Series B, No. 1, Feb. 1977, pp. 1-9.
5. A. Kish, D. P. McConnell, R. M. McCafferty, H. Moody, and A. Sluz. Track Structures Performance: Comparative Analysis of Specific Systems and Component Performance. Federal Railroad Administration, Rept. FRA/ORD-77/29, June 1977.

Development of Multilayer Analysis Model for Tie-Ballast Track Structures

James C. Kennedy, Jr., and Robert H. Prause, Applied Dynamics and Acoustics Section, Battelle Columbus Laboratories, Columbus, Ohio

A multilayer analysis model for tie-ballast track structures has been developed. The model includes the effects of rail bending, rail-fastener stiffness, tie bending, variable ballast and subgrade material types, and variable tie spacing and ballast depth. The results predicted by using the model are compared with experimental results and excellent agreement is shown. The model offers the advantages of simplicity of use and reduced computer run time when compared with the finite-element codes currently used.

The evaluation of track performance and track design for vertical loads requires the ability to predict realistic pressure distributions at the interfaces between the tie and the ballast and between the ballast and the subgrade. This requires a model that includes the effects of tie bending; rail-fastener stiffness; and changes in ballast depth, roadbed material properties, and tie spacing in a unified manner. In such a model, changes in roadbed configuration that affect track moduli and the distribution of loads from the rails to individual ties are apparent.

A track model and computer code that incorporates the above features has been developed. This paper compares its ease of use, computer time required per run, and accuracy of results with those of other existing analysis codes. Analytical validation and a comparison of computer predictions and experimental results are also presented.

The Multi Layer Track Analysis (MULTA) computer routine discussed here is a two-stage numerical procedure for determining the three-dimensional load and stress distribution in a railroad track system subjected to static loads.

MULTA can be used to evaluate new or existing track-system configurations for various combinations of concentrated vertical loads or moments exerted on either or both rails.

TYPICAL METHODS OF ANALYSIS OF TRACK STRUCTURES

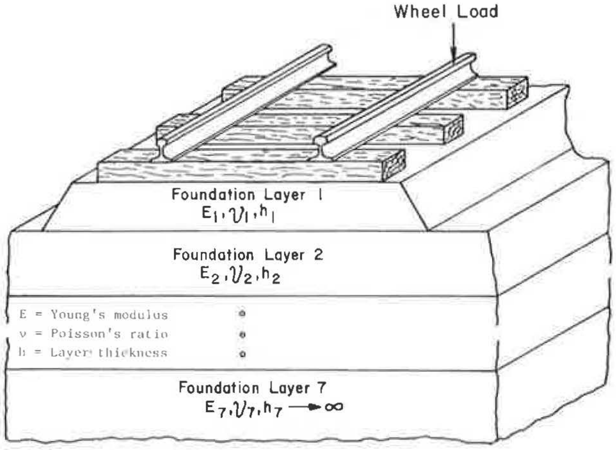
Currently, the analysis of track structures usually follows one of two paths: (a) the track structure is represented very simply (e.g., a beam on an elastic foundation wherein the substructure is represented as a series of discrete springs) or (b) the track structure is modeled in great detail by using a finite-element representation. In the first case, the system is represented so simply that individual contributions (such as ballast material type and depth, subgrade material type, and tie bending) are not sufficiently detailed or easily evaluated. On the other hand, the detail characteristic of most finite-element codes requires preparation of input data and running time for computer analysis of such magnitude that extensive analyses are quite often prohibitive.

A finite-element code was selected that could simulate variable ballast depth and material type and subgrade depth and material type so that the results obtained by using it could be compared with those obtained by using MULTA. MULTA is not a finite-element code as such; the differences between it and a typical finite-element code will be pointed out below. The finite-element code used for this comparison was the prismatic solid analysis (PSA) code originally developed at the University of California, Berkeley, and modified by the Association of American Railroads (AAR). The comparison between the results obtained by using the two codes showed negligible differences in predicted stresses and displacements. [A complete description of the PSA code and the comparison have been given by Prause and others (1)].

Typically, the preparation of input data for use in MULTA requires considerably less time than do seemingly equivalent finite-element codes. In the results that are discussed below, 11 ties are used in the simulation of the track structure. Preparation of input data for MULTA, including punched data cards, required about 3 person-h. Running time required about 400 computer s. On the other hand, the preparation of input data for the analysis that used the PSA finite-element code required about 8 person-h preparation time and about 750 s computer run time. Thus, the MULTA program has the advantage of being able to simulate and evaluate the effects of parameters such as ballast depth and material type, subgrade material type, tie bending, and rail-fastener stiffness where similar analysis codes (such as the beam-on-elastic-foundation formulation) do not. On the other hand, its relative ease of input-data preparation and considerably smaller amount of computer run time offer definite advantages over the more detailed finite-element codes without compromising the results for a vertical linear-elastic track-analysis tool.

The results predicted by using the MULTA code have also been compared with those predicted by using the ILLI-TRACK structures code. This is a two-dimensional finite-element code developed at the University of Illinois (2). The comparison shows that ballast pressure, rail deflection, and rail bending-moment predicted values can be in serious error if the effective bearing area of the tie is not properly chosen when the ILLI-TRACK model is used. This is a key difference between the two models. It is necessary to assume an initial tie bearing area when ILLI-TRACK is used, whereas tie deformation and contact area are included directly in MULTA. [The comparison of MULTA and ILLI-TRACK predictions has been given by Prause and Kennedy (3)].

Figure 1. Track model for MULTA program.



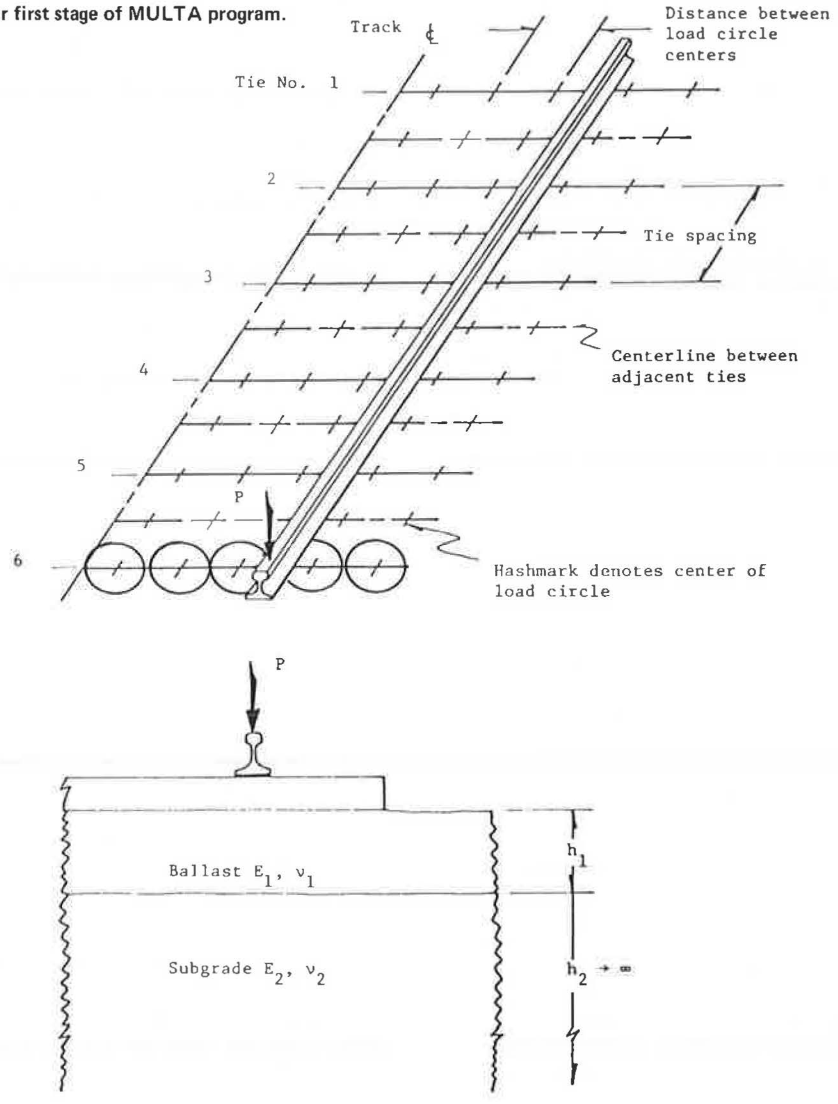
Development of Track Model

The two stages of solution in MULTA are modifications to two previously developed computer codes. The first stage is a modified version of the computer program developed by the AAR and models the ballast-subgrade system as a multilayered elastic system (4). The theoretical basis for the multilayered elastic system was first presented by Burmister (5). The second stage of solution in MULTA is a modified version of part of the program described by the AAR (6). The load-combination phase is that portion of the program that was revised for use in MULTA. This second stage of MULTA includes rail loads, rail bending, rail-fastener stiffness, and tie bending. The schematic for MULTA is shown in Figure 1.

Model Description

The first stage of MULTA analyzes the track substructure (ballast and subgrade) and provides information about displacement and stress influences as input to the second stage. The basic theory in the first stage assumes

Figure 2. Basic geometry for first stage of MULTA program.



the ballast-subgrade structure to be that of an elastic half space and, as such, the horizontal and vertical (downward) dimensions of the track structure are infinite in extent. This precludes the simulation of actual ballast-profile geometries, such as sloping shoulders. However, the effects of infinite dimensions in the horizontal and vertical directions on the stress and displacement predictions for vertical loads have been evaluated, and it was concluded that the finite dimension of the ballast shoulder had a negligible effect on the ballast and subgrade pressure under the ties (1).

MULTA calculates stress and displacement influence functions in the form of the stress and displacement responses of the ballast-subgrade structure to unit vertical loads applied to specific locations on the horizontal surface of the ballast. These specific locations are at the tie-ballast interface for the particular tie-track system being simulated. Critical in the simulation of how the loads are transmitted from the tie onto the ballast is the choice of the effective load-distribution area on the ballast. This distribution is in the form of load circles that distribute the tie loads onto the ballast (see Figure 2). [Load-circle size (radius) and number of load circles necessary to achieve simulation efficacy and solution accuracy have been discussed by Prause and others (1)].

The second stage of MULTA is basically an equation solver. The equations that are solved in this stage include the magnitude and position of a wheel load on each rail, rail displacement, rail force and equilibrium, rail-fastener stiffness, and tie bending.

MODEL ASSUMPTIONS, FEATURES, AND LIMITATIONS

The track system model includes the following assumptions:

1. The entire system behaves in a linear fashion.
2. The loads and moments applied to the rails are static and concentrated.
3. The material of each component of the system is homogeneous, isotropic, and linear elastic.
4. The depth of the last soil layer is infinite.
5. The tie spacing is constant for all ties.
6. The track gauge is constant.
7. The rail-tie system (including the first and last ties) deforms compatibly on the elastic foundation.

MULTA has available to the user the following options and features:

1. The ballast-subgrade system can be modeled by as few as two or by as many as seven layers of homogeneous, isotropic, elastic materials, each of which has distinct material properties and depths. However, the last layer must have an infinite depth.
2. The vertical stiffness of the spring used to represent the combined stiffness of a rail fastener and tie pad can be selected arbitrarily but must be greater than zero.
3. Unequal loads are permitted for each rail and at any position along a rail.

Use of MULTA is subject to the following limitations:

1. All ties must have identical material and geometric properties.
2. The track roadbed representation as an elastic half space with infinite horizontal dimensions does not permit modeling the actual cross-section of a ballast section having sloping shoulders.
3. The model does not permit missing ties.
4. The model does not allow external loading in the lateral or longitudinal directions and thermal loads cannot be included.

Test Description

As discussed above, MULTA is analytically equivalent to other, more detailed codes, but it was also desirable to compare MULTA results with experimental results. The experimental results were extracted from tests conducted on the Florida East Coast Railway (FEC). The FEC test sites included two concrete-tie tangent track sections, one that had a nominal tie spacing of 0.61 m (24 in) (site 1) and one that had a nominal tie spacing of 0.51 m (20 in) (site 2) and a concrete tie curve site that had 0.61-m tie spacing (site 3). All three sites included a main instrument array that extended over 7 ties. The purpose of this continuous section was to obtain a complete set of track load and response data over a nominally uniform track section. [A detailed description of the test sites and the instrumentation used to record the various track quantities of interest have been given by Prause and others (1)]. Only the instrumentation that pertains to the validation of the analysis code (MULTA) is described here.

Measurement of Vertical Track Loads

Rail-Seat Loads

The main array of each test section contained six instrumented tie plates, of which five were along one rail. The instrumented tie plates were used to record rail-seat loading throughout the influence zone of the center tie. Each instrumented tie plate had a pair of load-cell washers. The signals from the two load-cell washers were summed to measure total vertical rail-seat load.

Tie-Ballast Pressures

The Federal Railroad Administration-Portland Cement Association (FRA-PCA) load-cell ties developed for the Kansas test track were used to measure the tie-support reactions at the tie-ballast interface. These steel ties have 10 separate segments along the bottom to convert bearing pressures to discrete loads. Each rail seat is instrumented to measure vertical rail-seat loads. [A detailed description of the construction of the FRA-PCA load-cell tie and a comparison of the bending stiffness between the load-cell tie and the Railroad Concrete Crosstie Corporation tie have been given by Kennedy and others (1)].

Two of the load-cell ties were installed at site 1, and one load-cell tie was installed on the curve at site 3. The purpose of using these load-cell ties was to simultaneously measure vertical rail-seat loads and the resulting distribution of tie-ballast pressure on the 10 instrumented segments along the tie length.

Generation of Input Data for MULTA

The input-data requirements of the MULTA track-analysis model include the elastic properties for a layered representation of the ballast and the subgrade. The following plate-bearing test procedure was used to obtain representative data for the elastic properties:

1. Two adjacent ties were removed, sufficiently far away to avoid any effect on the instrumentation, and load-deflection plate-bearing measurements were made on the ballast surface in the footprint of one tie. A 0.20-m (8-in)

diameter, circular loading plate was used on the ballast surface, and this area was covered with plaster of paris (dental cement) so that the loading plate would bear uniformly on the ballast. A fixed wooden reference beam supported outside the track was used as a displacement reference for two displacement transducers attached to the plate. Displacements were recorded for ballast loadings of up to about 862 kPa (125 lbf/in^2), which exceeds the ballast pressure encountered in actual service by a considerable margin [typical ballast pressures in service rarely exceeded about 345 to 414 kPa (50 to 60 lbf/in^2)].

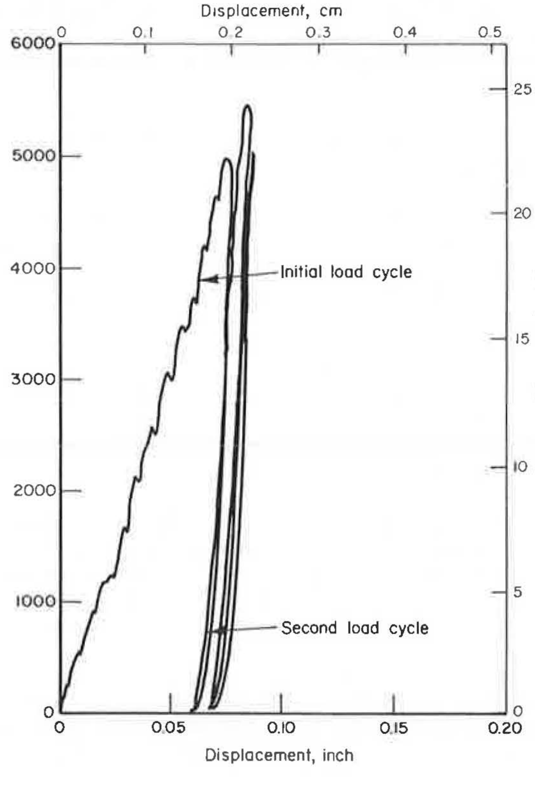
2. The ballast crib was excavated at the location of the two removed ties to determine the actual ballast depth. The ballast depth under the bottom of the tie was 16.5 cm (6.5 in) at both site 1 and site 2. The plate-bearing tests were repeated on the subgrade without using the dental cement.

3. Data from steps 1 and 2 were used with the multilayer track-analysis model to determine representative values of Young's modulus for the ballast and subgrade layers.

The loading cycle was repeated three consecutive times at each of three positions along the length of the tie. As shown in Figure 3, the initial load cycle has a much lower slope (force versus displacement) than does the second load cycle. In fact, after the initial load cycle, the subsequent load cycles have almost the same slope. Data shown in Figure 3 are for the site 1 subgrade at 16.5 cm on the gauge side of the rail. Data for the other locations are characteristically similar.

Initial and final slope values from the subgrade tests were used to estimate Young's modulus (E_2) for the subgrade, by using theory-of-elasticity solutions for the deflection of an elastic half space loaded by a rigid circular plate. After E_2 was determined, the ballast-stiffness data were used to estimate Young's modulus (E_1) for the ballast. This estimate was made by using the multilayer program in an iterative scheme until the predicted load-deflection values for the circular plate load were sufficiently close to the experimental values. It was hoped that using initial and final stiffness values would place a bound on the value of E_2 so that the predicted value of track modulus (U) would compare favorably with the measured data for track modulus.

Figure 3. Relationship between force and displacement for subgrade plate-bearing test at site 1.



The values of Poisson's ratio for the subgrade and ballast layers are also needed as input to the MULTA program. Typical values of $\nu_1 = 0.4$ for the ballast and $\nu_2 = 0.4$ for the subgrade were chosen from the subgrade property data obtained from the results of soil tests conducted by Pittsburgh Testing Laboratories [as reported by Prause and others (1)].

The table below shows the values of E_1, E_2, and U, based on the initial and final plate-bearing-test stiffness data in conjunction with the MULTA program (1 MPa = 145 lbf/in^2).

	E_1(MPa)		E_2(MPa)		
Location	Initial	Final	Initial	Final	U(MPa)
Site 1	193	207	61.4	123	105-176
Site 2	103	193	33.1	123	72.5-210

Track modulus U is defined here as the force per 2.5 cm (1 in) of rail required to depress the track roadbed 2.5 cm. This parameter has been used historically to quantify the effective stiffness, or resilience, of a track structure and is a key parameter in the beam-on-elastic-foundation analysis procedure used for conventional track design. The predicted values of U are based on the beam-on-elastic-foundation equation for vertical rail-seat load in the form:

$$U = 4EI\,[(2/\ell_t)\,(Q/P)]^4 \qquad (1)$$

where

Q = maximum rail-seat load predicted by MULTA,
P = wheel load,
ℓ_t = tie spacing, and
EI = rail bending stiffness.

COMPARISON OF MEASURED AND PREDICTED LOADS

Effect of Track Modulus on Rail-Seat Loads

Vertical rail-seat load (i.e., the load that is absorbed by a tie in a track structure; for example, if a static wheel load is placed on a rail directly over a particular tie, that particular tie will absorb 40 to 60 percent of the applied wheel load) data from a slow roll-by of the work train were used to determine U. The work train consisted of one empty and one loaded 90.7-Mg (100-ton) hopper car and a four-axle locomotive. The effect of tie-to-tie variations in the main array was minimized by averaging the maximum rail-seat loads for a known wheel load during a slow traverse of the work train. The average ratio of the rail-seat load to the wheel load (Q/P) was used with the theoretical relationship from the beam-on-elastic-foundation formulation to determine an experimental track modulus. This is the same formula that was used to calculate the values of U given above.

The table below gives the maximum measured values of Q/P.

Item	Q/P (%) Tie 1	Tie 2	Tie 3	Tie 4	Tie 5	Avg
Site 1						
Light car	43	71	31	–	33	44.5
Heavy car	47	58	53	–	65	55.8
Site 2						
Light car	22	38	64	–	76	50
Heavy car	44	31	56	–	64	48.8

These data show a considerable load-dependent effect as well as large tie-to-tie variations. The average rail-seat load for heavy cars on track that has 0.51-m tie spacing was 12.5 percent lower than that of track that has 0.61-m tie spacing. A 16 percent reduction would normally be expected based on conventional guides for track design. However, individual ties in both sections carried as much as 65 percent of the heavy-car wheel load and as much as 76 percent of the light-car wheel load.

Figure 4 shows a comparison of measured and predicted rail-seat loads for a heavy-car wheel centered in the main array of site 2. The model parameters corresponding to a track modulus of 210 MPa/rail [(30 400 lbf/in^2)/rail] (final values given above) were used for the predictions. It is evident from the load distribution shape that the actual track was stiffer than the analysis model.

As discussed above, it was hoped that the data from the initial and final load cycles of the plate-bearing load-deflection tests would provide bounds to the estimation of the roadbed parameters. However, the comparison in Figure 4 shows that the plate-bearing test data did not provide a reliable prediction of roadbed stiffness even though the values for subgrade and ballast modulus appear reasonable when compared with the laboratory subgrade measurements and typical values for ballast.

Because the FEC roadbed is stiffer than that predicted by using the plate-bearing data, the following procedure was adopted in an attempt to synthesize the model parameters that determine roadbed stiffness and track modulus. The ratio of the moduli of the ballast and the subgrade determined from the plate-bearing tests was retained, and the actual values of E_1 and E_2 were increased so that the maximum predicted rail-seat load equals the average maximum experimental rail-seat load for the heavy car. The heavy car was chosen to reduce the effect of any nonlinearities. This procedure was used to adjust the E_1 and E_2 values so that the maximum predicted vertical rail-seat load was within 1.2 percent of the average experimental data for the 0.51-m tie spacing (site 2) and within 1.6 percent for the 0.61-m tie spacing (site 1). The adjusted values of foundation properties are given below (1 MPa = 145 lbf/in^2).

Property	Value
E_1, MPa	414
E_2, MPa	246
ν_1	0.4
ν_2	0.4

Figure 5 compares the measured and the predicted rail-seat loads when a heavy-car wheel is centered in the main array of the track that has 0.61-m tie spacing. In the case of a very stiff track (a high value of U), the loaded tie absorbs a large percentage of the applied load (>50 percent) and the loads absorbed by the adjacent ties drop off rapidly. The average maximum experimental rail-seat load was 84 kN (18 900 lbf) for an applied load of 151 kN (33 900 lbf) at site 1 (Q/P = 55.8 percent). This gives a track modulus of U = 329 MPa (47 700 lbf/in^2). The maximum predicted rail-seat load was 82.8 kN (18 600 lbf), and the predicted track modulus was 308 MPa (44 700 lbf/in^2). The lower predicted modulus is apparent from the comparison of the rail-seat load-distribution shapes shown in Figure 5.

This comparison shows that the actual track structure is at least as stiff as the value predicted using the adjusted modulus values of E_1 and E_2. The tie-ballast pressure distribution data in the following section also support this conclusion.

Tie-Ballast Pressure Distribution

Tie bending moments at the rail seat and bending and torsional moments at the tie center have been identified as the major causes of concrete-tie failures. The distribution of the support reaction between the tie and the ballast is the principal unknown factor in validating the bending moments predicted by analytical models. Therefore, measurements of tie-ballast pressure distribution along the length of the tie were needed to fully validate the analytical prediction of bending moments at the tie rail seat and at the center.

The vertical tie-ballast pressures along the length of one load-cell tie for heavy, medium, and light cars are shown in Figure 6. These pressure profiles indicate that this particular tie was noticeably center-bound for light-car loads. That is, the tie center bears almost the entire load, and the outer ends of the tie carry almost no load. As the magnitude of the load is increased, the peak pressures moved outward from the tie center toward the rail-seat regions. The experimental data show that the peak pressure shift from the tie center to the rail-seat region reaches a maximum on the gauge side of the rail seat. Pressures up to about 276 kPa (40 lbf/in^2) were measured in the rail-seat region for normal heavy cars.

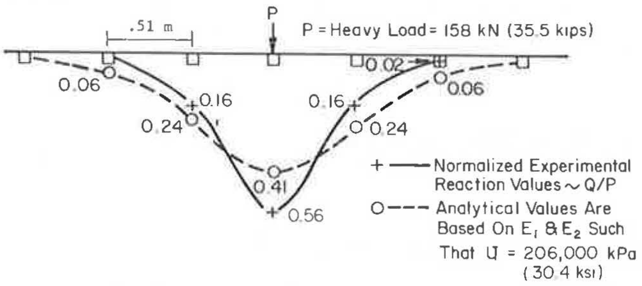
Predicted results from the MULTA program for the medium-car load are shown for comparison in Figure 6. The MULTA program assumes a uniform elastic support for the roadbed. The resulting tie-ballast pressure distribution reaches its maximum under the applied load (rail seat) and its minimum at the tie center. The maximum predicted pressure [228 kPa (33 lbf/in^2)] is within 14 percent of the measured data for the medium load despite the center-binding effect for this tie.

The experimental data from the load-cell tie in the curved track section (site 3) are shown in Figures 7 and 8. Tie-ballast pressure distributions along the length of the tie for light-, medium-, and heavy-car wheel loads are shown in Figure 7. An integration of the pressure distributions showed that vertical equilibrium was satisfied to within 3 percent of the respective applied loads.

The results of the MULTA program shown in Figure 7 for medium-car wheel loads are in good agreement with the experimental data. Maximum pressures are predicted to within 5 percent, and the shapes of the distributions are very similar. It is also evident that the vertical load is considerably greater on the high rail and the case of unequal loads can be used as input to the model.

The normalized pressure distributions for the three cases of light-, medium-, and heavy-car wheel loads are shown in Figure 8. The small variations show that the support reactions for this tie behaved in a linear manner and that the uniform elastic foundation used in the MULTA program gave good predictions for the pressure distributions for all wheel loads.

Figure 4. Comparison of experimental and analytical rail-seat loads at site 2.



Track Displacement Predictions

The results from the MULTA program were used to determine how the track displacement compares to that for a Winkler foundation. The data in Figure 9 show that the predicted displacements are distributed over a greater length of track than the tie-load distribution. The difference between the displacement shape predicted by MULTA and that predicted by the tie-load distribution indicates that the rail is not behaving like a beam on a Winkler-type foundation; the two distributions would be identical for a Winkler foundation.

Vertical rail displacements were measured at two locations at each test site—the middle tie of the main

Figure 5. Comparison of measured and predicted vertical rail-seat loads at site 1.

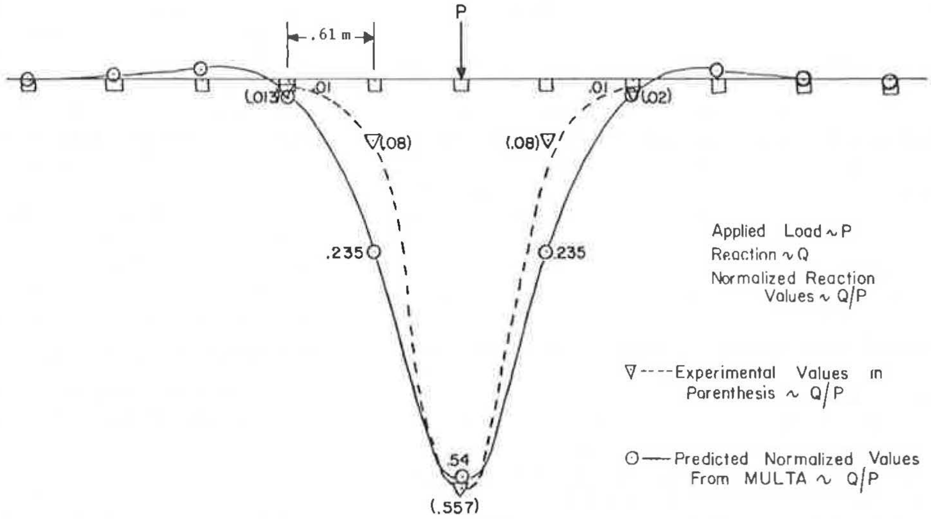
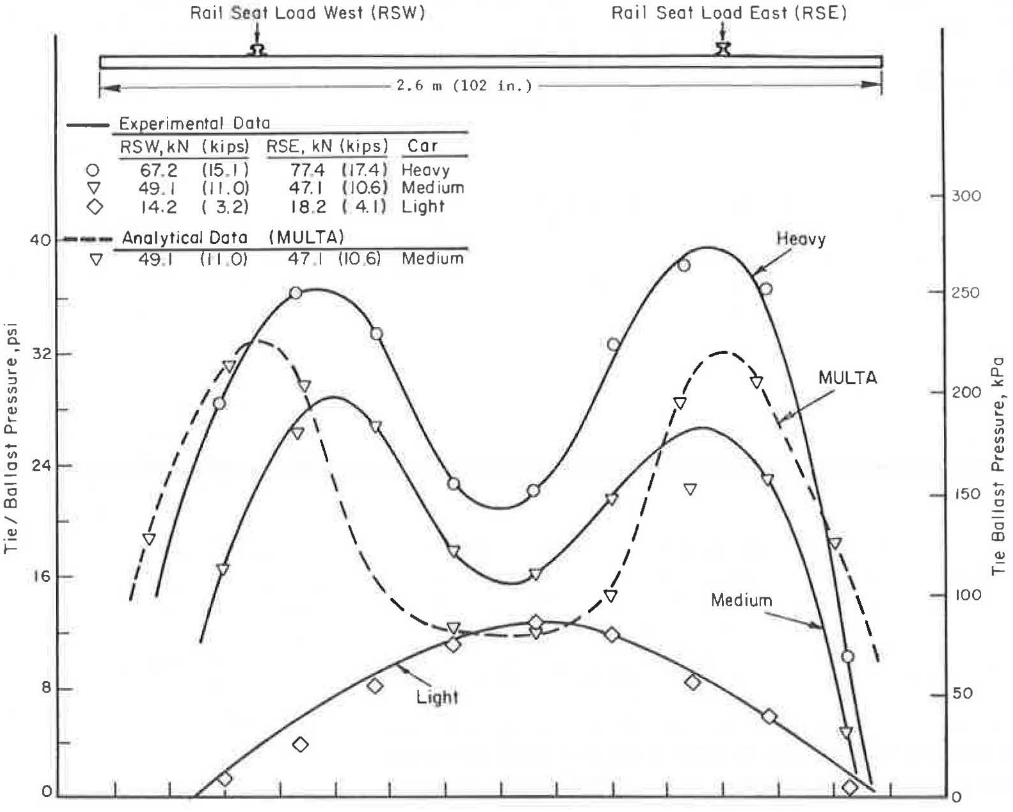


Figure 6. Tie-ballast pressure data at site 1.



array and a tie about 10.7 m (35 ft) outside the main array. Because only two locations were instrumented at each test site for these data, it was difficult (in view of the local variations discussed above) to characterize the track structure by using experimental displacement values. It is believed that more values of displacement (per test site) are required so that average maximum displacement values could be used to better predict track modulus. However, the alternative approach of averaging data from five instrumented tie plates gave good results.

Figure 7. Tie-ballast vertical pressure data at site 3.

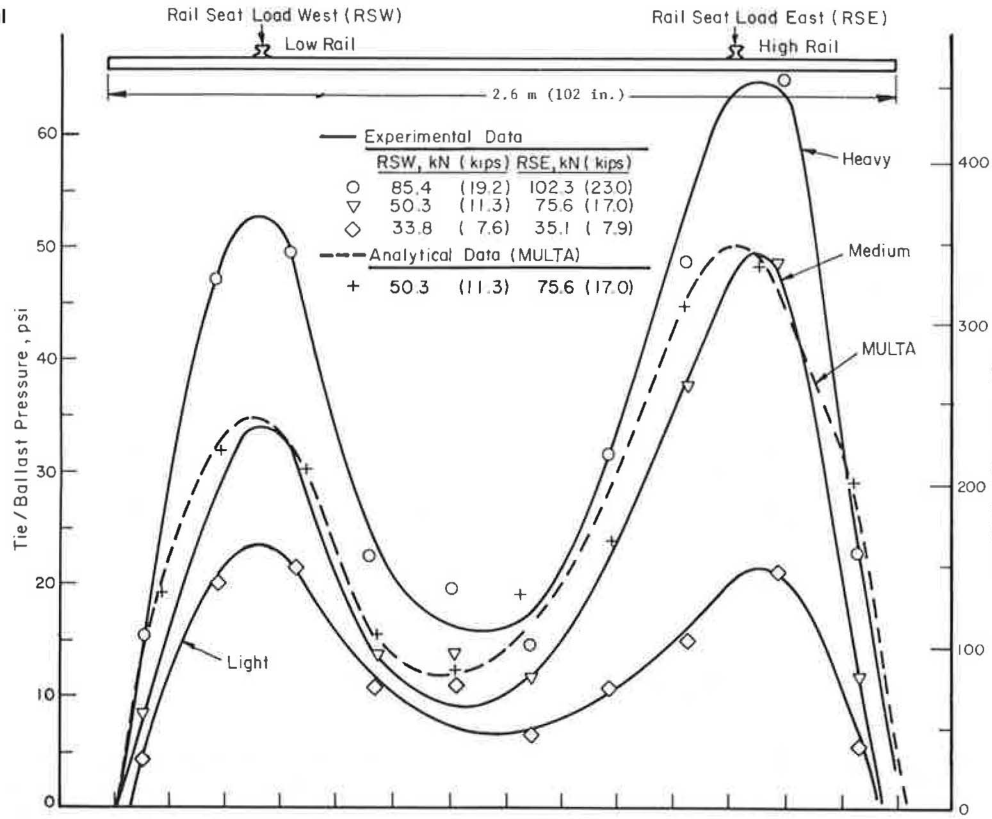
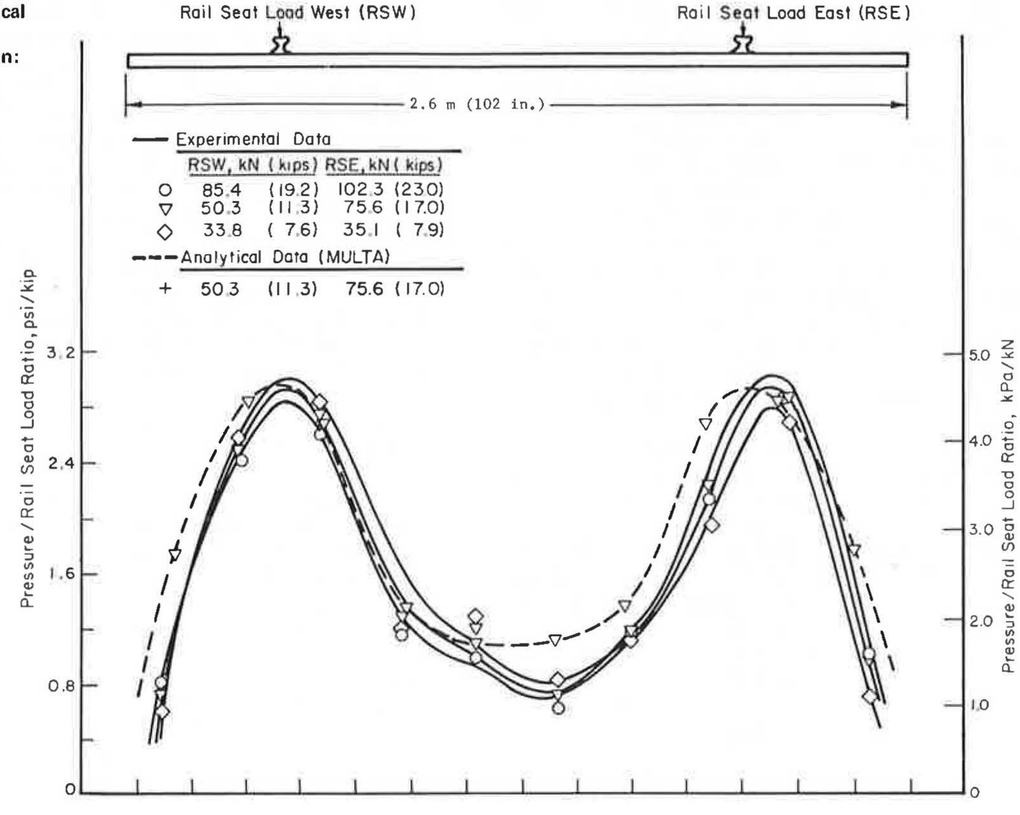


Figure 8. Tie-ballast vertical pressure normalized to respective rail-seat reaction: site 3.



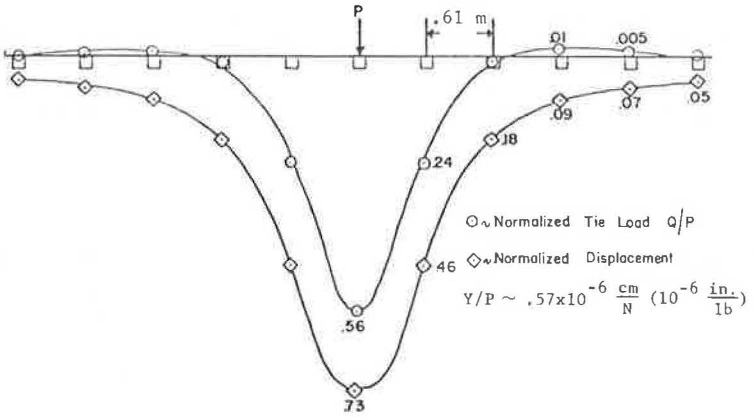


Figure 9. Predicted tie load and displacement distributions: site 1.

Table 1. Summary of track modulus values.

Location	Measured Track Modulus (MPa)				Predicted Track Modulus (MPa)	
			Avg Tie-Plate Loads[c]			
	Displacement[a]	Strain[b]	Light	Heavy	Foundation Parameters From Plate-Bearing Tests[d]	Adjusted Values of E_1 and E_2[e]
Site 1						
Main array	270	316	130	328	105-176	308
Outside main array	283				105-176	
Site 2						
Main array	126	600	432-401		72.4-206	382
Outside main array	565				72.4-206	

Note: 1 MPa = 145 lbf/in².

[a] Calculated by using rail displacement for light- and heavy-car wheel loads.

[b] Calculated by using rail bending strains for light- and heavy-car wheel loads.

[c] Based on average maximum tie-plate loads on four ties [light load = 35.6 kPa (≈ 8000 lbf/in²) and heavy load = 151.3 kPa (≈ 34 000 lbf/in²)].

[d] Range for initial to final values for model parameters based on predicted maximum tie-plate load.

[e] E_1 = ballast modulus and E_2 = subgrade modulus, adjusted so that maximum predicted rail-seat load equals average maximum experimental rail-seat load at site 1.

Track Modulus Measurements

It was originally planned that rail bending strains measured under heavy and light loads similar to those used for measuring displacements would be used to provide a check on the track modulus determined from the displacement data. However, the lack of a sufficient number of strain gauges (i.e., at many positions along the length of the rail) prevents the sort of averaging process that subsequently was determined essential to minimize local variations. Difference (heavy-load-minus-light-load) stress and displacement values and corresponding track moduli are given in Table 1.

The values of track modulus given in Table 1 indicate that the track structure is quite stiff. However, the data resulting from displacement and strain measurements are for one or two discrete points along a rail at a particular test site; they do not represent any sort of averaged values. As such, they should not be considered truly representative of the overall track modulus.

Thus, the predicted calculations of track modulus shown above and in Table 1 are based on the beam-on-elastic-foundation equation for vertical rail-seat load (Q) as shown in Equation 1. Equation 1 is one of two forms used to calculate U. The other form is based on the maximum rail displacement (Y_0). Both forms are derived from beam-on-elastic-foundation theory. If, in reality, the track system behaves as a beam-on-elastic-foundation, then either form can be used to calculate U and the answers will be identical. However, if the shear coupling in the roadbed is significant, the track will not behave according to the assumptions used for the beam-on-elastic-foundation and the results from estimates of track modulus that use measured data for Q and Y_0 will not give equivalent values for U. This is also true for the MULTA model, where there is appreciable shear coupling in the simulation of the roadbed.

As we have seen, the measurements on FEC showed that the use of the average maximum rail-seat load to calculate U gives results that are more consistent with the loads and moments than does the use of rail displacements. As mentioned above, the rail-seat load distribution predicted by MULTA is qualitatively similar to the results of the beam-on-elastic-foundation solution and the FEC measurements, whereas the displacement distribution is different from beam-on-elastic-foundation solution because of coupling in the roadbed. However, if the predicted modulus values are calculated by using the rail displacements, the values will be approximately one-half to one-third those calculated by MULTA and the use of rail-seat loads and in the range of typical measured track-modulus data for concrete-tie track.

SUMMARY OF RESULTS AND CONCLUSIONS

The comparison of predicted and measured track-response parameters discussed above shows that the MULTA track-analysis program is capable of making good predictions of tie loads and tie-ballast pressures. The inclusion of tie bending has been shown to be quite important in predicting ballast pressures. The program can also be used to predict rail bending stresses and tie bending moments.

No experimental data on stresses in the ballast and subgrade below the tie were measured for comparison. However, the good agreement with the predicted ballast pressures immediately under the tie gave confidence that pressures predicted elsewhere in the roadbed will be sufficiently accurate for track-design evaluations. Predictions of soil behavior are limited by the assumptions of linear elasticity in the MULTA model; thus, inelastic behavior of highly loaded soils could not be predicted accurately.

The major difficulty in using MULTA (or any other track-analysis program) is in the accurate modeling of the ballast and subgrade. The elastic continuum used in the MULTA model does show that the transfer of shear in the roadbed produces appreciable tie-to-tie coupling in displacements. This effect is also observed in track-response measurements, but it is not included in conventional beam-on-elastic-foundation models. However, the real difficulty is in establishing the material properties for a layered model of the ballast and subgrade that match the overall track-modulus measurements. The plate-bearing tests on the ballast and subgrade and independent vibroseismic measurements of subgrade properties did not give sufficiently accurate predictions of track modulus for the prediction of track loads under heavy-car wheel loads even though pressures greater than the maximum pressures under traffic were used for the plate-bearing tests. This difficulty cannot be explained at this time. In the meantime, it is recommended that the ballast and subgrade properties be adjusted to match the experimental measurements of track modulus under heavy-car wheel loads by using representative soil data for the relative ballast-soil stiffness. Predictions of tie loads, track deflections, and roadbed pressures will not be greatly influenced by changes in the relative ballast and soil stiffnesses as long as the track modulus is matched. Inaccurate estimates of these parameters will have their greatest effect on predictions of relative deflections in the ballast and subgrade layers.

ACKNOWLEDGMENT

This paper is based on the results of a research project conducted by Battelle Columbus Laboratories and Bechtel. The research was sponsored by the U.S. Department of Transportation, Federal Railroad Administration, through the Transportation Systems Center. We gratefully acknowledge the assistance and enthusiastic cooperation of the staffs of Battelle Columbus Laboratories, Bechtel, and FEC. This paper presents our views and positions and does not necessarily reflect those of the U.S. Department of Transportation.

REFERENCES

1. R. H. Prause, H. D. Harrison, J. C. Kennedy, and R. C. Arnlund. An Analytical and Experimental Evaluation of Concrete Crosstie and Fastener Loads. Federal Railroad Administration, Rept. FRA/ORD-77/71, Dec. 1977.
2. S. D. Tayabji and M. R. Thompson. Program ILLI-TRACK: A Finite-Element Analysis of Conventional Railway Support System—User's Manual and Program Listing. Federal Railroad Administration, Technical Rept. FRA-ORD-76-257, March 1976.
3. R. H. Prause and J. C. Kennedy. Parametric Study of Track Response and Performance. Federal Railroad Administration, Rept. FRA-ORD-77/75, Dec. 1977.
4. Ballast-Subgrade Model of Burmister Multilayer Elastic System. Report and Test Department, Association of American Railroads, Washington, DC, Rept. R262-13, Sept. 1975.
5. D. M. Burmister. The General Theory of Stresses and Displacements in Layered Systems. Journal of Applied Physics, Vol. 16, Feb. 1945, pp. 89-94.
6. Ballast-Subgrade Finite-Element Model: Prismatic Solid Analysis Program. Report and Test Department, Association of American Railroads, Washington, DC, Rept. 262-14, Vol. II, 14, Sept. 1975.

Permanent-Deformation Behavior of Railway Ballast

Reid M. Knutson, Department of Civil Engineering, University of Kansas
Marshall R. Thompson, Department of Civil Engineering, University of Illinois, Urbana-Champaign

Ballast materials were tested in the triaxial apparatus by using a repeated deviator stress and a constant confining pressure. Permanent deformation (plastic) characteristics at several stress levels were determined for a variety of types and gradations of material. Correlation analyses were made between the plastic response and the results of standard material-characterization tests. The results indicate that the most important factor influencing the repeated-load plastic-strain behavior of ballast is the degree of compaction. The stress level was also found to be an important factor; there was some indication that permanent deformation was less for the more nearly well graded specimens. Finally, unlike the resilient response, the permanent-deformation behavior of ballast is dependent on loading history.

One of the major problems of rail track support systems is the continual need for realignment of the rail-tie system by addition of ballast. Present maintenance practice dictates that only the portion of the ballast near the rail be tamped; the center is left undisturbed. This practice results in the addition of ballast primarily in the proximity of the rails; ballast pockets result (1).

Before the experience-oriented design of rail-tie support systems can be improved, the plastic-deformation behavior of ballast subjected to repeated loading must be investigated so that an understanding of its nature can be obtained. To accurately predict the deformation characteristics of ballast, the test method should simulate the in-service dynamic stress conditions.