflection data as collected during the course of this investigation were first considered to determine the embankment modulus at each test site. The results were then used as a basis for an evaluation of the correlation among the two deflection devices.

Figure 3 illustrates the level of agreement between the FWD and Dynaflect-produced embankment modulus values (E_{FWD} and E_{dyn}). This plot shows that there is a good correlation between the two test methods as reflected by the R-square value of 0.88. The regression curve (close to a straight line) intersects the equality line at a modulus value of approximately 40,000 psi. Such an observation indicates that, within the same test site, the current Dynaflect-based procedure would generally result in a relatively higher embankment modulus than that of FWD when this modulus is less that 40,000 psi. Above the 40,000-psi mark, the reverse would be obtained. In addition, Figure 3 shows that all the measurements lower than about 35,000-psi fall near a straight line with relatively little dispersion about the regression line. Otherwise, the moduli data are, relatively, more scattered. It has to be noted that the current FDOT procedure has set a limiting criteria (a maximum allowable) on the resilient modulus value since the latter has a significant effect on the resulting structural number. Incidentally, this maximum allowable embankment modulus is approximately 32,000 psi. Therefore, all the measurements above this value were not considered in any subsequent analysis.

An illustrative comparison of all the respective embankment modulus data lower than 32,000 psi as obtained using the two deflection devices is given in Figure 4. As previously stated, this Figure also illustrates that, within this test range, the AASHTO equation would generally result in lower moduli as compared to those generated using the present Dynaflect-based method. The latter are, on average, 1.2 times higher. An adjustment factor of approximately 1.2 may, therefore, be needed to make E_{FWD} values (the FWD-based procedure (or AASHTO equation) modulus data) more consistent with those of the current FDOT method (E_{Dyn}). Figure 5 shows a comparison of E_{FWD} and E_{Dyn} test results once such an adjustment is made. In this case, the trendline is much closer to the equality line (both lines are almost superimposed) than previously observed. A regression analysis of the E_{Dyn} and adjusted E_{FWD} values resulted, with an R-square of 0.84, in the following prediction equation:

$$E_{Dyn} = 2.8026 \cdot (E_{FWD\text{-}adusted})^{0.898} = 2.8026 \cdot (1.2E_{FWD})^{0.898} = 3.3012 \cdot (E_{FWD})^{0.898} \qquad (3)$$

Where:

E_{Dyn} = Embankment modulus as determined using Dynaflect-based procedure; and

E_{FWD} = Embankment modulus as determined using AASHTO equation with FWD data.

In addition, a further analysis indicated that a non-linear regression of the following form would result in a much closer match between E_{FWD} and E_{Dyn} results:

$$E_{Dyn} = 3.3863 \cdot (E_{FWD})^{0.898} \quad (4)$$

Therefore, in order to achieve a higher level of agreement between the FWD and Dynaflect produced embankment moduli, all the above findings suggest that, when using FWD data (deflections at 36 inches away from the load), embankment moduli be determined using the following prediction equation:

$$E_{FWD} = 3.3863 \cdot (E_{AASHTO})^{0.898} \quad (5)$$

Or $$E_{FWD} = 3.3863 \cdot (0.24P / d_r \cdot r)^{0.898} = 0.03764 \cdot (P / d_r)^{0.898} \quad (6)$$

Where:

E_{FWD} = Predicted embankment modulus based on FWD data, in psi;

E_{AASHTO} = Embankment modulus as determined using AASHTO equation, in psi;

P = Applied load, in pounds;

d_r = Deflection measured at a radial distance r, in inches (r = 36” in this case).

A comparison between the moduli values computed using the proposed equation and those obtained using the current FDOT procedure (based on the data collected during the course of this investigation) is plotted in Figure 6. The modulus data points seem to be evenly spread on both sides of the equality line. Again, all the measurements fall near a straight line with relatively little dispersion about the line. This observation is also reflected by R-square value of 0.84. Furthermore, both the trend and the equality lines are now superimposed. Figure 7 also shows a comparison between the FWD data as adjusted using, respectively, both the multiplier coefficient of 1.2 (thus, assuming a linear relationship) and the non-linear regression equation as described above. The good correlation between the two adjusted FWD data sets seems to suggest that both adjustment methods are viable options.

CONCLUSIONS

FDOT initiated the present investigation to assess the feasibility of using FWD-induced deflections in its current procedure for predicting the in-place modulus of a pavement embankment. The intent is to recommend a practical approach for using FWD deflections that would also ensure the compatibility of the latter data with those collected with the Dynaflect device. Deflection measurements were obtained using both FWD and Dynaflect devices on more than three hundred roadway test sites throughout the State. Based on the findings of this investigation, the following conclusions can be drawn:

- A strong non-linear correlation, of the form $y = \alpha \cdot x^{\beta}$ with an R-square value of 0.88, was obtained between the FWD (using AASHTO equation) and Dynaflect-produced embankment moduli.
- A regression analysis indicated that, within the same test site, the AASHTO equation would generally result in a higher in-place embankment modulus as compared to that of the current procedure when this modulus value is less than approximately 40,000 psi. Above the 40,000-psi mark, the reverse would be obtained.
- When only the modulus data lower than the current criteria of a maximum allowable value of 32,000 psi were considered, the modulus values generated using the present Dynaflect-based method were, on average, 1.2 times higher that those determined using the AASHTO equation with the FWD measurements.

- Once the FWD results were adjusted using a 1.2 multiplier, the embankment modulus trendline became much closer to the equality line. However, when the FWD modulus data were adjusted based on a non-liner regression of the form $E_{FWD} = 3.3863 \cdot (E_{AASHTO})^{0.898}$ where E_{AASHTO} are the corresponding embankment moduli as determined using AASHTO equation, both the resulting data trend and the equality lines were identical within the test range with a 0.84 coefficient of correlation.

RECOMMENDATIONS

The findings of the present study indicated that, when using FWD deflection data, the following simple power law equation was appropriate for determining the embankment moduli for pavement design purposes:

$$E_{FWD} = 0.03764 \cdot (P / d_r)^{0.898} \quad (7)$$

Where:

P = Applied load, in pounds; and

d_r = Deflection measured at a radial distance of 36 inches.

This prediction equation appears to result in a higher level of agreement between the FWD and the current Dynaflect-based method for the determination of embankment moduli. It is therefore recommended that, when considering FWD deflections, such an approach be implemented to predict the embankment moduli for pavement design purposes to ensure the compatibility of the latter data with those collected with the Dynaflect device.

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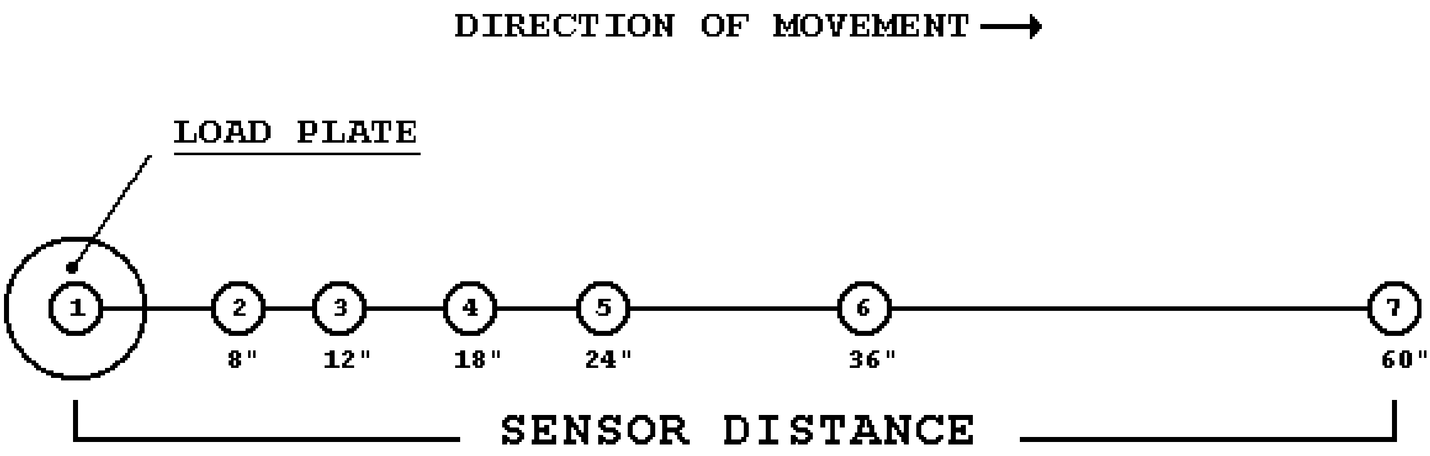

Figure 1 Schematic diagram of the FWD sensor positions used during this study

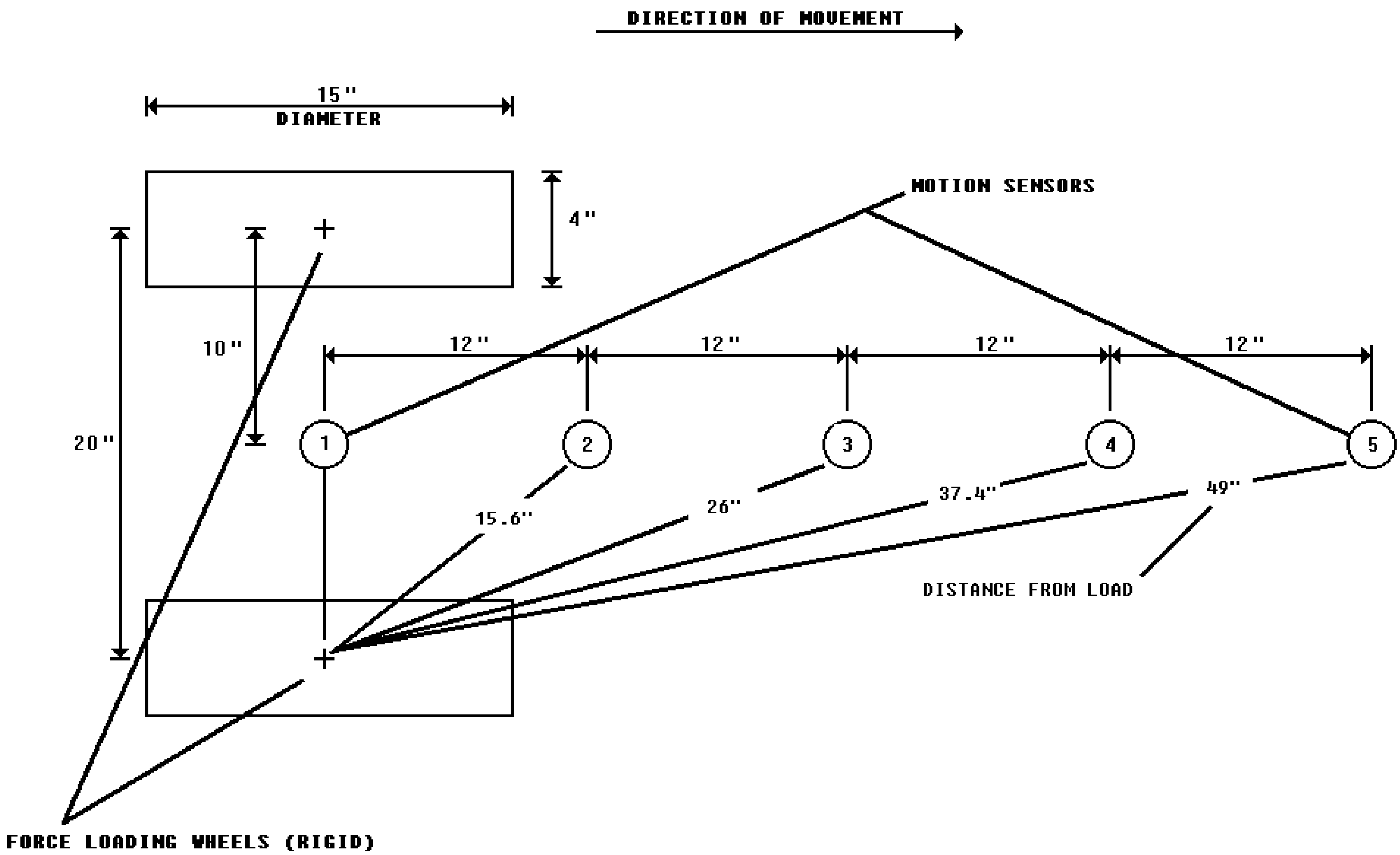

Figure 2 Schematic diagram of the Dynaflect sensor positions used during this study

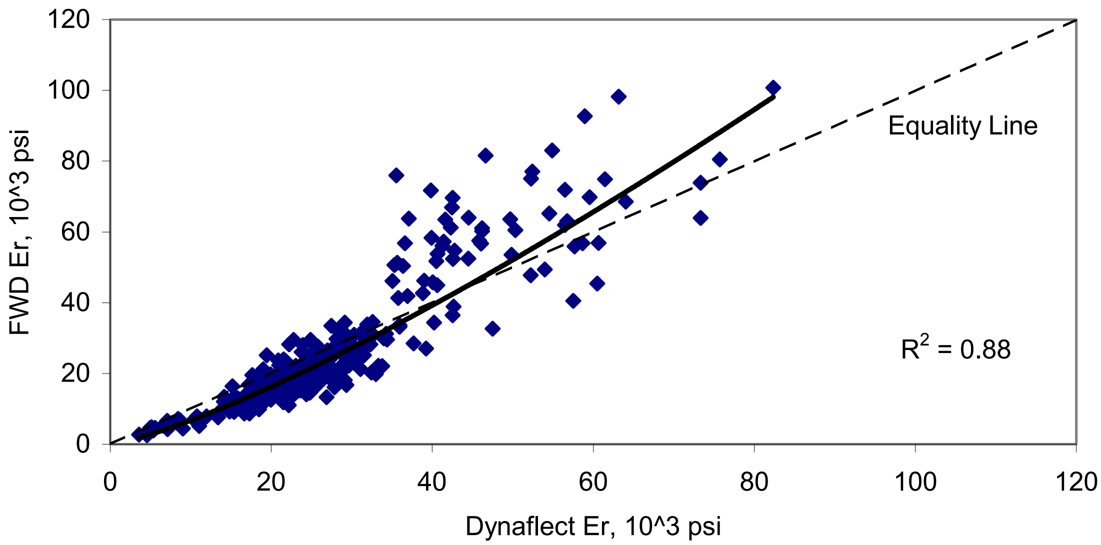

Figure 3 Illustrative comparison of FWD and Dynaflect embankment moduli

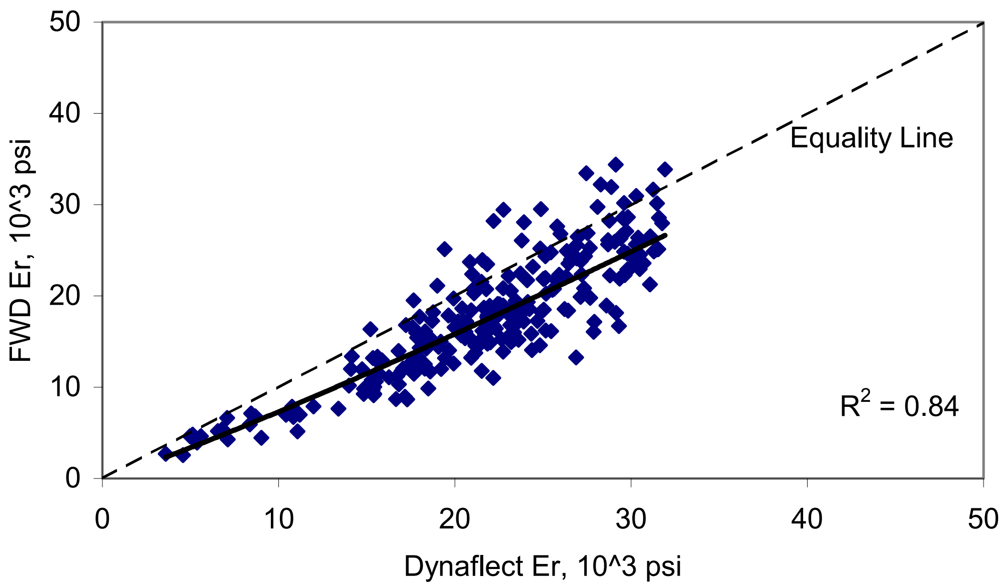

Figure 4 Illustrative comparison of FWD and Dynaflect moduli less than 32,000 psi

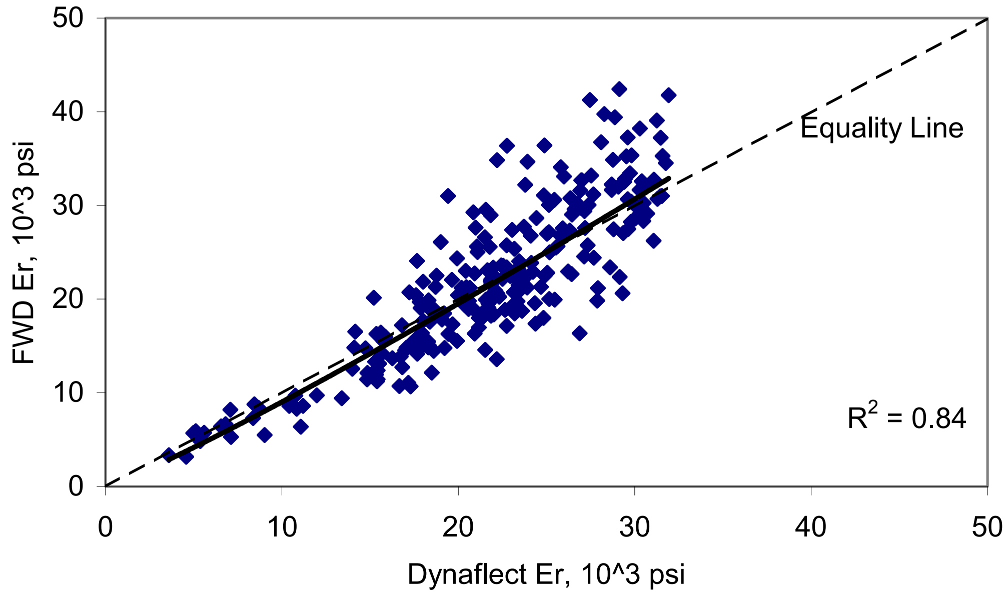

Figure 5 Illustrative comparison of adjusted FWD and Dynaflect moduli (FWD data adjusted using a 1.2 multiplier)

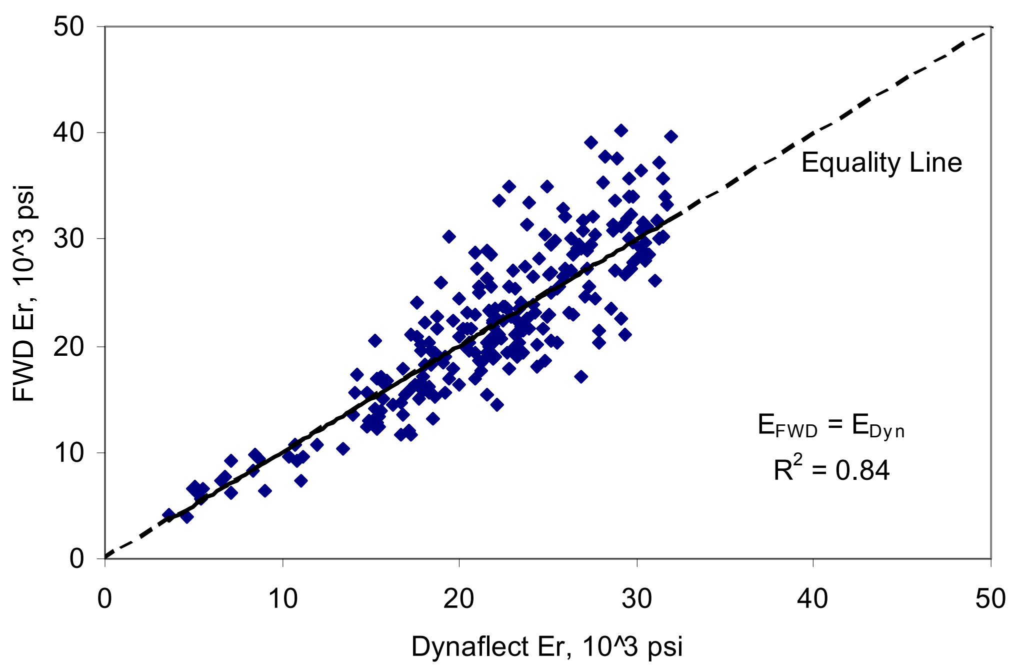

Figure 6 Illustrative comparison of adjusted FWD and Dynaflect moduli (FWD data adjustment based on a non-linear regression equation)

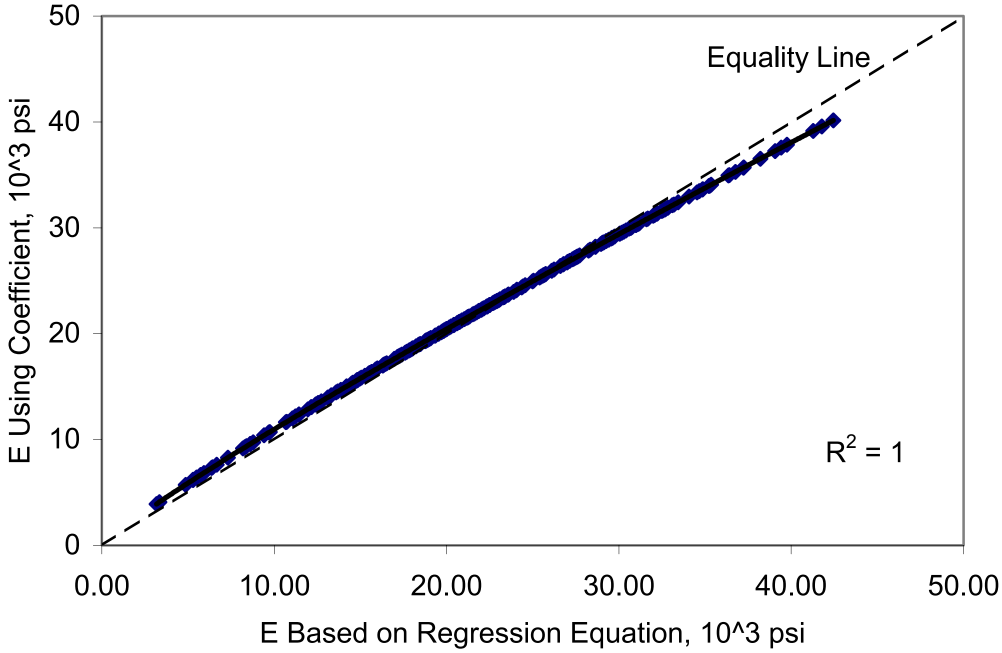

Figure 7 Illustrative comparison of FWD moduli as adjusted based on linear and non-linear relationships, respectively