

allows the calculation of contact forces between two structures (i.e., the ground and the tie-rail system). Triaxial test data for ballast or granular material can be processed in a cubical spline form to allow for variable Young's moduli and Poisson's ratios. A beam stiffness can be added to the total system if it is desired not to model the rails as three-dimensional elements. The input data are described in terms of a railroad, but the program could be used to describe other structures.

The following method is used: Loads and railroad details are defined for each point of the three-dimensional mesh (nodal system). Analysis is by the finite-element method with displacements as the primary variables. The maximum number of nodes is 999 nodal points. However, the size can be increased by changing the dimension statements in the main program. The programming language used is FORTRAN IV.

The input of the program includes node numbers, element numbers, nodal-point coordinates or element half lengths and side projections, boundary conditions, material properties (Young's modulus, Poisson's ratio, and unit self-weight), material tension identifier, triaxial test results (for nonlinear analysis only), rail-tie system geometry and material properties, contact-structure elements and nodes duplication (for contact-structure analysis only), loads (point and uniformly distributed or both), and nodal point displacements (optional). The output includes nodal-point incremental and total displacements, principal strains, nodal-point stresses and strains, and element total moments, stresses, and strains.

Typical running times are 25 min for 480 nodal points (approximately two days data preparation) and 110 min for 626 nodal points.

ACKNOWLEDGMENT

The work described in this paper is part of a general study of geotechnical problems of railroad structures and fills financed by the Canadian Institute of Guided Ground Transport, Queen's University. We wish to acknowledge the discussions with and the advice and help obtained from the personnel of the Canadian National and Canadian Pacific Railways, particularly L. Peckover, C. Dalton, and N. Caldwell.

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Publication of this paper sponsored by Committee on Earth Masses and Layered Systems.

Field Observations of Ballast and Subgrade Deformations in Track

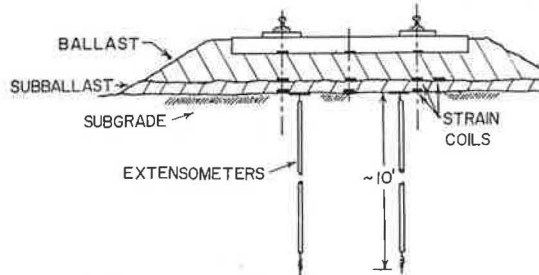
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An extensive instrumentation program has been undertaken at the Facility for Accelerated Service Testing track located at the Transportation Test Center in Pueblo, Colorado, to monitor the performance of ballast, subballast, and subgrade layers under repeated traffic loading. Test sections are involved that contain wooden and concrete ties, tangent and curved track, ballast depths of 36-53 cm (14-21 in), and three different types of ballast. Soil strain gauges were installed in the ballast and subballast layers to measure the vertical and horizontal strains caused by train traffic loading and by track maintenance operations. Vertical extensometers were used to determine the settlement of the subgrade surface, and soil stress gauges at the subballast-subgrade interface were used to measure the vertical stress on the subgrade. The monitoring included both long-term measurements of the permanent strain and deformation accumulated with traffic and dynamic measurements of the elastic response under train loading. The study has provided extensive and unique data on the nature of the deformation response of a track system as a function of various track parameters. The system responded elastically, but nonlinearly, under each repeated axle-load cycle. However, permanent deformation did accumulate and continue to develop even after 667 GN [75 million gross tons (MGT)] of train load. Most of the readjustment after tamping disturbances occurred within the first 89-178 GN (10-20 MGT) load, with about half complete within 8.9-17.8 GN (1-2 MGT).

The performance of track structures is significantly affected by the behavior of the ballast and the subgrade under the repeated stresses caused by train loadings. The properties of these materials are a function of their physical state, which is influenced by maintenance and traffic history. Very little data are available from previous experience of actual track structures that can provide direct information on the physical states and deformation responses of ballast and subgrade, a situation that leaves considerable uncertainty about the specific ways in which these materials affect track performance.

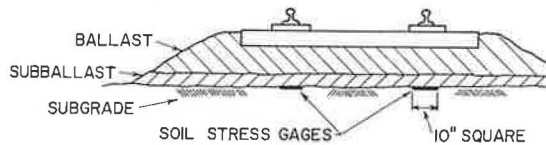
A significant advance in the understanding of track performance has resulted, however, from the instrumentation program initiated in 1976 at the Facility for Accelerated Service Testing (FAST) track at the Transportation Test Center (TTC), U.S. Department of Transportation, in Pueblo, Colorado, to monitor the response of the ballast and subgrade layers under traffic. The instrumented sections contain both wooden and concrete

Figure 1. Strain gauge layout beneath railroad tie.



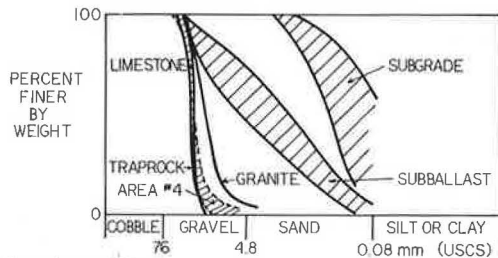
Note: Depth of extensometers = 3.05 m (10 ft).

Figure 2. Location of soil stress gauges beneath railroad tie.



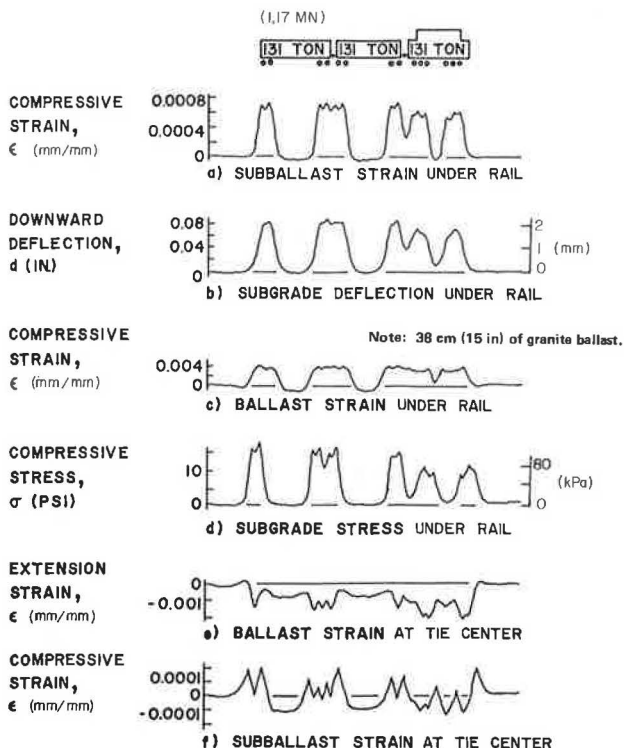
Note: Area of soil stress gauges = 25.4 x 25.4 cm (10 x 10 in).

Figure 3. Gradation of materials in instrumented sections at FAST.



Note: 1 mm = 0.039 in.

Figure 4. Dynamic measurements in wooden tie section.



ties, tangent and curved track, ballast nominal depths of 38-53 cm (15-21 in), and three different types of ballast (granite, limestone, and traprock).

In this program, soil-stress gauges at the subballast-subgrade interface are used to measure the vertical stress on the subgrade caused by vehicle loading on the rail. Strain gauges in the ballast and subballast are used to measure the vertical and horizontal strains, both the instantaneous elastic under vehicle loading and the cumulative inelastic caused by vehicle loading and by track maintenance operations. Vertical extensometers in the subgrade are used to measure the instantaneous elastic and the cumulative, inelastic vertical deformations of the subgrade-surface under vehicle loading relative to a reference anchor 3.05 m (10 ft) below the subgrade surface.

The trends for residual strains and deformations as a function of cumulative traffic loading are described for the first 1556 GN [175 million gross tons (MGT)] of traffic. The recorded peak values of the parameters measured during vehicle loading were examined after 26.7 GN (3 MGT) of train traffic and again after 667 GN (75 MGT) of traffic. The effects of track parameters on these results are illustrated.

INSTRUMENTATION PLAN

The stress, strain, and extensometer gauges were designed and fabricated based on previous experience (1,2). In each case, the transducer is a pair of inductance coils connected to a special signal conditioner and read-out device (3). [Details of the instrumentation and the installation procedures are given elsewhere (4).]

A typical instrumentation layout for ties involving strain coils in both the ballast and subballast and extensometers in the subgrade is shown in Figure 1. The top coils in the ballast are recessed into the bottoms of the wooden ties but are taped to the bottoms of the concrete ties. Each coil is electromagnetically coupled to a coil directly below it at or near the ballast-subballast interface. No physical connection exists between the coils, so that they are free to move with the track structure and also so that they will not be damaged by normal tamping operations or by tie movements in the horizontal plane. Each coil at the subballast surface is also electromagnetically coupled to the underlying coil on the subgrade surface. Each extensometer is installed in a 3.05-m-deep bore hole with the top anchor plate located at the subgrade surface.

Because the rails were already in position at the time of instrumentation, the bore holes for the extensometers could not be positioned directly under the rail-seat locations. Hence, they are located as close as possible to the inside of the rails at the centerline of the tie.

To obtain replicate measurements of the ballast and subballast strains, additional tie locations are instrumented in each test section by using some of the coils in Figure 1 but omitting the extensometers. Stress gauges are also placed at the subgrade surface under other ties as shown in Figure 2.

At each location to be instrumented, the tie was extracted and the ballast and subballast removed by hand shoveling. Backfilling was done by replacing the materials in about 15-cm (6-in) layers and compacting by using a heavy, pneumatic vibrating-plate tamper having a 15-cm-diameter circular-plate tamping foot. The tie was then carefully placed back into its previous position, and the cribs and shoulder were filled.

SITE CONDITIONS

Six sets of different track conditions are represented by

the instrumented sections. The defining variables are tie type, ballast type, ballast depth, and track geometry. The rail used is 68 kg/m (136 lb/yd), continuously welded on the concrete-tie sections and jointed on the wooden-tie sections. Two types of tie are used: 27.3-cm x 2.59-m (10.75-in x 8.5-ft) concrete on 61.0-cm (24-in) spacing and 17.8x22.9-cm x 2.59-m (7x9-in x 8.5-ft) hardwood on 49.5-cm (19.5-in) spacing. The subballast is a 15-cm layer of well-graded gravelly sand, and the subgrade is a silty, fine-to-medium sand. The six sections are described below (1 cm = 0.4 in).

Section	Tie Type	Ballast Type	Ballast Depth (cm)	Track Geometry
1	Concrete	Granite	41-48	Curved
2	Concrete	Granite	36	Tangent
3	Hardwood	Granite	53	Tangent
4	Hardwood	Granite	38	Tangent
5	Hardwood	Limestone	38	Tangent
6	Hardwood	Traprock	38	Tangent

Three different types of ballast are involved in the instrumented sections of the FAST track. Their index properties, as determined by tests conducted at the University of Illinois (5), are described below (1 mm = 0.04 in).

Property	Granite	Limestone	Traprock
Particle index	14.2	12.2	16.4
Flakiness index	20.8	9.4	22.7
Soundness	0.77	11.9	0.5
Los Angeles abrasion	18.8	25.7	13.2
Bulk specific gravity	2.68	2.68	2.94
Absorption (%)	0.40	1.65	0.20
Crushing value	18.4	19.3	13.1
Particle-size range (mm)	1-40	15-50	15-50

The limestone and traprock ballasts correspond to AREA no. 4 gradation, while the granite ballast is finer (see Figure 3).

The individual particles of all of the ballasts are relatively angular. The granite and traprock ballasts have sharper edges than the limestone, and the hardness of the particles is higher for the granite and traprock than the limestone. At the time of sensor installation, the ballasts were quite clean, without contamination.

The subballast material is a well-graded gravelly sand (Figure 3). It is designated SW in the Unified Soil Classification System (USCS) or A-1 in the American Association of State Highway and Transportation Officials (AASHTO) system. The subballast was compacted by using a vibratory roller before the track was constructed. Inspection records indicate that the compaction exceeds 90 percent of the AASHTO T-99 value at water contents of 6-12 percent. At the time of instrument installation, the moisture content was 3-5 percent.

The subgrade material is generally classified as a silty-to-very-silty, fine-to-medium sand, in some areas becoming a sandy silt (Figure 3). The principal designation is SM in the USCS system and A-1 to A-4 in the AASHTO system. No distinct subgrade layer boundaries are evident from borings; however, observations made during drilling of the extensometer holes suggest a general tendency toward increasing silt content with depth. In general, the moisture content of the subgrade material decreases from 6-12 percent in the top 1.2 m (4 ft) to 1-5 percent in the next 1.8 m (6 ft).

DYNAMIC MEASUREMENTS

The dynamic measurements to monitor instantaneous

responses under wheel loading were first obtained after 26.7 GN of accumulated train traffic and have since been taken periodically at 222-GN(25-MGT) intervals. Throughout the dynamic measurements, very consistent patterns of the ballast, subballast, and subgrade responses have been observed. A typical response, that obtained during the 26.7 GN recording, is shown in Figure 4. The loading during the measurements was produced by a work train consisting of a six-axle locomotive and two four-axle hopper cars, each weighing about 1.17 MN [262 000 lbf (262 kips)].

Except for the ballast strain at the tie center, the maximum response for each measurement occurred directly under an axle. However, the reduction between two adjacent axles on a truck was generally minor. When the sensor location is beneath the center of a car, the subgrade deflections and stresses are generally zero, although some extensional strains are registered in the ballast and subballast locations under the rail, possibly due to rail spring-up.

The responses of the coils located under the center of the tie follow a different trend from the responses of those under the rail. For the center ballast strain, the response amplitudes are greater when the tie is located between two adjacent axles than when it is directly under an axle. This is probably because the tie experiences a greater bending moment under this loading condition.

Both the ballast and subballast coils under the center of the tie exhibit marked extensional strains. The subballast center strain is extensional under the middle of a car, but it is compressional directly under a truck. On the other hand, the ballast center strain is consistently extensional regardless of its location relative to the axles, except for the first and last wheel applications, when some relatively small compressive strains are registered. The extensional strains in the ballast could have two causes: (a) tie bending, because the top coil is fastened to the tie, and (b) extensional deformation caused by a horizontal stress that is incrementally greater than the vertical stress. However, the extensional strains in the subballast from traffic loading can have only the latter cause.

One of the most significant features shown by the dynamic records is the almost completely recoverable deformation of the track system under the transient axle loads, as indicated by the fact that none of the recorded base lines shows any noticeable permanent set. However, the static measurements taken periodically between the applications of train traffic show that there is a gradual accumulation of permanent strains with traffic.

What these records show is that, for each application of the transient wheel loads, the deformations of the track support system are mostly elastic and the plastic deformations are negligible. This, therefore, justifies the use of elastic models and resilient soil properties for predicting the response of the track system under vehicle loads.

Figures 5 and 6 summarize the dynamic responses of the ballast, subballast, and subgrade. The lines shown in Figures 5 and 6 represent the average values of peak responses under the rails when the car axle is directly over the sensor. Although significant variability occurred in each measurement, the average, which represents a minimum of eight measurements within each set of track conditions, should provide a reasonably reliable indication of the general trends of track response.

As shown in Figure 5, the ballast strains in the granite and limestone sections were about the same and consistently larger than those in the traprock section throughout the loading range studied. However, the strains in the subballast and subgrade layers under the traprock-ballast section exhibited the largest values,

and those under the limestone- and granite-ballast sections followed in decreasing order.

In the 53- to 147-kN [12 000- to 33 000-lbf (12- to 33-kip)] axle-load range, the measured parameters are approximately linearly related to wheel load. However, the intercept is not zero, which indicates that the stiff-

Figure 5. Effect of ballast type on dynamic measurements under rail ballast during 667 GN recordings.

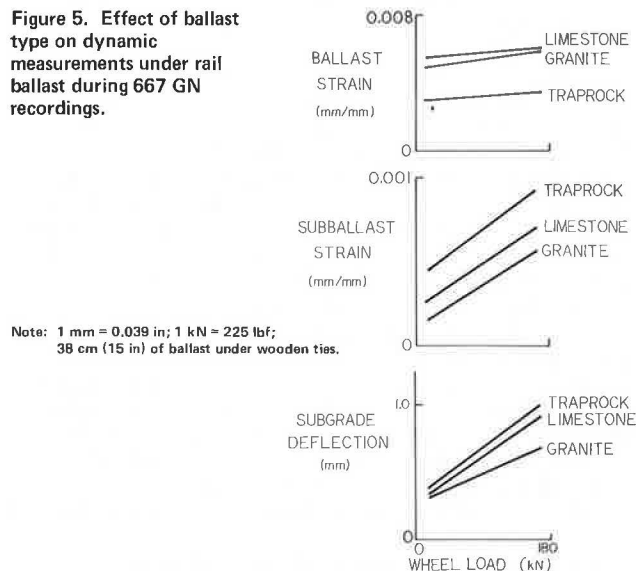


Figure 6. Effect of ballast depth, tie type, and track geometry on dynamic measurements under rail during 667 GN recordings.

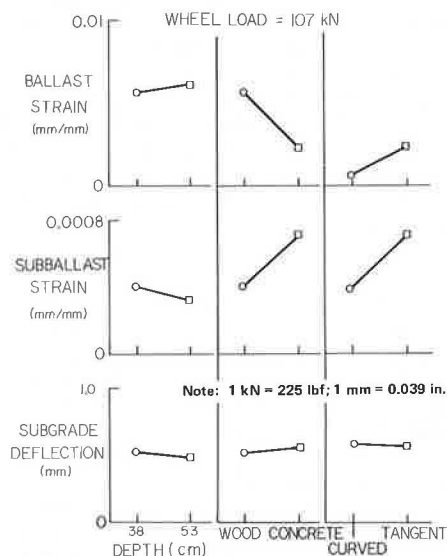


Table 1. Coefficient of variation of dynamic measurements: 147-kN wheel loads after 667 GN of traffic.

Measurement	Test Section											
	1		2		3		4		5		6	
	CV	N	CV	N	CV	N	CV	N	CV	N	CV	N
Ballast strain	0.32	3			0.35	4	0.29	8	1.10	7	1.08	8
Subballast strain	0.34	3	0.96	4	0.27	3	0.30	4	0.25	4	0.54	4
Subgrade relative deformation	0.12	4	0.16	4	0.15	4	0.47	4	0.13	4	0.23	4
Subgrade stress			0.69	4			0.33	4				

Note: 1 kN = 225 lbf (0.225 kip).

ness properties of the materials are nonlinear. Thus, superposition of the effects of different wheel loads cannot be done simply by direct proportion.

Similar comparisons for the effect of ballast depth are shown in the left column of Figure 6. Both the 38- and the 53-cm-thick sections had granite ballast and wood ties. The ballast strain in the 53-cm-thick ballast layer was slightly larger than that in the 38-cm-thick layer, the difference being greater with increased axle load. As expected, the subballast strain under the 38-cm-thick ballast section was greater than that under the 53-cm-thick section. The subgrade deflections are also slightly larger under the 38-cm-thick ballast section.

The effect of tie type is illustrated in the center column of Figure 6. Larger ballast strain occurred in the wooden-tie section and larger subballast strain occurred in the concrete-tie section [although both had the same (38-cm-thick granite) ballast]. However, the subgrade deformations were almost the same, even though the subgrade stress was considerably higher in the concrete-tie section. The difference in the stresses between the two different tie types increases as the wheel load increases. The reasons for these differences are complicated because (a) the concrete-tie section had a larger tie spacing (61-cm nominal) than the wooden-tie section (49.5-cm nominal), (b) the concrete-tie section had continuously welded rail while the wooden-tie section had jointed rail, and (c) the concrete tie was stiffer and had a larger bearing area than the wooden tie.

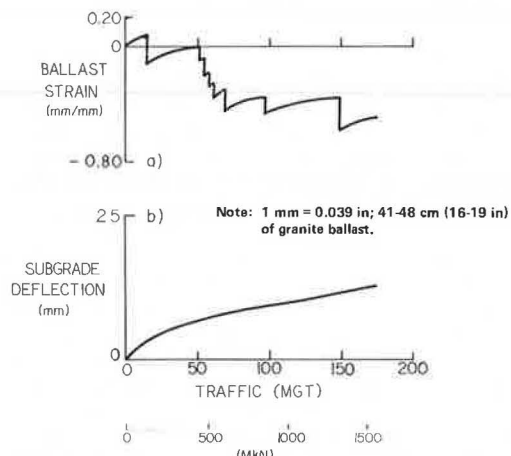
The comparisons between the tangent and curved sections are shown in the right column of Figure 6. Both sections had concrete ties with the same tie spacing and granite ballast. However, the average ballast thickness was greater for the curved track because of the required superelevation. The tangent section exhibited considerably higher ballast and subballast strains under the rail than did the curved section, but the subgrade deformations were about the same.

DYNAMIC DATA VARIABILITY

Further work is needed to evaluate the statistical significance of the trends for the static and the dynamic response measurements. The results given in this paper represent the averages of all replicate measurements within a test section. However, there was considerable variation among the values for different locations in a section. These variations were a function of location; there was little variation among the values obtained by repetitive measurements of the effects of the same wheel load at any given location.

To assist in judging the significance of the differences between the average values for each section, the coefficient of variation (CV) (i.e., the ratio of the standard deviation to the mean) for each dynamic measurement was calculated for the 147-kN [33 000-lbf (33-kip)] wheel load (see Table 1). The subgrade deformation had the smallest CV, averaging 0.21 for the five sections.

Figure 7. Accumulated ballast strain and subgrade deflection in curved concrete-tie section.



The ballast strain had the largest with an average of 0.63. The subballast strain and subgrade stress were intermediate with average values 0.44 and 0.51, respectively. The relatively large magnitude of the variability represented by these numbers limits the degree of certainty with which conclusions can be drawn when comparing results from the different test sections.

INELASTIC MEASUREMENTS

The static or long-term measurements were periodically obtained to determine the cumulative changes in the ballast strains, subballast strains, and subgrade deformations that resulted from the traffic and various track maintenance procedures. Static stress measurements were also taken, but these have not been evaluated because they represent only the pressure from the track and the ballast mass.

In general, the inelastic ballast strain, subballast strain, and subgrade deformation increased at a decreasing rate with accumulated traffic so long as no external disturbance (such as track maintenance) occurred. The ballast and subballast strains, regardless of location and direction of measurement, accumulated rapidly at the beginning of the traffic application. Accumulation of the subgrade deformation was relatively slower than that of the strains but continued for a longer period of traffic.

The strain-growth pattern was significantly changed by the disturbance caused by maintenance. Most of the track maintenance, particularly tamping, surfacing, lining, and tie and fastener replacement, involved raising the track structure and therefore created extension strain in the ballast layer.

An example of the effect of track maintenance on the ballast strain and the subgrade deflection is illustrated in Figure 7. This ballast strain clearly shows that the track rose with each tamping operation and subsequently settled after maintenance. In fact, in those examples, the amount of track raise was so large that the thickness of the ballast layer increased with each successive maintenance operation because the settlement under traffic was less than the raise. The associated subgrade-permanent-deformation pattern does not appear to be affected by the maintenance operation.

The vertical-strain accumulation in the ballast layer seems to be very rapid after the commencement of traffic. Although there were some variations from one tie location to another, about 50 percent of the probable ul-

timate strain that would be achieved without additional tamping or maintenance disturbance generally occurred during the first 8.9 or 17.8 GN (1 or 2 MGT) of traffic and about 90 percent by 89-178 GN (10-20 MGT). After that, the strain accumulation seemed to diminish and the growth rate slowed. Immediately after maintenance or tamping, however, the pattern was repeated. In most cases, the frequency of measurements following maintenance was not sufficient to determine the regrowth pattern adequately.

Unlike the dynamic strains, the static ballast strain under the rails shows the same trends as that under the center of the tie. The cumulative permanent strain at the center of the tie was compressive, except for a few ties that exhibited definite evidence of center binding.

Compared with the vertical ballast strain, the longitudinal and transverse ballast strains seem to have a much faster strain-growth pattern. As the track apparently settles to achieve a stable condition at the very early stage of traffic, the horizontal strains seem to reach a constant level at 8-9 GN and remain essentially the same until 356-445 GN (40-50 MGT) when the maintenance-caused irregularities begin to occur.

The magnitude of the transverse and longitudinal ballast strains was much smaller than that of the vertical ballast strain, as would be expected. However, it is interesting to note that these strains were generally extensional under traffic conditions without maintenance or disturbance. This indicates lateral spreading of the ballast or subballast.

The accumulation pattern of the vertical subballast strain is very similar to that of the vertical ballast strain, although the magnitude of the subballast strain was much smaller than that of the ballast strain. However, the subballast strain was obviously less sensitive to maintenance than was the ballast strain, which indicates that most of the maintenance procedures involved only the ballast layer (as would be expected).

In contrast to the ballast and subballast strains, the subgrade deformation accumulated gradually with traffic after the first 44.5-89 GN (5-10 MGT) of traffic. The subgrade deformation in the concrete-tie section increased more rapidly than that in the wooden-tie section. This difference seems to be due to the fact that the dynamic subgrade stress developed during train operation is higher in the concrete-tie section than in the wooden-tie section.

Again, a direct comparison of results for the three different ballast sections throughout the entire period of train operation is very difficult, especially in terms of ballast and subballast strains, because of the different amounts and nature of maintenance work involved in each section. However, the measurements obtained during the initial portion of traffic (when no maintenance was involved) are directly comparable.

The average accumulated ballast strains under the rails were compared for the three different ballast types. During the period without any disturbance from maintenance, the limestone and granite ballasts had about the same strains and the traprock slightly less. However, in the subballast layer, as shown in Figure 8a, the traprock section showed the largest strain, and this was followed by those of the limestone and granite sections in decreasing order. In contrast, the trend is exactly reversed for subgrade deformation (Figure 8b).

It is not known at present why the traprock section deformed less in the ballast layer, more in the subballast layer, and again less in the subgrade than did the other ballast sections. But these trends are generally consistent with those observed in the dynamic records. Also, these strain data do not conclusively show which

ballast performed better in terms of overall track performance.

As for the dynamic responses, the 53-cm granite ballast layer accumulated a larger strain under the rails than did the 38-cm granite ballast layer (see Figure 9a), but the subballast strain showed the reverse trend (Figure 9b).

Figure 8. Comparison of accumulated subballast strain and subgrade deflection under rails in three types of ballast.

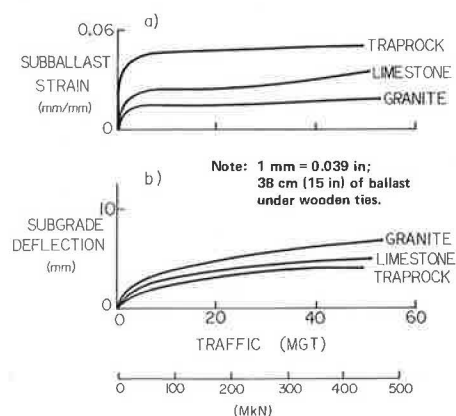


Figure 9. Comparison of accumulated ballast and subballast strains under rails: depth of granite ballast under wooden ties.

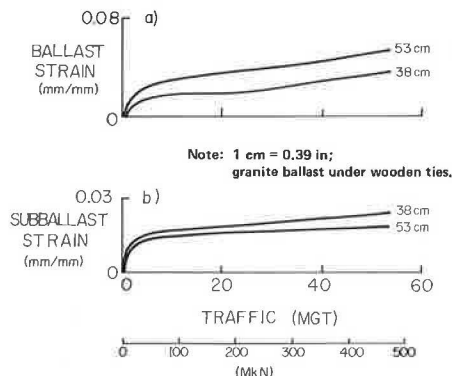
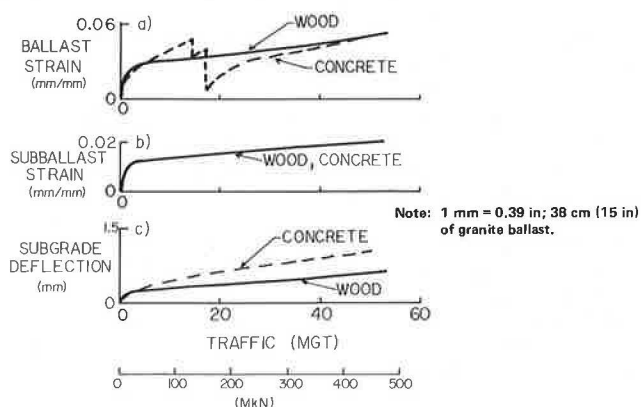


Figure 10. Comparison of accumulated ballast strain, subballast strain, and subgrade deflection under rails for concrete and wooden ties.



The subgrade deformation was about the same for the two ballast depths.

The concrete-tie section and the wooden-tie section showed about the same accumulated ballast and subballast strains (see Figures 10a and 10b), but the subgrade deformation was considerably larger in the concrete-tie section (Figure 10c). Again, the role of the different types of tie on the results is not clear because of the reasons discussed above. However, the higher dynamic pressure on the subgrade layer in the concrete-tie section might explain its higher subgrade deformation.

The curved concrete-tie section had a higher ballast deformation than did the tangent section. But, again, the trend is reversed in both the subballast and the subgrade layers. These trends are the same as those observed for different ballast thicknesses, which suggests that they might be mainly attributable to the difference in ballast thickness of the two types of sections.

SUMMARY

This paper presents experimental results that illustrate the static and dynamic responses of ballast, subballast, and subgrade to train loading. The absence of previous data of this type has limited the understanding of track behavior and prevented a needed assessment of alternative analytical models for track structure. The difficulty in making such measurements is considerable, and the observed experimental variability was large. Nevertheless, the outcome is believed to be highly successful.

An important observation was that, under repeated train loading, the system response is almost completely recoverable. The permanent deformation from any cycle was negligible. Only after many cycles did permanent strain begin to accumulate to values that could be observed.

Because of the rail stiffness, the two adjacent axes on a truck create a single load pulse that has little ballast unloading between them. Most of the strains and deformations were compressive under the load. However, midway between the rails under the tie center, extension strains were observed in the ballast and in the subballast. Tie spring-up in the center during loading at the rail seats may be a related cause.

In the 53- to 147-kN range, the response was related approximately linearly to the wheel load. However, the response for the first 53 kN of load was proportionally greater than that for the increase from 53 to 147 kN. Thus, the behavior of the track system was highly nonlinear. As a result, superposition of load response must be done with caution.

After tamping disturbance, most ballast readjustment occurred within 89-178 GN additional traffic load, with half of the change developing by 8.9-17.8 GN. This pattern was repeated after each successive raise and tamping in any section. The residual-strain development in the subballast and the subgrade was not affected by tamping. The subgrade continued to settle under the influence of the repeated load more gradually than did the ballast, but continuously throughout the 667-GN period of observation.

The transverse and longitudinal residual strains indicated that some lateral spreading of ballast accompanied the vertical ballast compression.

The smallest dynamic ballast strain and the largest dynamic subballast strain occurred with the traprock-ballast section.

The 38-cm-thick ballast section had the smallest dynamic ballast strain and the largest dynamic subballast strain.

The wooden-tie section had much larger dynamic ballast strains, but lower dynamic subballast strain and

subgrade stress than did the concrete-tie section. The larger ballast strain could have resulted from the development of a gap between the tie and the ballast because the upper part of the ballast strain gauge was fixed to the tie.

The ballast and subballast dynamic strains were greater for the tangent concrete track than for the curved concrete track, possibly because the tangent track had a thinner ballast layer.

ACKNOWLEDGMENT

This study was conducted at the State University of New York at Buffalo (SUNYAB) for the Transportation Systems Center (TSC) of the U.S. Department of Transportation and supported by funds from the Federal Railroad Administration. Technical monitor was Andrew Sluz. The installed gauges were designed by E. T. Selig and Irvine G. Reinig of Buffalo and fabricated under the direction of I. G. Reinig. Clement W. Adegoke and Hwang-Ming Chen of SUNYAB assisted with the gauge installation. Participating staff from TTC were Gerald W. Matthews, Richard Reiff, John Connors, and Mel Levine, and from TSC was Bruce Bosserman. The static data and the dynamic data after 667 kN of traffic were recorded by staff at TTC. The casings for the extensometer were installed by Jerold W. Klug of Denver, Colorado, and Charles W. Lockhart, Jr., of Colorado Springs, who also assisted with the gauge installation.

Data processing for the 26.7- and 667-kN dynamic recordings was performed by Clement W. Adegoke and Harry E. Stewart, also of SUNYAB, respectively. The static data were processed by Michael J. Mann.

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Publication of this paper sponsored by Committee on Mechanics of Earth Masses and Layered Systems.

Study of Analytical Models for Track Support Systems

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Data on the dynamic responses of ballast, subballast, and subgrade of track sections at the Facility for Accelerated Service Testing track in Pueblo, Colorado, are compared with predictions from three available analytical models for track support systems. The response data include ballast strain, subballast strain, subgrade deflection, and subgrade stress. The analytical solutions are provided by (a) a model that combines Burmister's three-dimensional elasticity solution with a structural analysis model that solves for the tie-ballast reaction (MULTA), (b) a finite-element, three-dimensional model that has prismatic elements combined with a structural analysis model (PSA), and (c) a quasi-three-dimensional, finite-element model, in which a longitudinal two-dimensional analysis is followed by a transverse two-dimensional analysis (ILLI-TRACK). The results show that all three models can reasonably predict the behavior of the track system, provided that values for the material properties and model parameters are correctly specified. Each model has advantages and limitations compared with the others. ILLI-TRACK is the only model that can vary properties in the vertical, longitudinal, and transverse directions and also the only one having a nonlinear stress-strain representation. However, the accuracy of ILLI-TRACK predictions is less certain because it depends on two empirical parameters, the effective tie-bearing length and the angle of distribution. The PSA model permits property variation in the transverse and vertical directions, but its computer costs are an order of magnitude greater than those for the other two models. The MULTA model is restricted to homogeneous layers of ballast and underlying materials, but it combines the features of both three-dimensionality and economy.

To provide a foundation for the prediction of track performance, which is a prerequisite for rational track design and maintenance-life prediction, it is necessary to have an analytical model that realistically represents the actual behavior of a track system subjected to various vehicle-loading conditions. One of the requirements for such a model is that it adequately characterize the three-dimensional aspects of the problem. Another is that it must distinguish the various soil and ballast layers and give them independent properties.

Several models that use the beam-on-elastic-foundation approach (1-3) have been employed to provide a basis for track design procedures in the past (4, 5). Although this approach has been extended to include a nonuniform foundation modulus (6) and a nonuniform finite-beam section (3, 7) to represent more closely the rail-tie system, its significant limitations are that it does not adequately model the ballast and subgrade system and that the interaction between the soil and the track structure is not properly represented.

To interrelate the components of the track structure to properly represent its complex interactions in determining the net effect of traffic loads on the stresses, strains, and deformations developed, several more-