part of a larger cooperative effort between the Federal Railroad Administration and the Association of American Railroads. This paper represents our views and positions and does not necessarily reflect those of the Federal Railroad Administration or the Association of American Railroads.

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Ballast and Subgrade Response to Train Loads

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Ballast and subgrade play major roles in the maintenance life of track structures because they are the source of the cumulative permanent deformation associated with the deterioration of surface and line. Ballast is also the principal means of correcting for this deterioration, which is caused by traffic and environmental factors. Better methods are still needed for the prediction of the effects of the controlling parameters on track performance for more rational track design and maintenance planning. The purpose of this paper is to provide a better understanding of these problems and describe progress being made toward their solution. The functions of ballast and subgrade are briefly discussed, and the mechanisms of permanent deformation are described. Newly developed or improved methods to measure the in situ physical state of ballast are presented, and examples of results from field tests are given. The capabilities of existing analytical track structure models for the prediction of track deterioration are assessed. New instrumentation techniques used for measuring the dynamic and permanent strains and deformations in ballast and subgrade are described. Finally, the characteristics of the stress, strain, and deformation in ballast and subgrade are illustrated with results of both analytical and experimental studies.

The type and condition of the ballast and the subgrade are key factors in the performance of a track structure. During the service life of a track, permanent strains accumulate in its substructure and cause permanent deformation that is visible as deterioration of surface and line. This deterioration of the track geometry leads to decreased safety (including increased potential for derailments) and increased damage to equipment and lading unless additional track maintenance is provided or train speed (and hence service level) is reduced. During the past few decades, traffic loads have increased and, at the same time, economic factors have restricted the amount of maintenance that can be done each year. In practice, the maintenance cycle frequency is often dictated by factors such as the availability of money and equipment to do the required work rather than by the amount of track deterioration. Thus, U.S. railroads have had increasing difficulty in maintaining the high service level desired. A recent estimate of the dollar value of the maintenance deficit for all of U.S. railroads was reported by Ward (1) to be $10 billion.

Raymond (2) has reported that approximately 40 percent of the $100 million that Canadian railroads spend on track-structure maintenance relates to ballast maintenance alone. Therefore, it is a safe assumption that, at least in dollar value, both the ballast and the subgrade parts of the track substructure are important in the upkeep of the service level of the track.

Ballast maintenance is the means by which the deterioration of track geometry is controlled, irrespective of the driving forces behind the geometry changes. Whether the structural deficiency is in the ballast, the subgrade, or the track superstructure (the crossties and up), or even if the track degradation has been caused by an overloading of the normal traffic-carrying capacity of the track, the correction is usually affected by reworking the ballast. However, reworking of the ballast, in turn, changes its physical state and leaves it prone to increased deformation and, hence, track settlement. This problem is compounded not only by the limited amount of maintenance funds but also by an insufficiency of tools for assessing the cause of the problem and optimizing the use of the maintenance funds. Unfortunately, there are no uniform criteria for maintenance that can be applied to railroads in general. Although many railroads do keep some type of maintenance records, the definition of performance for any particular section of track is usually dependent on the subjective evaluation of the track foreman.

Some solutions to these problems are being developed and becoming available as a result of research sponsored by the Federal Railroad Administration (FRA), Office of Research and Development. Performance data are being generated and measurement tools are being tested under FRA sponsorship at the facility for accelerated service testing (FAST) track at the Transportation Test Center in Pueblo, Colorado.

In addition to discussing the responses of ballast and subgrade to train loading, this paper will present some of the ideas that are currently being developed under FRA sponsorship, including concepts in performance assessment and methods of measuring the physical state of the substructure.

FUNCTIONS OF BALLAST, SUBBALLAST, AND SUBGRADE

Ballast is the selected material placed on top of the track subgrade to support the track structure. Conventional ballast is a coarse-sized, noncohesive, granular material, that usually has a uniform gradation. This aggregate layer, tamped under and around the ties, has several important functions:

1. It limits tie movement by resisting vertical, lateral, and longitudinal forces from the train and the track.
2. It reduces the stresses from train loads that are applied to the subgrade of the roadbed and thus limits permanent settlement.
3. It provides immediate water drainage from the track structure.
4. It helps to alleviate frost problems.
5. It facilitates maintenance surfacing and lining operations.
6. It retards the growth of vegetation and resists the effects of fouling from surface-deposited materials.
7. It provides support for the ties and the necessary resilience to absorb the shock from dynamic loads.

Traditionally, angular, crushed, hard stones and rocks, uniformly graded to drain freely, free of dust and dirt, and not prone to cementing action have been considered good ballast materials. However, availability and economic considerations have often been the prime factors considered in the selection of ballast materials. Thus, a wide variety of materials—such as crushed granite, basalt, limestone, slag, and gravel—have been used for ballast in the United States and Canada.

Subballast is material that is used as a transition layer between the upper layer of large-particle good-quality ballast and the lower layer of fine-graded subgrade. The subballast used in most new construction, in addition to fulfilling some of the functions of the ballast (particularly nos. 2, 4, and 7 cited above), is intended to prevent the mutual penetration or intermixing of the subgrade and the ballast and to reduce frost penetration into the subgrade. Any free-draining sand or gravel materials can serve as a subballast as long as they meet the proper requirements of a filtering material.

The mechanical properties of ballast result mostly from its physical state. Physical state is defined by (a) the in-place density and (b) the index properties of the individual material particles, such as size, distribution, shape, angularity, and hardness. The in-place density of ballast is the result of some type of compaction process. Typically, the resulting initial density is created by maintenance tamping and the subsequent density changes result from train traffic and environmental factors. Experience has shown that tamping does not produce a high degree of compaction, and there is clearly little control of geometry when compaction is achieved by train traffic. Therefore, consideration is now being given to additional compaction during maintenance by using special machines or new techniques.

The need for more information on the subject of ballast compaction has resulted in a research project at the State University of New York at Buffalo sponsored by the FRA. In this study the mechanics of ballast compaction and the optimization of the maintenance process by using compaction to improve the ballast physical state and reduce traffic-induced track settlement are being investigated.

Subgrade is the layer of material on which the ballast and subballast layers rest; it has the following functions and requirements.

1. It must support, without appreciable permanent deformation, the maximum dynamic, traffic-induced stresses transmitted through the ballast.
2. It must resist the cyclic stresses without excessive cumulative volume or strength reductions.
3. It must be nonfrost susceptible and volumetrically stable during cycles of wetting and drying.
4. It must resist softening that could cause pumping and penetration into the ballast.

The subgrade is a very important component in the track structure and has frequently been the cause of track failure and the development of poor track. Unfortunately, in existing track, the subgrade is not involved in the maintenance operation and little can be done to alter its characteristics without major track reconstruction, i.e., removal and replacement of track, ballast, and subballast.

The present state of the art of track design as it concerns the ballast and the subgrade is mostly empirical, and the factors that control performance are poorly understood. Reliance on past experience can be very misleading, because not only is the experience at a particular site a complex and unknown function of many factors, but the controlling factors are often not even adequately documented. For example, to assess the reasons why a particular section of track is in the poor-track category, it is necessary to know (a) the characteristics of the ballast and the subgrade, (b) the maintenance history (including frequency and type of operation), (c) the environmental history, and (d) the traffic history. Usually, only the last item is readily available, although the second and third can sometimes be estimated from records. Necessary information of the characteristics of the ballasts and subgrades of existing track, however, is practically nonexistent. Even the classification of these materials is in doubt, not to mention their physical state. Often, knowledge of the present conditions of a site based on a field examination is all that is possible, because past records are not normally available.

MECHANISMS OF PERMANENT DEFORMATION

The major causes of track settlement can be grouped into two general categories: (a) repeated loading from rail traffic and (b) environmental factors such as moisture changes, frost action, and mechanical and chemical weathering. In addition, the subgrade, including the foundation soil strata, can undergo settlement because of consolidation over a period of time. Although this category is also important and deserves consideration, this paper will focus on the effects of traffic loading and related phenomena only.

Permanent deformation of track structure results from four basic mechanisms of ballast and subgrade mechanical behavior. The first is volume reduction or densification caused by particle rearrangement under the cyclic shear straining produced by repeated trainloads. The second is inelastic recovery on unloading or stress removal and is a function of both stress history and stress state. The third is volume reduction caused by particle breakdown from train loading or environmental factors. The fourth is subgrade penetration into ballast voids that allow the ballast to sink into the subgrade. The first two apply to both ballast and subgrade, but the third applies mainly to ballast and the fourth to subgrade.

Normally, ballast is initially open graded, which facilitates maintenance operations and allows free drainage. In service, the ballast gradation changes as a result of (a) mechanical particle degradation during construction and maintenance work and under traffic loading, (b) chemical and weathering degradation from environmental changes, and (c) migration of fine particles. As the ballast degrades, it loses its open-graded characteristics and, in some cases, cementing may occur, which produces a layer of undesirable rigidity and reduces resiliency.

Traffic-induced stresses at the ballast-subgrade interface may be high enough relative to the strength of the subgrade soil that the soil is squeezed into the voids in the ballast. Under repeated cycles of loading, the amount of intermixing may be substantial, particularly with soft soil conditions. Water is trapped in depressions that develop under the rail seat, and both drainage and drying are impeded by the fines in the ballast. Thus, the soft conditions and ballast fouling are extended and the track settlement is self-perpetuating. In existing track, this problem occurs most frequently at rail joints. In new construction and in major rehabilitation work, this source of track settlement can be reduced by the use of a layer of subballast or a filter fabric placed over the subgrade.

Ballast fouling can also be caused by internal abrasion of the ballast particles or by surface infiltration of fines. Whatever the cause, the track-supporting capability of such ballast decreases when it is wet and the permanent settlement under load increases. When the fouled ballast is dried, its resiliency decreases. In either case, maintenance operations to correct surface and line are inhibited.

Frost heaving may occur in subgrades and ballasts when fine-grained material in the track is wet and then freezes. Soils display volume changes during freezing and thawing, and significant volume increases occur when ice lenses develop. Differences in volume changes in the subgrade soil over short distances along or across the track can cause rough track.

The tamping process used in track maintenance is generally believed to loosen the ballast under a tie and decrease the density state that had developed over time under traffic loading. Tamping also leaves the crib ballast very loose. Loose crib ballast is a disadvantage because it does not contribute significantly to tie lateral resistance and because it reduces the supporting capacity of the ballast under the tie by providing less lateral confinement than does dense crib ballast. For this reason, machines to recompact the crib and shoulder ballast after tamping are now being considered in the United States and Canada to speed up the process of traffic-induced densification and to provide higher lateral track stability immediately after maintenance.

Very little direct evidence is available to support many of these conclusions because in situ methods of measuring the physical state of ballast have been inadequate. However, new or refined methods have recently been developed to provide tools for the study of the behavior of ballast. A few examples are shown in Figures 1 to 6 to illustrate some of the methods and the resulting observations; a detailed evaluation of the techniques is given elsewhere (3).

A device that measures the resistance of individual ties to lateral force is shown in Figure 1. This type of test is the only one extensively used in the past that provides a measure of the physical state of ballast. However, it is only an indirect test of physical state, its primary function having been to assess lateral track stability. Typical results that relate lateral force to displacement are shown in Figure 2. Crib and shoulder compaction following tamping significantly increases tie lateral resistance.

A device that measures ballast stiffness by means of the vertical settlement of a small loaded plate is shown in Figure 3. The 12.7-cm (5-in) diameter plate can be seated anywhere on the crib or shoulder surface or on the tie-bearing area after the tie is carefully removed. The preliminary field results (see Figure 4) show that there is a significant increase in stiffness in the compacted crib near the rail and a lesser, but still noticeable, increase beneath the tie.

A newly developed method for the measurement of the in-place density of ballast is illustrated in Figure 5. The results of one set of tests (see Figure 6) show the density increase achieved by applying crib and shoulder compaction after tamping compared with only tamping the ballast.

ANALYTICAL TRACK MODELS

The principal function of a track model is to interrelate the components of the track structure so that their complex interactions in determining the net effect on the stresses, strains, and deformations of the system of the traffic loads is properly represented. Such a model provides the foundation for predicting track performance and, therefore, the technical and economic feasibility of track design and maintenance procedures. Analyses are complicated, however, by the fact that the physical states of the ballast and the subgrade, but especially the ballast, change with time. Because maintenance life is measured in years, these long-term effects must be considered. Considerable effort has been devoted to the development of track models that could realistically represent the actual behavior of a track system subjected to various loading conditions. However, more research is needed for several reasons: (a) the difficulty of handling the complexities inherent to each component of the track structure and their interactions under loads, (b) the lack of adequate understanding of the ballast and subgrade behavior to define the model requirements, (c) the lack of field data on track performance for validating the models, and (d) the high computer costs of running the more elaborate of the models.

Because a railroad track is generally subjected to three-dimensional loads, i.e., loads in vertical, lateral, and longitudinal directions, various analytical models have been suggested for each of these components of the track response or for multidimensional representations. However, the vertical behavior of the track structure has received the greatest attention. The following is a brief summary of the existing models for vertical-response analysis of conventional railroad track.

Figure 1. Apparatus for determination of lateral resistance of individual ties.

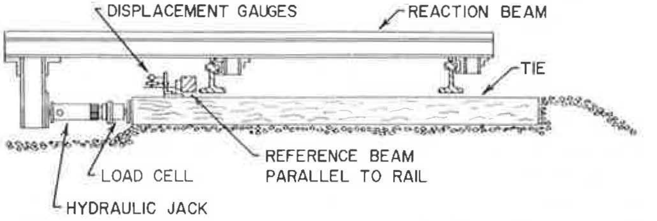


Figure 2. Effect on lateral resistance of crib and shoulder compaction after maintenance tamping: wooden tie in limestone ballast.

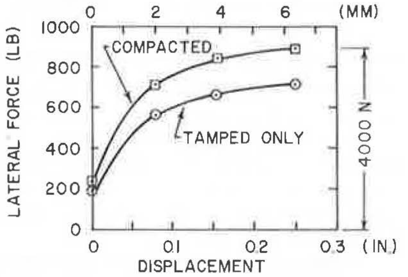


Figure 3. Apparatus for determination of ballast stiffness by plate-load method.

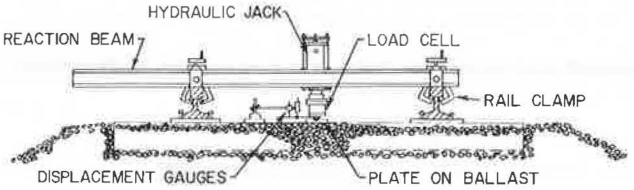
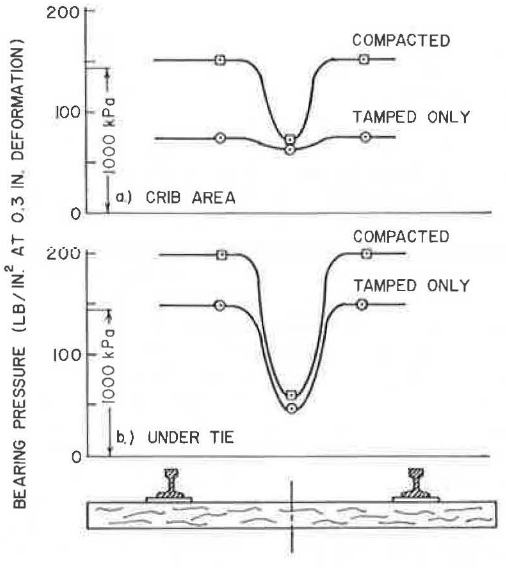


Figure 4. Effect on ballast bearing resistance of crib and shoulder compaction after maintenance tamping of limestone ballast.



Based on the theory of a continuous beam on an elastic foundation, Talbot's work (4) was a significant contribution to understanding the behavior of a railway track system under vehicle loading. The concept of "track foundation modulus" was introduced, and mathematical formulations were developed for calculation of the deflection and moment in the rail. Clarke (5, 6) has summarized this approach to present a basis for track design procedures. However, this theory does not include several important factors that are known to affect the stresses and deflections in railroad track, such as longitudinal loads from thermal stresses, a restoring moment proportional to the rotation of the rail and ties, the eccentricity of the vertical load on the rail head, or any track-dynamic effects. In addition, a rather significant limitation to the approach is that it does not adequately model the stress-strain behavior of the ballast and the subgrade.

Figure 5. Apparatus for determination of ballast density by water-replacement method.

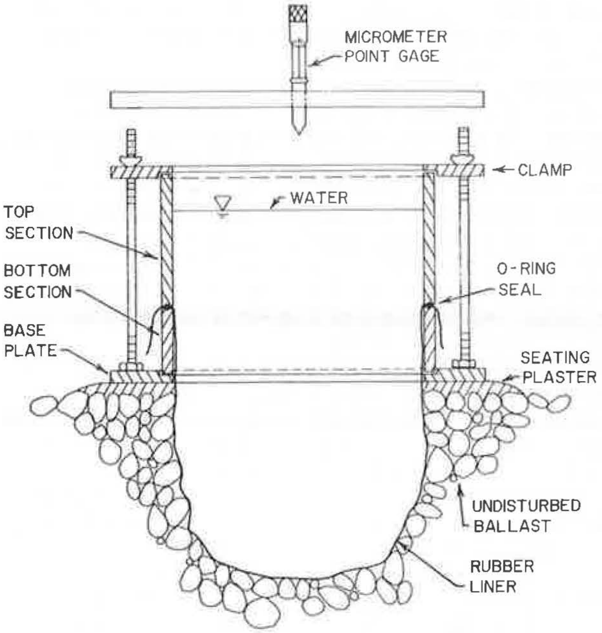
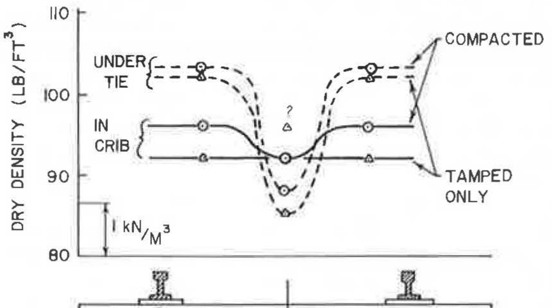


Figure 6. Effect on ballast density of crib and shoulder compaction after maintenance tamping of limestone ballast.



Meacham and others (7, 8) and Prause and others (9) have attempted to overcome some of the limitations of the earlier beam-on-elastic-foundation approaches by developing a theoretical method for the determination of the track-modulus value. In this method, each component of track structure is represented by a series of elastic springs, and the spring stiffnesses are computed by considering various track parameters (such as rail type, tie type, ballast depth, ballast type, subgrade type, and tie spacing).

The finite-beam-on-elastic-foundation approach is basically similar to the above theories, except that it considers the tie as a finite beam resting on an elastic (Winkler-type) foundation as the representation of the response of a tie resting on the ballast. The approach has been extensively studied by Hetenyi (10), and various analysis methods for the solution have been presented. For example, Barden (11) has considered a nonuniform foundation modulus, and Harrison and others (12) have included both a nonuniform beam section and a nonuniform foundation. An approximate analytical method was developed that makes assumptions about the distribution of wheel load over the rail and across the ties. The vertical stress distribution with depth in the ballast and subgrade layers under any given tie is then computed by using the Boussinesq theory. Ireland (13) has presented a design chart for ballast-subballast depth selection versus cohesive strength of subgrade soil by using this approach.

An approach has been developed at the Association of American Railroads that uses Burmister's multilayer theory for the ballast and subgrade and a structural model for the rail-tie interaction. The contact between a tie and the ballast is represented by a series of circular areas that have uniform pressure. The superstructure and the substructure models were then combined and extended to form the model termed MULTA (14). This is a three-dimensional model; however, the properties within any layer are constant and cannot be varied with horizontal position.

Finite-element methods have also been used for track-structure analysis. Lundgren and others (15) have developed a two-dimensional system by assuming plain-strain behavior of a longitudinal section of unit thickness along the vertical centerline of the rail. Svec and others (16) used a three-dimensional model that represents a detailed description of the physical system. The rail-tie system was added to the model as simple beams, and nonlinear mechanical properties of ballast, subballast, and subgrade were obtained from laboratory tests. One feature of the procedure was the representation of the ballast and subballast as no-tension materials. However, the model did not have clearly defined failure criteria.

Another finite-element model—ILLI-TRACK—has been developed at the University of Illinois (17). This is not a three-dimensional model but consists essentially of two two-dimensional models, one transverse and the other longitudinal, and uses the output from the longitudinal model as the input to the transverse model. This gives a three-dimensional effect at less computer cost than a three-dimensional model. Nonlinear mechanical properties for the materials were obtained in the laboratory from repeated-load triaxial tests. An incremental load technique was used to affect a solution. Explicit failure criteria were developed for the ballast, subballast, and subgrade material. However, the model does not prevent tension from being transferred across the rail base into the tie plate, and further study is needed to determine whether the combined two-dimensional models accurately represent three-dimensional physical conditions. Certainly, the three-dimensional qualities of track structure must be fully accounted for if the behavior of a track system is to be successfully predicted by using finite-element models.

The mathematical models developed for the prediction of track performance under dynamic loads have been limited almost entirely to recoverable deformations; thus, they do not adequately represent the factors involved in maintenance-life prediction. However, even the properties associated with recoverable deformation do not fully represent the stress-state-dependent behavior of ballast and soil under cyclic loads. Although there has recently been considerable study of the cyclic behavior of these materials, measures such as resilient modulus should be designated as cyclic-index properties rather than as behavioral properties, because they represent only a few special stress paths and cannot be used without a factor that compensates for the effect of stress path.

Currently, the approach to the prediction of permanent deformation of track caused by ballast and subgrade behavior is patterned after methods used in highway flexible-pavement design (18). An elastic track model is used to predict the stresses in the ballast and subgrade from traffic loads, and repeated-load triaxial tests are used to determine limiting the threshold stress and cumulative strain as a function of confining pressure and number of cycles of deviator stress. Repeated loads are started from a zero load, increased to some predetermined magnitude, and then decreased to zero, thus never putting the sample in extension in the axial direction. The process is repeated until either the desired number of cycles or a limiting permanent strain is reached. Track settlement is predicted by summing the inelastic strains from the triaxial tests for the stress conditions determined from the elastic model.

MEASURED AND PREDICTED RESPONSES

The nature of the recoverable deformations of ballast and subgrade, as well as the stresses and strains in these materials from traffic loading, have been predicted by using the various available track analytical models. These response parameters have also been determined experimentally on actual track structures. The resulting data have been used not only to study the track behavior, but also to evaluate the analytical models. However, the difficulty of measuring stresses and strains, particularly in ballast, has greatly restricted the amount of such data that has been obtained. The examples that follow will illustrate the general trends in both the analytical and the experimental studies.

Salem (19) has studied the vertical stress distributions in ballast and subgrade under statically loaded wooden ties in a series of laboratory tests that used various ballast depths, tie spacings, and types of ballast. Figure 7 (19) shows that chat, pit-run gravel, and crushed slag ballast produce nearly the same vertical pressure below the centerline of a single tie. Figure 8 (19) illustrates the average vertical pressure distribution when varying depths of ballast were used at a constant tie spacing. Figure 9 (19) illustrates the average vertical pressure distribution on the subgrade in a longitudinal direction parallel to the tie and below its centerline at a constant depth of ballast. These tests indicated that the depth of ballast needed to obtain a fairly uniform pressure on the subgrade equals the tie spacing minus 7.6 cm (3 in). A comparison of measured and calculated values also indicated that, although the shapes of the measured and the calculated curves are similar, the calculated pressures may be considerably different than the measured data.

Analytical predictions of track responses have been made by using MULTA for a particular range of track parameters. This analysis assumed uniform properties under the tie, which is usually not the case, and the ballast was assumed to be much stiffer than the subgrade. The following general trends were observed (14):

1. The maximum bending moments at the center of the tie decrease as the ballast depth increases. However, the maximum rail-seat bending moments increase by a small amount (approximately 5 percent) when the ballast depth increases from 31 to 91 cm (12 to 36 in).
2. The vertical rail displacement and the rail bending moment decrease and the rail-seat load increases as the ballast depth increases.
3. The deviatoric and bulk stresses at the middepth of the ballast decrease rapidly as the ballast-layer thickness increases. However, this decrease is a result of stress attenuation with depth. Because the rail-seat load and the maximum pressure at the bottom of the tie increase as the ballast depth increases, at a common depth in the ballast, the stresses should actually increase as the thickness of the ballast layer increases.
4. The maximum vertical stress on the subgrade surface and the stresses in the subgrade decrease

Figure 7. Vertical pressure distribution below centerline of a single tie.

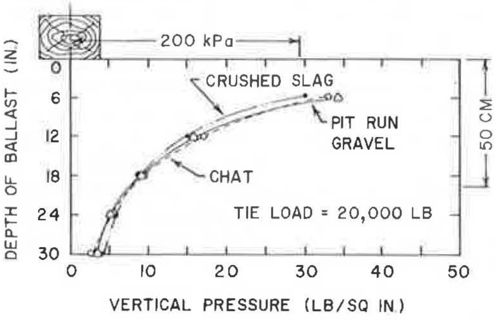


Figure 8. Average vertical pressure distribution on subgrade at different depths of ballast.

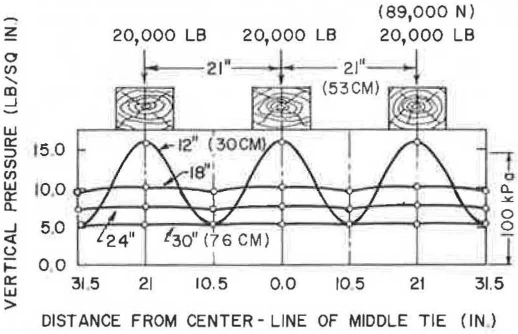
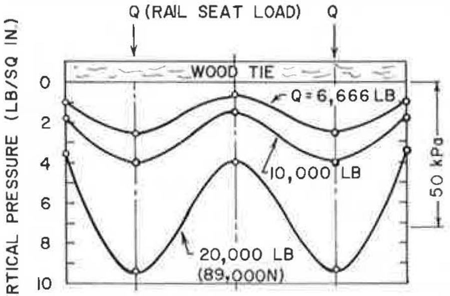


Figure 9. Average vertical pressure distribution below a single tie on subgrade at ballast depth of 45.7 cm.



Note: 1 cm = 0.4 in.

Figure 10. Typical gauge layout at FAST track.

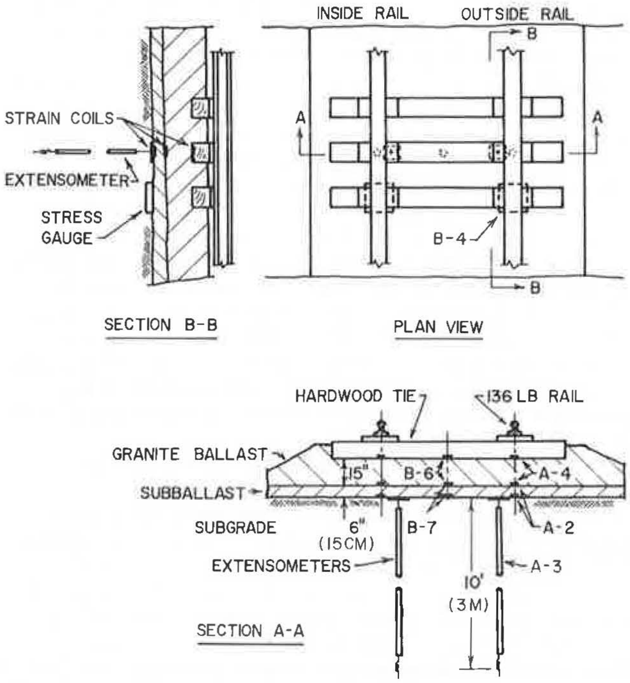
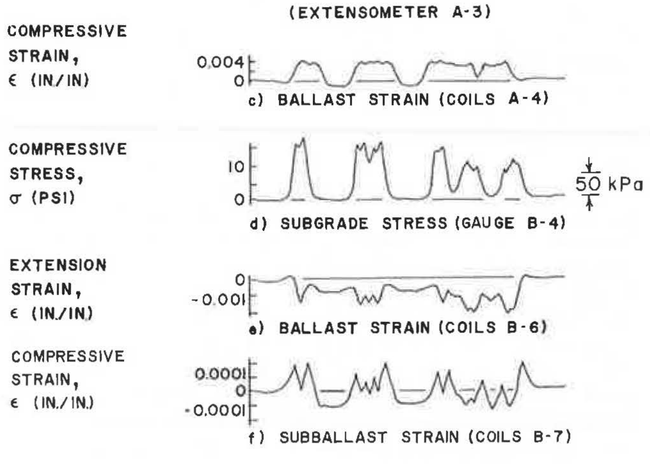


Figure 11. Dynamic response of inductance-coil instruments in FAST track section shown in Figure 10.



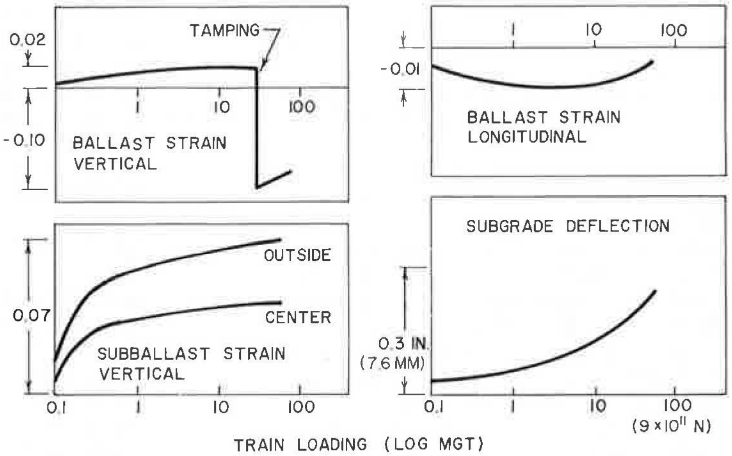


Figure 12. Cumulative substructure strain and displacement in FAST track section shown in Figure 10.

rapidly as the ballast-layer thickness increases. This trend is also largely a result of attenuation of stress with depth.

The most extensive track response measurement program undertaken to date is that being conducted at the FAST track. This program includes strains in the ballast and subballast, vertical stress at the subballast-subgrade interface, and vertical deformation of the subgrade surface relative to an anchor point approximately 305 cm (10 ft) below this surface. A typical layout is shown in Figure 10. The strain measurement method in particular is new and provides important data not previously available. This instrumentation is described in detail elsewhere (20).

A typical set of dynamic records is shown in Figure 11 and illustrates the elastic response when a three-car train passes slowly over the instrumented wooden tie section. The observations that can be made from these records include the following:

1. The permanent strain and deformation from one pass of the train is negligible compared with the elastic components.
2. The 119-metric ton (131-ton) hopper cars produce larger responses than does the 119-metric ton locomotive (because of the higher axle loads).
3. The variation in stress, strain, or deformation as each individual axle in a group passes over the gauge is small compared with the group average, indicating that the rail is distributing the axle loads over distances greater than the axle spacing.
4. The vertical strain in the ballast is mostly negative (extension) beneath the center of the tie at the centerline of the track. The extension and compression strains beneath this point in the subballast are approximately equal.
5. The subgrade deflection is always downward relative to the unloaded track position, and the subballast strains beneath the rail are essentially only compressive.
6. The ballast strains are extensional at the midpoint of the cars because of the spring-up of the rail. However, part of this extension could be a result of the lifting of the tie from the ballast because the top part of the strain gauge was attached to the tie rather than to the ballast surface.

Analytical models that directly predict permanent ballast strain and cumulative track settlement from traffic loading have not been developed. Also, very few experimental data are available from the field. The current project at FAST is providing important new information on this subject, however. Cumulative ballast and subballast strain and subgrade deflection have been measured as a function of total traffic load for a variety of track conditions. A typical set of results is shown in Figure 12 for one track section. Strain measurements of this type have not previously been available. The slopes of all of these curves decrease rapidly as the traffic increases but permanent subgrade settlement was still continuing to accumulate significantly even after 91 million gross metric tons (100 million gross tons) of loading.

CONCLUSIONS

A general understanding of the functions and behavior of ballast, subballast, and subgrade has been achieved. Analytical models exist for track structure that predict elastic response under train loading. A beginning has been made in obtaining needed field data on dynamic and permanent strains in the substructure. Field test methods are available to investigate the ballast physical state, and data are being obtained on operating track.

Continued development of analytical tools for the prediction of stress and strain (both elastic and inelastic) that are consistent with material behavior and track-structure boundary conditions is necessary. It is especially important to account for stress-state-dependent material behavior and the effects of the mechanisms that cause permanent deformation. Simultaneously, the collection of field data on track performance should be encouraged with emphasis on the behavior of ballasts and subgrades. The FAST track is currently the principal source of such information.

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Techniques for Evaluating Effects of Track and Vehicle Wear on Freight-Car Performance

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Track and vehicle wear affect the dynamic performance and therefore the economic performance of the railcar-track system. A multiphase test program has been designed to determine the relationship between the dynamic performance of freight vehicles and track condition, vehicle-component wear, and variations in track structure. The first part of this program has been completed, i.e., the development of test, instrumentation, and analysis techniques and the determination of their applications to a baseline dynamic-performance test. The test methodology involves dynamic testing of a high-travel car and a reference or low-travel car. Two test tracks at the Transportation Test Center were used, the facility for accelerated services testing track and sections of the railroad test track. The instrumentation for each test vehicle included precision accelerometers to measure accelerations on the car body, bolsters, and trucks and instrumented wheel sets to measure lateral and vertical forces on the wheels. The analysis of the acceleration data is based on the use of six degrees of freedom, or rigid-body modes, for each primary mass (car body and truck). Statistical processing of the computed modal data is used to determine the effects of track structure and condition on vehicle performance. Transmissibility between truck and car body is calculated to determine the effect of component wear on vehicle performance. Finally, statistical processing of wheel-rail forces is used to obtain lateral-to-vertical force ratios and lateral wheel forces as functions of the track section. The instrumentation and data-processing techniques designed for this program proved effective in evaluating freight-car dynamics. Evaluation of the effects of variations in track structure on vehicle dynamics led to the following conclusions: (a) track containing unsupported bonded joints produced the highest car-body accelerations; (b) curves greater than 4 degrees and discrete events such as turnouts produced high accelerations and wheel forces; and (c) variations in track and roadbed such as ballast-shoulder width and depth, spiking patterns, tie material, and rail anchor type had little if any effect on the dynamic response of the vehicle.

The dynamic performance of the railcar-track system has a direct effect on the economics of railroad operations in terms of lading damage and maintenance costs. This performance changes with accumulated use as a