Measurement and Prediction of Vertical Track Modulus

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ABSTRACT

Field measurements of vertical deflections and track modulus under static loading conditions were obtained at four revenue service track locations. The track sections contained both concrete and wood ties. The measurements were made before a scheduled track maintenance operation and were repeated after the surfacing to determine the effects of maintenance on the vertical track response. Differences between the pre- and postmaintenance results were found and are discussed in terms of physical state of the ballast and the characteristics of the layered track systems. The resilient foundation properties of the field sites were obtained from both field and laboratory measurements. Predictions of vertical track response at the sites were then made using a three-dimensional, nonlinear, elastic, multilayer track analysis program. The predicted values of vertical track response were in general agreement with the measured values, although some differences were evident. The major variables affecting track modulus are identified and conclusions are presented on the usefulness of vertical track modulus as a measure of track performance.

The supporting capacity of conventional track is frequently characterized by the track modulus. An understanding of the factors influencing track modulus and of the effects of maintenance on the track support values is important. This is particularly evident when track modulus values are used for design purposes or in assessing track performance.

The results of field measurements of vertical track response, under static loading conditions, from four revenue service track locations are presented. The measurements were made before a scheduled track maintenance operation and were repeated after the surfacing. In addition, field and laboratory measurements of the resilient foundation properties were made. These properties were used to predict the track responses at each of the sites so that a further understanding of the factors influencing vertical track response could be developed by comparing measured and predicted track moduli.

DESCRIPTION OF SITES

Four revenue service track locations were selected as test areas for this project. The revenue service sites included three locations that contained concrete cross ties and a control section with wood cross ties. The wood tie control section and one concrete tie section are located in Leeds near Streator, Illinois, in the north-central section of the state. The remaining two concrete tie test sections are located at Aberdeen, Maryland, and Lorraine, Virginia. A detailed description of each of these four sites is given elsewhere (1).

The wood tie test section at Leeds is an 800-ft-long portion of tangent track owned by the Atchison, Topeka, and Santa Fe (ATSF) Railroad. It is built on a fill embankment approximately 12 ft high. The ballast in this section is slag, and the ties are hardwood at 19.5-in. nominal center-to-center spacing.

The Leeds concrete tie test section is contiguous to the wood tie section on the same track. This concrete tie section contains granite ballast, and both RT-7S and Costain Conforce CC244C ties at 24-in. center-to-center spacing. The total test section length is 800 ft, but the tests and measurements were confined to the track section having the Costain ties. Pandrol spring-clip fasteners are used on the Costain-type ties.

The Lorraine, Virginia, concrete tie test installation is owned by the Chessie system and is located in the western Richmond suburb of Lorraine, on the north bank floodplain of the James River. The test section is on a single main-line track built on an embankment about 7 ft high on the south side. This Lorraine concrete tie test section contains both CC224 ties and RT-7S ties. The test section is in the middle of a 3-degree curve, with a 3-in. superelevation on the outside rail. The ballast is predominantly gneiss and limestone. The ties are located at 25-in. center-to-center spacings.

The Aberdeen, Maryland, site is on one of three parallel main-line electrified tracks, owned by Consolidated Rail Corporation (Conrail), that carry traffic between Baltimore and New York. The ballast in the test section is a traprock. The track is tangent with RT7-SS2 concrete cross ties at 24-in. center-to-center spacings.

TRACK MODULUS FORMULATION

The use of track modulus for assessing track performance is common in the railroad industry. The theoretical formulation of track modulus is based on the assumption that the rail acts like a beam continuously supported on an elastic foundation. Track modulus (u) is defined as the supporting force per unit length of rail per unit deflection in the track system. A diagram of the assumed conditions for the formulation of track modulus is shown in Figure 1.

The differential equation describing the deflection, due to an applied vertical load, of a uniformly supported rail on a linear elastic foundation is given by

$$EI(d^4\delta/dx^4) = q = -u\delta \quad (1)$$

where

EI = rail bending stiffness (units = FL^2);
δ = vertical rail deflection (units = L);

x = horizontal distance along the rail, measured from the applied load point (units = L);
u = track modulus (units = F/L/L); and
q = vertical foundation supporting force (units = F/L).

The solution to Equation 1 is given by

$$\delta = [(\beta P/2u)e]^{-\beta x}(\cos \beta x + \sin \beta x) \quad (2)$$

where P is the applied load and

$$\beta = (u/4EI)^{1/4} \qquad (\text{units} = 1/L) \quad (3)$$

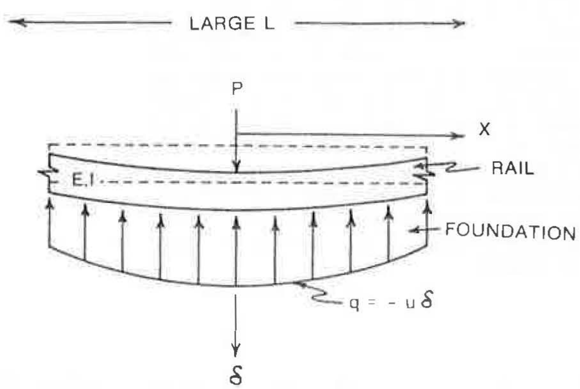

FIGURE 1 Assumed conditions for beam theory formulation of track modulus.

The maximum rail deflection occurs at x = 0, and is given by

$$\delta_{x=0} = \beta P/2u \quad (4)$$

The equation for maximum rail deflection can be re-arranged by substituting β from Equation 1 and solving for u. The resulting equation for track modulus is

$$u = 1/4[(P/\delta)^4 \cdot 1/EI]^{1/3} \quad (5)$$

An important difference between the actual track support and the idealized formulation of a rail on an elastic support is that the rail load is actually applied to the foundation through discrete supports, which are the ties, not through support distributed along the track foundation. Another difference, for concrete tie track systems, is the inclusion of flexible tie pads between the rails and the tie rail seats. Even though these differences exist between the actual track structure and the theoretical formulation, the track modulus has historically been used as a measure of track quality. Further details on the historical development and interpretation of track modulus can be found elsewhere (2,3).

TABLE 1 Track Structural Properties for Field Sites

Parameter	Leeds Wood	Leeds Concrete	Aberdeen	Lorraine
Tie type	Hardwood	CC244C	RT7-SS2	CC244
Tie spacing (in.)	19.5	24.0	24.0	25.0
Tie length (in.)	102	102	102	102
Tie bottom width (in.)	9.00	10.75	10.75	10.75
Tie bending stiffness [EI(lb/in.^{2} x 10^6)]	386	1740	1740	1740
Rail section	136RE	136RE	140RE	122RE
Rail bending stiffness [EI(lb/in.^{2} x 10^6)]	2742.6	2742.6	2797.5	2138.6
Rail fastener type	Cut spikes	Pandrol	Pandrol	Pandrol
Rail fastener or pad stiffness (lb/in.^{2} x 10^6)	6	4	4	4

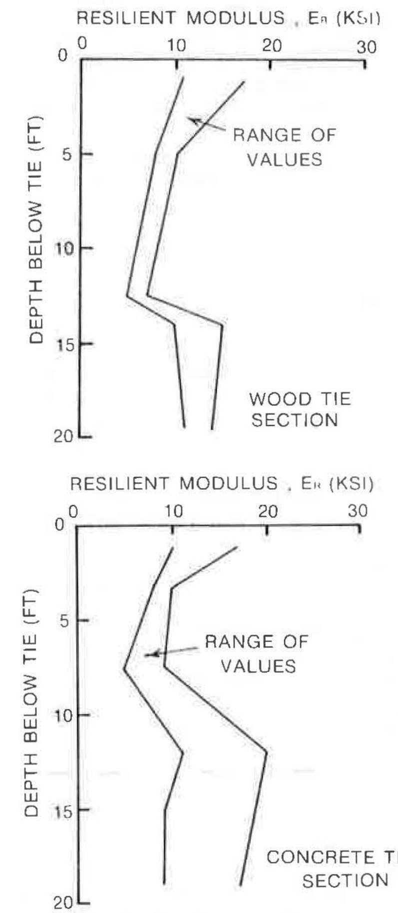

FIGURE 2 Resilient modulus versus depth for Leeds wood and concrete tie sections.

SELECTION OF PARAMETERS FOR PREDICTIONS

The GEOTRACK model (4,5) was used to determine track deflections for predicting values of track modulus for the revenue field sites. To do this, the track structural properties and foundation characteristics of each site had to be chosen. Table 1 gives the structural properties representing each of the sites.

The subgrade layer properties used for the GEOTRACK analyses were chosen on the basis of the results shown in Figures 2 and 3. The subgrade values shown in Figures 2 and 3 were derived from repeated load triaxial tests (6) and additional correlations made between cone and standard penetration data (7). Layer divisions for the subgrades were made where there appeared to be significant changes in the measured resilient properties. The average resilient modulus for each layer was used as the representative value for the layer. The moduli for the subgrade layers were held constant because stress-state-dependent relationships were not available for the subgrade.

A shear stress-resilient strain formulation (8) was used to characterize the stress-dependent ballast properties for these sites. The moduli (E_r) of the ballast from the final iteration of the

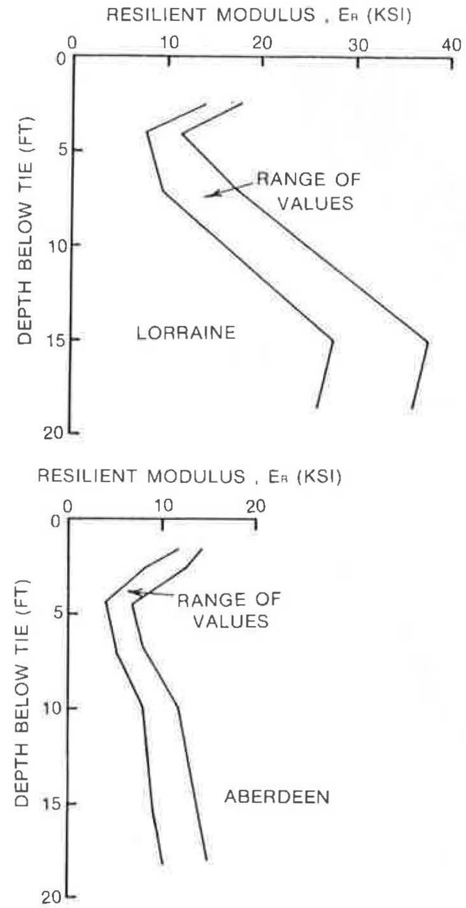

FIGURE 3 Resilient modulus versus depth for Lorraine and Aberdeen.

GEOTRACK program for the track modulus predictions are given in Table 2. The dependency of the ballast resilient modulus (E_r) on stress state is evident from the change in modulus with wheel load.

COMPARISON WITH FIELD MEASUREMENTS

Measurements of track vertical load-deflection response were made at each of the revenue field sites by Battelle-Columbus Laboratories (BCL). For the test, a point load of known magnitude was simultaneously applied to both rails using vertical hydraulic jacks reacting against a loaded freight car. Rail deflections were measured by sighting a steel scale with a surveyor's theodolite. The scale was attached to the rail. Seven to ten measurements at

TABLE 2 Ballast Moduli Determined for Track Modulus Predictions

Site	Thickness of Ballast Layer (in.)	Resilient Modulus (E_r) in psi: Wheel Load = 6 Kips	Wheel Load = 30 Kips
Leeds			
Wood	9	5,300	25,500
Concrete	7	10,000	35,000
	7	7,800	15,500
Lorraine	14	8,700	29,000
	14	6,500	17,200
Aberdeen	10	10,800	34,500
	10	9,500	15,000

random tie locations were made to assess the variability in the load-deformation responses within the track sections. These measurements were made both before and after the maintenance operations to determine what differences in track support resulted from the surfacing operation.

The measured averages and standard deviations for the pre- and postmaintenance load-deflection curves are shown in Figures 4-7 for the Leeds wood, Leeds concrete, Lorraine, and Aberdeen sites, respectively. The premaintenance curve for the Leeds concrete section (Figure 5) was based on measurements taken after about 1 month of traffic had passed instead of immediately before maintenance because a surfacing operation had taken place just before the initial site visit. Although both pre- and postmaintenance values for the Aberdeen site were recorded, only the postmaintenance results were reported by BCL.

A small amount of slack may have been present in the track structure as indicated by an initial break in the curves as shown in Figures 4-7. This initial slack was assumed to have been eliminated after about a 6-kip load was applied. To remove this effect, the track modulus values were calculated for the 6- to 30-kip load range.

The variabilities of the track modulus measurements were estimated using the mean track deflections from the averaged load-deflection curves, and the deflections at ± 1 standard deviation at the 6- and 30-kip load levels shown in Figures 4-7. However, the actual variabilities of the track modulus measurements were probably greater than the estimates determined in this manner. For the purposes of this paper, the standard deviations of the track modulus values will refer to the limits calculated on the basis of the standard deviations of the rail deflections. It must be noted that these are not the true standard deviations, and these values of standard deviation are not symmetrical about the mean values.

To determine track modulus with GEOTRACK, deflections were calculated for the single-axle solution with loads of 6 and 30 kips. The difference in loads and the difference in deflections were substituted into Equation 5 to obtain track modulus.

The measured values of track modulus and the estimated standard deviations for all of the revenue field sites are given in Tables 3 and 4 and shown in Figure 8, along with the predicted values based on the GEOTRACK analyses. Several items on Figure 8 deserve attention. First, there were no significant changes in the track modulus values as a result of the surfacing operations. However, the premaintenance values did appear to be less variable than the postmaintenance values. This variation is also apparent in the average load-deflection curves (Figures 4-7) where the scatter about the mean is visibly larger for the postmaintenance values. That the average measured values were greater in the Leeds wood and Lorraine sections after maintenance is probably not statistically significant because the estimated standard deviations all overlap.

Another observation from Figure 8 is that there did not appear to be a correlation between height of raise and postmaintenance track modulus. Raises of 1.5 to 2 in. were given to the Leeds and Lorraine sections and only about 0.1 in. to the Aberdeen section. In spite of this, the pre- and postmaintenance values for any one test section were approximately equal, and the Aberdeen value was between the Lorraine and Leeds values.

An explanation of the increased variability of the postmaintenance modulus values compared to the premaintenance values could be that the surfacing decreased the uniformity of track support conditions

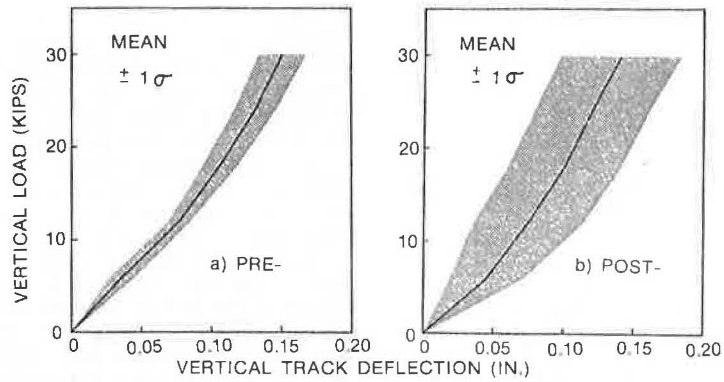

FIGURE 4 Track load-deflection curves for Leeds wood.

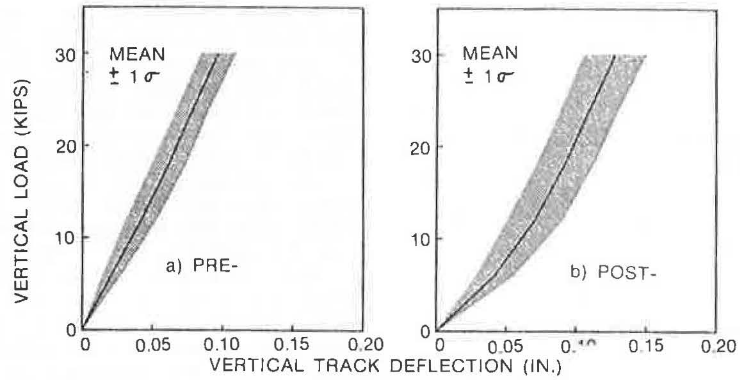

FIGURE 5 Track load-deflection curves for Leeds concrete.

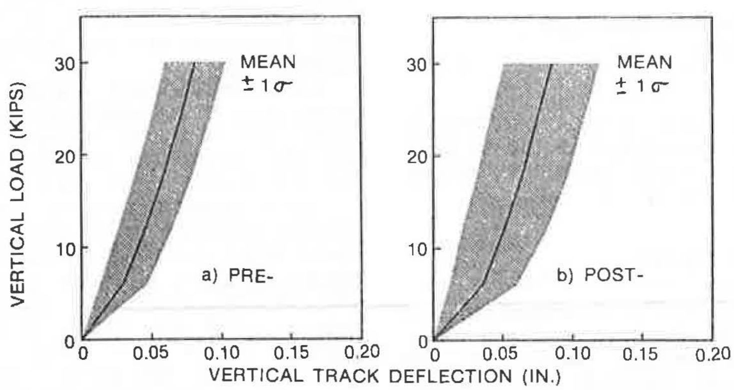

FIGURE 6 Track load-deflection curves for Lorraine.

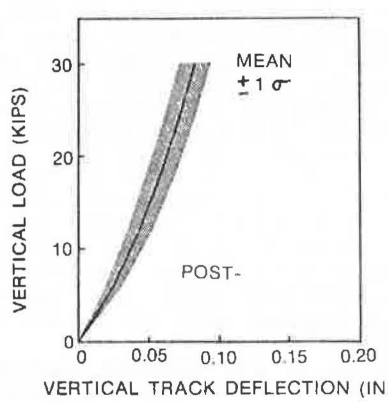

FIGURE 7 Track load-deflection curve for Aberdeen.

between the locations. One purpose of track maintenance is to improve the overall track surface by smoothing out longitudinal differential track deformations. Varying amounts of raise must be applied beneath the ties to achieve a uniform surface. Variations in the actual raises applied beneath the individual ties could cause local differences in the amount of ballast disturbance, hence variations in physical state of the ballast from one tie to another.

Part of the difference in absolute magnitude of the average field track modulus measurements can be explained in terms of the differences in the track substructures. A parametric study using the GEOTRACK model (5) indicated that track modulus increased as ballast depth increased. The Leeds wood section had only about 9 in. of ballast beneath the tie, whereas the Leeds concrete section contained about 14 in. The Aberdeen site had 20 in. of ballast, and the

TABLE 3 Measured Averages and Estimated Standard Deviations for Revenue Field Sites

	Track Modulus for 6- to 30-Kips Load Range					
	Premaintenance			Postmaintenance		
Field Site	$-\sigma$	Average	$+\sigma$	$-\sigma$	Average	$+\sigma$
Leeds						
Wood	2.1	2.2	2.5	2.3	2.9	3.7
Concrete	3.5	3.9	4.3	2.9	3.3	3.8
Lorraine	6.4	7.0	7.9	6.0	7.6	10.6
Aberdeen				4.9	5.5	6.5

TABLE 4 Predicted Values for Revenue Field Sites

Field Site	Track Modulus (u)
Leeds	
Wood	5.2
Concrete	5.5
Lorraine	8.9
Aberdeen	5.6

Note: Units of u = $kips/in.^2$

ballast depth at Lorraine was estimated to be 28 in. below the tie. Although the influence of site location cannot be separated from the results, this trend of increasing track modulus with increasing ballast depth for the field sites was confirmed by the field measurements as shown in Figure 9.

SUBGRADE EFFECTS

The track modulus is also influenced by the subgrade characteristics. The GEOTRACK model indicates that the compression of the ballast layer accounts for about 10 to 20 percent of the total vertical deflection of the track structure. The remainder of the total deflection is due to the compression of the subgrade materials. Furthermore, 25 to 40 percent of the subgrade deformation indicated by GEOTRACK occurs below a depth of about 10 ft, even though the stresses below this depth are low (5).

The Lorraine test section was found to have the greatest depth of ballast-type material and the stiffest subgrade. Correspondingly, the Lorraine section had the highest values of measured and predicted track modulus. As can be seen in Figure 9, the predicted value of track modulus was higher than the average measured values but well within the estimated standard deviations.

The Aberdeen postmaintenance value was lower than the Lorraine value because of a combination of reduced ballast thickness and lower overall subgrade stiffness. The predicted track modulus for the Aberdeen site was in close agreement with the measured values.

For the Leeds sites, the predicted values of track modulus were higher than the field values. However, the field values appear to be unusually low. The lower ballast thickness at the Leeds sites can account for some of the differences between the Leeds sites and the other two field sites, but these differences in ballast layer thicknesses were not enough to cause the low values measured at both Leeds sites.

Given the similarity between the subgrade stiffnesses at the Leeds sites and the Aberdeen site, closer agreement between the field measurements from these sites would be expected. It is possible that the embankment in the Leeds wood section resulted in reduced subgrade confinement and hence increased vertical deflections. This would result in lower values of track modulus. However, the concrete section at Leeds, which was built at grade, had comparably low track modulus values. Thus the embankment condition must not have been a major factor.

It would be necessary to reduce the subgrade stiffnesses that were used in the GEOTRACK analyses by at least 50 percent to match the field track modulus measurements at the Leeds test sections. However, no rational justification for making adjustments of these magnitudes could be found. If the soil moduli were overestimated at the Leeds sites, a similar systematic error should have occurred with the Lorraine and Aberdeen subgrades. Because the predicted Lorraine and Aberdeen values were in good agreement with the measurements, a similar adjustment to the subgrade moduli at those sites would shift the predicted values away from the measurements.

SUPPORT CONDITIONS AND MAINTENANCE EFFECTS

The measured and predicted values of track modulus are dependent on several factors, one of which is the support condition of the tie. Support conditions are a function of track settlement and maintenance

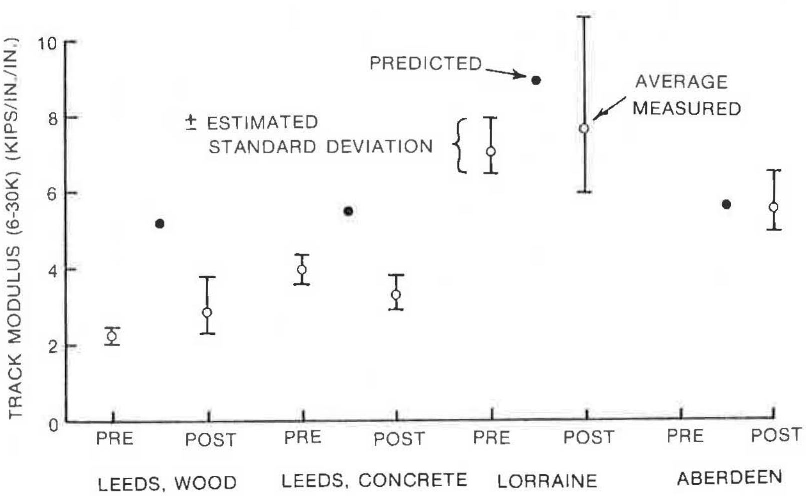

FIGURE 8 Measured and predicted track moduli for field sites, 6- to 30-kip load range.

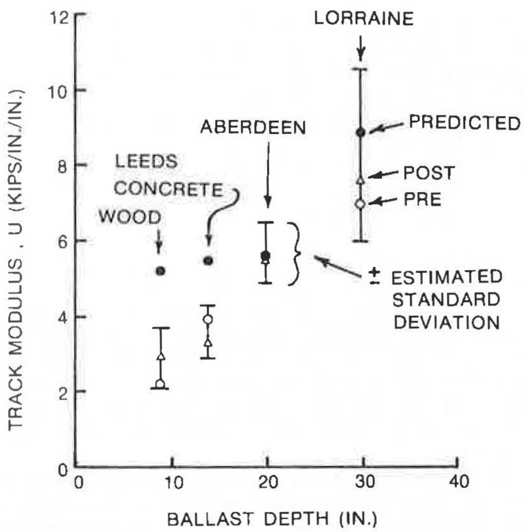

FIGURE 9 Ballast depth versus track modulus for field sites.

effects. The support conditions would affect concrete and wood ties in different fashions.

The GEOTRACK model uses uniform properties throughout each layer, including under all ties. Field plate load tests (9) showed that the ballast stiffness was not uniform under the ties: it was greater near the rail seat areas than under the tie centers. Furthermore, after maintenance the physical state of the ballast was more uniform than before maintenance. However, even uniform physical state or modulus does not result in uniform support conditions along the tie.

After a maintenance operation in which a high raise was given to the track, the physical properties of the ballast would be more uniform. However, the tamping and raise during the maintenance is done only near the rail seats, which would cause a gap near the center of the ties. This causes the actual load-bearing areas to be near the rail seats because of the lack of contact near the tie centers. This increased load bearing near the rail seats would cause higher rail deflections directly under the applied load than would result from a continuously supported condition. The GEOTRACK model uses continuous contact between the tie directly under the applied vertical load and the ballast surface, leading to a lower rail deflection and a higher track modulus than measured in the field after maintenance.

As traffic accumulates over the track, the ballast beneath the rail seats is recompacted and becomes stiffer, but the tie contact becomes continuous. The more uniform support across the tie leads to a lower rail deflection and hence a higher track modulus. In the case of a small maintenance raise, the initial physical state of the ballast may be less uniform under the tie than after a large raise. However, the contact may be more continuous. This would result in a higher track modulus after a small raise than after a large raise, or at least not much change in the pre- and postmaintenance values.

In the case of centerbound track, for example, a greater portion of the rail loads would be carried by the central portion of the ties. In this situation, as the applied loads increased, the wood ties would begin to conform more to the ballast surface and this would probably lead to a more uniformly distributed surface load than the concrete ties because the bending stiffness of concrete ties is about 4.5 to 6 times greater than that of wood ties. Load transfer to the tie center would cause lower rail deflections under a particular applied load and, therefore, comparatively higher values of track modulus.

The interactions among variable physical states of ballast, tie support conditions, and structural factors such as tie stiffness and rail size make generalizations about track modulus uncertain. This is particularly true because the degree and type of maintenance disturbance and traffic history of a site can change the physical state of ballast in varying amounts. The scatter of the field measurements was such that there were no clear trends distinguishing the premaintenance track modulus values from the postmaintenance values. The predictions of track modulus using the GEOTRACK program are somewhat limited by the uniform layer property, the full contact representations, and the inability to represent the maintenance factors for the field sites. For these reasons variations between the measured and the predicted track modulus values for the sites can be expected because of the variations in ballast properties and support conditions that were affected by the maintenance operations.

The possible centerbinding and uniformity of support conditions beneath the tie bottom may not, however, be a significant factor contributing to the track modulus values, although the effects are physically rational. Differences between the bending stiffnesses of wood and concrete ties would also not result in large differences in track moduli. Because only 10 to 20 percent of the total track deformation is due to ballast compression, the subgrade deflections appear to be much more important. It has been shown that variations in tie stiffnesses (8) do not have a major effect on the vertical subgrade stresses beneath the rail seats. Thus the subgrade contribution to track modulus should be about the same for wood and concrete ties. Also, dynamic measurements of resilient subgrade deflection (5) showed no significant difference between the deflections in wood and in concrete sections. This would indicate that, although the stress distributions and deformations in the ballast layer were affected by tie stiffness and possibly centerbinding, the subgrade responses were controlled mainly by the subgrade properties, with some effects of ballast layer thickness.

SUMMARY

The main purpose of this paper was to make available the experimental results of maintenance effects on track modulus and, by comparing the field measurements with predictions of track modulus for the revenue sites, to develop a further understanding of the factors affecting vertical track response.

Several observations were made on the basis of the results presented. The field measurements did not indicate that significant changes in the magnitude of track modulus could be attributed to maintenance. Also, the longitudinal variability of the track support was not improved as a result of the surfacing, as shown by the increased variability of the postmaintenance load-deflection curves.

The uniformity of ballast properties under individual ties was improved by the raise and tamping operations, as was indicated by the plate load tests (9). The uniformity of contact between the ties and ballast surface, however, may not be improved. Uniformity of ballast properties and contact should lead to a lower track modulus, but because the ballast is always relatively stiff compared to the subgrade and the relative contribution of the ballast deformation to the overall track deflection is small, maintenance does not have a great effect on track modulus.

The major factors contributing to the magnitude of vertical track modulus were ballast depth and subgrade stiffness. Variations due to tie spacing or tie stiffness were not significant factors. Predictions of track vertical deflections made with GEOTRACK were generally in reasonable agreement with the field measurements. The use of track modulus alone for assessment of the quality of track may not be too helpful, especially if the assessment is based only on the average magnitude of track modulus. The variability of track modulus between tie locations is a direct measure of the longitudinal uniformity of the track, which is extremely important.

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