Track Modulus Measurements on a Heavy Haul Line

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Measurement of track deflection under vertical load is proposed as a means of assessing the structural condition of the track. The results can be presented in the form of (*a*) vertical rail deflection under a specified load or change in load, (*b*) track stiffness defined as the ratio of change in load to change in rail deflection, or (*c*) track (foundation) modulus as defined by the beam-on-elastic-foundation model. Examples of such data are given from tests on a heavy haul line. The single vertical load point method was used. Characteristics of the load-deflection relationships are shown. The curves were subdivided into two parts. The first part is the seating deflection, which indicates the voids under the rails and ties. The second part is the contact deflection, a function of the substructure layer stiffness properties. Deflection basins were also measured and compared with basins calculated using a computer model. The study showed that continuous deflection profiles along the track are useful in characterizing the track support conditions and their variations.

The condition of a track is reflected by both the roughness of the track and the strength and stiffness of its support. A high level of roughness is a symptom indicating that something is wrong with the functional condition of a section of track, but not why; whereas a measure of the strength and stiffness, or structural condition of the section of track, will give information on what is causing the high level of roughness. The strength and stiffness of a track is usually expressed as track modulus.

Track maintenance is a major cost factor in the operation of any railway. A better knowledge of track condition and the mechanisms of track deterioration will result in the optimal use of maintenance resources. This investigation was aimed at evaluating the use of track deflection measurements or track modulus to get an indication of the track structural condition and to investigate changes in condition. A companion paper in this Record presents the corresponding measurements of functional condition using a track geometry car.

The Heavy Haul Coal Line in South Africa was chosen for this investigation because it is an ideal site for conducting applied railway research due to its high annual tonnage and heavy axle loads. The Coal Line of SPOORNET (South African Railway Organization) links the Transvaal coal fields with the east coast of South Africa (*1*). The length of the line is 586 km and it was built between 1973 and 1976. The axle loads were initially limited to 185 kN (18.5 tonnes) for the wagons and 220 kN (22 tonnes) for the locomotives. The axle loads were gradually increased to 260 kN (26 tonnes) for the wagons and 292.5 kN (29.25 tonnes) for the locomotives in 1988. To handle these increased loads a major track upgrading program was carried out by doubling the line, strengthening the superstructure and reducing the grades for the loaded trains.

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SITE DESCRIPTION

Two sections of tangent track on the loaded line were selected which provided both "good" and "bad" track under the same traffic and environmental conditions. The track structure consists of double track with concrete surface drains and lateral subsurface drains. The good section required little maintenance and the bad section needed frequent spot maintenance. The high maintenance input was associated with substructure-related problems resulting in rapid loss of surface geometry. The spot maintenance consisted of cleaning the ballast and tamping to improve the geometry.

The superstructure consisted of continuously welded 60-kg/m (121-lb/yd) S60 chrome manganese steel rails fastened to the 285-kg (628-lb) concrete ties with Fist type fasteners on high density polyethylene rail seat pads. The butt (shop) welds and thermit (field) welds were evenly spaced throughout each section, with one additional thermit weld in the bad section. The surface of each section was visually inspected for mud boils, ballast breakdown and surface drainage conditions. Evidence of these problems was only observed in the bad section, and these occurred randomly along the length of the section.

The ballast is a dolorite crushed rock with an average layer thickness of 300 mm (12 in.) below the ties in the bad section and 415 mm (16 in.) in the good section. The ballast thickness variation in both sections is shown in Figure 1. Ballast samples were taken at three ties in the bad section and two in the good section. The ballast bed associated with each sampled tie was divided into 13 sampling zones as indicated in Figure 2(a). This provided information on the extent and variation of the ballast fouling in the bad and the good sections as shown in Figures 2(b) to 2(d). Note the high percent passing the 0.075-mm (No. 200) sieve, indicating mud forming, in Figure 2(c); and the high percent passing the 13.2-mm (0.5-in.) sieve in Figure 2(d), indicating ballast breakdown in some of the bad section samples.

To determine the subgrade properties and to define the profile of the layered system, one cross trench was excavated beyond the end of each site. Additional inspection holes were excavated in both sections at the toe of the ballast on the field side of the track. The substructure in the bad section consisted of a variable thickness of imported subballast mixed randomly with local shale, and the good section had uniform substructure layer thickness.

TRACK STRUCTURAL MEASUREMENT

The structural condition of a track refers to its structural properties, such as strength and stiffness of the superstructure and substructure components. Structural condition measurements include deflection under vertical track loading and substructure cone penetrometer

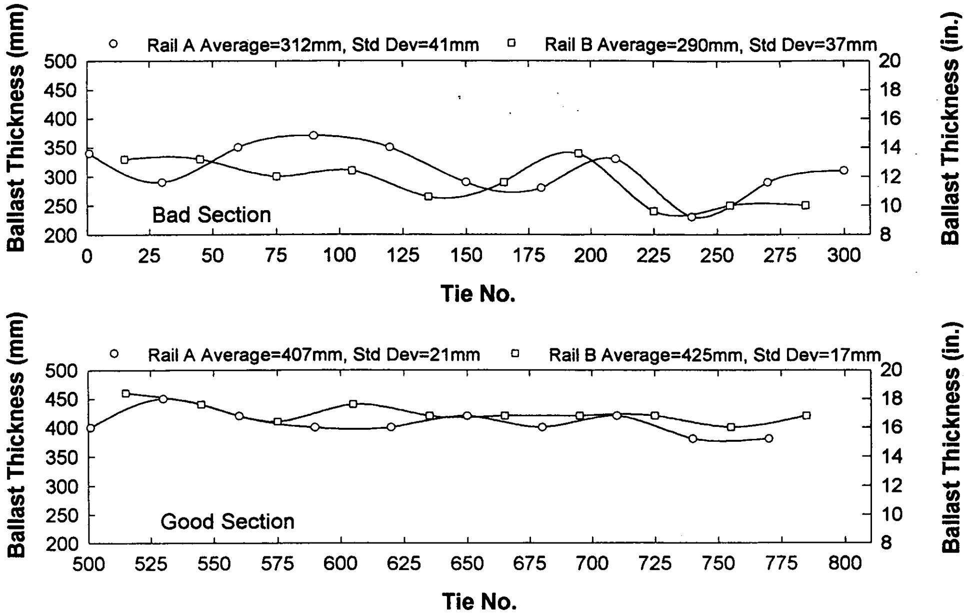

FIGURE 1 Ballast thickness variation.

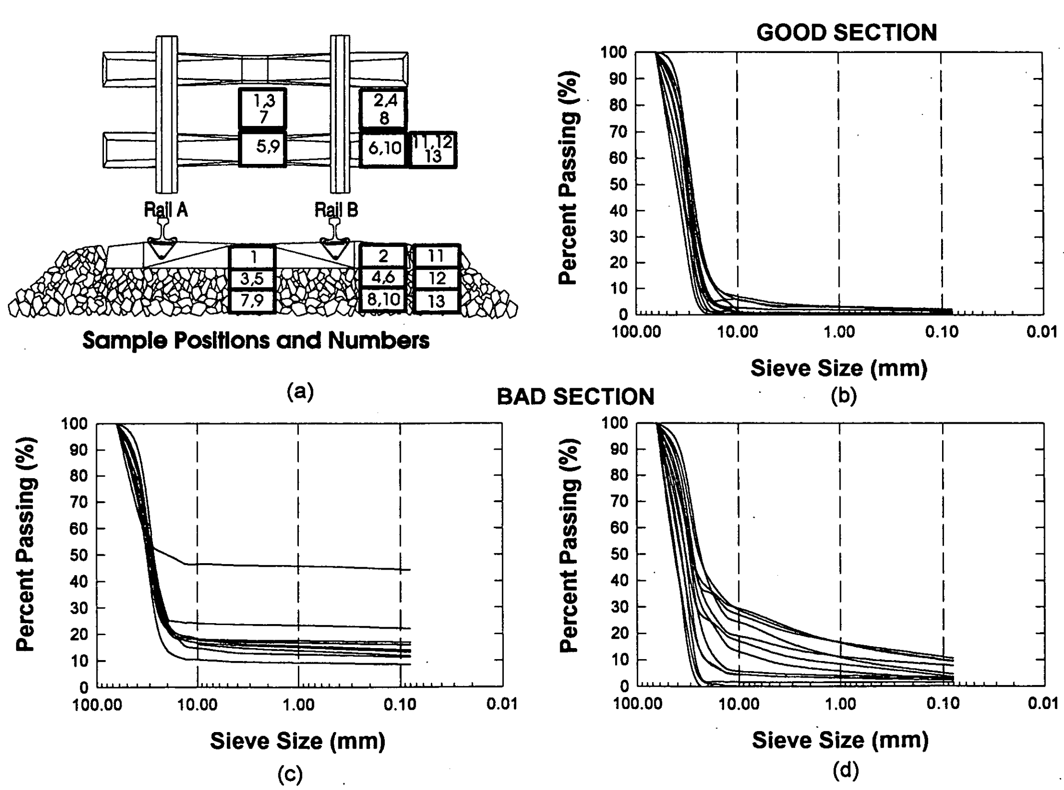

FIGURE 2 Ballast gradations.

probing. The stiffness of a track is usually expressed as a track modulus and the subgrade layer stiffness properties are defined by resilient modulus.

Vertical Track Loading

A single load test at a point in the track causes the track to deflect over some length as shown in Figure 3(top). A variation in deflected shape measured under the same load on different sections of track with the same superstructure indicates different substructure stiffness conditions. The depth and the deflected shape of the basins depend on the variation in layer properties supporting the sections of track. In Figure 3(top) the smallest basin represents a substructure with a high bound layer stiffness. The large basin represents a substructure consisting of a low layer stiffness. The middle basin represents the deflected shape of a track consisting of nominal layer stiffness. Figure 3(top) shows the deflected track condition with no voids or slack present in the track structure. The load-deflection relationships as shown in Figure 3(bottom) should then have a relatively constant slope.

The shape of the deflection basin and the load-deflection relationship shown in Figure 3 were calculated using a computer model GEOTRACK that permits the analysis of track responses as influenced by individual superstructure and substructure parameters. GEOTRACK (*2*) is a three-dimensional, multilayered model for determining the elastic response of the track structure under vertical load, using stress-dependent properties for the ballast, subballast and subgrade materials. The superstructure properties of the coal line track were used and a range of variables for the substructure as indicated in Table 1 were considered to obtain the nominal, lower and upper bound basins shown in Figure 3(top).

If voids or slack exist between the bottom of the tie and the ballast or between the rail and tie, the deflected shapes under 25 percent and 100 percent load levels, for the nominal subgrade conditions, are as shown by the solid lines in Figure 4(top). The dashed lines indicate the corresponding deflections without the voids. The initial slope of the load-deflection curve in Figure 4(bottom) is less steep for the case with voids (solid line) than for the case without voids (dashed line), and the initial slope will depend on the extent of the voids under each tie. The 25 percent load level is assumed to close the voids, although the actual load level for this will vary, and will be referred to as the "seating load." The deflection caused by an increase from the seating load to the maximum load will be referred to as the "contact deflection." The contact deflection represents the elastic deflection of the track structure without voids.

The extent of the voids present and the stiffness of the support are shown in the load-deflection relationship at a point in the track. The size of the void under a set of ties can be estimated by extending the contact stiffness line to the horizontal axis as indicated in Figure 4(bottom). This eliminates the elastic deflection due to the seating load. It can be concluded that the shapes and magnitudes of the load-deflection relationship and the basin are a direct indication of the track support condition.

The track stiffness, S, is determined from a load-deflection test for a selected load increment by:

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

where

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

The track modulus, u, based on the beam-on-elastic-foundation model, also known as the Winkler theory, is then calculated from

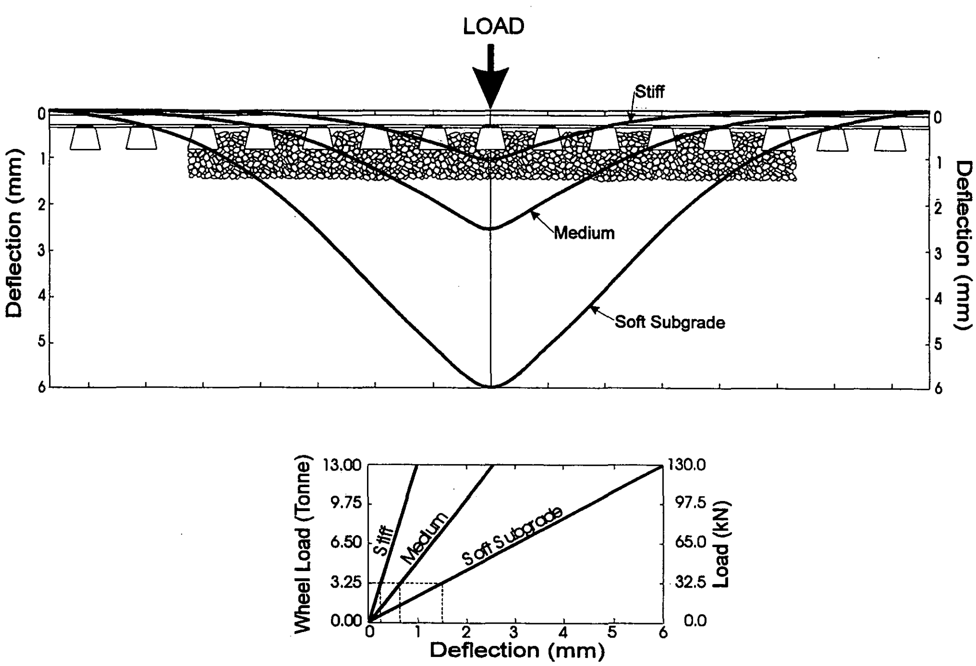

FIGURE 3 Track deflection characteristics with no voids.

TABLE 1 Superstructure and Substructure Parameters

Rail				
Cross Area	mm^2 (in.^{2})	7 703 (12)		
Weight	kg/m (lb/yd)	60 (121)		
EI	kNm^2 (kip in.^{2})	6 558 (22840)		
Gauge	mm (in.)	1 065 (42)		
Tie and Fastener				
Length	mm (in.)	2 200 (87)		
Width	mm (in.)	260 (10)		
EI	kNm^2 (kip in.^{2})	12350 (43000)		
Spacing	mm (in.)	650 (26)		
Fastener stiffness	kN/m (kip/in.)	789x10^3 (4500)		
Substructure Thickness				
Ballast	mm (in.)	300 (12)		
Subballast	mm (in.)	150 (6)		
Subgrade		Infinite		
Substructure Modulus				
		Lower Bound	Nominal	Upper Bound
Ballast	MPa (ksi)	138 (20)	275 (40)	550 (80)
Subballast	MPa (ksi)	69 (10)	138 (20)	276 (40)
Subgrade	MPa (ksi)	14 (2)	40 (6)	138 (20)

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

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

Track modulus and track stiffness are directly related, as indicated in Equations 1 and 2. The only difference is that the modulus is independent of the rail properties and should not change with a change of rail stiffness, whereas the stiffness includes the effect of the rail. However, the modulus as well as the stiffness will change with a change in type of tie and tie spacing. If the purpose of measuring the track load-deflection characteristics is to obtain the track modulus for use with the Winkler theory for track design, then all the superstructure properties and the changes in properties along the length of the track should be recorded. If the purpose is to investigate the support condition, the variation in support is more important than obtaining the track modulus value for the track. Using the track stiffness or measuring the variation in track deflection under a set of constant loads gives a direct indication of the change in support conditions.

Calculating the track modulus or stiffness between zero load and maximum load, on a length of track with voids present, as indicated in Figure 4, will result in substantial underestimation of the support stiffness, and no distinction can thus be made between the voids and the actual stiffness of the support. At least three load levels should be applied in a test for track stiffness (including zero load) to ensure that the void can be distinguished and the correct indication of the support condition obtained.

Track Loading Tests

The track loading tests were done by applying a single point load to each rail using a converted tamper. The load was applied to each rail in four 31.25-kN (3.2-tonne) load increments up to 125 kN (12.8 tonne), using two independent hydraulic cylinders. At the end of each load increment the track deflection was measured by reading the bar-coded scales mounted on the rail on both sides of the track, using two digital levels. These measurements were repeated before and directly after tamping as well as at regular intervals during traffic. The tests were done at every fourth tie each time to obtain a semicontinuous indication of the track support conditions.

Two typical sets of load-deflection results are shown in Figure 5. Figures 5(a) to 5(c) show the effects of a void on track support during a tamping cycle. The void is reduced by tamping and the contact deflection is increased, but the void redevelops after traffic and the contact deflection return to the level prior to tamping. The ballast at this tie location was highly contaminated with fines. Figures 5(d) to 5(f) show that tamping reduced the stiffness of the track sup-

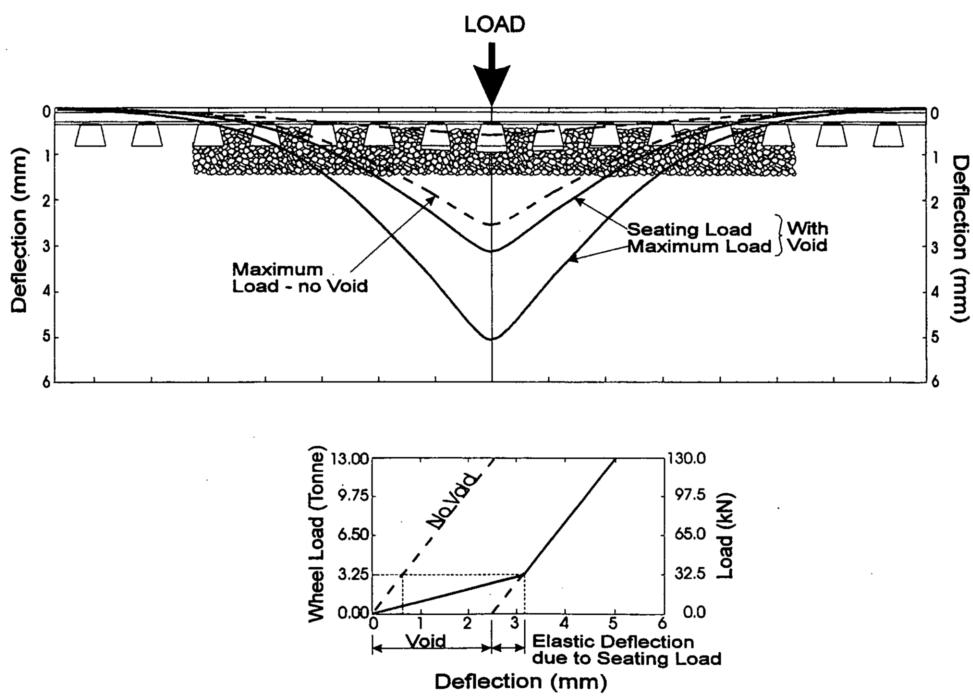

FIGURE 4 Track deflection characteristics with and without voids.

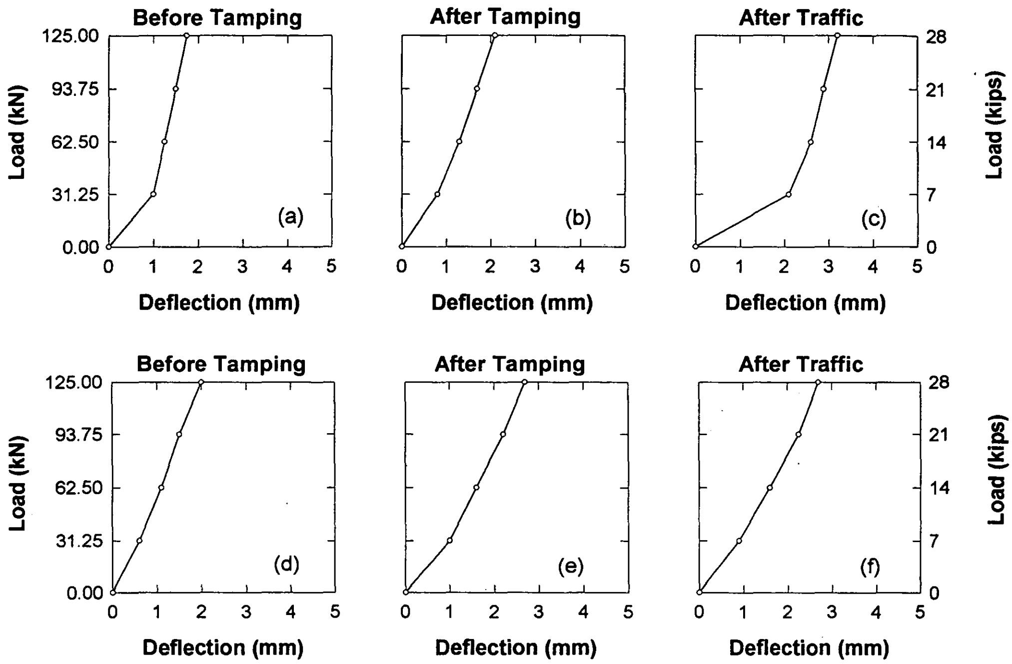

FIGURE 5 Typical vertical load-deflection results.

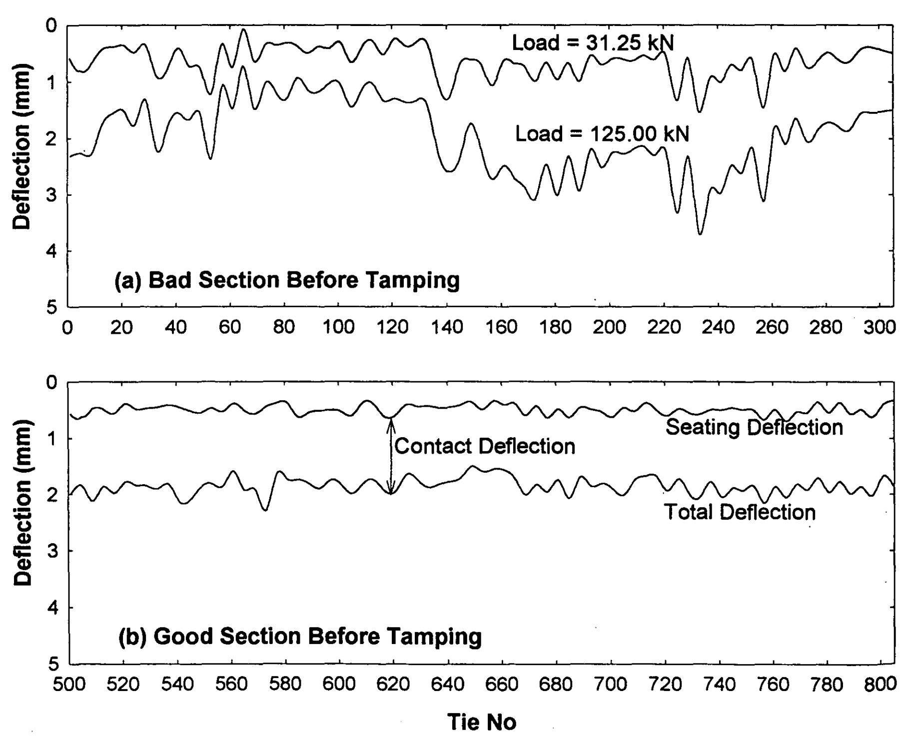

FIGURE 6 Variation of seating and contact deflection along track.

port and that the reduction is maintained after traffic without a void forming. The ballast at this tie location was clean.

To get a continuous indication of the support condition, the seating deflection and the total deflection were plotted for the first set of tests before tamping, as indicated in Figure 6. The difference between the seating and total deflection lines, which is the contact deflection, indicates that variable support conditions exist in the bad section. The good section shows uniform deflection characteristics over the length of the site.

Two sites will be compared, consisting of the first 140 ties in the bad section and the first 140 ties in the good section. These sites will represent the extremes of the support conditions at this track location. The total deflection line in Figure 6 combines the voids and the elastic deflection at each point in the track. The profile formed by the total deflection line is the actual profile a loaded wheel will follow when it is traveling over the track. The more variation there is in the total deflection, the higher the dynamic influences will be on the moving wheel.

Track Deflection Basins Tests

Deflection basins tests were conducted every 12th tie during each set of the track loading tests. The deflections were measured under the point of the applied load and at the next three ties to one side of the applied load. An additional measurement was taken between the first and second tie. Figure 7 shows the average deflection basins under the seating and total deflection loads, before and after tamping, and after 6.381 MGT of traffic following tamping for each test site.

Substructure Probing

The thickness and the relative strength of the substructure layers for each section were determined using a Cone Penetrometer Test (CPT) set-up mounted on the front of the track-loading vehicle. The cone is pushed into the substructure layers starting at the bottom of the tie, and the tip resistance is recorded with depth. Figure 8 shows the mean of the recorded tip resistance for each site. The layer thicknesses as determined from the cone profile, are indicated with the solid horizontal line, and the connecting vertical lines indicate the tip resistance associated with each layer. The high tip resistance over much of the bad site depth and from 1 to 1.2 m (3 to 4 ft) depth in the good section indicates shale rock. Problems at the bad site resulted from subgrade attrition and mud pumping because the ballast was placed directly on the soft rock.

DETERMINING SUBSTRUCTURE CHARACTERISTICS

GEOTRACK was used to determine the layer properties of the test sites and the stresses exerted on each layer in the substructure. The procedure was to indirectly determine the resilient modulus of each layer by a back-calculating procedure demonstrated by El-Sharkawi et al. (*3*). This was achieved by using the measured basin profiles as boundary values and the tip resistance profiles as relative indications of the substructure layer-resilient modulus. The ratios of tip resistance between layers, as given in Figure 8, were used to estimate the relative initial resilient modulus values and these values were iterated, maintaining the same tip resistance ratio, until the contact deflections calculated with GEOTRACK resembled those measured in the field. Conceptually, the layer-resilient moduli may be determined directly by testing samples from each layer. However, this difficult and time-consuming process is subject to sampling and testing errors. Backcalculation ensures that the moduli used result in the correct deflection.

Figure 9 compares the measured contact deflection basins (total-seating basins), indicated with the symbols, with the backcalculated contact basins, indicated with the solid lines. The solid lines in all the plots in Figure 9 are the backcalculated basins prior to tamping for each site. Hence the difference between the measured values and

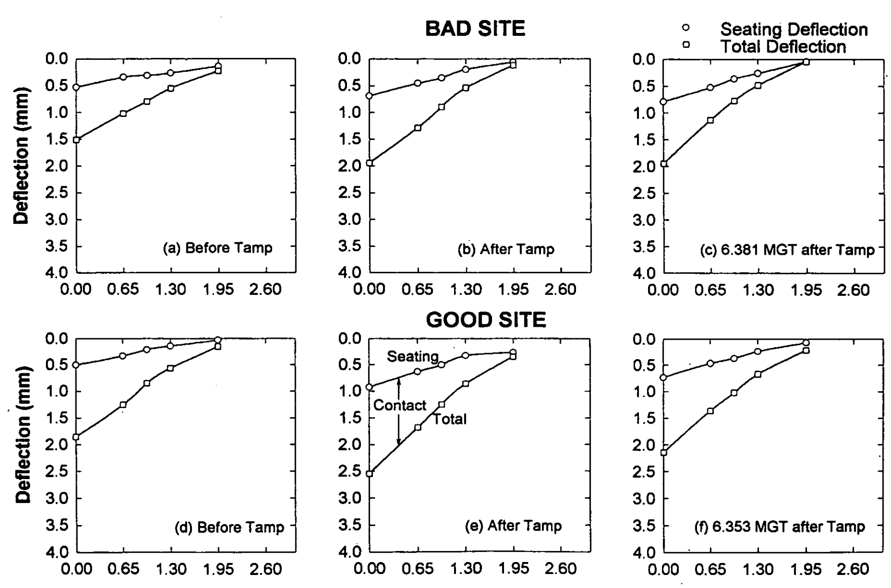

FIGURE 7 Average seating and total deflection basins.

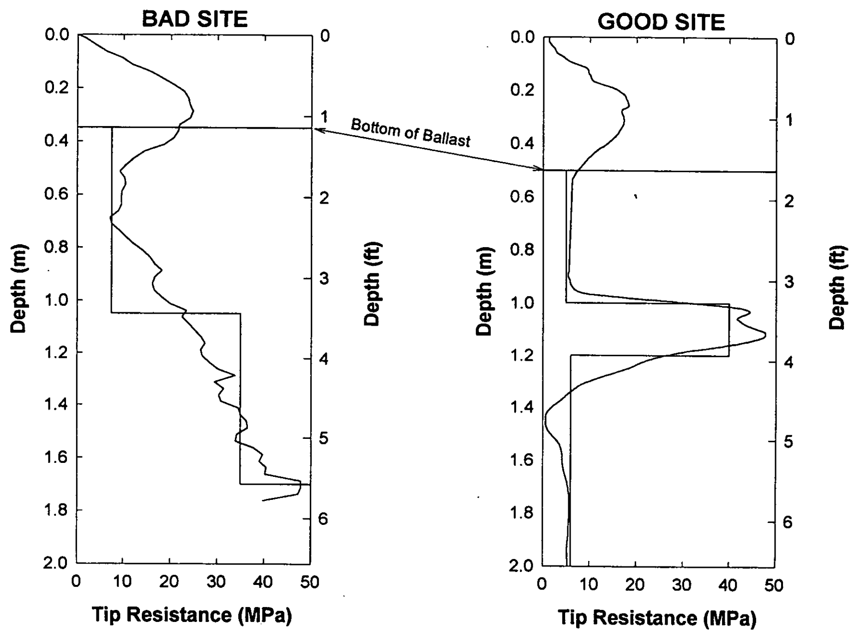

FIGURE 8 Average cone penetrometer profiles for test sites.

these lines shows the extent of the change in the basins over the tamping cycle. The after-tamp plots in Figures 9(b) and 9(e) also show the after-tamp backcalculated basin indicated with the dashed lines. Tamping reduces the ballast stiffness temporarily and hence increases the deflection. Table 2 summarizes the measured properties and backcalculated characteristics for each layer, for both the before- and after-tamping conditions. The vertical stress given for each layer is the maximum compressive stress acting at the top of each layer.

To quantify the change in shape of the basin with traffic and maintenance, the following function was fitted to the measured data points:

$$\text{Deflection} = \frac{a}{[1 + e^{b(x-c)}]} \qquad (3)$$

where

a = range of the deflection,
b = the slope coefficient,
c = the distance to the maximum rate of change,
d = minimum deflection, and
x = distance from the load point.

The slope coefficient for the backcalculated contact deflection basin is given for all the before- and after-tamp graphs in Figure 9.

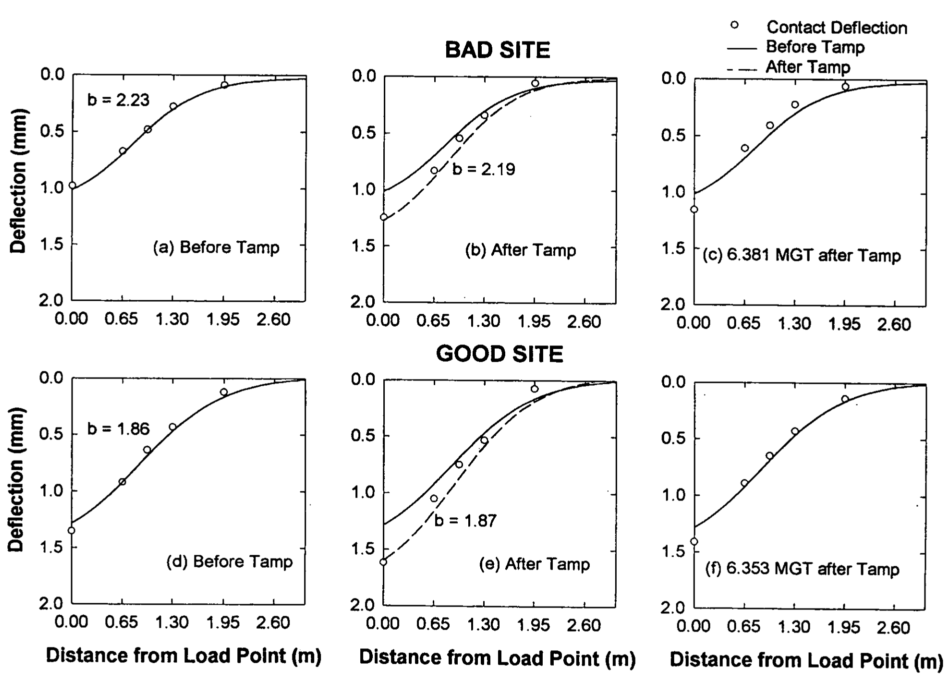

FIGURE 9 Comparison of calculated and measured contact deflection basins.

TABLE 2 Layer Information and Backcalculated Properties

Before Tamp			Test Sites	
			Bad	Good
Thickness	mm (in.)	Ballast	300 (12)	450 (18)
Tip resistance	MPa (ksi)	Layer 1	25 (3.6)	20 (2.9)
Resilient Modulus	MPa (ksi)		275 (40)	220 (32)
Vertical stress	kPa (psi)		220 (32)	282 (41)
Thickness	mm (in.)	Subgrade	700 (28)	500 (20)
Tip resistance	MPa (ksi)	Layer 2	7.5 (1.1)	5 (0.7)
Resilient Modulus	MPa (ksi)		37.5 (5.4)	25 (3.6)
Vertical stress	kPa (psi)		72 (10.4)	52 (7.5)
Thickness	mm (in.)	Subgrade	650 (26)	200 (8)
Tip resistance	MPa (ksi)	Layer 3	35 (5.1)	40 (5.8)
Resilient Modulus	MPa (ksi)		175 (25)	200 (29)
Vertical stress	kPa (psi)		48 (7.0)	39 (5.7)
Thickness	mm (in.)	Subgrade	∞	800 (31)
Tip resistance	MPa (ksi)	Layer 4	50 (7.3)	6 (0.9)
Resilient Modulus	MPa (ksi)		250 (36)	30 (4.4)
Vertical stress	kPa (psi)		25 (at 2m) (3.6)	35 (5.1)
Thickness	mm (in.)	Subgrade		∞
Tip resistance	MPa (ksi)	Layer 5		>50 (>7)
Resilient Modulus	MPa (ksi)			400 (58)
Vertical stress	kPa (psi)			27(at 2m) (3.9)
Track Modulus before tamp	MPa (ksi)		57.4 (8.3)	42.2 (6.1)
After Tamp			**Test Sites**	
			Bad	Good
Resilient Modulus	MPa (ksi)	Ballast	70 (10)	70 (10)
Vertical stress	kPa (psi)	Layer 1	162 (24)	211 (31)
Resilient Modulus	MPa (ksi)	Subgrade	37.5 (5.4)	25 (3.6)
Vertical stress	kPa (psi)	Layer 2	81 (12)	57 (8)
Resilient Modulus	MPa (ksi)	Subgrade	175 (25)	200 (29)
Vertical stress	kPa (psi)	Layer 3	48 (7.0)	41 (6.0)
Resilient Modulus	MPa (ksi)	Subgrade	250 (36)	30 (4.4)
Vertical stress	kPa (psi)	Layer 4	25 (at 2m) (3.6)	37 (5.4)
Resilient Modulus	MPa (ksi)	Subgrade		400 (58)
Vertical stress	kPa (psi)	Layer 5		28 (at 2m) (4.1)
Track Modulus after tamp	MPa (ksi)		42.6 (6.2)	31.5 (4.6)

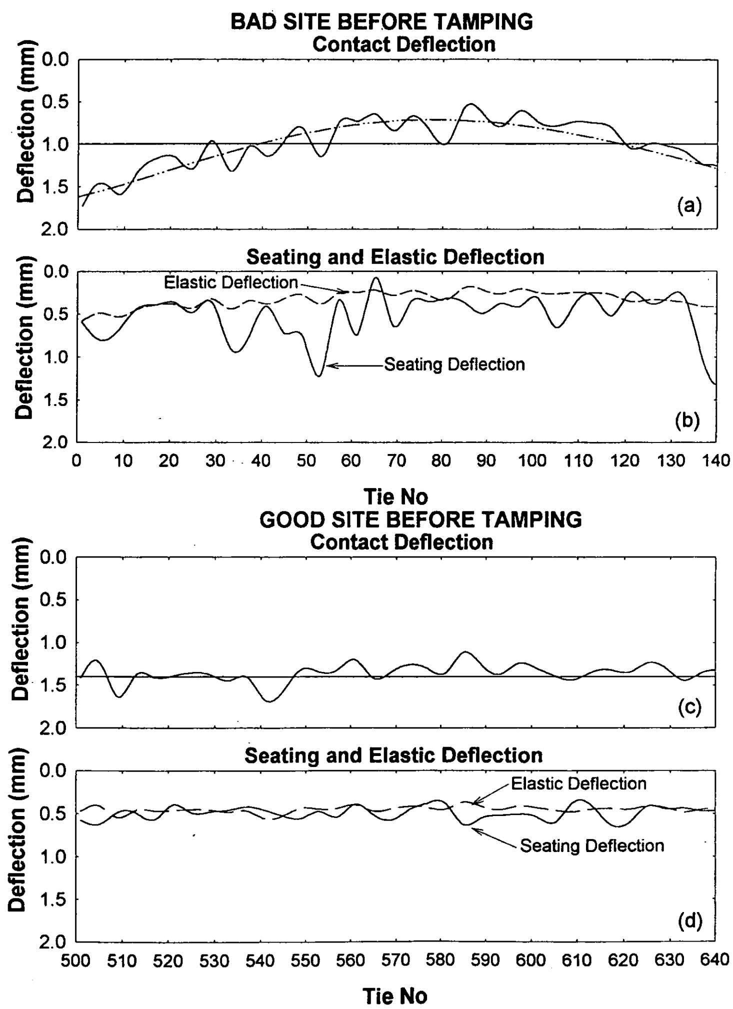

FIGURE 10 Variations in contact and seating deflection along sites.

The shape of the deflection basins does not change after tamping, only their depth. This indicates a reduction of the ballast stiffness due to tamping over the length of the deflection basin. The deflected shape of the basins after tamping was obtained by reducing the ballast-resilient modulus until the deflections resembled the measured basins, without changing the properties of the substructure layers. A 70 percent to 75 percent change in ballast modulus caused a 20 to 27 percent change in deflections to simulate the after-tamping basins. The shape of the basin is almost back to the original shape prior to tamping within 6.4 MGT as indicated in Figures 9(c) and 9(f).

CONTINUOUS DEFLECTION MEASUREMENTS

Plots of seating and total deflections along the track, illustrated in Figure 6, may be converted into contact and void deflections to separate the deflections into two important components. The contact deflection for the bad site is depicted in Figure 10(a). The average contact deflection has been plotted as a horizontal line. A smooth curve plotted as a dashed line has been drawn through the actual data to show the long wave-length support variation. The location of the smallest contact deflection corresponds to the high point in the underlying shale layer. The contact deflection in the good site is shown in Figure 10(c). The support condition is uniform in this section. The variation in the contact deflection is caused by the variation in the stiffness of the substructure. The difference in stiffness could be due to the natural variation in subgrade conditions or due to the variation in ballast contamination levels. The average contact deflection in the good site is greater than the average contact deflection in the bad site. Thus the track support in the bad site is much stiffer than in the good site.

The seating and elastic deflections for the bad site are plotted together in Figure 10(b), and for the good site in Figure 10(d). The difference between these two curves is the void deflection as illustrated in Figure 4. Note that the voids in the bad section are much greater than in the good section. The voids that develop are an indication of the plastic deformation of the ballast and subgrade and are directly related to the tamping requirements. When the voids develop to a certain extent in terms of void variation and size, tamping is required to prevent an excessive roughness development.

EFFECT OF MAINTENANCE AND TRAFFIC

To illustrate the effect of maintenance and traffic on the changes in substructure condition, the changes in contact and void deflection with traffic for the two sites are indicated in Figures 11 and 12. The solid lines represent the change in average deflection and the broken

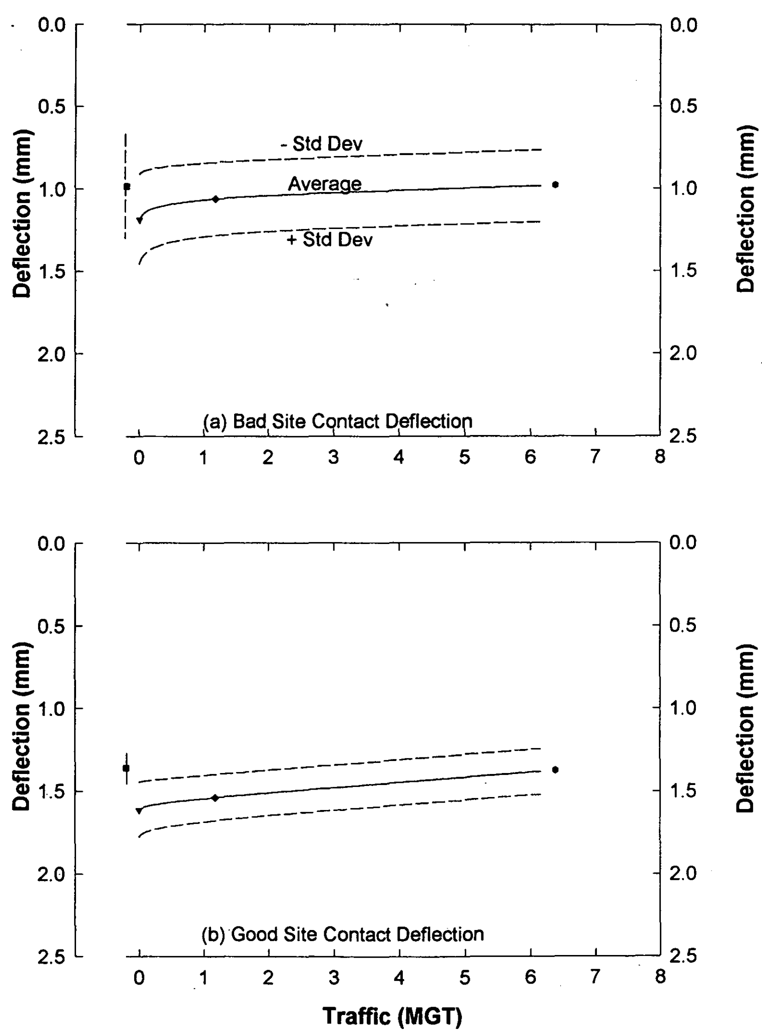

FIGURE 11 Change in contact deflection with traffic.

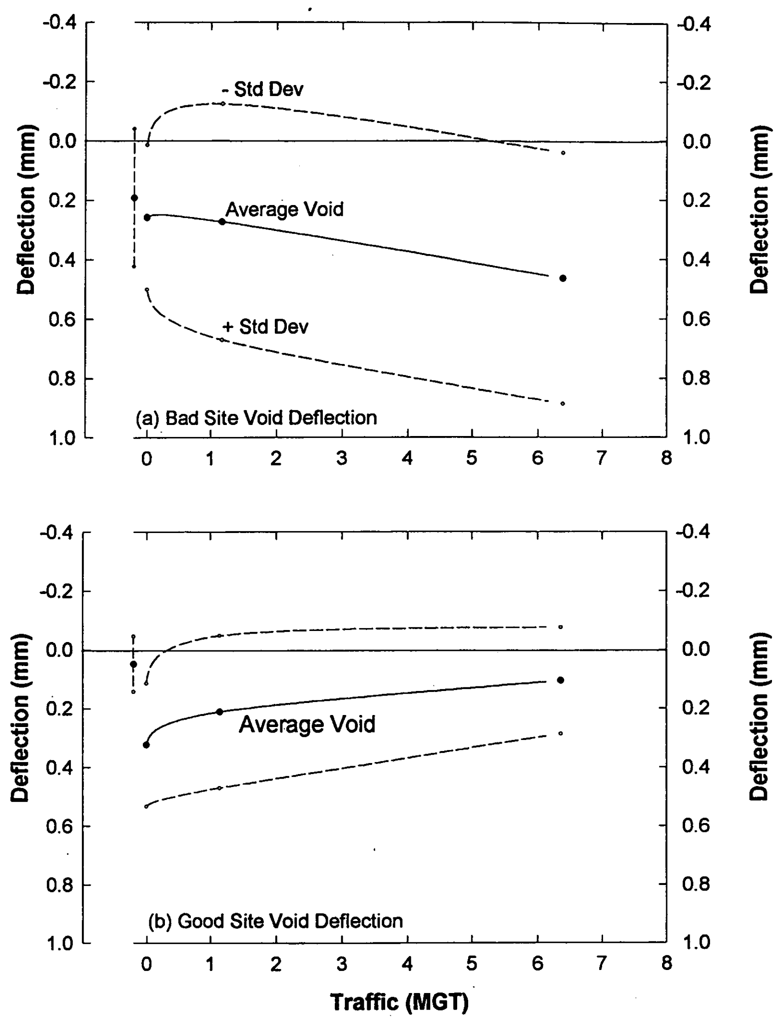

FIGURE 12 Change in void deflection with traffic.

lines represent one standard deviation each side of the average. In each plot at 0 MGT the before- and after-tamp values are indicated.

For both sites the contact deflection is increased by tamping, representing a reduction in stiffness of the ballast. The effect of traffic is to rapidly decrease the contact deflection after tamping to levels that existed before tamping. The spacing of the standard deviation lines indicates that the variation in contact deflection in the good site is less than in the bad site.

For both sites the average void deflection increased with tamping. The void deflection continued to increase with traffic for the bad site while it decreased with traffic for the good site.

The ballast fouling and breakdown in the bad section made compaction of the ballast during tamping ineffective. The alignment of the track was improved but the ballast could not hold the vertical profile. The variation in substructure conditions results in the nonuniform support and rapid increase in void development as indicated in Figures 6 and 10.

Tamping also increased the contact deflection in the good section, thus reducing the track stiffness, but disturbed the stable ballast bed as indicated in Figures 11 and 12. The traffic tends to reduce the disturbance, but the same level of uniform support that existed before tamping was not regained. This indicates that tamping of a stable ballast bed should not be done except if the geometry requires realignment.

CONCLUSIONS

The track stiffness tests along the length of the track clearly identified the areas of nonuniform support. This nonuniformity was verified by the layer probing, inspection holes and ballast sampling.

The elastic modeling of the track accurately represented the track deflection and identified higher stress areas in the problem zones where subgrade attrition occurred.

A detailed investigation of the track conditions indicated that surfacing of the track was not the correct maintenance action in either site. The stable, good section should not have been tamped, and in the bad section tamping did not alleviate the attrition problem. The good site should not have been touched, while the bad site needed a subballast layer to prevent the mud from forming due to attrition of the shale subgrade.

The continuous measurement of track deflection or stiffness and the correct interpretation of the results will be a tool for the track maintenance engineer to correctly direct the maintenance activities which will result in optimal use of the maintenance budget.

To evaluate the track condition, it is desirable that the structural conditions be measured continuously along the track. This is best done by measuring deflection at several load levels. However, a machine to do this is presently not available. An alternative is to measure the geometry continuously and use it to determine the problem areas in the track. With the problem areas known the structural condition can be measured at these areas to help determine the cause of the problems. The method could be similar to that used in this study. The vehicle that measures the structural condition can also be used to collect other necessary information, such as subgrade penetration resistance or ballast condition, to make the correct maintenance decisions.

The measurement of the vertical load-deflection relationship should be detailed enough to permit the seating deflection to be distinguished from the contact deflection. If this is not done, useful information will be lost and misinterpretation of the support conditions will result.

Track vertical stiffness and track vertical deflection under known load increases are useful measures of track structural condition. They complement track geometry measurements representing the track functional condition. Track modulus cannot be measured, but must be calculated from track stiffness. The main advantages of track modulus are to eliminate the effect of the rail bending stiffness when assessing track stiffness, and to perform calculations with the beam-on-elastic-foundation model.

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