Track Modulus Measurements at the Pueblo Soft Subgrade Site

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At the Pueblo test facility a clay subgrade layer 1.5 m (5 ft) thick was installed to provide a low modulus track. The performance and maintenance requirements of this track under accumulated traffic (with a 170-kN or 39-kip wheel load) were compared with those of an adjacent track section with natural stiff subgrade. In this way the effect of substructure condition on track performance was distinguished. It was determined that the low modulus track produced a more variable support condition than did the stiffer track. Larger variation in support provided more differential settlement and, therefore, required more smoothing maintenance. Track deflection under load provides information regarding substructure support and related track maintenance needs. Three ways of characterizing the load-deflection characteristics of track were considered: track deflection, track stiffness, and track modulus. The results of these measurements are shown and compared, and the implications of using each are discussed. Whichever technique is used, a system that can take measurements on a continuous basis is recommended to determine the support characteristics along the track. Such a system could be used to identify those sections requiring differing amounts of maintenance and those that may need rehabilitation to increase the modulus to an acceptable level.

The natural silty sand at the Pueblo Transportation Test Center (TTC) is an excellent subgrade for track support. As a consequence, track performance at TTC is based on track modulus values believed to be larger than the average encountered in typical revenue track. It was decided to determine the performance of a low modulus track by installing a section of low stiffness subgrade.

To evaluate the feasibility of such a test, a trial low track modulus (TLTM) section 30 m (100 ft) in length was first constructed (*1*). Based on the results and experience gained from this trial section, a low track modulus (LTM) track section 180 m (600 ft) long was designed and constructed. The goal was to provide a stiffness simulating the lower end of mainline track, not a worst-case situation. A similar length of track with the same construction, but with the natural Pueblo subgrade, was selected to be the control section.

The purpose of this paper is to show how track modulus and the associated deflections relate to track performance. Substructure conditions and maintenance requirements may be indicated by such deflection-based measurements. Track modulus, track stiffness, and track deflection were obtained from vertical load deflection curves. Track geometry and deflected rail shape (basin) were also measured. These values were calculated under both a small "tie seating" load and under a larger "full tie contact" load.

SITE DESCRIPTION

The LTM was located in Section 29 on the test loop as shown in Figure 1. Also shown is the location of the control section (Section 33). The low modulus subgrade was constructed by digging a trench and filling it with clay. The LTM was constructed with a ramp on one end of the trench and a vertical cut at the other end.

The cross-section for the LTM is shown in Figure 2. The depth and width of the trench were selected based on a GEOTRACK (*2*) analysis which indicated a track modulus of about 14 MPa (2000 psi) would result from such a design (*1*). Track modulus with the natural subgrade was typically 21 to 41 MPa (3000 to 6000 psi). The clay used is known as Mississippi Buckshot clay, a CH-type soil under the Unified Soil Classification System, with a plasticity index (PI) of 15 to 20 and a liquid limit (LL) of 60 to 70. The as-installed moisture content was in the range of 30 to 35 percent (*1*).

A 20 mil PVC liner was placed along the sides and bottom of the trench to prevent the loss of moisture from the clay subgrade into the surrounding natural subgrade. Longitudinal drains were installed to remedy decreases in the clay moisture from the as-installed moisture content, by the addition of water if the moisture sensors indicate a loss.

Although a small portion of the rail in the LTM test was 65.9 kg/m (133 lb/yd), only the track with 67.6 kg/m (136 lb/yd) was used in the analysis. No joints were present within the track used in analysis. Wood ties of dimensions 175 mm (7 in.) high by 225 mm (9 in.) wide by 2.6 m (102 in.) long were used at 495-mm (19.5-in.) spacing.

A 300-mm (12-in.) depth of dolomite ballast was used. The subballast was a 150-mm-thick (6 in.) layer consisting of broadly graded sand with silt and gravel. The clay was compacted with pneumatic tire rollers in 250-mm (10-in.) layers to a dry density equal to or exceeding 90 percent ASTM D698 maximum dry density. In the control section the natural subgrade was leveled and compacted. Then the subballast, ballast, and track were placed over the test sections.

The relative strength of the substructure layers was determined using a cone penetrometer test (CPT) setup as shown in Figure 3. Figure 4 shows the CPT profiles with depth averaged over the clay and control test section lengths. The depth is measured from the top of the subballast and the tip resistance measurements started at the top of the subballast.

When maintenance was needed anywhere in the section, tamping was applied over the entire section. When the track geometry exceeded FRA Class 4 standards of cross level or profile, the section was lined and surfaced with a tamper. Recurring tamping cycles were required in the LTM test clay section about every 15

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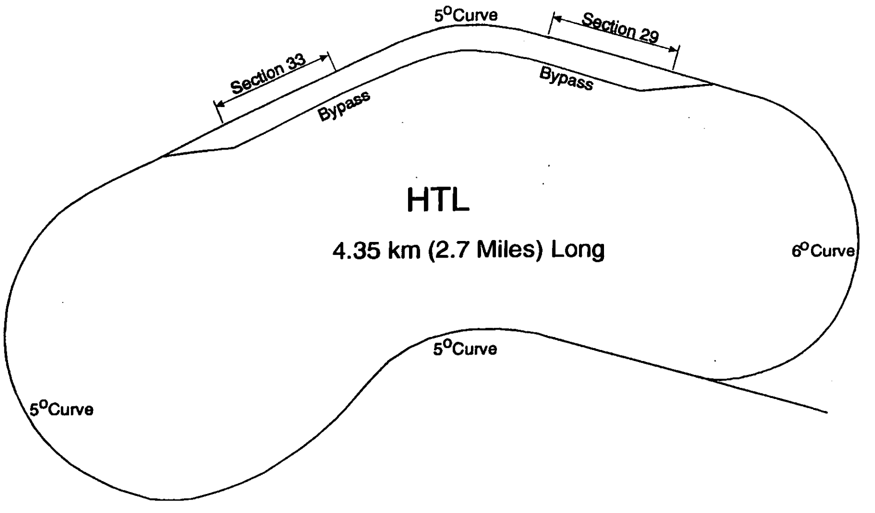

FIGURE 1 Layout of high-tonnage loop.

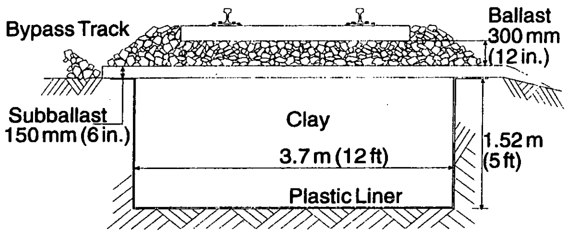

FIGURE 2 Cross section of LTM clay subgrade section.

MGT due to progressive deformation of the subgrade. Cross-trench excavations revealed the subgrade profile to be depressed under the tie ends with most excavations exhibiting heaving beyond the tie ends. While this subgrade deformation pattern seemed to be present throughout most of the test zone, its severity in a few locations controlled the tamping requirements.

TRACK DEFLECTION MEASUREMENTS

Track deflection was measured under the load provided by the vehicle shown in Figure 5. The load was applied to each rail in increments of 44.5 kN (10 kips) up to a maximum of 178 kN (40 kips). At each load increment the track deflection was measured using a digital level. These measurements were made initially after construction prior to traffic, at regular intervals of traffic, and before

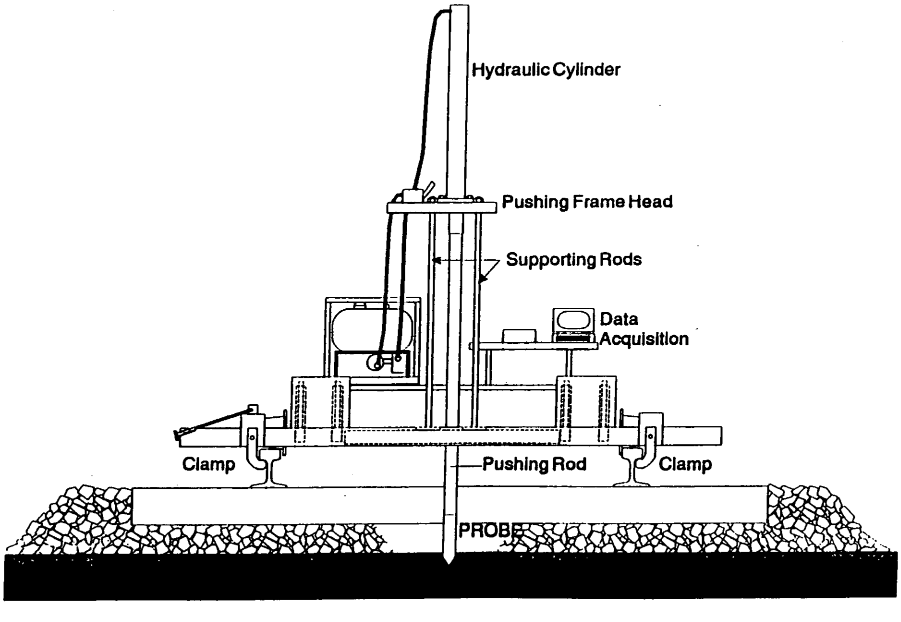

FIGURE 3 CPT test setup.

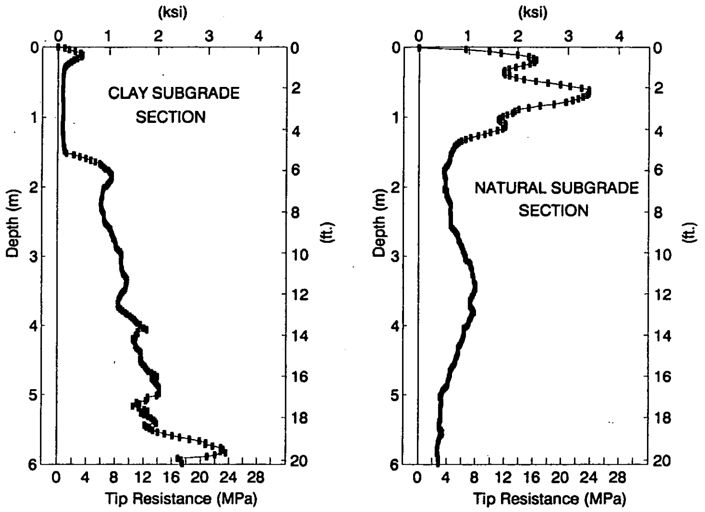

FIGURE 4 Average cone penetrometer test profiles.

and after tamping when subsequent tamping maintenance had occurred.

Stiffness and Modulus

The slope of the load-deflection line between 0 and 44.5 kN (10 kips) gives an indication of the voids or slack between the ties and the ballast in the influence length of the wheel. This 44.5 kN (10 kip) load is referred to as the tie "seating" load and the modulus or stiffness calculated for this interval will be referred to as the seating modulus or seating stiffness.

In most tests the load-deflection relationship between 44.5 and 178 kN (10 and 40 kips) was found to be approximately linear, although in some cases stiffening was found at the maximum load range. The slope of the line between the 44.5 kN and 178 kN (10 and 40 kip) loads where the tie is in contact with the ballast is an indication of the support condition of the substructure. The modulus or stiffness in this load range will be referred to as the contact modulus or contact stiffness.

To calculate track stiffness and modulus, the following procedure was used. Track Stiffness, S, for a selected load increment is given by

$$S = \frac{P_f - P_o}{y_f - y_o} \qquad (1)$$

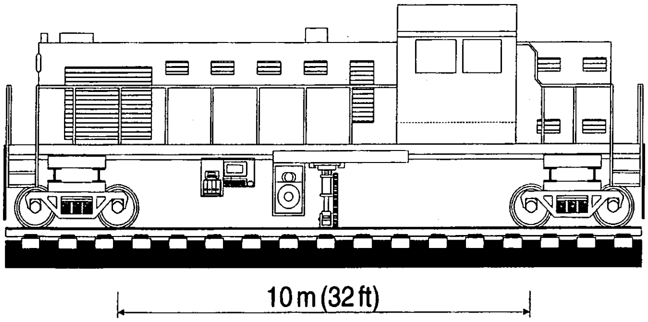

FIGURE 5 Track loading equipment.

where

P_f = final vertical rail force,
P_o = initial vertical rail force,
y_f = final rail elevation, and
y_o = initial rail elevation.

Track modulus, u, is determined using the beam-on-elastic-foundation model as given by Zarembski and Choros (*3*) as follows:

$$u = \frac{(S)^{\frac{4}{3}}}{(64EI)^{\frac{1}{3}}} \qquad (2)$$

where E is Young's modulus of rail steel and I is rail moment of inertia.

Deflection Basins

The shape of a deflected track under a single-wheel load (deflection basin) was measured using the same loading equipment (Figure 5). Deflections were measured at the point of applied load and at the next five ties to one side of the applied load. The seating basin is obtained from the deflections measured at each tie between 0 and 44.5 kN (10 kips), and the contact basin is obtained from the deflection difference at each tie between 44.5 kN and 178 kN (10 kips and 40 kips).

The track modulus can be calculated from the deflection basin measurements. Based on the fact that for vertical equilibrium of forces with the beam-on-elastic-foundation model, the integral of the supporting line force must be equal to the applied force. Hence,

$$P = \int_{-\infty}^{\infty} uy\,dx \qquad (3)$$

If u is considered constant along the rail then Equation 3 becomes

$$P = uA_y \qquad (4)$$

where A_y is the area of the deflection basin caused by the vertical force P.

RESULTS

Track Deflection Results

A comparison of modulus values between the control section and the clay section of the LTM test is demonstrated in Tables 1 and 2. Because track modulus can be highly variable from tie to tie, a single measure can be very misleading. With several such measurements a characteristic trend will emerge as shown by the distinct average modulus values in the table for the two sections.

The data in Table 1 also indicate that a significant difference in modulus may be obtained depending upon whether Equation 2 or 4 is used. Use of Equation 2 assumes (*a*) a deflected rail shape based on the *EI* value of the rail, and (*b*) support conditions that are constant under each tie in the influence length of the load applied. These assumptions are not made in Equation 4 where the actual deflected

TABLE 1 Modulus Calculation Comparison in SI Units

Clay Subgrade				
Tie No.	Modulus from Eq. 2 (MPa)		Modulus from Eq. 4 (MPa)	
	Seating	Contact	Seating	Contact
135	6.4	31.4	8.1	25.6
216	8.8	20.2	6.5	13.1
297	5.1	20.1	6.2	15.6
378	3.6	37.5	5.8	26.5
459	6.8	38.0	4.9	23.9
507	3.7	115.6	3.7	59.5
Average	**5.7**	**43.8**	**5.9**	**27.4**
Natural Subgrade				
188	13.4	65.8	14.3	37.4
269	27.1	72.5	23.3	57.4
350	12.9	77.5	10.3	33.7
431	7.8	121.3	8.2	61.3
Average	**15.3**	**84.3**	**14.0**	**47.5**

TABLE 2 Modulus Calculation Comparison in U.S. Units

Clay Subgrade				
Tie No.	Modulus from Eq. 2 (psi)		Modulus from Eq. 4 (psi)	
	Seating	Contact	Seating	Contact
135	910	14000	1200	3700
216	1300	3000	930	1900
297	740	3000	880	2300
378	1100	5500	820	3900
459	1000	5500	690	3500
507	530	17000	540	8500
Average	**930**	**7100**	**840**	**4000**
Natural Subgrade				
188	2000	10000	2000	5400
269	3900	11000	3400	8300
350	1900	11000	1500	4900
431	1100	17000	1200	9000
Average	**2200**	**12000**	**2000**	**6900**

rail shape is obtained at certain ties. Not surprisingly, these two moduli calculations often give different results. The contact moduli values appear to be more affected by the calculation method than are the seating moduli values. The calculated contact moduli are consistently and significantly lower using Equation 4 compared with Equation 2. Use of Equation 2 (the single point deflection measurement) is often more convenient than measuring the deflection at several points. However, using the basin area method of Equation 4 to calculate modulus is probably more accurate.

Load-Deflection Curve Shapes

Figure 6 shows the typical shapes of the load-deflection curves for both subgrade test sections in the LTM test. In most cases, the characteristic load-deflection curves at 0 MGT for both subsections were approximately linear beyond the 44.5 kN (10 kip) seating load. With traffic accumulation the curves were less linear (although this is still a good approximation) and there was more variability in stiffness both from tie to tie and between rails of the same tie in the clay section. The shape of the load-deflection curves in the natural subgrade section was relatively constant with MGT. The average deflection at full load in the clay subsection was approximately double that in the natural subgrade subsection.

Running Deflections

The running deflections (seating and contact) are shown in Figure 7 for the clay and natural subgrade sections. Note the larger and less uniform deflections in the clay section. Track with a lower modulus subgrade appears to exhibit both larger deflections and less uniform support compared to track with the stiffer subgrade. Figures 8 and 9 show the variation in average contact deflections with traffic for

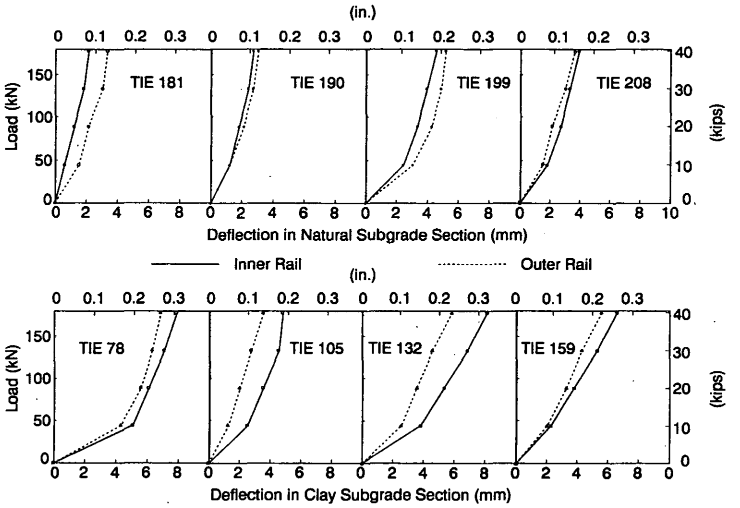

FIGURE 6 Stiffness tests in natural and clay subgrade sections.

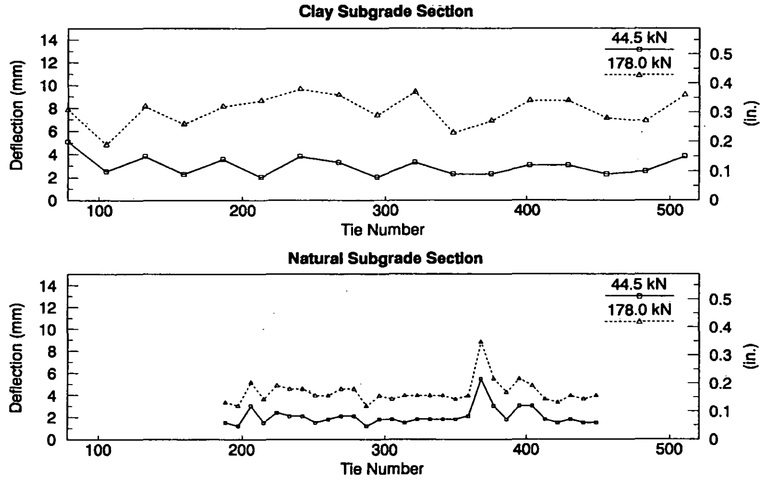

FIGURE 7 Loaded deflections of inner rail for clay and natural subgrade sections.

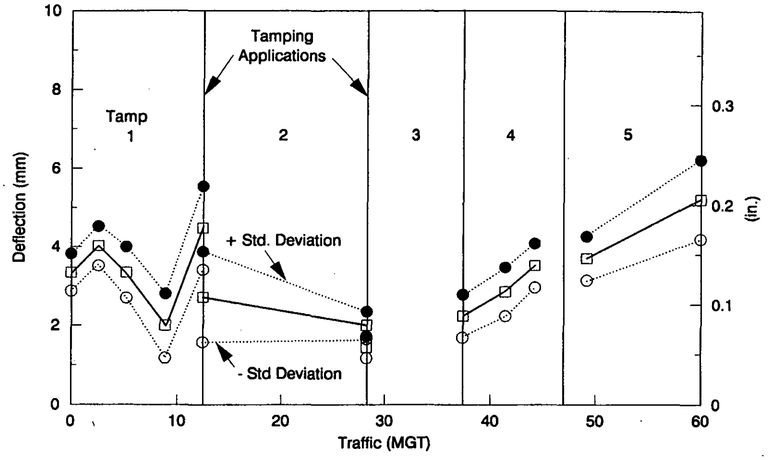

FIGURE 8 Change in average contact deflection with traffic for clay subgrade section.

both sections and the range of values as indicated by the standard deviation. The increased variation of contact deflection in the clay section, compared to the control section, is clearly illustrated in these figures. Maintenance requirements are thought to be indicated by such a measure of variation in support.

Track Modulus—Seating and Contact

The seating and contact moduli averaged over the clay and natural subgrade section lengths, and averaged between the two rails, are shown in Figures 10 and 11, respectively. The vertical lines in Figure 10 indicate the MGT at which maintenance was performed within the test section. Note that the modulus measurement taken at 10 MGT was obtained during an extended cold period with precipitation, which may help explain the larger modulus values. The freezing temperatures and recent precipitation may have resulted in a frozen ballast section (and possibly frozen the subballast and a portion of the upper subgrade) which produced a very stiff track. Figure 10 shows that frozen conditions seem to have a greater effect on the contact modulus compared to the seating modulus. With subsequent thawing the track moduli returned to their nominal values. Maintenance appears to produce a stiffer track after tamping as shown in the tamping application at 12 MGT in the clay subgrade section (Figure 10). However the apparent trend is a modulus decrease with tonnage accumulation and the track modulus returning to its nominal value.

Basin Results

Figure 12 shows the seating and total deflection basins averaged between the two rails and over the lengths of the clay and natural subgrade sections. Note that the maximum total deflection measured (directly under the wheel) in the clay section is about double that in the natural subgrade.

The average contact basins in Figure 13 have the slack effect from the voids under tie removed. Here the basins in the two sub-

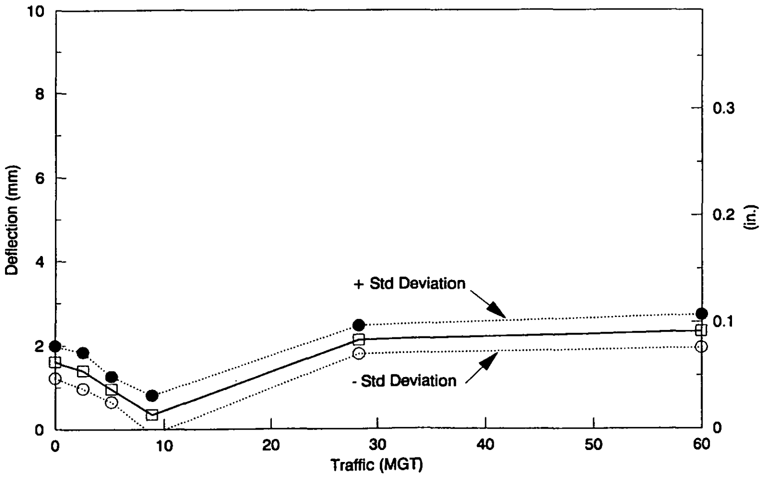

FIGURE 9 Change in average contact deflection with traffic for natural subgrade section.

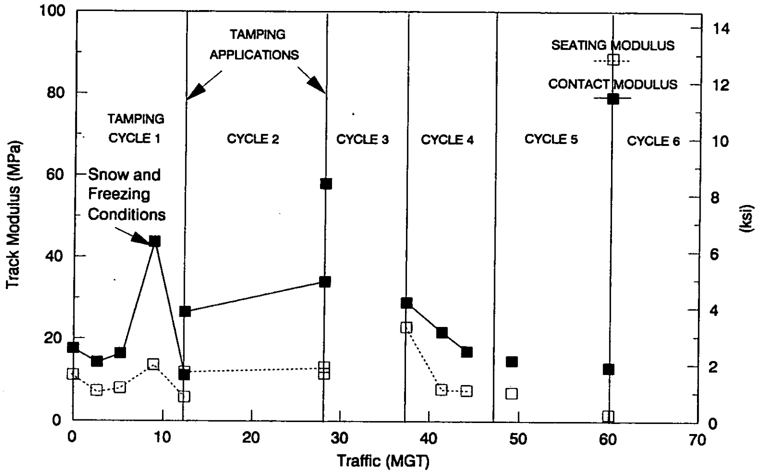

FIGURE 10 Average modulus values in clay subgrade section.

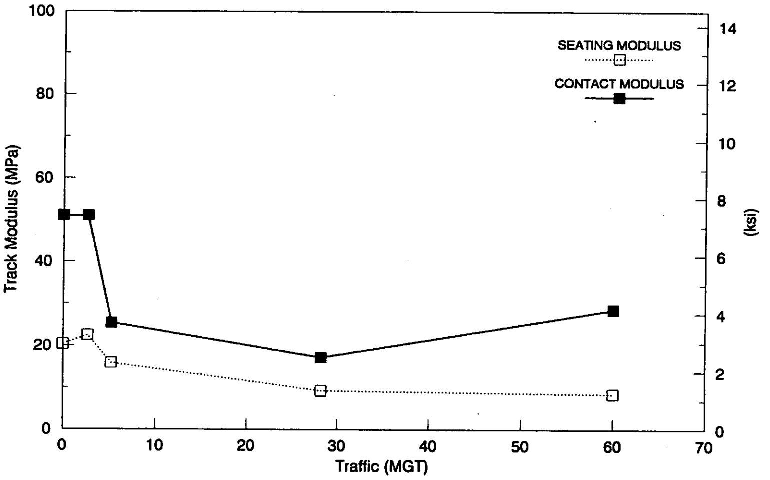

FIGURE 11 Average modulus values in natural subgrade section.

grade sections may be more meaningfully compared, since the difference between them is now almost entirely due to subgrade deformation. Note the difference in deflected rail area between the two sections. The deflection under the load point in the clay section is approximately twice that in the natural subgrade section.

A rolling wheel load is always trying to "climb out" of the total deflection curve. The difference in rolling resistance and consequent train energy consumption between these two track sections may be significant.

Comparison with GEOTRACK

The GEOTRACK model was used to determine if the measured load-deflection curves could be predicted by the model for the known track properties. For both the clay and natural subgrade sections, the subgrade was subdivided into two separate layers with moduli determined by the following equation (*4*):

$$E_r = 20q_c \qquad (5)$$

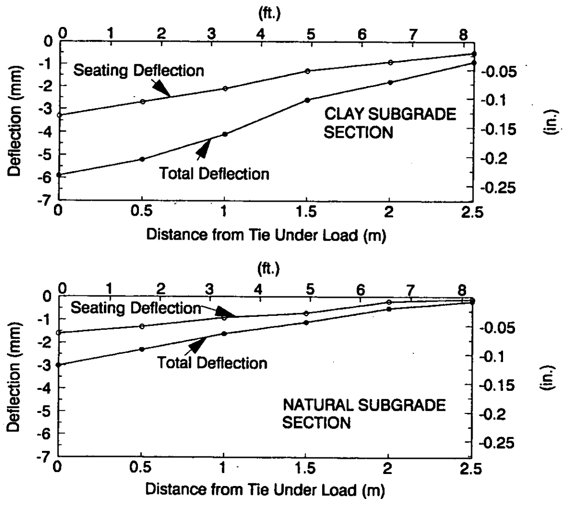

FIGURE 12 Average seating and total deflection basins in clay and natural subgrade sections.

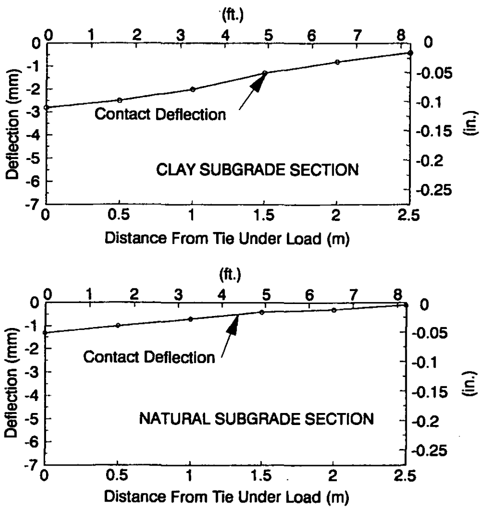

FIGURE 13 Average contact deflection basins in clay and natural subgrade sections.

where E_r and q_c are in psi, using the CPT tip resistance values from Figure 4. The subgrade layer profiles and parameters are shown in Table 3 along with the predicted contact deflections of the rail under a wheel load of between 44.5 kN and 178 kN (10 kips to 40 kips). Note that the GEOTRACK model does not predict any slack between the tie and ballast. Therefore, the model should only be used to compare with the measured contact deflections. If these predicted contact deflections of the rail under the load in Table 3 are compared with the measured average contact deflections under the wheel for both sections (Figure 13) the load-deflection can be predicted reasonably well by the CPT results and GEOTRACK.

The GEOTRACK model was also used to determine if the measured basins could be predicted by the model for the known track properties. Again the subgrade properties listed in Table 3 were used in the analysis. A comparison (Figure 14) showed that the measured average contact basins for both subgrade sections agreed reasonably well with the model prediction.

Relationship Between Modulus and Maintenance

By determining track stiffness or modulus, the track engineer can make some estimates regarding substructure conditions. These conditions are believed to be related to maintenance requirements. For example, Figure 15 shows the measured relation between cross-level deviations and track modulus in the LTM test. The track modulus and cross-level measurements were made at the same tie locations after 13 MGT. A power-curve relation shows the large impact track modulus can have on track performance when modulus decreases much below about 21 MPa (3,000 psi).

Because track stiffness or modulus can distinguish substructure conditions, such measures taken continually can identify track sections requiring different levels of maintenance. These measures can also help determine sections that are too soft and may require a remedy to increase the modulus to an acceptable minimum.

SUMMARY AND CONCLUSIONS

Tests to determine the effect of low-modulus track on track performance were performed at the Transportation Test Facility at Pueblo, Colorado. A site with the natural subgrade provided a relatively high track modulus section used as a comparison with a test section with a 1.5-m (5-ft) clay subgrade layer (the low track modulus section or LTM). One of the main goals of the test was to determine the relation between track support characteristics and track performance.

Three ways of representing the load-deflection characteristics of track were presented: track stiffness, track modulus, and track deflection. Track stiffness is the change of load divided by the change in deflection of the track at the point of loading. The minimum load used, taken in this study to be 44.5 kN (10 kips), is judged sufficient to "seat" the tie by removing the void space between the tie and ballast. The load-deflection response above this seating load was relatively linear. Track modulus, *u*, can be computed from the stiffness. However, *u* is derived based on the beam-on-elastic-foundation model which includes the effects of ties and fasteners. Unless an analysis is to be performed which requires this kind of model, a simpler approach is to use track stiffness, which is a more

TABLE 3 Subgrade Section Depths and Moduli, Predicted Track Moduli, and Rail Contact Deflections

Clay Subgrade Section

Subgrade Layer	Depth	Subgrade Layer Modulus	Track Modulus	Peak Rail Contact Deflection
I	1.5 m (5.0 ft.)	18 MPa (2.6 ksi)	2.2 MPa (3.1 ksi)	2.8 mm (0.11 in.)
II	∞	190 MPa (28 ksi)		

Natural Subgrade Section

Subgrade Layer	Depth	Subgrade Layer Modulus	Track Modulus	Peak Rail Contact Deflection
I	1.1 m (4.5 ft.)	280 MPa (40 ksi)	50 MPa (7.2 ksi)	1.5 mm (0.06 in.)
II	∞	110 MPa (16 ksi)		

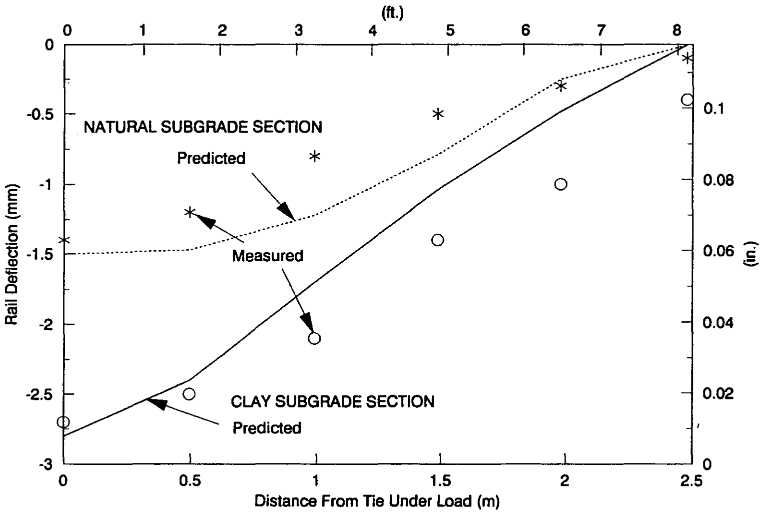

FIGURE 14 LTM-measured and GEOTRACK-predicted contact rail deflection basins.

direct measurement of track response as felt by vehicles. Two track stiffnesses or moduli should be determined. One is based on deflection under the seating load, a measure of the voids under the ties. The other is based on the deflection under the load change above the seating load, which is a measure of the substructure support stiffness.

Another method holds promise and is potentially even simpler than stiffness: measuring the deflection both under a seating load and a representative operating load. The difference between the two deflections is the contact deflection. The value of such an approach could be appreciated if measurements could be taken on a moving, continuous basis with a special track vehicle. Such a vehicle would need to be developed.

Also discussed was the comparison of the benefits of measuring track deflection only at the point of application of the single load, with the deflected track shape measured over all the ties affected by the load. A weaker soil will cause a larger deflection and basin area. It is possible that the basin area provides a better measure of track support than the single point deflection. To obtain this basin area, the deflection over several ties was measured. Track modulus values calculated on the basis of the basin area were found to be significantly lower, for the case of contact modulus, from those values obtained by measuring deflection at a single tie location. Track modulus calculated from a single point deflection assumes that the support for the other nearby ties is the same as that under the tie with the load. Obtaining this deflected rail shape or basin may provide a more accurate modulus value and the track modulus so obtained should be distinguished from the one calculated on the basis of deflection measured at a single tie.

Track support can vary significantly along the track. Because the measure of this variance is thought to provide indications of maintenance requirements, the continuous measurement of track stiffness or modulus may be highly beneficial. Such an arrangement could continuously measure the deflection or basin area and indicate the seating and contact deflections and modulus. This has the

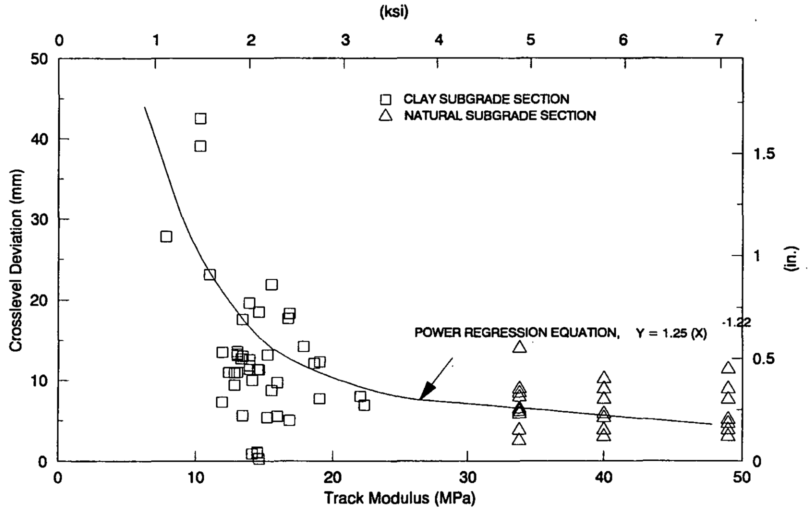

FIGURE 15 Relationship of LTM cross-level deviations to track modulus.

potential to indicate track segments needing different levels of maintenance.

Although it is not yet certain whether track stiffness, track modulus, or merely a measured deflection under a given load—moving or static—is the best way to determine track support characteristics, any such measurements have the potential to indicate substructure-related maintenance needs and costs.

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