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# Mechanics of Ballast Compaction

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## Volume 5: Summary Report

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March 1982

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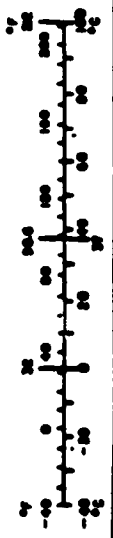
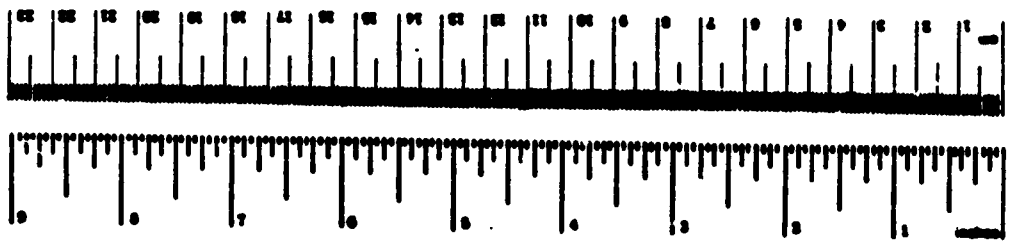
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16. Abstract  This report summarizes the results of research on the mechanics of ballast compaction. Details are provided in four preceding reports. The scope of this summary includes: 1) a description of ballast physical state, 2) methods developed for measuring the physical state in-situ, 3) the effects of tamping, traffic and compaction on ballast physical state, 4) the influence of compaction parameters on the amount of compaction, 5) an assessment of the benefits of crib and shoulder compaction, and 6) recommendations for further research.					
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**METRIC CONVERSION FACTORS**

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
m	inches	0.0254	millimeters	m
cm	centimeters	0.01	millimeters	cm
mm	millimeters	0.001	centimeters	mm
km	kilometers	1000	meters	km
m	meters	1.1	yards	m
m	meters	0.9144	feet	m
<b>AREA</b>				
m <sup>2</sup>	square meters	1.196	square yards	m <sup>2</sup>
m <sup>2</sup>	square meters	1.2	square yards	m <sup>2</sup>
m <sup>2</sup>	square meters	0.42	square feet	m <sup>2</sup>
ha	hectares (10,000 m <sup>2</sup> )	2.5	acres	ha
<b>MASS (weights)</b>				
kg	grams	0.001	grams	kg
kg	kilograms	2.2	pounds	kg
kg	kilograms (1000 kg)	1.1	short tons	kg
<b>VOLUME</b>				
m <sup>3</sup>	cubic meters	0.001	liters	m <sup>3</sup>
m <sup>3</sup>	cubic meters	2.1	gallons	m <sup>3</sup>
m <sup>3</sup>	cubic meters	1.35	gallons	m <sup>3</sup>
m <sup>3</sup>	cubic meters	35.2	gallons	m <sup>3</sup>
m <sup>3</sup>	cubic meters	1.35	gallons	m <sup>3</sup>
<b>TEMPERATURE (degrees)</b>				
°C	Fahrenheit temperature	$(F - 32) \div 1.8$	Celsius temperature	°C
°C	Celsius temperature	$(C \times 1.8) + 32$	Fahrenheit temperature	°C



\* U.S. Metric Conversion Tables, Part 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200.

## PREFACE

This report is a collective summary and assessment of the important findings obtained from the research on the mechanics of ballast compaction. The work is part of a contract to evaluate ballast compaction and recommend guidelines for using compaction to improve track performance. In addition, recommendations for further studies are presented. This study was conducted by the Research Foundation of the State University of New York at Buffalo (SUNYAB) under contract to the U.S. Department of Transportation, Transportation Systems Center, in Cambridge, Massachusetts, sponsored by the U.S. Department of Transportation, Federal Railroad Administration, Office of Research. The contract number was DOT/TSC/1115. The technical monitor was Andrew Sluz.

The Principal Investigator for the study was Ernest T. Selig, Professor of Civil Engineering at SUNYAB. Technical direction of the work described in this report was also provided by Tai-Sung Yoo, Research Assistant Professor, and Carmen M. Panuccio, Research Engineer. Participating in the various phases of this study were Clement W. Adegoke, Jorge E. Alva, Hwang-Ming Chen, Adrian T. Ciolko, James I. Johnson, Michael J. Mann, Donald R. McMahon, Brian C. Dorwart, Harry E. Stewart, and Robert C. Wayne, former Graduate Research Assistants at SUNYAB.

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ADDITIONAL CONVERSION FACTORS

<u>Units</u>	<u>Symbol</u>	<u>To Convert</u>		<u>Multiply By</u>	<u>Symbol</u>
		<u>From</u>	<u>To</u>		
length	in.	inches	millimeters	25.4	mm
	ft	feet	meters	0.305	m
area	sq in. (in. <sup>2</sup> )	square inches	square centimeters	6.45	cm <sup>2</sup>
	sq ft (ft <sup>2</sup> )	square feet	square meters	0.0929	m <sup>2</sup>
force (weight)	lb	pounds	newtons	4.45	N
pressure	lb/sq in. (psi)	pounds per square inch	kilonewtons per square meter	6.89	kN/m <sup>2</sup>
volume	cu ft (ft <sup>3</sup> )	cubic feet	cubic meters	0.03	m <sup>3</sup>
density	lb/ft <sup>3</sup> (pcf)	pounds per cubic feet	megagrams per cubic meter	0.016	Mg/m <sup>3</sup>

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## LIST OF ABBREVIATIONS AND SYMBOLS

- a = intercept of linear equation from transformed hyperbolic fitting technique, MGT
- A = area of PLT plate in square inches ( $m^2$ )
- AT = after applied train traffic track condition
- b = slope of linear equation from transformed hyperbolic fitting technique
- B = ballast bearing index value (P/A) in psi ( $kN/m^2$ )
- BDT = ballast density test
- C = tie resistance in lb (N) at a given displacement level and at a certain amount of traffic for the tamped-compacted condition.
- $C_c$  = concavity coefficient
- $C_u$  = uniformity coefficient
- CNR = Canadian National Railway
- CR = compaction ratio (C/U)
- CWR = continuously welded rail
- $D_{50}$  = mean particle size in in. (mm) at which 50 percent of the sample is finer
- e = void ratio
- f = frequency in Hz
- FAST = Facility for Accelerated Service Testing
- I = initial series of ballast physical state tests at FAST
- ICG = Illinois Central Gulf Railroad
- L = tie resistance at a given displacement level for a specific track condition in lb (N)
- $L_o$  = tie resistance in lb (N) at the same displacement level as L, but for the tamped-uncompacted condition with zero applied traffic
- LR = load ratio for LTPT results ( $L/L_o$ )
- $LR_{ult}$  = ultimate load ratio for LTPT results (1/b)
- LTPT = lateral tie push (pull) test
- MGT = million gross tons

- P = load in lb (N) at a given displacement level
- PLT = plate load test
- S = supplemental series of ballast physical state tests at FAST
- SR = Southern Railways
- SUNYAB = State University of New York at Buffalo
- TC = tamped-compacted track condition with crib and shoulder compaction applied immediately after tamping
- TU = tamped-uncompacted track condition
- U = tie resistance in lb (N) at the same displacement level and amount of applied traffic as C, but for the tamped-uncompacted condition
- UU = undisturbed track condition
- $\gamma_{\text{box}}$  = dry density in pcf ( $\text{Mg/m}^3$ ) determined with container volume
- $\gamma_{\text{BDT}}, \gamma_d$  = dry density in pcf ( $\text{Mg/m}^3$ ) measured with BDT apparatus
- $\gamma_{\text{REF}}$  = ultimate dry density in pcf ( $\text{Mg/m}^3$ ) as computed from the reference density test results

## EXECUTIVE SUMMARY

A study was carried out to obtain information on the physical state of ballast in track and its influence on track performance. Particular emphasis was placed on improvement of ballast properties by compaction. Methods of measuring the physical state were developed and then used to investigate a wide variety of track conditions.

As might be expected, no evidence was found that the tamping operation has any significant effect on the subballast and subgrade performance. However, the influence of traffic was felt even down into the subgrade. Cyclic stresses from the succession of train axle loads caused cumulative vertical strains which produced a contribution to settlement from the subgrade, as well as from the ballast and subballast layers.

No subballast and subgrade measurements were available in tests in which crib and shoulder compaction were involved. However, based on experience with compaction, as well as the observations associated with tamping, no significant effects on the subballast and subgrade behavior are expected from surface crib and shoulder compaction using available machines.

Newly deposited ballast conditions occur with such maintenance operations as undercutting, slidding, and new construction. The ballast density is usually lowest for these conditions. As a result, the density is usually increased under the tie by tamping. However, under the center of the tie, as well as in the crib, the ballast will remain loose.

The primary effect of the crib and shoulder compactor is in the crib near the rail where the compacting plates are applied. When a crib and shoulder compactor is used following tamping of newly deposited ballast, the ballast density in the crib near the rail increases significantly. A small increase

may also occur under the tie near the rail.

Traffic significantly increases the amount of compaction in the crib and under the tie from that provided by tamping and crib and shoulder compaction. A valuable objective of further research would be to find out how to produce the traffic-induced level of compaction as part of the maintenance operation so that the track will be stable before the application of traffic, rather than be stabilized by traffic.

Traffic degrades track by creating permanent settlement, which is generally associated with irregularities in surface and line. Thus, maintenance tamping is required periodically as part of the process of reestablishing surface and line. At that time, however, the ballast is compacted by the action of traffic so that its properties will be improved unless the ballast degrades by mechanical breakdown or pumping. Unfortunately, this tamping loosens the ballast from its improved state after traffic. The amount of disturbance is directly related to the amount of the raise, such that the greater the raise, the lower the ballast density becomes.

The research results show that crib and shoulder compaction increases the ballast stiffness, both under the tie and in the crib, compared to the effects of tamping only. The percentage of stiffness increase, of course, is greatest in the crib, where tamping is applied. The stiffness increase under the tie may be a result of greater ballast confinement from crib compaction, rather than the change in physical state of the ballast under the tie.

Crib and shoulder compaction was also observed to consistently increase the lateral tie resistance compared with the resistance following tamping only. However, the percentage increase measured with the LIPT is believed to be much greater than the corresponding increase in track lateral resistance which would develop under train load with the ties fastened to the rail.

Furthermore, this increased resistance may only be temporary.

One of the accepted benefits of crib and shoulder compaction of ballast is to reduce the slow order time for traffic imposed because of the reduced lateral stability after tamping. The results suggest that the compaction process provides the equivalent of about 0.2 million gross tons (MGT) of train traffic in stabilizing the track. Thus, immediate operation of trains at the speed otherwise permitted after 0.2 MGT of slow orders could be initiated immediately. Low traffic density lines might benefit more than higher density lines, since the period of time for slow orders would be much longer on the low density lines.

Slow orders should be more necessary in maintenance operations involving undercutting and ballast replacement because the ballast bed will generally be much looser. Normally, the compaction process follows the final camping-surfacing-lining operation with fully ballasted cribs. However, consideration should be given to compaction before the cribs are filled in order to provide a greater depth of penetration of the compaction effect into the ballast below the bottom of tie. The benefits of this approach might be particularly useful for the rebalasted track. Test results have shown that the lateral tie resistance is greater when compaction is done on a fully ballasted crib than on a partially-filled crib. To conclude from this that compaction is most effective using full cribs may be misleading, because in the LIPT measurements, a substantial part of the lateral resistance comes from the crib. However, the bottom of the tie provides a much greater proportion of the resistance for loaded ties under train traffic. Possibly the benefits of compaction would be increased by a sequence which first provides compaction with low cribs, followed by crib filling and a second application of compaction. Further studies are needed to evaluate this possibility.

Another important application of crib and shoulder compaction is in conjunction with spot maintenance, where loosening of the ballast has occurred around only some of the ties. The use of crib and shoulder compaction will reduce the physical state difference in the ballast between the disturbed cribs and the undisturbed cribs.

By far the most significant benefit of using crib and shoulder compactors that has been expressed by railroad users is associated with maintenance that must be done during hot weather. For a variety of reasons, track maintenance involving tamping may be impossible to defer until a sufficiently cool period. In such cases, immediate stabilization is a very important safeguard that even slow order traffic cannot provide.

Economically, the benefits of crib and shoulder compaction would be greatest if a substantial lengthening of the maintenance life of the track were to result. This would occur either if the rate of settlement were reduced by compaction, or the uniformity of settlement were improved by compaction. Unfortunately, the available field information is not adequate to confirm this benefit, although intuition suggests that it must be true to a certain extent.

In general, the results of this study suggest that:

- 1) The addition of crib and shoulder compaction to the maintenance operation is beneficial,
- 2) Crib and shoulder compaction with existing machines and procedures does not restore the ballast to the same degree of stability that is provided by traffic, and
- 3) The full potential of compaction of ballast, including the optimal use of the vibratory compaction parameters, has not yet been reached.

Continued research on ballast physical state and its relationship to track maintenance and track performance is needed. This effort will lead to



an improved methodology for predicting track degradation. An important and much-needed benefit will also be to determine how to classify ballast in relation to its influence on track performance.

## 1. INTRODUCTION

The type and condition of ballast and subgrade are key factors in the performance of track structures. During the service life of the track, permanent strains accumulate in the substructure, causing permanent deformation, which is visible as deterioration of surface and line. This degradation of the track geometry leads to decreased safety, including increased potential for derailment, and increased damage to equipment and lading, unless additional track maintenance is provided, or train speed, hence service level, is reduced. Over 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 availability of money and equipment to do the required work, rather than by the amount of track deterioration. Thus, American railroads have had increasing difficulty in maintaining the desired high service level. An estimate of the dollar value of the maintenance deficit for all of U.S. railroads was reported by Ward (Ref. 1) to be \$10 billion.

Raymond (Ref. 2) reports that approximately 40% of the \$100 million that Canadian railroads spend on track structure maintenance relates to ballast maintenance alone. It is a safe assumption, therefore, that at least in dollar value, the ballast, as well as the subgrade part of the track substructure, is important in the upkeep of a track's service level.

Ballast maintenance is the means for controlling the deterioration of track geometry, irrespective of what the driving forces behind the geometry changes are. Whether the structural deficiency is in the ballast, the subgrade, or the track superstructure (cross-tie and up), or

even if the track degradation is due to 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 a limitation of maintenance funds, but also by an insufficiency of the tools available to the railroads for assessing the cause of the problem and optimizing the use of the maintenance funds. Unfortunately, there exists 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.

Specifically, the mechanical properties of ballast that are involved in the ballast-compaction/track-performance problem result from the physical state of the ballast. Physical state is commonly defined by 1) the in-place density, and 2) by the index properties of the individual material particles such as size, distribution, shape, angularity, and hardness. The in-place density of ballast is a result of some type of compaction process. Typically, the resulting initial density is created by maintenance tamping, and subsequent density changes result from train traffic as well as environmental factors. Experience has shown that tamping does not produce a high degree of compaction, and there is clearly little geometry control in achieving compaction by train traffic. Therefore, consideration is now being given to additional compaction during maintenance using special machines or new techniques.

The need for more information on the subject of ballast compaction has resulted in this research project. This study seeks to investigate the mechanics of ballast compaction and the optimization of the maintenance process using compaction to improve the ballast physical state and reduce traffic-induced track settlement.

Several relevant questions identified at the onset of this study were as follows:

1. How much can ballast be compacted?
2. What degree of compaction can be achieved by various mechanical processes involved in track construction and maintenance operations and by train traffic?
3. How much additional compaction can be achieved by altering normal processes or by adding new processes, such as those involving compactors?
4. What are the best means to achieve compaction?
5. What are the benefits of providing additional compaction in comparison to the effort and cost involved?

The research subsequently focused upon establishing and, where possible, implementing the methods by which answers could be obtained. The collective findings are summarized in this final report. Section 2 covers the technical review of ballast compaction and related topics from Ref. 3. Section 3 covers the laboratory and field ballast physical state measurements from Refs. 4, 5 and 6. The research summary and conclusions are presented in Section 4. Section 5 recommends several areas of study requiring further and more detailed research. Two other reports prepared in this study concern stress and strain measurements in the ballast, subballast and subgrade at the FAST track (Refs. 7 and 8). These will be summarized separately.

## 2. REVIEW OF RELATED TOPICS

The subject of ballast compaction and its influence on track performance encompasses a variety of specific, related topics. In this study, these topics have been individually treated in sufficient detail to present their relative importance and contributions to the ballast-compaction/track-performance problem (Ref. 3). A comprehensive summary and the associated critical assessment of the reviewed materials will be presented herein.

The performance of conventional railroad track systems is directly a function of the complex interactions and subsequent responses of the track system components under train traffic and environmentally induced stresses. The functional relationships existing between track performance and the individual track system components, which include the rails, ties, and fasteners, and in particular, the ballast, subballast, and subgrade, have not been established. Other conditions being equal, the ballast and subgrade behavior associated with the in-situ physical states, especially that existing after programmed track maintenance operations, have been identified as the most significant contributing factors which affect the performance of the track in service. Available field measurements or criteria which have been used as indicators of overall track performance are those relating to vertical and lateral track stiffness, track geometry, safety, ride quality, and maintenance effort. However, each individual item has not proved to be sufficient alone for representation of the overall track system performance.

Several empirical track design methods in current usage and the recent development of analytical track models, with the emphasis

concentrated upon the representation of the ballast and subgrade materials, are available. However, these techniques are presently limited in their capability for predicting track performance. The primary reason is the lack of corroboration with field data. This situation has recently been shown to be improved by Adegoke's (Ref. 9) analysis and comparison of the predicted responses to the generated substructure stress and strain measurements from the field instrumentation installed at the FAST track.

Ballast materials, as derived from various rock sources or from by-products of manufacturing processes, also inherently possess different particle physical and chemical properties. Many standard laboratory index property tests, such as those for abrasion resistance, absorption, shape, and soundness, are currently utilized to quantify and categorize the relative merits of these different ballast types. However, an individual index property test by itself cannot clearly be used as a direct indicator of expected field performance of the ballast matrix in the track structure under traffic loading and environmental conditions. This latter feature is particularly evident from the lack of suitably defined trends and from the differences in published opinions, which in fact are primarily subjective interpretations, as to what values of what index properties represent the best ballast.

Granular materials, which include ballast, are typically categorized as discrete particulate systems having discernable particle dimensions, ranging from sand to boulder sizes. The fundamental soil mechanics principles representing strength determination apply equally well to all granular soils. However, most of the available information defining the characteristic static or dynamic stress-deformation behavior is related to sand-size particles and is determined from laboratory strength property

tests. Alternative methods based upon shear strength parameters obtained from modelled gradation curves have been proposed as a viable means of estimating the properties of larger-sized materials. However, these techniques have only a limited amount of supportive data. Therefore, the behavior of ballast-sized materials must be determined directly from laboratory strength tests, in lieu of applying previously published strength information on granular materials. An assessment of the conventional static and dynamic test apparatus and procedures indicates that the cyclic or repeated load triaxial test offers the greatest potential for realistically determining the ballast behavior. For this test, the imposed stress conditions and types of drainage can be controlled for specimens prepared at given levels of compaction. Ballast behavior, as determined from laboratory tests, needs to be supplemented with in-situ strength data on the ballast physical state. An evaluation of the available field methods indicates that the plate bearing test is best suited for this purpose.

The strength and compressibility characteristics associated with the relative degree of compaction of ballast within the track structure are directly related to the levels of track performance, in at least a qualitative sense. In the past, for most geotechnical engineering applications, this relative degree of compaction, as used as a means of field compaction control, has been most easily and conveniently determined by comparing in-situ soil moisture-density measurements with the appropriate laboratory compaction test results. Several laboratory compaction methods, such as impact, kneading, static, and vibratory tests, have been developed in an attempt to simulate the characteristics or the anticipated end-product results of conventional field compaction equipment. However, these

methods have limited application for determining the compactibility of ballast materials. At present, no quantitative ballast compaction specifications are available. Furthermore, measurement of the degree of ballast compaction is rarely done. However, in this study, three tests have been identified as potential means of representing the ballast physical state (Ref. 4). These are: 1) an in-situ ballast density test with a reference density test, 2) a single lateral tie push test on an unloaded tie, and 3) a small plate load test.

The rate of change in the ballast physical state within the track structure caused by train traffic loading and environmental conditions is highly dependent upon the initial state achieved from normal track maintenance operations. Ideally, an "undisturbed" ballast trackbed after considerable traffic is the most desirable condition from a stability viewpoint. The reason is that the subsequent correction of track geometry defects with mechanized track maintenance equipment inevitably disturbs the stable condition created by traffic. Therefore, the effect that present track maintenance processes have upon changing the ballast physical state requires considerable attention. To aid in understanding these effects, both researchers and practitioners should be completely familiar with the principal types of track maintenance equipment and the associated field procedures in current use.

Several field methods have been devised as measures of track performance under traffic following the tamping, leveling and lining operation, and the more recent ballast crib and shoulder compaction process after tamping. Lateral resistance of single tie and multi-tie track sections is the method most frequently used for measuring track performance, but alternative means including track geometry, track settlement, vertical



ballast stiffness, and ballast density measurements appear to be gaining popularity. A broad and detailed interpretation of all results is limited because several factors, such as the differences in testing equipment and techniques, and track conditions, exercise some influence on the measured results, and each field method in itself is not indicative of the overall track system performance. In addition, the amount that the ballast is compacted with crib and shoulder compactors is a complex function of ballast-compactor interaction. Besides the initial ballast physical state and other in-situ track conditions, the compactor characteristics of static force, generated dynamic force, vibration frequency, and duration of vibration have an influence on the results. Insufficient information is available to predict their quantitative effect on ballast compaction. However, in a qualitative sense, the supporting evidence and published opinion appears to indicate benefits of mechanical ballast compaction following the usual tamping operation.

The relationships between the ballast compaction parameters and the track performance level parameters are quite complex, and hence an economic assessment is difficult. Limited published information is available on costs related to track maintenance, such as materials, labor, and equipment, and significantly less with regard to ballast crib and shoulder compaction equipment. The methods of economic analysis available for track maintenance operations are dependent upon the geographic location and the specific in-situ track conditions. Thus, they are presently of limited capability in assessing the actual cost-benefit relationships derived from ballast compaction.

The practices and principles of geotechnical engineering provide direct and valuable input into understanding the behavior of the ballast,

subballast, and subgrade within the track structure from the imposed loading environment. But due to the variability of the train loading conditions and the associated environmental influences, as well as the changes in ballast physical state with track maintenance operations such as out-of-face surfacing and lining, and crib and shoulder compaction, the development of a quantitative understanding of the mechanisms causing ballast compaction is inherently more complex. The lack of in-situ measurements and the limited applicability of laboratory property test results and computer-oriented track design models, still prohibit a thorough understanding of all the factors influencing these ballast compaction mechanisms. Thus, further research is necessary in order to reasonably establish a foundation toward these goals.

### 3. BALLAST PHYSICAL STATE MEASUREMENTS

The lack of suitable methods of quantitatively measuring compaction became evident after a review of the state-of-the-art of ballast compaction. Therefore, effort was devoted to developing methods that could be used to measure the physical state of ballast in the field. After considering possibly alternatives, the three most promising methods were selected for study. These tests are as follows:

1. The ballast density test (BDT) determines the in-situ density, which is a direct measure of compaction (Fig. 3.1). Used in conjunction with this measurement is the reference density test, which provides the means to assess the amount of ballast compaction achieved in the field (Fig. 3.2).

2. The plate load test (PLT) determines the vertical ballast stiffness, which is a measure of the effect of compaction on the ballast physical state (Fig. 3.3).

3. The lateral tie push test (LTPT) determines the resistance offered by the ballast to a tie displaced laterally, which is an indirect measure of the physical state and compaction (Fig. 3.4).

Each of the final ballast physical state test apparatus and the associated test procedures were the refined products developed after several iterations of testing. Detailed component descriptions of each apparatus, the proper field testing sequence, and the appropriate data reduction processes are provided by Selig, et al. (Ref. 4). Particularly noteworthy is the fact that these methods can easily be employed by practicing railroad engineers.

In order to assess the potential of this equipment and the reliability of the test results, extensive laboratory and field investigations were conducted in an effort to evaluate the sensitivity of the measurements to

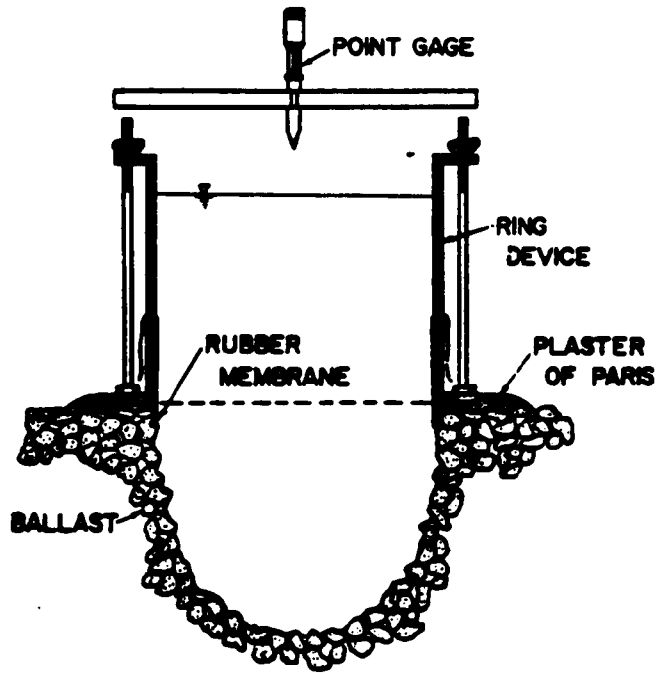


Figure 3.1. Schematic Diagram of Improved Ballast Density Apparatus

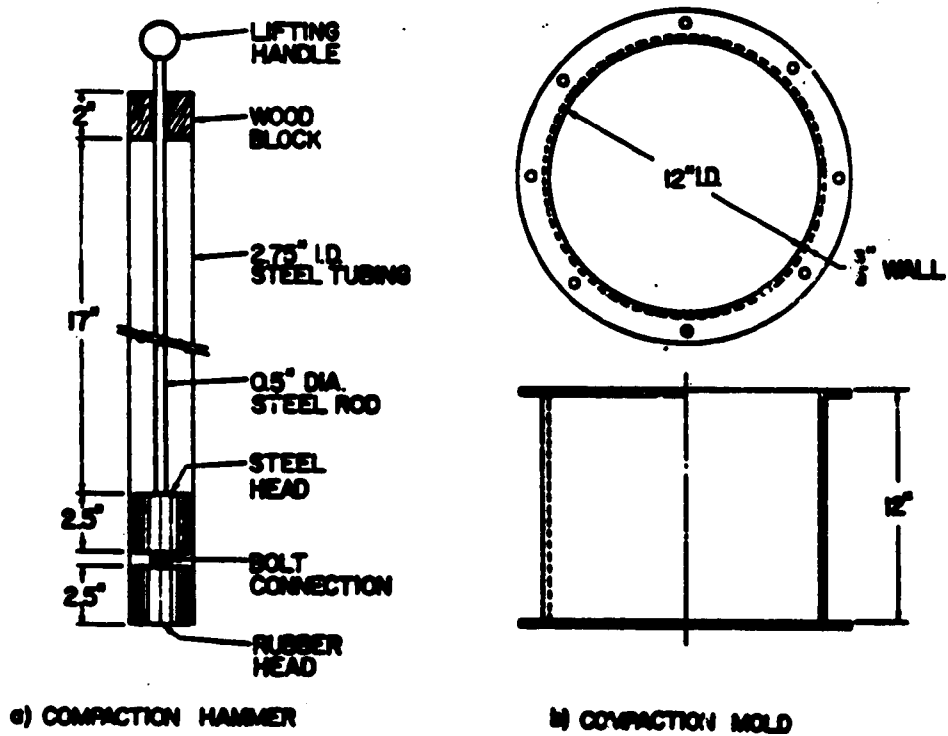


Figure 3.2. Reference Density Apparatus

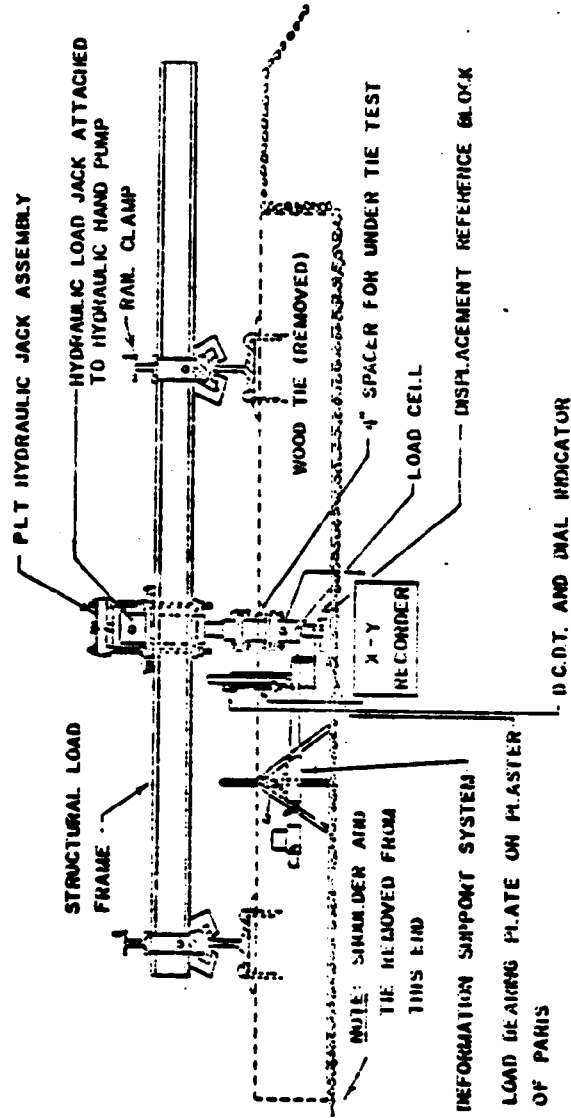


Figure 3.3. Assembled Plate Load Test Apparatus

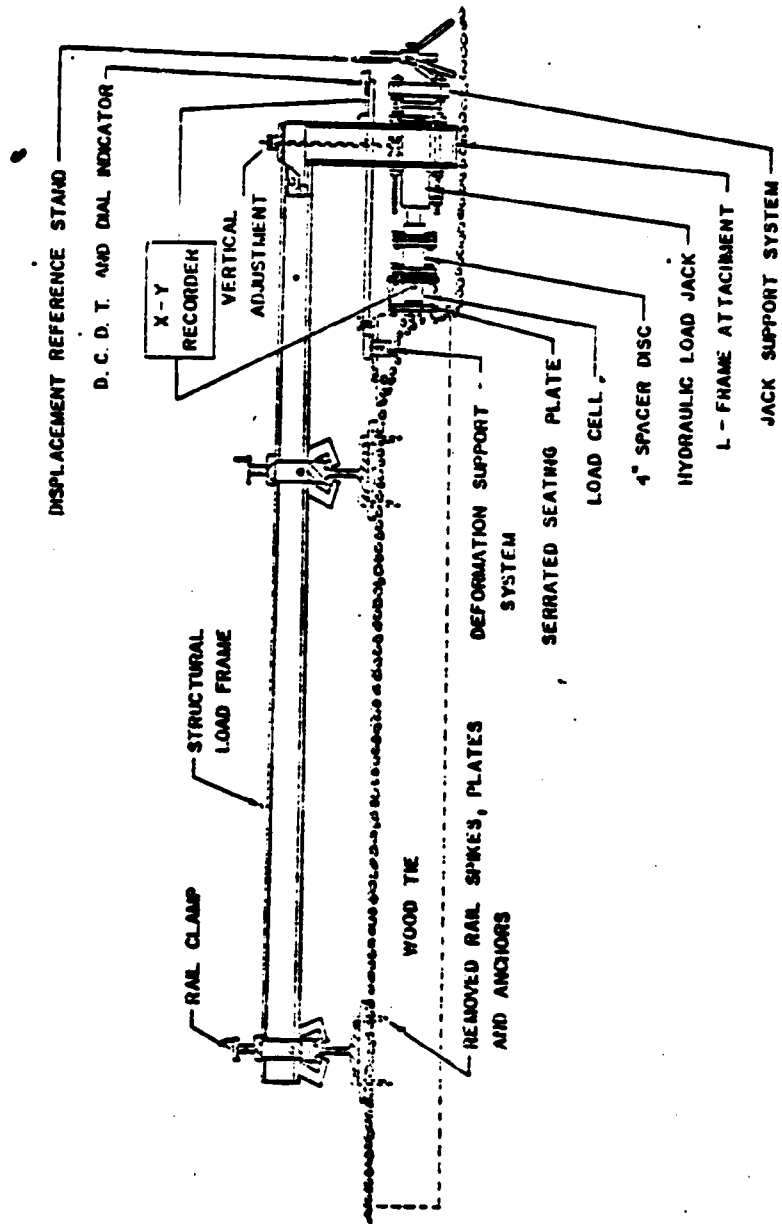


Figure 3.4. Assembled Lateral Tie Push Test Apparatus

differences in ballast types and in the amount of ballast compaction achieved. The average ballast index properties of the materials selected for testing are compiled in Table 3.1, which, in fact, displays a representative cross section of ballast types currently being utilized. Differences in the ballast mineralogies, particle shapes, and gradations are particularly evident. Previous analysis (Ref. 5) of the changes in the in-situ ballast gradations at FAST indicated only slight differences for several different track conditions; thus, the average gradation values shown in Table 3.1 are considered representative. The supplemental index values obtained from other published sources demonstrate fairly good agreement and consistency of results with those determined in this study.

The initial laboratory test programs (Ref. 4) were designed such that an evaluation of factors influencing the test results accompanied improvements to the apparatus and procedures. Follow-up testing (Ref. 6) specifically focused upon laboratory simulation of certain field compaction processes, such as a compacted track bed, manual tie tamping, and ballast crib and shoulder compaction. The claimed advantages offered by the last process as an integral part of normal programmed track maintenance are especially important, since the popular opinion is in their favor. Therefore, the machine parameters considered for investigation were obtained from available specifications of commercial equipment (Table 3.2). In each of the preceding cases, laboratory tests were performed either in a test box duplicating a field track structure, or in containers having boundary conditions equivalent to those experienced in the field. Ballast sample preparation procedures were dictated by the type of field compaction process to be simulated.

Table 3.1. Average Index Properties of Laboratory and Field Ballast Materials Tested

Property	Crushed Limestone		Steel Slag (ref. 10)		Crushed Limestone (ref. 23)		Crushed Limestone (ref. 11)		Crushed Granite (100)	
	Angular	Bounded	Angular	Bounded	Angular	Bounded	Angular	Bounded	Angular	Bounded
Shape	Angular	Bounded	Angular	Subangular	Angular	Subangular	Angular	Subangular	Angular	Subangular
Screen Size (in.)	3/8 - 1-1/2	3/8 - 2	1-1/2 - 2	1-1/2 - 2	1/4 - 2	1/4 - 2	1 - 2	1/4 - 2-1/2	1/2 - 1-1/2	3/4 - 1
Mean Size, $\mu_m$ (in.)	1.1	1.1	1.0	1.0	6.6	6.6	1.2	1.2	0.9 (1.1)	1.1 (1.3)
AMSA Gradation	6	--	3	3	--	3	3	3	4 (6)	4
Uniformity Coefficient, $C_u$	1.4	1.4	1.1	1.1	0.1	0.1	1.4	1.6	2.0 (1.5)	1.6 (1.6)
Coarseness Coefficient, $C_c$	1.0	1.0	1.1	1.1	2.5	2.5	1.2	1.1	1.3 (1.0)	1.7 (1.0)
Modified Sd Classification	GP	GP	GP	GP	GM	GM	GP	GP	GP (GP)	GP (GP)
Specific Gravity	2.71	2.71	2.71	2.71	2.67	2.67	2.67	2.67	2.65	2.65
Apparent	2.71	2.71	2.70	2.70	3.40(3.16)	3.42(3.43)	2.71	2.69 & 2.68	--	--
Absorption, %	0.50	0.55	0.53(1.0 - 5.0)	0.53(0.37)	1.95	1.95	--	--	(1.65)	(0.2)
Flakiness Index	--	--	--	--	(5)	(5)	--	--	(9.4)	(22.7)
Particle Index	--	--	--	--	--	--	--	--	(12.2)	(16.4)
Los Angeles Abrasion, %	--	--	--	--	(22.1)	(22.1)	--	--	(25.2)	(13.2)
Crushing Value, %	--	--	--	--	(10.5)	(10.5)	--	--	(19.3)	(13.1)
Soundness, % (5 cycles)	--	--	--	--	(0.22)	(0.22)	--	--	(11.9)	(0.55)
Swelling, % (after cycles)	--	--	--	--	(0.42)	(0.42)	--	--	--	--
Soil Content	--	--	--	--	--	--	--	--	--	--
Moisture	--	--	--	--	--	--	--	--	--	--

\*The index properties are specified separately for the two ballast types by an "A" or "B" as subscripts combined.  
 †Values shown in parentheses are obtained from the cited reference.  
 ‡Type of soundness test not specified



Table 3.2. Characteristics of Ballast Crib and Shoulder Compaction Equipment

Reference	Manufacturer	Model Number	Application Time (Sec.)	Crib Compaction Plates			
				Frequency f (Hz)	Size	Rated Force (lb)	
						Static	Dynamic
12	Plasser and Theurer	VDH800U	Variable 1-15	38.5	114.7 in <sup>2</sup>	1729	1101
13	Plasser-American	VDH800R	Variable 1-20 Used 3	35-38	≈6 in. x 12 in.	--	--
14	Plasser	VDH800	Variable†	38.5†	9.8 in. x 8.5 in.	--	--
15	Plasser and Theurer	CPH800R	Variable†	38.5	≈10 in. Length	--	--
16	Plasser-American	CPH800R	Variable†	38.5	14 in. x 8-7/8 in.	--	--
17	Plasser-American	CPH800U	Variable† 3 and 5 Used	38.8	14.5 in. x 5.5 in.	1250	1600
18	Plasser and Theurer	Mainliner Universal 06-16CTH	Variable†	38.5	≈10 in.† Length	--	--
15	Plasser and Theurer, Windhoff	903 SW	Used 3	-	-	--	--
14 & 18	Windhoff	BV 102	Variable† Used 4 - 8	48	10.25 in. x 9.4 in.	--	2203†
		BV 102S	Variable†	48	" †	--	2203
		BV 103	Variable†	48	" †	--	2203†
		FD 41	Variable 2 - 20	48	--	--	1542- 3745
19	Tamper	CSC	Variable	--	--	--	--
13	Tamper	CSC	1 - 9 Used 3-4	≈33.3	≈12 in. x 7-1/2 in.	--	--
19	Natica	D-912	Variable 0 - 10	50	--	--	0-5500
		D-912R, D-9	Variable† 0 - 10	50†	--	--	0-5500†
20	Natica	--	3 - 20	46.7	8 in. x 10 in.	--	2200- 3750
20	Penn Central w/Jackson Vib- rators	--	Variable†	--	--	--	--
20	Jackson	--	2 - 20	60-75	8 in. x 12 in.	275	6900

† Assumed

The field tests were conducted on operating track at the following railroad sites: 1) Canadian National Railways station yard in Belleville, Ontario, 2) Southern Railways site near Lynchburg, Virginia, 3) Illinois Central Gulf (ICG) site near Kankakee, Illinois, and 4) the Department of Transportation Facility for Accelerated Service Testing (FAST) near Pueblo, Colorado. The pertinent track and test conditions are summarized in Tables 3.3 and 3.4, respectively. The primary objective of these field tests was to investigate the changes in the physical state of various ballast types with respect to different track maintenance operations and traffic conditions (Ref. 5). In addition, the feasibility of utilizing the results of these methods as potential indicators of track performance will require further consideration.

The following sections will effectively summarize the major findings and general trends resulting from the analysis of all laboratory and field investigations with the ballast physical state tests. Laboratory and field data for similar conditions are illustrated in a combined fashion for comparative purposes and, where possible, will be compared and assessed with the conclusions obtained from other published sources. The techniques have proven suitable for railroad application, and the measurements are considered reliable with an adequate accuracy. The test results presented in this report provide very important and badly needed information on the in-situ ballast physical states under various conditions. They constitute a significant enhancement of knowledge toward a better understanding of track response and its relationship to track performance.

Table 3.3. Track Conditions for SUNYAB Test Sites

<u>Railroad</u>	<u>Track Classification</u>	<u>Maximum Speed (mph)</u>	<u>Annual Traffic (MGT)</u>	<u>Type of Track</u>	<u>Type of Rail</u>	<u>Ties</u>	
						<u>Type</u>	<u>Dimensions Spacing</u>
CNR	No. 2 mainline station yard	--	--	Tangent	78 ft bolted	Wood (#1)	-- 19 1/2 in.
Southern	---	--	20 to 30	Tangent	132 RE CWR	Wood	8.6 ft length 20 in.
ICC	Freight Class #5	50	23	Tangent	132 RE CWR	Wood (oak) old & new	7 in. x 9 in. x 8.4 ft 20 to 22 in.
FAST	Test Track	48	135 to 150	Tangent	136 RE bolted	Wood (oak) new	7 in. x 9 in. x 8.5 ft 19 1/2 in.

Table 3.4. Test Conditions for SUNYAB Test Sites

Railroad	Test Loads	Ballast Type	Height of Tamping Rate (in.)	Compactor Vibration Time (sec)	Average Number of Ballast Physical State Tests		
					Under Center Rail of Track	Under Center Rail of Track	Under Center Rail of Track
					MFT	PLT	LTFT
CNR	Before Tamping	Michel Slag			4		
	Tamped Only		1-1/2		2		
	Tamped-Compacted			3 to 4	4		
Southern	Tamped Only	Crushed Granite			4		
	Tamped-Compacted				4		
ICC	Tamped Only	Limestone and Steel Slag			8	4	9
	Tamped-Compacted			3-1/2	8	4	10
	Tamped Plus 5 MFT		1 to 1-1/2		16	8	21
PAST	After Track Construction; Before Traffic	a) Crushed Granite b) Crushed Limestone c) Crushed Traprock			8	4	
	35 MFT	Only b) and c)			8	4	5
	0.1 MFT	" " " "	1 (b) 2 (c)		8	4	5

(Half of Tests in Grub; Half of Tests Under Tie.)  
(Total Number of Tests for Each Ballast Type)

Total No. of Tests: MFT = 174, PLT = 135, LTFT = 70



### 3.1 BALLAST DENSITY TEST

This ballast density physical state is generally expressed in terms of the following parameters: 1) dry density ( $\gamma_d$ ), 2) void ratio ( $e$ ), and 3) percent compaction. The percent compaction normalizes the measured dry density by an ultimate density computed from the reference density test results on the same graded material. This approach establishes a comparative basis for different ballast types. One significant point is that the resulting percentages achieved from the field tests are often in excess of 100 percent. This occurs to a large extent because the density test boundary conditions give computed ultimate density values which are typically low by approximately ten percent.

The field measurements obtained at four railroad sites are summarized in Table 3.5. The average percent compaction values were selected for comparison with laboratory data for the tamping, tamping plus crib and shoulder compaction operations, and heavily trafficked conditions (Fig. 3.5). The void ratio values would have generated a similar series of curves, but not the dry density. Conceptually, the tamping operation produces a loose density state in the cribs and under the ties, which would indicate that the ballast dry density for materials possessing similar gradations is a function of the particle specific gravity (see Tables 3.1 and 3.5).

Principally, Fig. 3.5 illustrates that the ballast density test results obtained from simulated field compaction operations can be reasonably reproduced in the laboratory. For ballast in zones under the rail (average of inside and outside rail tests), manual tie tamping in the laboratory produced nearly identical values for both the 2-in. (51-mm) and 3-in. (76-mm) track raises at locations in the crib and under the tie. Note that the cribs were reballasted following tamping, except in one case for the 3-in. (76-mm) raise in which a BDT measurement produced essentially the same density (Ref. 6). These laboratory results also compare

Table 3.5. Average Ballast Density Test Results for all Railroad Sites

Railroad	Ballast Type	Track Condition	Measured Dry Density (pcf)			Void Ratio (e)			In Grift			Percent Compaction (%)		
			Center	Under	Track	Center	Under	Track	Center	Under	Track	Center	Under	Track
CRM	Metal Slop	Before Tamping	163.6			0.59						93.9		
		Tamped Only	163.3			0.50						93.5		
		Tamped-Compacted	166.2			0.48						93.5		
Seaboard	Crushed Granite	Tamped Only	107.3			0.63						101.1		
		Tamped-Compacted	121.8			0.62						118.1		
ISCO	Limestone and Steel Slop	Tamped Only	96.2	91.9	102.5	0.60	0.68	0.77	0.74	0.74	0.74	96.2	91.6	102.2
		Tamped-Compacted	91.6	87.9	103.1	0.69	0.76	0.72	0.81	0.81	0.81	91.4	86.0	101.2
		Tamped plus 5 MST	107.6	101.6	117.1	0.51	0.69	0.59	0.46	0.46	0.46	107.1	100.8	101.6
FAST	Crushed Granite	Tamped Only	101.0	100.3	106.4	0.67	0.67	0.77	0.60	0.60	0.60	98.6	98.2	105.2
Limestone	Crushed	Tamped Only	106.9	106.1	112.7	0.62	0.65	0.76	0.52	0.52	0.52	101.5	100.8	109.1
		135 MST	112.2	117.9	116.4	0.53	0.51	0.55	0.59	0.59	0.59	107.7	108.2	110.4
		Tamped Only	110.6	96.6	115.1	0.55	0.78	0.57	0.49	0.49	0.49	102.0	93.5	110.5
		0.1 MST	112.3	110.5	112.2	0.52	0.55	0.61	0.52	0.52	0.52	108.7	107.0	101.0
Crushed Trackage	Crushed	Tamped Only	107.6	110.2	118.3	0.68	0.65	0.77	0.54	0.54	0.54	97.8	99.9	107.3
		135 MST	118.2	118.3	127.2	0.52	0.56	0.57	0.45	0.45	0.45	107.2	108.2	115.3
		Tamped Only	117.9	115.9	119.8	0.55	0.59	0.62	0.56	0.56	0.56	106.9	105.0	101.9
		0.1 MST	120.1	113.1	119.8	0.52	0.63	0.58	0.54	0.54	0.54	108.9	92.5	106.6

dry density converted to an equivalent limestone density

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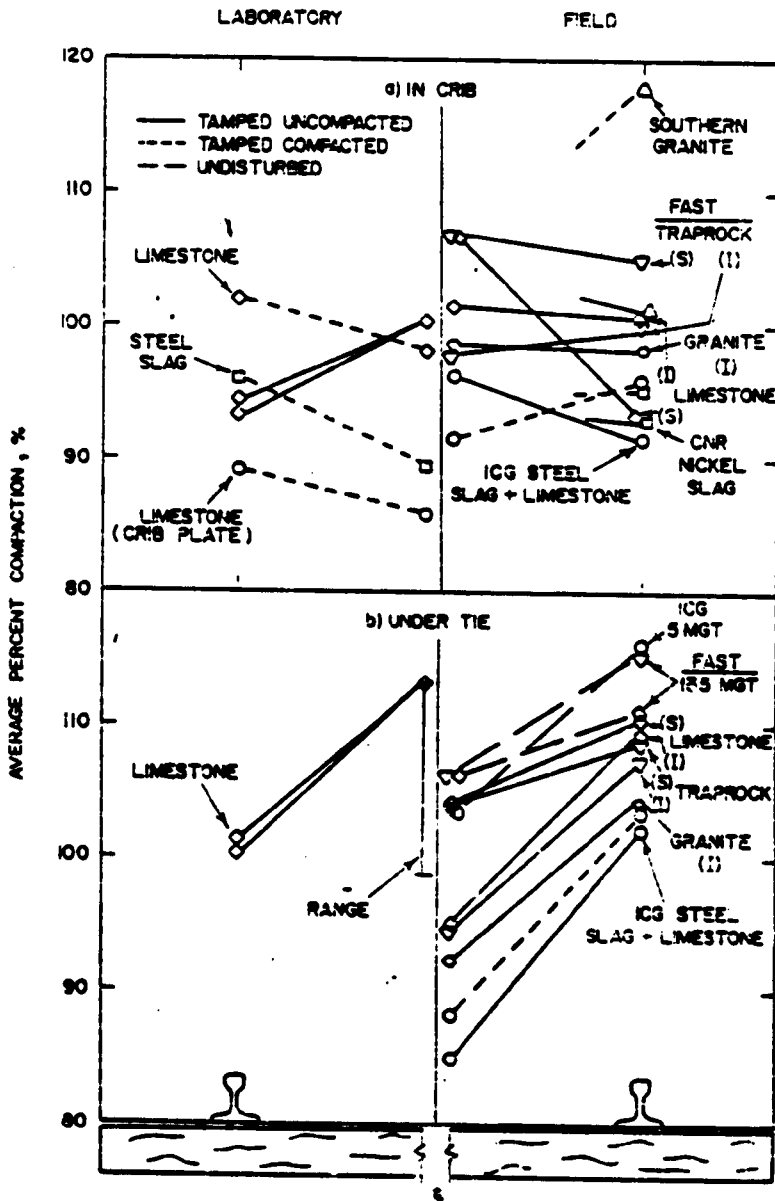


Figure 3.5. Comparison of Laboratory and Field Average Percent Compaction Measurements for Several Track Conditions

favorably to the field measurements obtained after tamping, leveling and lining, although some differences in magnitude are evident.

Two test series are shown for the FAST field measurements. One is the initial test series (I) conducted at the time of initial track construction following maintenance tamping with some intermittent work train traffic. The second is the supplemental test series (S), which represents 135 MGT of applied train traffic followed by maintenance tamping. It is particularly interesting to note that the under-the-tie values at FAST for these two series produced similar average percent compaction results each for the limestone and traprock ballasts. This implies that tamping equipment is somewhat consistent in achieving a certain ballast physical state for the same ballast material. However, this fact has not entirely been validated.

Crib and shoulder compaction following tamping demonstrated increased percent compaction over that of tamping only in the crib near the rails for both laboratory and field data (Fig. 3.5). In general, this effect is difficult to quantify, since the adequacy of the laboratory simulation of the field compaction process is uncertain. This is evidenced by the small change in compaction achieved from a very loose density state for the laboratory limestone (crib plate) tests (Fig. 3.5a). For the wide range of parameters considered (Ref. 6), frequency was determined to have a significant effect upon the changes in the ballast physical state.



In the center of the track (Fig. 3.5a), the laboratory reballasting technique in the crib resulted in comparable amounts of compaction to that obtained in-situ after track maintenance. The FAST supplemental tests are an exception, since traffic history is a likely influencing factor. Under the tie (Fig. 3.5b), a simulated old trackbed condition was apparently prepared with approximately 50 passes from a vibratory plate compactor when compared to the undisturbed state created by train traffic (Ref. 6). However, the limited sampling depth of the ballast density measuring device, that is 4 to 5 in. (0.1 to 0.13 m), limits the generalization of this conclusion.

Throughout the field study, the four typical track conditions tested were: a) after initial tamping during new construction or complete ballast undercutting, b) after compaction immediately following tamping, c) after accumulation of traffic, and d) after maintenance tamping. For each of these track conditions, changes in the measured ballast density and its distribution along the tie are examined to assess the effects on the ballast physical state of important track parameters such as ballast type, tamping, ballast compaction, and traffic. Ballast degradation, as reflected by gradation changes, was analyzed (Ref. 5), but provided only marginally useful information, and thus will not be discussed. This section will summarize the field results to present important aspects of ballast physical state based on the in-situ ballast density measurements.

a) Initial Tamping. The effects of initial ballast tamping of a newly constructed or freshly undercut track can be well characterized from the ballast density profiles obtained from ICG and FAST. The measurements after such tamping are qualitatively summarized in Figure 3.6a. The results generally indicated similar ballast density distributions along the tie at

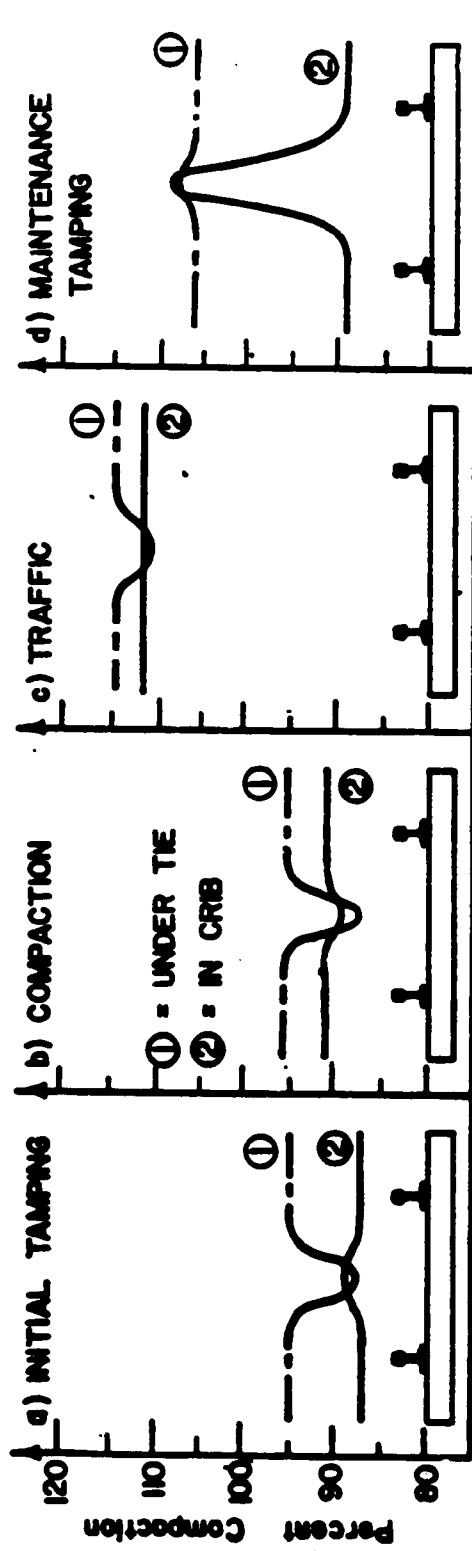


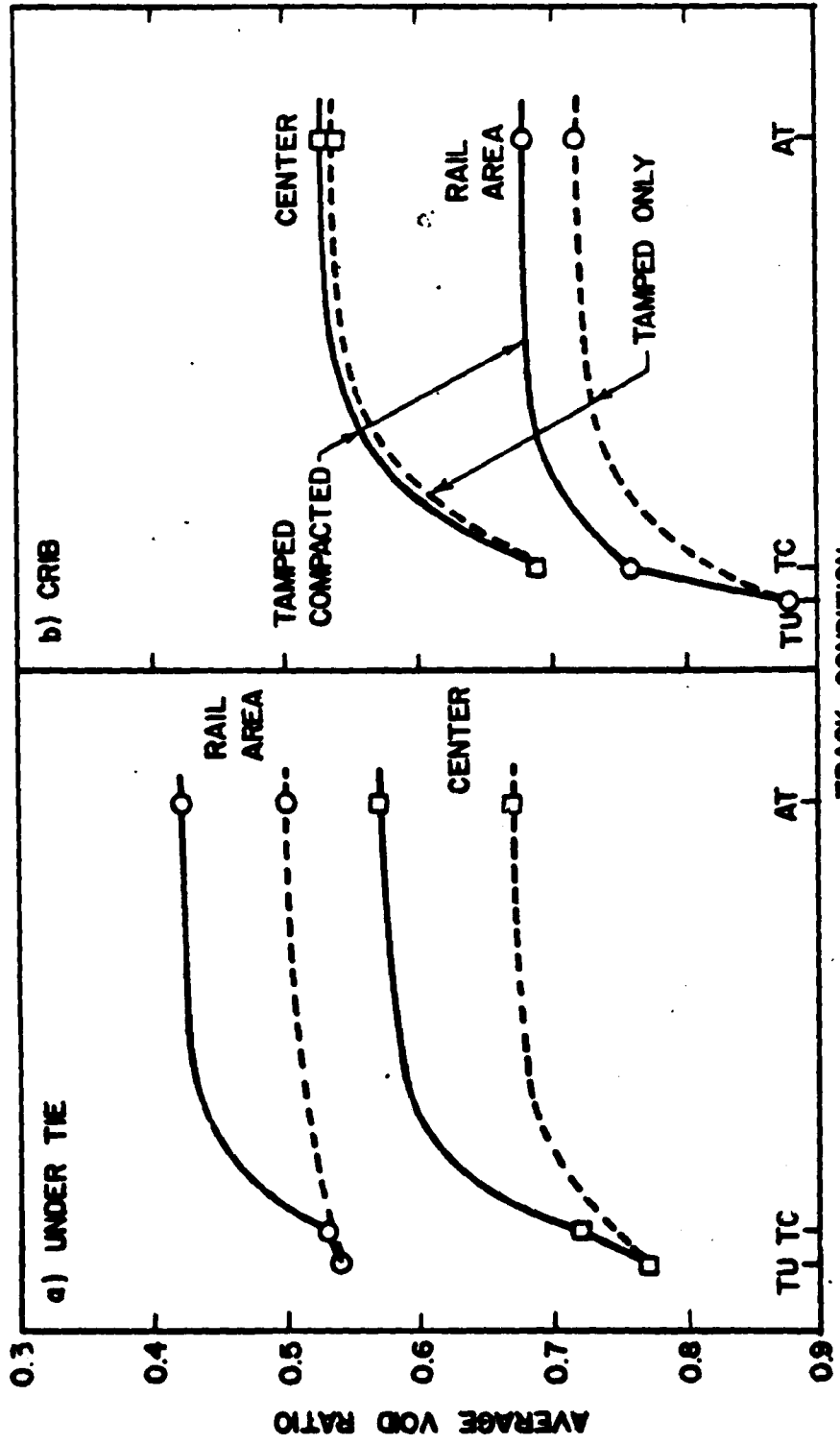
Figure 3.6. Schematic Illustration of Ballast Density Profiles Under Different Track Conditions

both test sites, even though the two sites had quite different track conditions, notably ballast conditions and nature of track work. The ballast density in the crib is relatively uniform along the tie, with the magnitude being slightly lower in the rail area than in the center, except for the FAST traprock. For the same track condition, the ballast density under the tie varied significantly along the tie, and it consistently demonstrated a much denser state in the rail area than in the center.

In the center of the track, the under-tie density was lower than the crib density, but in the rail area the density was much higher under the tie than in the crib. The latter was approximately 11 to 15 pcf (0.18 to 0.24 Mg/m<sup>3</sup>) higher at FAST, and 9 to 12 pcf (0.14 to 0.19 Mg/m<sup>3</sup>) at ICG. The above density difference in the rail area where the tamping operation is concentrated illustrates an important aspect of ballast densification during tamping. When the ballast layer is initially very loose, as in a newly constructed or completely undercut track, ballast densification may very well occur from particle vibrations imposed by the vibrating tamping feet and from the squeezing action, along with the confinement provided by the tie bottom.

b) Crib and Shoulder Compaction. It is a widely accepted conviction that crib and shoulder compaction reduces the adverse loosening effects of ballast tamping and contributes to the restoration of track stability by ballast density increase. However, the compaction mechanisms producing these changes have not been completely understood.

Figure 3.7 summarizes the results from ICG regarding ballast density, in terms of average void ratio, changes with ballast crib and shoulder compaction, and tamping at different locations in the ballast layer. The long-term effects of the ballast compaction are also



NOTE: TU = Tamped-Uncompacted; TC = Tamped-Compacted; AT = After Applied Train Traffic

Figure 3.7. Effect of Crib and Shoulder Compaction on the Ballast Density, ICG

illustrated with measurements assumed to have been obtained after at least 10 MGT of traffic. However, this situation is questionable (Ref. 5), but will be discussed due to the possible implications which may result.

Comparison of the measurements obtained from the tamped-only (TU) and the tamped and compacted (TC) conditions generally indicate ballast density increases from compaction, as expected. But the magnitude of such increases differed from location to location in the ballast layer. Obviously, the ballast density increase due to crib and shoulder compaction was concentrated in the crib where the compaction operation is performed. As shown in Fig. 37, ballast density increase in the crib in the rail area was quite significant. However, the effect of the same ballast compaction procedures on other locations, i.e., in the center and under the tie, appears to be very limited, even though a slight density increase was often noticed in those areas.

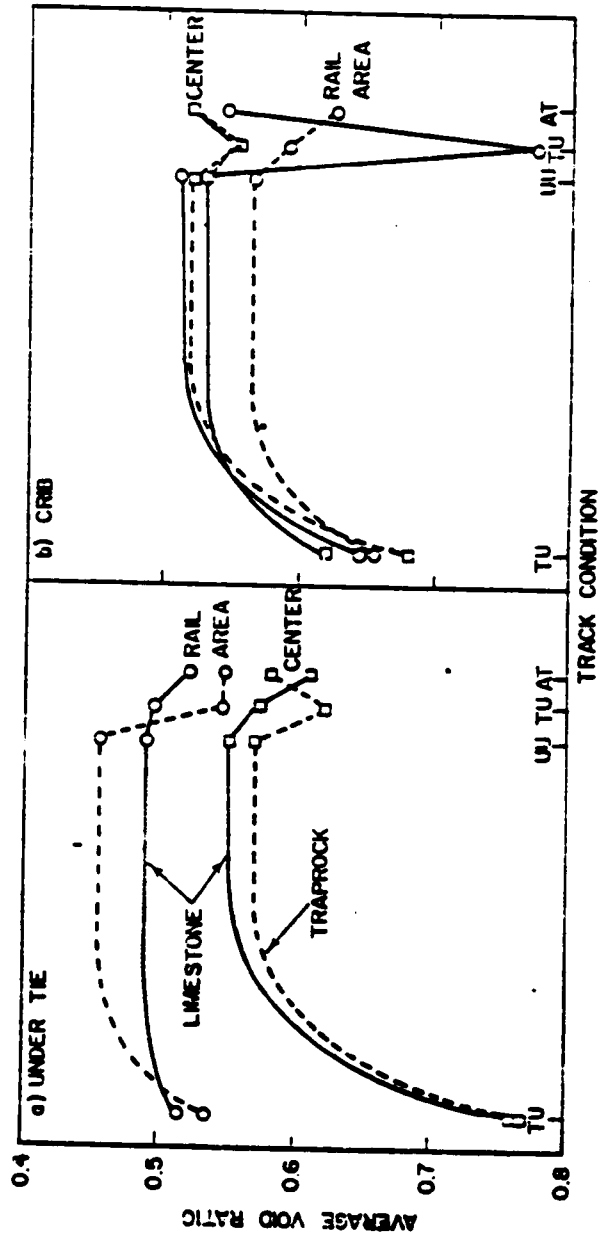
As previously stated, the long-term effect of ballast compaction on the ballast physical state after accumulation of a significant amount of traffic is not conclusive. Generally, the measurements at ICG seem to indicate that the density increase due to ballast compaction subsequent to tamping diminishes with accumulation of traffic in the crib, but somehow the effects of ballast compaction under the tie appear to have been accentuated. It is not clear at the moment, due to insufficient data, whether or not the trends are representative and correct. But, interestingly, Birman and Cabos (Ref. 21) observed with nuclear density measurements that the initial density difference before traffic, which had resulted from different ballast compaction methods, still remained preserved even after significant traffic.

The magnitude of ballast density increase from crib and shoulder compaction varied significantly among different sites, presumably due to different track conditions and compaction procedures. There was about a two percent increase over the in-crib density achieved after tamping at the CNR site, and about four percent and seventeen percent at the ICG and SR sites, respectively.

Figure 3.6b shows generalized ballast density distribution along the tie after crib and shoulder compaction. Since the ballast density increase is mainly concentrated in the rail area in the crib, ballast density distributions basically similar to those after tamping are expected. However, the amount of scatter in the measured ballast density from one tie to another appeared to be quite reduced, compared to the TU conditions. As Hardy (Ref. 22) asserted from a series of field tests at a Canadian National line, the uniformity of ballast density distribution along the track could be one of the important factors contributing to the track performance.

Compared to the density obtained after traffic, the magnitude of ballast density increase from ballast compaction appears to be significant. However, it is questionable whether the same degree of track stability restoration will be achieved from compaction as from traffic.

c) Accumulation of Traffic. Summarizing the measurements at FAST, Fig. 3.8 illustrates ballast compaction changes with accumulation of traffic. Ballast densities at different locations within the track structure are compared for two different levels of accumulated traffic, i.e., during the first 134.6 MGT after initial construction and tamping, and during an additional 0.1 MGT after maintenance tamping. Although the data do not provide sufficient information on the exact patterns



NOTE: TU = Tamped-Uncompacted; UU = Undisturbed; AT = After Applied Train Traffic

Figure 3.8. Changes in Ballast Compaction with Traffic and Maintenance, PAST

of compaction growth for different ballast types, the results explain well the overall trends of ballast density changes throughout the traffic history tested.

The two different ballasts, having similar particle shapes and gradations, exhibited very similar ballast compaction changes during the first 134.6 MGT of traffic. Regardless of ballast types, the most significant increase was noticed under the tie in the center where the ballast was initially very loose. The smallest increase was under the tie in the rail area where the ballast was generally dense prior to traffic. The change in the crib was intermediate, and was about the same along the tie.

The basic pattern of ballast density state along the tie did not alter with traffic (Fig. 3.6c). The under-tie density was still higher in the rail area than in the center, but the difference was smaller than those after tamping or after compaction. The crib ballast density was relatively consistent along the tie, and the magnitude was about the same as under the tie in the center.

Data obtained after traffic often indicated a trend of ballast density decrease from inside the rail to outside, particularly in the crib. For example, an average difference of 5.6 pcf ( $0.1 \text{ Mg/m}^3$ ) was noticed in the crib density after traffic at the ICG site. Presumably, with lack of confinement, ballast particles in the crib and outside the rail could easily have flowed toward the shoulder during vibration and repeated loading cycles imposed by traffic, instead of being densified in place.

The effect of the additional 0.1 MGT of traffic at FAST after maintenance tamping is not conclusive. The density change and its magnitude were quite irregular, varying with ballast types and measurement



locations. The 0.1 MGT of traffic after such tamping does not appear to be significant enough to cause any ballast densification under traffic loading. Instead, it could either densify or loosen the ballast layer depending on the ballast conditions. With accumulation of sufficient traffic, ballast will eventually be densified as shown after 134.6 MGT of traffic. There is not enough data at this time to determine when and how fast the ballast compaction increases with traffic.

d) Maintenance Tamping. Effects of maintenance tamping on the ballast density change can also be examined from Fig. 3.8. Compared to the measurements after traffic, tamping on a track previously subjected to traffic is shown to have consistently loosened the ballast layer regardless of location of measurements. The density decrease was quite significant in the rail area, almost totally eliminating the compaction achieved during traffic after initial tamping. Even in the center where no insertion of tamping feet was made, the ballast density is shown to have consistently been reduced. Figure 3.6d illustrates schematically the probable ballast density distribution after maintenance tamping.

The amount of such density decreases due to maintenance tamping appears to be dependent on various factors such as track conditions, particularly ballast type and condition. For example, less than one percent density decrease from the undisturbed track condition in the crib under the rail was noticed at the CNR site, while more than fourteen percent decrease was observed in the limestone section at FAST. In fact, the ballast density in the limestone section after maintenance tamping was even lower than that after initial tamping. One of the possible reasons for such a significant decrease in the limestone section might be fouling from the degraded ballast particles.

### 3.2 PLATE LOAD TEST

For the plate load test, several strength and deformation indices were obtained from the recorded load-displacement curves in order to evaluate the changes in the ballast physical state. The index determined to be most suitable for the data analysis is the

$$\text{Ballast Bearing Index, } B = \frac{P}{A} \quad (3.1)$$

The parameters are defined as:

P = load in lb (N) at 0.1, 0.2, and 0.3 in. (2.5, 5.1, and 7.6 mm) displacement,

A = area of the 5-in. (127-mm) diameter plate in square inches

= 19.63 in.<sup>2</sup> (0.0127 m<sup>2</sup>). In particular, the B value at 0.2-in.

(5.1-mm) plate displacement of the first loading cycle was considered representative for an adequate and reliable comparison of the conditions investigated (Ref. 5).

As illustrated in Fig. 3.5 for the ballast density measurements, the laboratory and field plate load test results are similarly compared in Fig. 3.9. The values are shown symmetrical about the center of the track. For each specific ballast type, the B values demonstrate a nearly parallel consistency with the average percent compaction values for the same respective track conditions. This, in part, indicates the capability and sensitivity of each test to identify and monitor the ballast physical state changes.

For the under-rail locations, the laboratory manual tie tamping produced comparable B values to those obtained with the mechanized field tamping equipment (Fig. 3.9). After tamping a pre-existing compacted trackbed, the ballast stiffness will apparently reflect differences in the amount of track raise. This effect is especially more pronounced

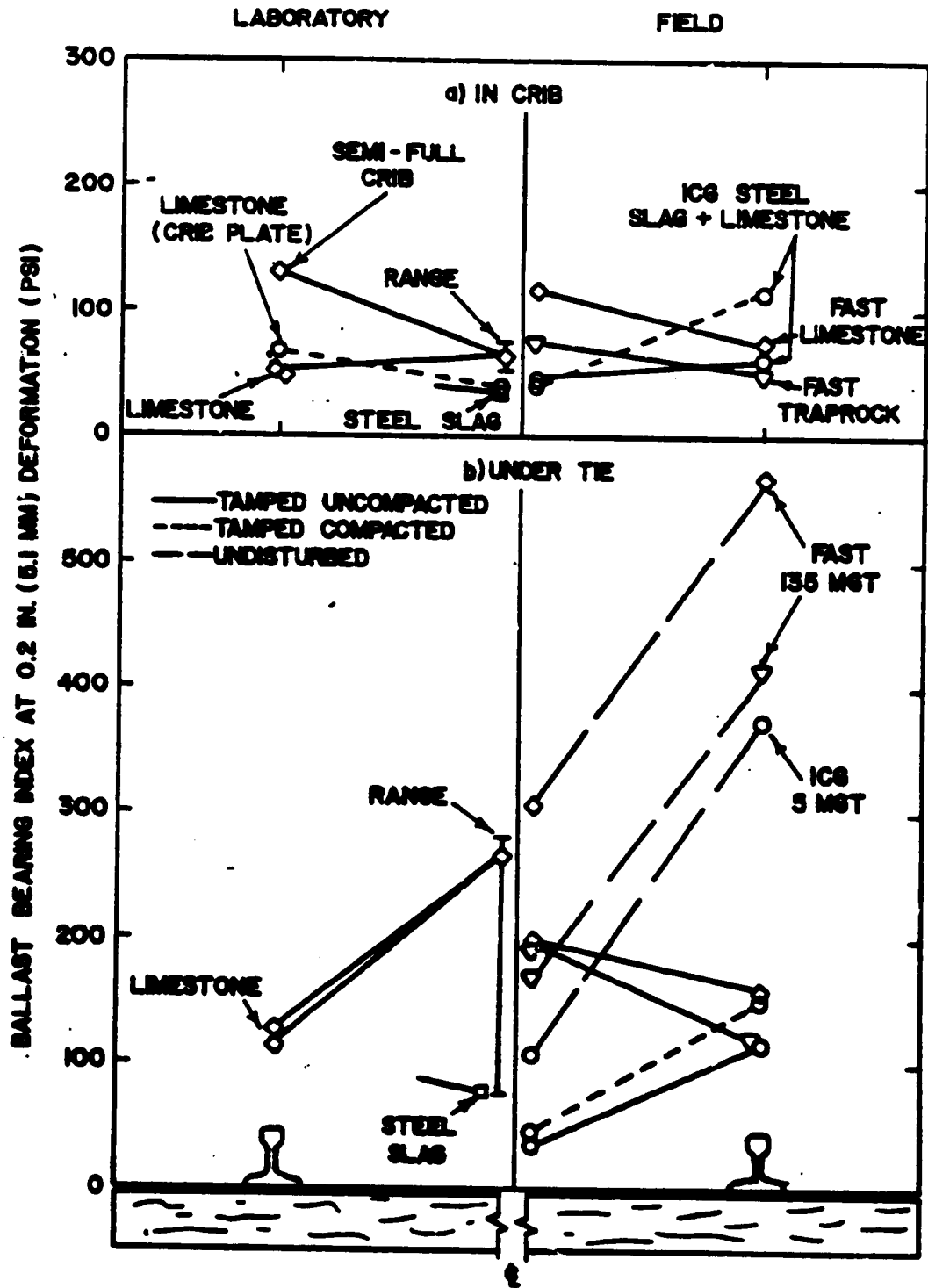


Figure 3.9. Comparison of the Laboratory and Field PLI Strength Profiles for Several Track Conditions

in the crib than under the tie when reballasting is not performed. The B value for the slightly less than semi-full crib, resulting from a 3-in. (76 mm) raise, in the laboratory was more than twice the respective fully ballasted condition in the crib and also equal to the under-tie values. The reason for the latter is that the thickness of the loose ballast layer created by the manual tamping operation, which overlies the compacted trackbed, was approximately equal for the two cases. This result was expected because several tests conducted in this study indicated that rigid bottom boundaries encountered at distances less than 6 to 9 in. (152 to 229 mm) below the ballast testing surface would significantly increase the measured ballast stiffness. Also noted in the laboratory tests was that a 2 in. (51 mm) raise resulted in a slightly greater stiffness under the tie than a 3 in. (76 mm) raise. However, the in-crib B values were equal for these two cases, since full crib ballast conditions existed.

The FAST traprock, which received approximately a 2 in. (51 mm) tamping raise, and the mixture of steel slag and limestone at ICG, which was undercut and then tamped, both demonstrated good agreement with the laboratory limestone ballast B values under the rail. The FAST limestone section, however, was raised approximately 1 in. (25 mm) and yielded slightly higher stiffness values than the preceding ballast types. Since the tamping tools are generally inserted 4 to 7 in. (102 to 178 mm) below the tie bottom, the ballast mass is expected to be disturbed for a sufficient depth. However, environmental and traffic history apparently influenced the FAST limestone, since the tamped ballast directly under the tie was observed to have retained its compacted state and not entirely become disaggregated due to the tamping (Ref. 5). In general,

the tamping operation appears to have produced similar stiffness values for different ballast types under the rail.

The effect that crib compaction has upon the ballast physical state is illustrated in Fig. 3.9a for the limestone (crib plate) tests. The laboratory compaction was accomplished with a low frequency oscillating crib plate, as previously described for the ballast density test. Although a small increase in ballast stiffness is obtained with this crib compaction method compared to the very loose density state existing after tamping without compaction, the B value after compaction is significantly lower than the corresponding field values from ICG. This observation is consistent with the ballast density test results as well. The better compaction effectiveness because of the vibration effects from the much higher frequency used with the field equipment apparently accounts for this difference (Ref. 6).

The laboratory sample preparation techniques, employed to place in the crib either the limestone or the steel slag ballast, quite effectively simulated the reballasting methods used in the field when the ICG data in the center of the track are considered (Fig. 3.9a). Although the FAST supplemental tests include traffic history effects, the traprock ballast demonstrates fairly good agreement with the laboratory data. The traprock at the track center may have loosened when the tamping operation was performed, thus reducing the ballast stiffness. However, this same effect was not indicated by the ballast density test results (Fig. 3.5a) and, therefore, this conclusion is presently unconfirmed.

In the center of the track under the tie, several different levels of compactive effort were applied to the laboratory limestone ballast trackbed in an attempt to achieve the range of ballast stiffness observed in the field (Fig. 3.9b). The laboratory results were consistent with

those obtained at ICG and FAST after ballast placement.

Based on a comparison of laboratory stiffness values with those obtained at 135 MGT of traffic applied at FAST, approximately 500 passes with a vibratory plate compactor are required to simulate a compacted trackbed condition in the field resulting from years of traffic. This appears contradictory to the ballast density test results, in which only 50 compactor passes in the laboratory established the field trackbed density condition. The reason may be because the depth of compaction increases as the number of compactor passes increases. The ballast density test measured the top 4 to 5 in. (102 to 127 mm), while the plate test was influenced by ballast conditions as deep as 12 in. (305 mm). Thus, the stiffness measured by the plate test will continue to increase for more passes than the density. Another possible reason is that very small density increases, after the ballast is in a relatively dense state, can cause a large increase in ballast stiffness because of the increased particle interlocking effects.

The preceding discussion is illustrated in Fig. 3.10, which compares the measured ballast stiffness with the measured density for a representative portion of all the laboratory and field data. The density values are divided by the reference density,  $\gamma_{REF}$ , to adjust for differences in effects of ballast gradation, particle specific gravity, and to a certain extent, the particle shape.

In Fig. 3.10a, the ballast density,  $\gamma_{BOX}$ , was obtained by dividing the ballast weight by the container volume. Because of excess ballast void space at the box boundaries, the calculated density with this approach is known to be significantly lower than the more representative in-situ ballast density,  $\gamma_{BDT}$  (Ref. 4). The excess void space is that part of the

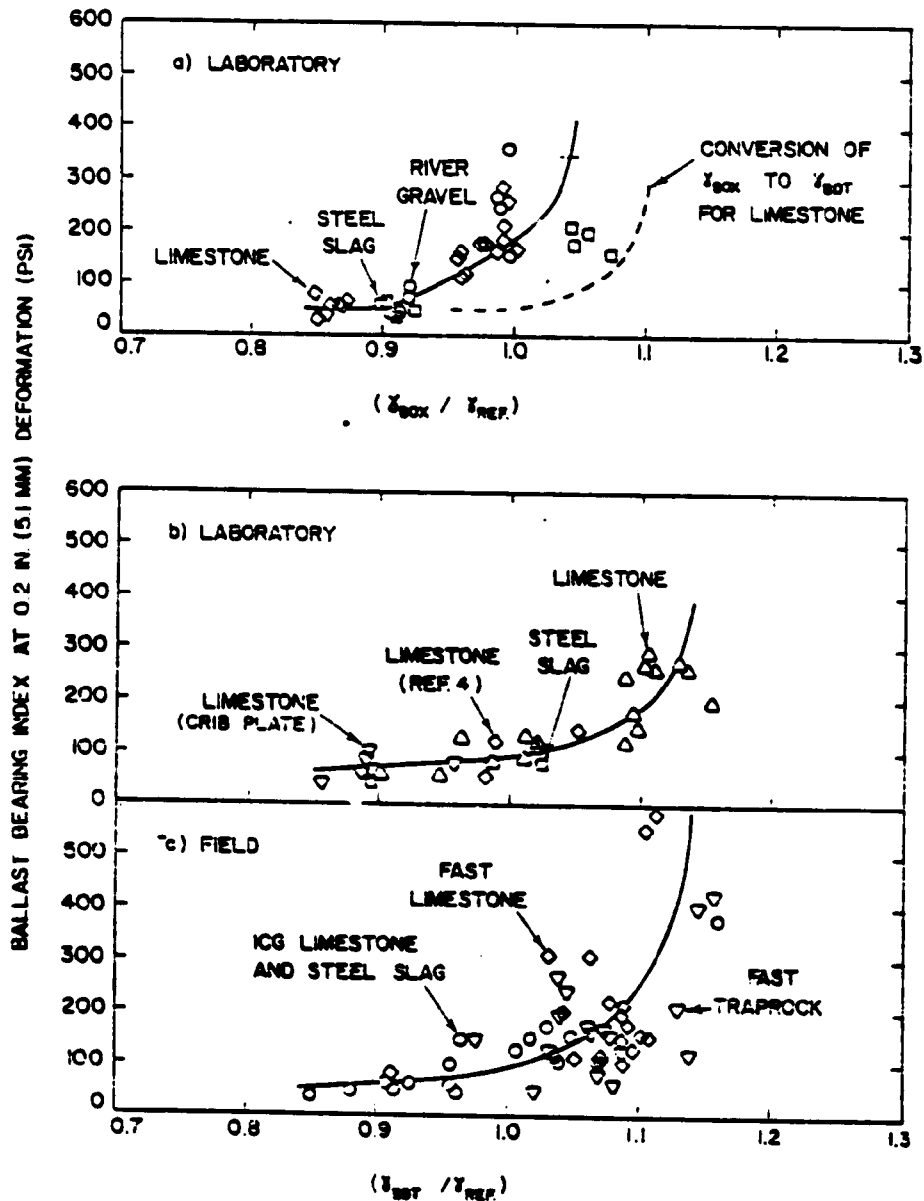


Figure 3.10. Strength-Density Relationships for Laboratory and Field Data

voids in the sample adjacent to a container boundary which would be filled with parts of other particles, if the sample were instead surrounded by ballast rather than a container. This void space represents a significant volume for material as coarse and uniformly graded as ballast.

Based upon previous correlations of these two density measuring techniques for limestone ballast, corrections to the values of  $\gamma_{\text{BOX}}$  were estimated for several states of compaction. This subsequently resulted in shifting the solid curve for the limestone strength-density trend in Fig. 3.10a to the dashed curve. This dashed curve agrees reasonably well with the laboratory and field trends in Fig. 3.10b. In each case, the ballast stiffness represented by the ballast bearing index appears to increase at a growing rate with increasing density.

While the ballast density test is limited in its ability to detect the small changes that can still affect stiffness, it may provide useful information for identifying the relative degree of compaction when used in conjunction with the reference density test. The ultimate density computed from the reference density test, with the appropriate surface boundary void corrections incorporated, would most likely represent a good estimate of the maximum possible compaction state. As was previously noted, the ultimate density value was estimated to be low by at least ten percent as a result of the boundary void error. If this correction were made to the values of  $\gamma_{\text{REF}}$  used with the data in Fig. 3.10, the density,  $\gamma_{\text{BDT}}$ , at which the rapid increase in ballast stiffness occurred would be approximately equal to  $\gamma_{\text{REF}}$ .



In order to place the plate load test and the in-situ ballast density test results in a practical perspective, typical track conditions are listed in Table 3.6 with tentatively assigned values. The average percent compaction (density state) was qualitatively ranked, since the lack of suitably defined trends prohibited specific quantitative subdivision. The average ballast stiffness values were determined from and limited to the several field track conditions investigated in this study, which will be elaborated upon in the following paragraphs. The specified limits are insufficient for general use and definitely require additional in-situ data for confirmation.

Except for the in-crib values at 5 MGT, the ballast strength profiles for the ICG track system are shown in Fig. 3.9. The crib and shoulder compaction and traffic clearly increased the ballast stiffness near the rail, both in the crib and under the tie from the tamped-only condition. The center of the track location both under the tie and in the crib appears to be little affected by the compaction process, but is significantly affected by the application of traffic. Traffic causes increases of 145 to 206% under the tie and in the crib, respectively, at the center of track.

The under-rail location increased in strength both with compaction and traffic. The under-tie, tamped-only values increased 27% with compaction and 213% with 5 MGT of applied traffic when compared to the tamped-only condition. Note that some of the B values at 5 MGT were estimated, since the ballast was extremely stiff; therefore, the tests could not be conducted to 0.2 in. (5.1 mm) deformation. The in-crib, tamped-only values increased 93% with compaction, and 187% with 5 MGT of traffic.

Table 3.6. Strength Distribution for Various Conditions on Wooden Tie Tangent Track

Qualitative Density State	Typical Track* Conditions	Location			Average Ballast Bearing Index at 0.2 in. (5.1 mm) (psi)
		Center of Track	In-Crib Under Rail	Under-Tie Under Rail	
very loose	a) undercut and reballasted	X		X	< 75
	b) tamped only		X		
loose	a) tamped only	X		X	< 150
	b) tamped-compacted	X	X	X	
	c) low MGT traffic	X			
medium-dense	a) low MGT traffic			X	< 250
	b) low to high MGT traffic		X		
	c) moderate to high MGT traffic	X			
dense	a) moderate MGT traffic			X	< 375
	a) high MGT traffic			X	

\*Arbitrary MGT traffic levels: low < 1 to 2, medium 1 to 2 → 5 to 10, high > 5 to 10; and assuming no intermediate maintenance.

†This location is dependent upon the previous traffic and maintenance history.

For the FAST track, the ballast bearing index values are not shown in Fig. 3.9 for the 0.1 MGT traffic condition nor for the 135 MGT condition in the crib. These results will be briefly discussed, but the details can be obtained elsewhere (Ref. 5).

The limestone ballast measurements show increasing ballast strength after tamping with the application of traffic. At the center of track under the tie, the bearing index increased 57% from the loose state after tamping to a value equal to the undisturbed condition with the application of 0.1 MGT of traffic. The bearing index in the crib at the center of the track increased by 22% with 0.1 MGT of traffic, becoming 64% of the undisturbed value.

The near-the-rail locations for both under the tie and in the crib increase consistently with the applied traffic. The under-tie strength increased 34% from the tamped condition with the application of 0.1 MGT of traffic, and 276% with the application of 135 MGT of traffic. The crib strength increased 48% and 115% for the same respective traffic conditions.

The under-rail plate resistance for traprock appears to rapidly increase with applied traffic. The under-tie B values increase 100% from a tamped condition with the application of 0.1 MGT of traffic, and 236% with the application of 135 MGT. The in-crib values increase after the application of 0.1 MGT of traffic to values equal to the undisturbed condition, approximately 193%.

Under the tie, the center of track strength values for traprock were erratic with traffic conditions. However, an increase of 59% occurred in the crib with 0.1 MGT of traffic after tamping, which was also approximately equal to the undisturbed condition.

The most pronounced feature displayed in Fig. 3.9 for the FAST data is the increase in the under-rail, under-tie B values with increasing traffic. However, the amount of data scatter also increases simultaneously (Ref. 5). The trends in the crib are much less pronounced. The difference in strength with ballast type under similar conditions is evident. The limestone after tamping has a slightly greater strength than traprock. However, the traprock demonstrates a greater rate of strength increase than limestone with the application of 0.1 MGT of traffic, both in the crib and under the tie. For the undisturbed state at 135 MGT, the limestone has a significantly greater strength than the traprock under the tie, but in the crib the strengths are nearly equal.

A general comparison of the FAST and ICG sites for the tamped-only condition indicates that the under-tie and in-crib strengths under the rail are similar in magnitude for all ballast types. The slightly lower values at ICG may be accounted for by the ballast undercutting and cleaning operation. Crib and shoulder ballast compaction at ICG increases the ballast strength in the crib to values comparable to the 0.1 MGT traffic condition for the FAST limestone. However, the under-tie strengths with ballast compaction at ICG are considerably less than the 0.1 MGT condition at FAST. For the 5 MGT traffic condition at ICG, the under-rail ballast strength increases considerably, both under the tie and in the crib. This might possibly be attributed to environmental influences in addition to applied train traffic. Apparently the former is a more significant factor at ICG than at the FAST site.

The center of track stiffness values are dependent upon the track history, and the results are not necessarily indicative of the traffic condition or maintenance operation performed at the time of testing.

This point has been emphasized elsewhere (Ref. 5). The trends associated for the center of track values are valid for each particular track system; however, comparisons between track systems is not justified.

The in-situ plate load test (PLT) has previously received very little attention with respect to measuring the relative changes in the ballast physical state. The only available source of information to supplement SUNYAB's data was supplied by Peckover (Ref. 20) for the CNR, which also motivated the work in the present study.

Peckover (Ref. 20) utilized the PLT as a means of evaluating the effectiveness of different track maintenance operations on the vertical ballast stiffness. A 5-in. (0.127 m)-diameter plate was used for this study, and the test procedure was similar to SUNYAB's with some slight differences (Ref. 5). The test results obtained by Peckover (Ref. 20) were, however, considered representative.

The plate load tests were conducted on a tangent section of CNR track with wooden ties. The principal ballast type was an in-situ crushed rock. However, at two different locations the ballast trackbed was removed and replaced with a new crushed rock ballast and a new slag ballast, after a ballast undercutting operation was performed.

For the test sections containing the in-situ crushed rock ballast, the track was tamped, leveled, and lined, but the height of track raise was not specified. This operation was followed by crib and shoulder compaction in which both Matista and Jackson ballast compactors were used (Table 3.2). Sections of both undercut sites were also compacted. However, it is assumed that this track first received tamping, and possibly surfacing and lining, after reballasting and prior to compaction. The final test condition investigated was on an "undisturbed" ballast

for which the amount of train traffic loading was not reported. Full crib ballast conditions are assumed to exist at the time of testing.

The PLT's of concern here were performed adjacent to the rail in the crib and under the tie. Since the test locations are only qualitatively known, these locations will be referred to as under-the-rail.

The average ballast bearing index (B) values at 0.3 in. (7.6 mm) displacement are graphically illustrated in Fig. 3.11a for the various track conditions. Peckover indicates a large variation in these test results. Also, the plate resistance values have apparently been combined for the two ballast compactors and for the two ballast types tested for the undercutting operation.

Figure 3.11a indicates that the tamped-uncompacted condition (TU) produces the lowest B values both in the crib and under the tie for the crushed rock ballast. These values are approximately 25% of the respective undisturbed track condition values. With the application of crib and shoulder compaction to a tamped-only track (TC condition), the B values increase by a factor of 5 in the crib and a factor of 3 under the tie with respect to the TU condition. The tamped-compacted condition yields B values comparable to the undisturbed track condition. The reasons for such a remarkable increase cannot presently be explained.

The effect of undercutting and replacement with a new ballast is also illustrated in Fig. 3.11a. The under-tie values are slightly higher but are still comparable to the tamped-uncompacted condition. However, the in-crib values are a factor of 2 greater. Since the results of the two new ballast types were combined for the undercutting operation, the differences in B values with the TU condition may be attributed to differences in particle shape, in gradation, or in ballast types. With

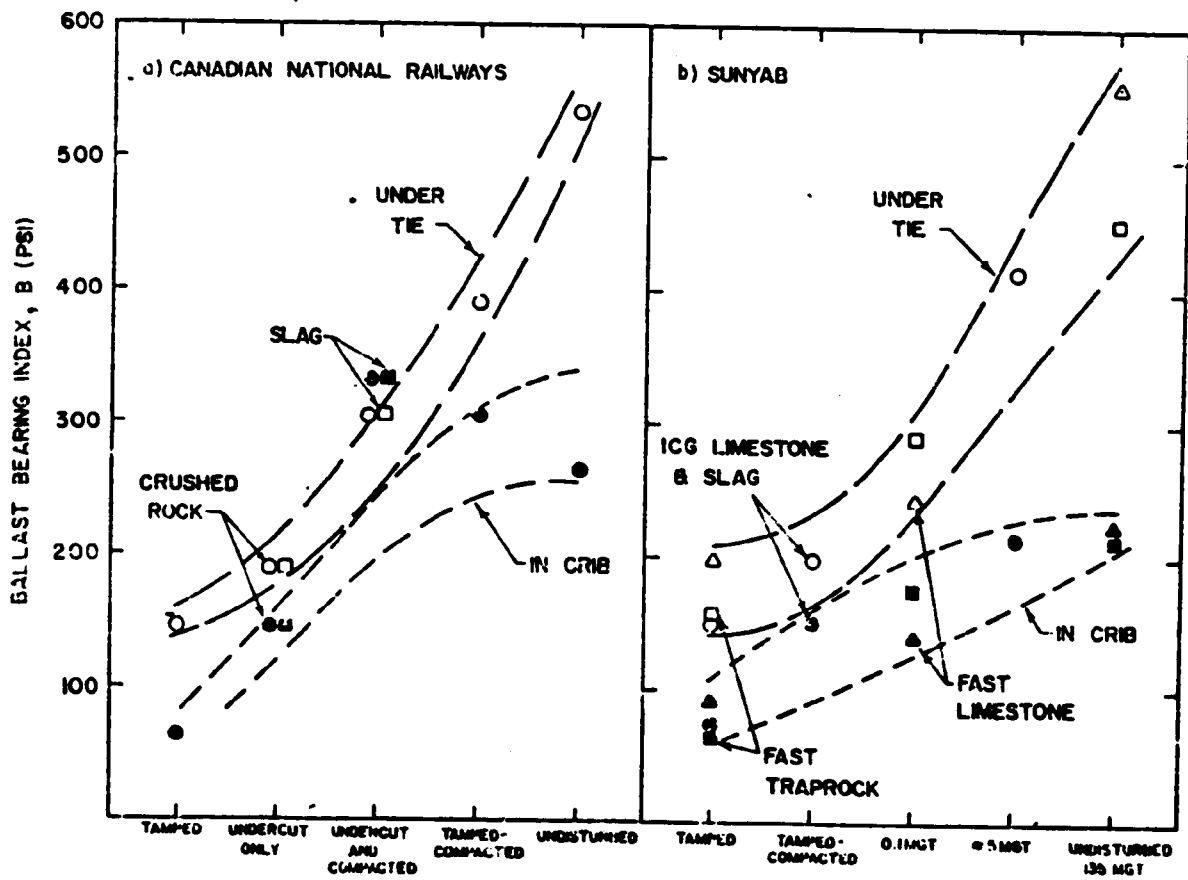


Figure 3.11. Ballast Bearing Index at 0.3 in. (7.6 mm) Plate Displacement Under the Rail for Various Track Conditions

the data in the present form, this situation cannot be resolved.

When crib and shoulder compaction are applied to the undercut condition, the B values increase by a factor of at least 2 for both under-tie and in-crib values. The interesting feature for this condition is that the in-crib values are slightly greater than the under-tie values. This opposes the trends established for the other track conditions, and again, no apparent explanation is available. In general, the undercut and compacted condition yields B values comparable to the tamped-compacted (TC) condition, and follows a trend similar to the respective tamped-only condition.

Peckover's (Ref. 20) investigation revealed several other important findings. For the undisturbed track condition and for the several different types of track maintenance operations, plate load tests performed on the flat portion of the ballast shoulder produced stiffness values indicative of a relatively loose density state. With the categories established in Table 3.6, the equivalent B values would be in the very loose to loose range. For an undisturbed track, the B values in the crib-near the rails were approximately equal for test locations at the top of the crib ballast and at the base elevation of the tie between ties, which were both significantly less than B values directly under the tie. The test results also indicate that ballast crib and shoulder compaction is generally superior to either crib or shoulder compaction separately.

The ballast bearing index (B) values for SUNYAB's under-rail PLT data at 0.3-in. (7.6-mm) displacement are illustrated in Fig. 3.11b along with CNR's data in Fig. 3.11a. This figure displays two particularly interesting features. First for the undisturbed condition, the under-tie



and in-crib B values are of comparable orders of magnitude for CNR and SUNYAB. The second is that very good agreement exists for the tamped-uncompacted (TU) condition for both data sets in the crib and under the tie. Also, the CNR undercut-only condition, i.e., assumed tamped and possibly surfaced and lined, yields under-tie B values comparable to the SUNYAB TU condition. In general, this latter factor indicates a reliable degree of reproducibility for the tamped-only condition for different ballast materials of different test programs. Note that the ICG track for the TU condition was undercut 10 to 12 in. (0.25 to 0.31 m) while the CNR undercut-only condition was approximated as a 6 in. (0.16 m) cut (Ref. 5). The slightly higher CNR B value may be attributed to an influence of a more rigid base.

A comparison of the tamped-compacted (TC) conditions for CNR and SUNYAB produced the greatest difference in test results. The CNR B values are 1-1/2 to 2 times larger than those for SUNYAB. This discrepancy is presently not explainable.

Due to the nature of SUNYAB's data, an attempt will be made in order to determine an equivalent amount of train traffic, as implied by the plate load test, that is initially offered by ballast crib and shoulder compaction on a tamped-only track. By combining the three ballast types tested, the TC condition under-the-rail is shown to be somewhat in between the TU and 0.1 MGT traffic conditions for both under the tie and in the crib. If the relative change in B values for the FAST limestone from the TU to 0.1 MGT traffic conditions for both under the tie and in the crib is compared to the relative change for the ICG data from TU to TC conditions, the result is that the TC condition is equivalent to slightly greater than 0.1 MGT of traffic. Considering both

cases previously presented, a reasonable equivalent traffic estimate appears to be 0.1 MGT. The lack of any trafficked conditions for the CNR data prohibits such an estimate; however, a 0.1 MGT value appears to be low.

In general, insufficient quantities of under-rail plate load test data, especially at intermediate traffic levels, limits the establishment of clearly defined plate resistance trends with track maintenance operations and train traffic loading. Thus, the differences for the tamped-uncompacted and tamped-compacted conditions, as well as differences in ballast type and the effectiveness of different ballast crib and shoulder compaction equipment, cannot easily be quantified. In addition, both a reasonable MGT of traffic which provides a stable or "undisturbed" track condition and the amount of traffic at which plate resistance cannot be differentiated for either track condition are presently indeterminate due to the lack of available data.

### 3.3 LATERAL TIE PUSH TEST

The lateral tie push test has previously received a considerable amount of field use in order to evaluate the in-situ track conditions. An analysis of the load-displacement curves for single tie tests on wooden ties (track panel tests excluded) indicated that lateral tie resistance can be adequately compared from the 0.0394 to 0.25 in. (1 to 6.35 mm) displacement levels (Refs. 4 and 5). The following discussion will deal more specifically with the test results at 0.157 in. (4 mm) displacement, which is considered representative. In certain instances, the maximum and minimum values measured for a particular condition will be illustrated to provide an indication of the amount of data variation associated with displacement.

Several load-displacement curves obtained in the laboratory from simulated field track maintenance processes are compared to the field results in Fig. 3.12. Except for the deficient crib and shoulder ballast after tamping at FAST, the track structures were similar in all cases. Also, in some of the laboratory tests, the base component of lateral tie resistance was adjusted to an equivalent wood tie weight of 208 lb (926 N). The laboratory trackbed conditions were defined with descriptive terms for the different ballast physical states, since this was sufficient enough for most purposes. A rough correlation with the rankings established in Table 3.6 would have the loose, compact, and very compact states equivalent to the very loose, loose to medium-dense, and dense states, respectively.

In general Fig. 3.12 indicates that the average lateral tie resistances measured at the various track sites were greater than the values obtained from the simulated laboratory tests. For the tamped-uncompacted condition (Fig. 3.12 a and b), a favorable agreement for the load-displacement curves might be assumed, since a loose ballast density state generally exists around the ties. However, a detailed analysis of the field data, which is presented later, will demonstrate that these lateral tie resistance values (Fig. 3.12 b) are low by approximately 100 lb (445 N). The difference in the laboratory and field data is possibly due to slight differences in the structural arrangement of the ballast particles, even though density measurements indicate the existence of a loose density state. In the field, a greater number of ballast particle contacts are likely to occur in the vicinity of the tie, due to vibrations imposed by the track maintenance equipment of worktrains. In fact, a similar effect has been measured elsewhere (Ref. 23) in the field with limestone ballast.

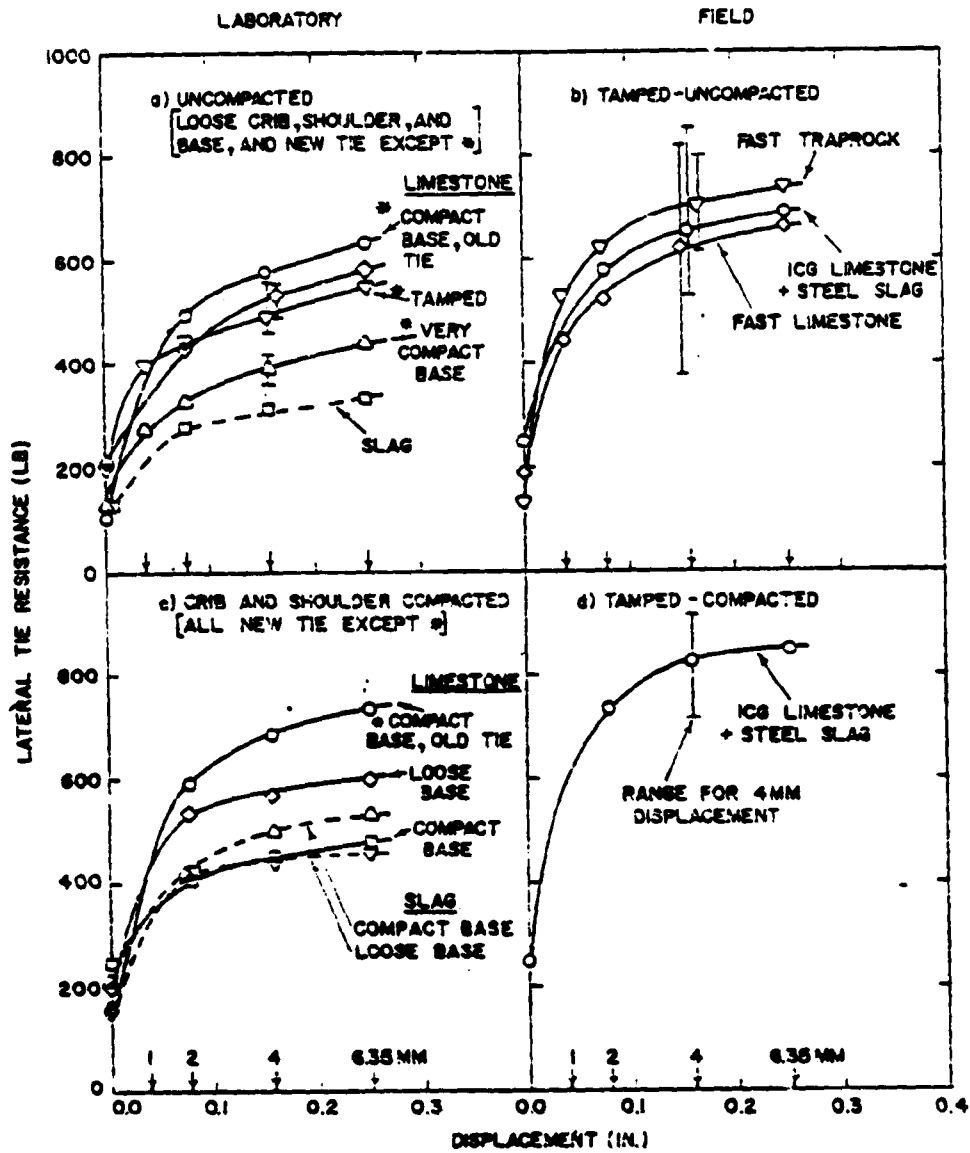


Figure 3.12. Comparison of Laboratory and Field First Cycle LIFT Results for Several Different Conditions

although on concrete ties. In the present laboratory investigation, it was also determined that a second cycle of reloading on a wood tie with full loose crib and shoulder conditions would result in a 75 to 150 lb (334 to 668 N) increase in lateral tie resistance at 0.157 in. (4 mm) displacement (Refs. 4 and 6). Thus, the differences between the laboratory and field data may have been partially explained, but requires further consideration.

The differences in the tamped-compacted condition results (Fig. 3.12 c and d) may arise from the fact that the method and amount of compactive effort applied by the pneumatic tamper in the laboratory tests was insufficient when compared to that of the ballast crib and shoulder compactor. The one trend consistent for both the laboratory and field data is that crib and shoulder compaction increases the lateral tie resistance. This feature is particularly evident for each of the respective test conditions shown in Fig. 3.12 a and c.

The laboratory lateral tie push test data do reveal several findings which are applicable to in-situ conditions.

1. The lateral tie resistance of a new wood tie after manual tie tamping and reballasting does not appear to be affected by the height of the tamping raise, from 1/2 to 3 in. (13 to 76 mm), nor the type of raising operation, that is, a full raise or in lifts.
2. Reballasting entirely under the tie, in the crib, and on the shoulder yields results nearly identical to manual tie tamping plus reballasting.
3. In the loose density state (Fig. 3.12 a), the ratio of the lateral resistances of new ties for limestone and steel slag

ballasts appears to be directly proportional to the ratio of the in-situ ballast densities; that is, approximately 1.6. Other conditions being equal, the bulk specific gravity would be the determining factor (Table 3.1).

4. Note, however, that the preceding observation pertains only to the loose density state, since the introduction of an appreciable amount of compactive effort will predominate as the influencing factor. Figure 3.12b appropriately demonstrates this point. For equivalent compactive efforts in the crib areas near the rails and on the shoulder slope, the steel slag ballast is more responsive, as indicated by the greater increase in lateral resistance to the applied compaction than the limestone ballast. While the particle shapes of the two ballast types are somewhat different, the most plausible explanation is the differences in the surface roughness characteristics of the ballast particles. The honeycombed surface and the lower fracturing strength of the asperities for the slag apparently contributed significantly to having a greater number of particle-tie contacts, a higher degree of particle interlocking, and larger residual lateral stresses being retained after compaction, which subsequently increased the lateral tie resistance.
5. For the simulated old tie on a slightly compact limestone trackbed condition, the greater lateral tie resistance, over that of a new tie, can primarily be attributed to the extremely rough characteristics near the rail areas on the underside of the tie. This is noticeable for both the reballasted condition (Fig. 3.12a) and the crib and shoulder compacted condition (Fig. 3.12c).

In order to illustrate the independent effects on the total lateral tie resistance, the contributions of the individual components of tie resistance; that is, the base, crib, and shoulder, are shown in Fig. 3.13 for the laboratory conditions investigated. The testing was performed with standard railroad wood ties having dimensions of 9 in. (229 mm) wide by 7 in. (178 mm) deep by 102 in. (2.59 m) long and various weights. Ties with geometric or physical dissimilarities to that used here, different ballast types and densities, or especially, the methods utilized for crib and shoulder compaction may produce somewhat different trends. This type of data may be found elsewhere (Refs. 24 and 25), but must be extensively evaluated to place it in a compatible form.

The average relationships displayed in Fig. 3.13 are the combined efforts of two laboratory test series (Refs. 4 and 6), which represent numerous tests. Within and between programs, several duplicated test conditions, which included cyclic tie loading, yielded fairly reproducible lateral tie resistance values. The data variation between duplicate conditions was approximately the same order of magnitude as that existing with cyclic tie loading, both of which may be the result of slightly different ballast placement conditions. Thus, the averaging technique used, although quantitatively not entirely valid for general purposes, still appropriately reflects the general trends.

In Fig. 3.13a, the base component of tie resistance demonstrates distinctly linear relationships with the equivalent weight on the tie. The most interesting point here is that the compacted limestone and steel slag ballasts exhibited the same trends; that is, the tie resistance is approximately one-half the tie weight. Also noteworthy is the fact that very little compactive effort is required to create a smooth limestone

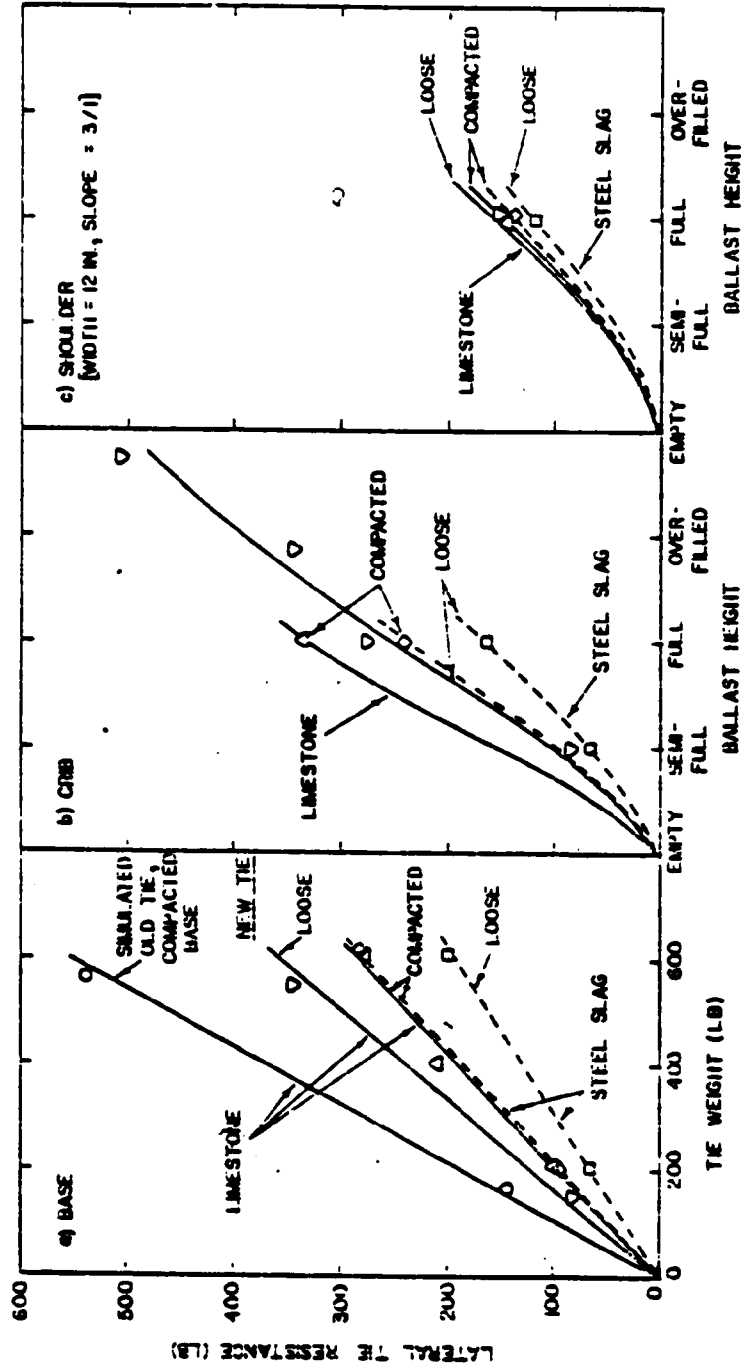


Figure 3.13. The Three Components of Lateral Tile Resistance at 0.157 in. (4mm) Displacement Obtained from Several Laboratory Test Conditions



ballast trackbed surface, since the compact and very compact states yielded nearly identical results. The loose limestone ballast definitely produced a rougher ballast surface; thus, an increase in lateral tie resistance is expected. Assuming the effects of ballast fouling or ballast cementation, which may result from traffic-induced degradation, are minimal in-situ, then the behavior of the limestone ballast might also be typical for traprock and granite. The steel slag, however, opposes the trend of decreased lateral resistance for new wood ties with increased ballast compaction. A greater number of ballast particle surface contact points with the tie and the associated increase in particle interlocking would possibly explain this phenomenon. This does require further experimental verification. In summary, the contribution of the base component to the total lateral tie resistance is reasonably and realistically displayed in Fig. 3.13a and establishes a foundation for future estimation purposes.

The contributions of the crib (Fig. 3.13b) and shoulder (Fig. 3.13c) ballast to lateral tie resistance exceed that offered by the base (Fig. 3.13a) for fully ballasted conditions. The relationships are apparently nonlinear and most likely second-order polynomials with respect to ballast depth. It must be stressed that the relationships presented for the compacted condition are only approximate, and are valid only for the amount of compactive effort applied by the pneumatic tamper in the laboratory programs. None-the less, the data do reveal, as also indicated in Fig. 3.12, increases in lateral tie resistance with compaction, more so in the crib than on the shoulder. In part, this latter fact is consistent with the findings of others in that crib compaction is apparently better than just shoulder compaction (Refs. 25 and 26), and crib and shoulder

compaction combined appears to be better than either operation performed independently (Ref. 25). In addition, crib and shoulder compaction after the tamping operation appears to be more effective when the cribs and shoulders have been overfilled with ballast (Ref. 23). However, as shown in Fig. 3.13b for the loose density state, the effect of just the additional ballast from overfilling would partially account for an increase in lateral tie resistance. This track condition was prepared, but not tested, in Ref. 23. The effectiveness of compacting an overfilled ballast section may not be as pronounced, but still appears to be significant.

As previously stated, the magnitude of the ballast density in the loose state is roughly correlated to the measured lateral tie resistance. The limestone ballast was 60% denser than the steel slag ballast, which produced approximately the same difference in tie resistance (Figs. 3.12 and 3.13). This effect is more pronounced for the crib ballast than for the shoulder, and for a fully ballasted condition than the semi-full case. In addition, loose full cribs for this limestone and steel slag ballast account for 40 to 50 percent of the total resistance (Fig. 3.13), which is consistent with the ORE (Ref. 25) findings.

The preceding discussion focused upon the contributions that the base, the crib, and the shoulder have upon the total lateral tie resistance. Although the relationships were developed under controlled laboratory conditions, the resulting trends provide valuable guides by which to aid in the assessment of measured field data. To demonstrate the usefulness and applicability of these results, one typical field situation will be considered.

Readdressing Fig. 3.12b, the field tamped-uncompacted condition shows comparable lateral tie resistances for the three cases tested, although several features unique to each case, such as differences in ballast type, height of tamping raise, and deficient crib ballast, existed during testing and will affect the results. The conclusion that the field tamping operation should produce approximately the same lateral tie resistances for different sites is still valid, because it can qualitatively be shown that the effects of the preceding features essentially counterbalanced each other. This strongly stresses the importance of adequately documenting records of field test conditions, so that the results can be properly evaluated.

At the FAST track in which reballasting was not performed, the average tamping raises were 1 and 2 in. (25 and 51 mm) for limestone and traprock, respectively. However, the individual raise from tie to tie can vary from the average by as much as the average tie raise. This is particularly evident for the limestone ballast in Fig. 3.12b, which, for the low tie resistance value at 0.157 in. (4 mm) displacement, is actually a test performed on a semi-full crib and shoulder. In all the other tests in limestone and also for those in the traprock ballast, the crib ballast was generally an average of 1 to 2 in. (25 to 51 mm) below the top of the tie. If the semi-full crib test is not considered, then the average lateral tie resistance at 0.157 in. (4 mm) displacement for limestone is approximately equal to that for the traprock ballast. Using the relationships developed in Fig. 3.13, the deficiency of crib and shoulder ballast accounts for approximately 110 lb (490 N) or 16% loss in tie resistance, which is the result of not reballasting. The resulting average lateral tie resistances for the FAST ballasts would have

been higher than that at ICG, which was reballasted. However, the steel slag used at ICG accounted for approximately 1/2 to 2/3 of the ballast-tie contact area (Ref. 5), which, if converted to the equivalent limestone density effect on lateral tie resistance (Fig. 3.13), will increase the lateral resistance at 0.157 in. (4 mm) displacement by approximately 120 lb (535 N). Note that the ICG steel slag ballast is the reason for this difference in resistance for the loose ballast density state created by tamping and reballasting, but the same effects are uncertain with mechanical or traffic-induced ballast compaction. Thus, the effect of the crib and shoulder ballast deficiency at FAST offset the use of steel slag ballast at ICG. In either case, comparable load-displacement curves are produced after the tamping operation.

The load-displacement curves in Fig. 3.12b will be used as is for correlation purposes, since an exact quantification of the component tie resistance changes is not possible, and the correlations are only preliminary. More importantly, any such changes with traffic, which is the case for the 0.1 MGT condition at FAST, are presently unknown.

Although the functional relationships for the three components of lateral tie resistance with applied train traffic are nonexistent, the trends in Fig. 3.13 can be used in conjunction with field measurements, observations, and experience in an effort to generate the possible relationships for conventional wood tie track structures. Firstly, the total lateral tie resistance generally increases with traffic after track maintenance tamping and, as will be demonstrated later, has a form which is hyperbolic in shape (Fig. 3.14). Assuming a fully ballasted condition and the occurrence and influence of ballast cementation and fouling are minimal, the lateral tie resistance growth curves and the respective

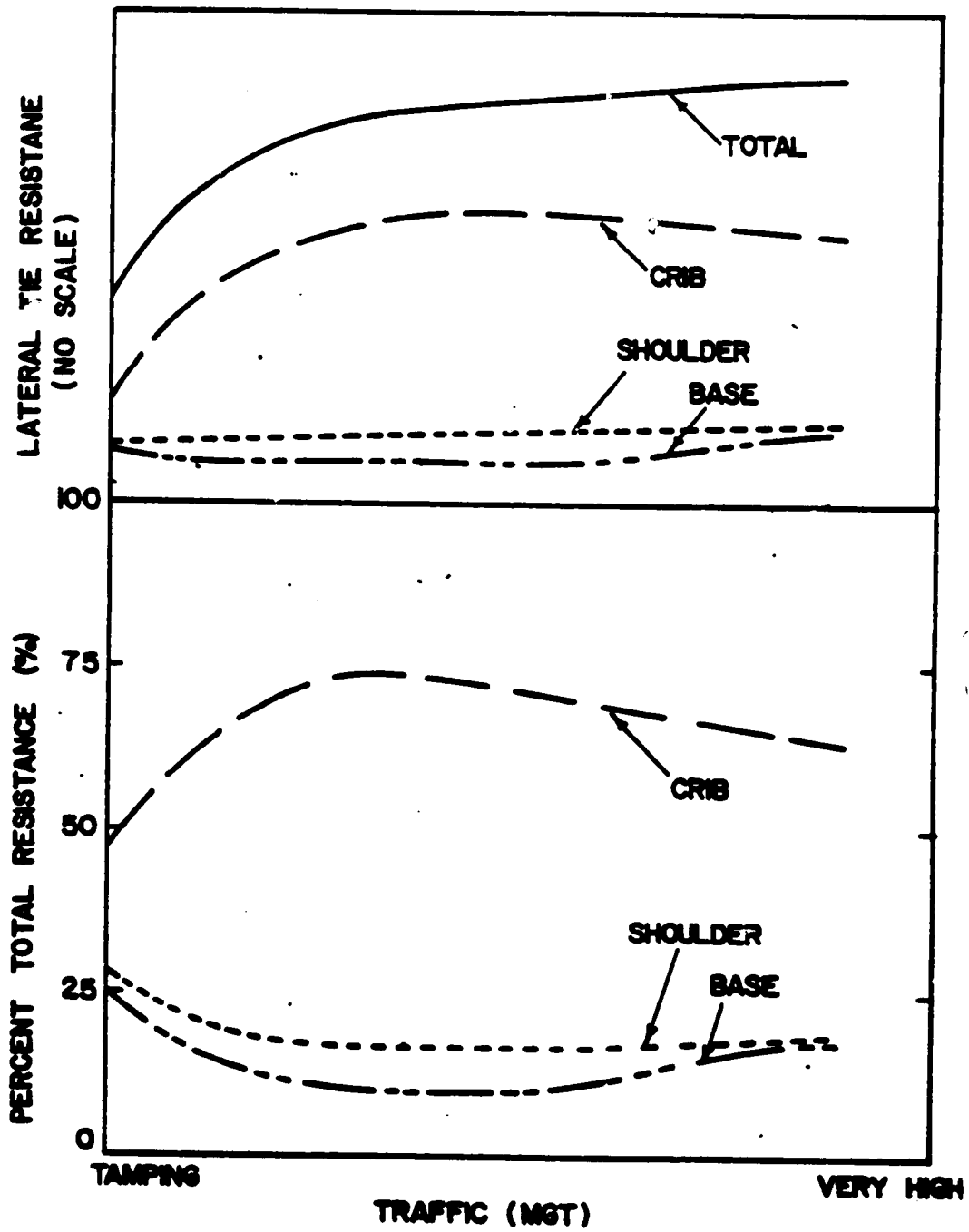


Figure 3.14. Qualitative Interpretation of the Changes in the Lateral Tie Resistance Components for Wood Ties After Track Maintenance with Traffic

percentages of total resistance are qualitatively represented in Fig. 3.14 for the three components of resistance. The crib component was determined by speculating the changes that were expected to occur for the base and shoulder.

After major track work, the mechanisms which might cause a loose ballast shoulder to densify and simultaneously increase tie resistance are: 1) vibrations from train traffic, and 2) slight cyclic lateral tie movements from traffic and thermally-induced forces. The effects of these mechanisms, however, are not expected to produce a substantial increase in lateral tie resistance, since the tendency will be for the ballast particles to move laterally from the lack of confinement rather than to continually stabilize into a compacted mass. Incidentally, loose ballast shoulders were observed after 5 MGT on the ICG site, after 135 MGT at FAST, and were also noted by Peckover (Ref. 20).

A hardwood tie installed in a clean, freshly tamped ballast trackbed would initially have a smooth underside resting upon a rough ballast surface. With applied train traffic, small indentations would occur under the tie in the rail seat areas due to the abrasive action of the ballast; but the trackbed would simultaneously become compact and exhibit a rather smooth appearance. Note that for the trafficked conditions at ICG and FAST, the newer ties removed from the track revealed indentations on the bottom, but the ballast surface under the ties (old ties also) was fairly flat with almost no visible signs of protruding ballast particles. Thus, a decrease in lateral tie resistance would be expected. However, the ballast trackbed progressively becomes stiffer with increased traffic, which would subsequently inhibit further wear and distortion to the tie bottom. This would result in a slightly rougher tie surface and, thus,

increase the base component of lateral tie resistance.

Figure 3.14 adequately displays the changes in lateral tie resistance with train traffic for the base and shoulder components previously discussed. Each component may contribute from 10 to 25% of the total resistance, depending upon the traffic level. This would imply, as illustrated in Fig. 3.14, that the crib ballast is the principal component of lateral resistance. Particle vibrations from traffic, acceleration and braking forces from trains, and cyclic longitudinal tie movements from changes in thermal stresses are most likely the inter-tie compaction mechanisms, which would produce high degrees of ballast particle interlocking and large residual lateral stresses. Apparently, the initial tie spacing after track tamping, and the relative changes in tie spacing with traffic, which is also dependent upon the rail anchor locations, are important factors to be considered when evaluating the variation in lateral tie resistance measurements.

Thus, the importance of maintaining full crib and shoulder ballast conditions must be emphasized. For this purpose, mathematical expressions can be derived for the geometry of a ballast cross section and tie spacing, which can be used in determining if a sufficient amount of shoulder ballast is available to fill the cribs and the remaining flat shoulder width after a normal tamping raise. These expressions can also be modified for differences in ballast density or void ratio. Since the shoulder ballast is essentially in a loose density state, and since 12 in. (305 mm) wide shoulders are expected to offer only slightly greater tie resistance than 9 in. (229 mm) shoulders (Refs. 25 and 27), then, reducing the shoulder by 3 in. (76 mm) will provide a sufficient amount of ballast to fill the cribs and flat shoulders after a 1 to 1-1/2 in. (25 to 38 mm) tamping

raise for most standard wood track structures. A similar observation was noted by Reissberger (Ref. 26) for the commonly used U.S. shoulder slopes.

Of the three ballast physical state tests, the lateral tie push (pull) test has been applied most frequently and, thus, supplied in-situ data to supplement that obtained in this program. Information was compiled from the following sources and will be identified herein with the associated titles: a) United States by ENSCO, et al. (Ref. 17), and Southern Number Two (Ref. 28), and b) Foreign by Canadian National Railways, CNR (Ref. 29), and Austrian Wesel Station (Refs. 26 and 30).

In general, the track structures of these railroads were similar to the ICG and FAST sites except for the Austrian Wesel station (Ref. 30) tests, which had concrete ties and gravel ballast. ENSCO (Ref. 17) tests were performed on four different tracks having crushed granite ballast and on one track site with a crushed limestone ballast. At the Southern Number Two (Ref. 28) and CNR (Ref. 29) sites, crushed granite and crushed rock ballasts were respectively present.

The individual lateral tie push test results for the tamped-uncompacted and tamped-compacted conditions with applied train traffic have been discussed and evaluated in detail for the available United States, SUNYAB, and foreign data (Ref. 5). In lieu of presenting the individual data points, only the final curves summarizing the trends will be illustrated for convenience.

In general, lateral tie resistance increased with the application of train traffic (Fig. 315). The tamped-compacted condition initially demonstrated a 33 percent greater tie resistance than the tamped-uncompacted condition for all U.S. railroads. The results of SUNYAB's tests



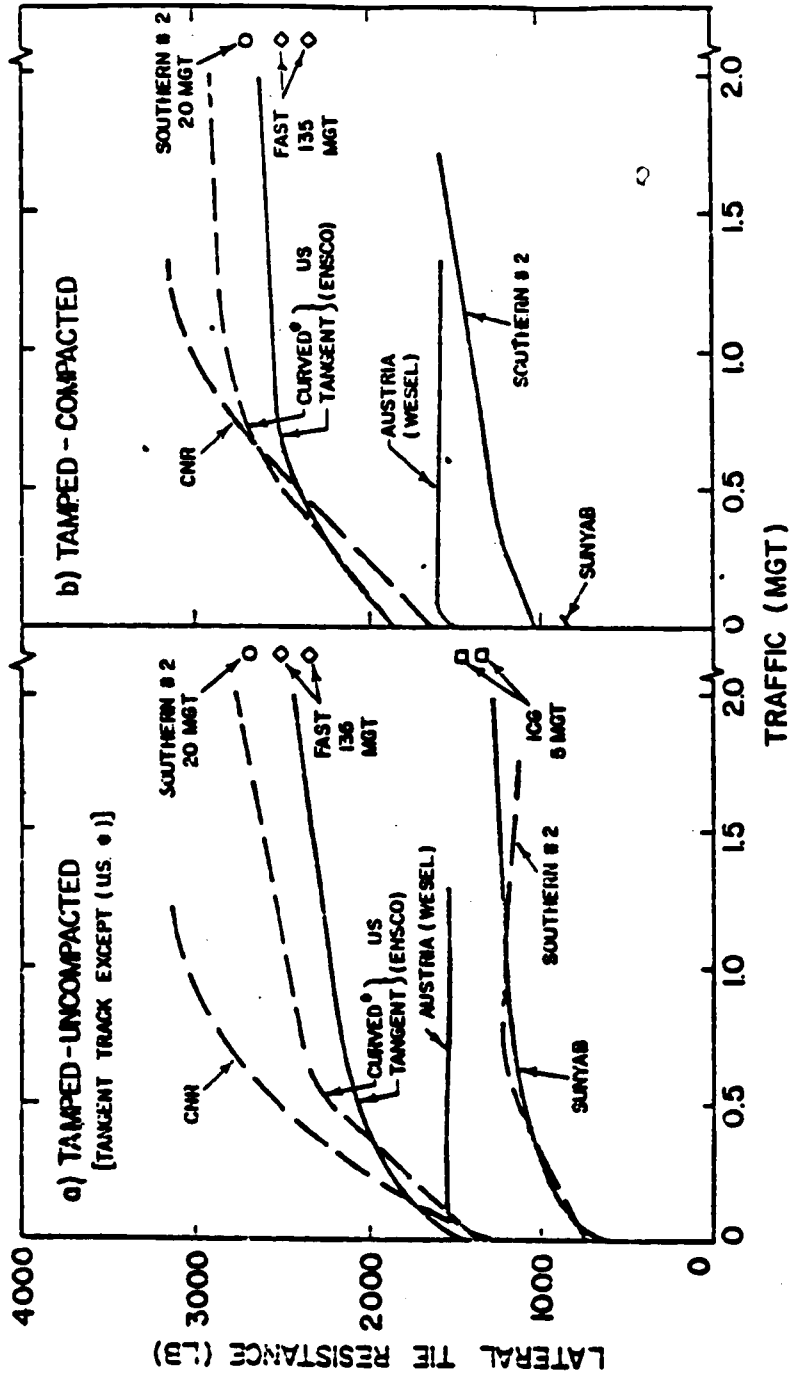


Figure 3.15. Summary of LIFT Trends for All Data at 0.157 in. (4 mm) Displacement for Different Track Maintenance Operations and for Different Types of Track

on ICG produced almost the same percent increase. This percent increase in resistance was consistent for both 0.0787 and 0.157 in. (2 and 4 mm) displacement levels on tangent and curved track. As traffic was applied to the two different track conditions, the difference in tie resistance steadily decreased and approached the same value. Wet ballast conditions were noted during certain intervals of testing, but this did not noticeably change the general trends. The tie resistance trends were similar for the foreign data.

The lateral tie resistances at high MGT traffic conditions, i.e., 20 MGT (a reasonably assumed value, Ref. 5) for Southern Number Two (Ref. 28) and 135 MGT for FAST, were significantly greater than the values at low amount of traffic. From a previous discussion for the FAST data, the base and shoulder components of resistance were probably a small portion of the total lateral resistance per tie; thus, the crib ballast is apparently the principal component. Since the crib ballast is initially in a loose state after tie tamping, the tie movements resulting from train loadings apparently produce a high degree of interlocking of the crib ballast between the ties. This is the most plausible explanation of the changes in lateral tie resistance from initial track maintenance with traffic other than environmental influences or highly fouled ballast. A similar reasoning was deduced by the engineers for the 20 MGT condition on the Southern track (Ref. 28).

The greatest variation in results between sites was obtained from ENSCO's (Ref. 17) test series which was on five participating railroads with each site having similar test conditions. The principal ballast type was granite. These lateral tie resistances were significantly greater than the results obtained from the test series performed by

Southern Railways (Ref. 28) and SUNYAB. The ballasts tested by SUNYAB were limestone, traprock, and a limestone and steel slag mixture, which showed very good agreement in lateral resistance for the tamped-uncompacted condition at zero MGT. The granite should produce lateral resistances comparable to the limestone and traprock. However, the large difference in the lateral tie resistances obtained by ENSCO and SUNYAB were primarily attributed to the locations of the load applying and measuring systems (Ref. 5).

The large differences in reported lateral tie resistance values between data sources complicates the problem of utilizing the lateral tie push test results on different sites as a means of identifying the changes in the physical state of the ballast. With the limited quantity of available data, this study could not isolate the effect of differences in amount of track raise or ballast type, let alone the differences in types of crib and shoulder compaction equipment. The latter would encompass the effect of such factors as vibration frequency, cycle time, and static and dynamic forces. Thus, clearly, the selection of the most suitable ballast type or ballast compactor is not possible.

In considering the previously stated factors, certain approaches were devised in order to correlate the lateral tie resistance values for each railroad. Two data-normalization techniques used to correlate the results were the load ratio (LR) and the compaction ratio (CR). These ratios appeared effective in negating the differences in test apparatus, and test procedures and tie age, and in properly establishing the trends due to applied traffic and to crib and shoulder compaction (Ref. 5).

The load ratio (LR) approach provided a reasonable method of relating the tie resistance values in a form such that the data were more directly

comparable (Fig. 3.16). This dimensionless ratio is defined as:

$$LR = L/L_0, \quad (3.2)$$

in which  $L$  = tie resistance at a given displacement level for either the tamped-only or the tamped-compacted condition, with or without applied traffic, and  $L_0$  = tie resistance at the same displacement level as  $L$ , but for the tamped-uncompacted condition with zero applied traffic. As shown in Fig. 3.16, the LR trends with traffic were similar at 0.157 in. (4 mm) displacement level for both tangent and curved track for all U.S. data.

This ratio was also used to determine the equivalent amount of traffic on a tamped-only track for which crib and shoulder compaction immediately after tamping was effective. The 0.0787 and 0.157 (2 and 4 mm) displacement levels yielded consistent values for each railroad and resulted in an average value of 0.17 to 0.19 MGT of traffic for all railroads (Ref. 5). For the reported annual MGT's of traffic, 3 to 4 days of train traffic on a tamped-only track apparently produces the same effect as ballast compactors.

A transformed hyperbolic fitting technique for the LR - MGT curves (Fig. 3.15) was utilized in order to estimate a "stable" value for a load ratio and the associated amount of traffic loading. This technique has successfully been used in linearizing hyperbolic-shaped stress-strain curves for cohesive soils (Ref. 31) and for granular soils (Ref. 32). The linear form of the hyperbolic equation is:

$$\frac{MGT}{LR} = a + b (MGT), \quad (3.3)$$

in which  $a$  and  $b$  are constants. The stable or ultimate value for a load ratio is:

$$LR_{ult} = 1/b. \quad (3.4)$$

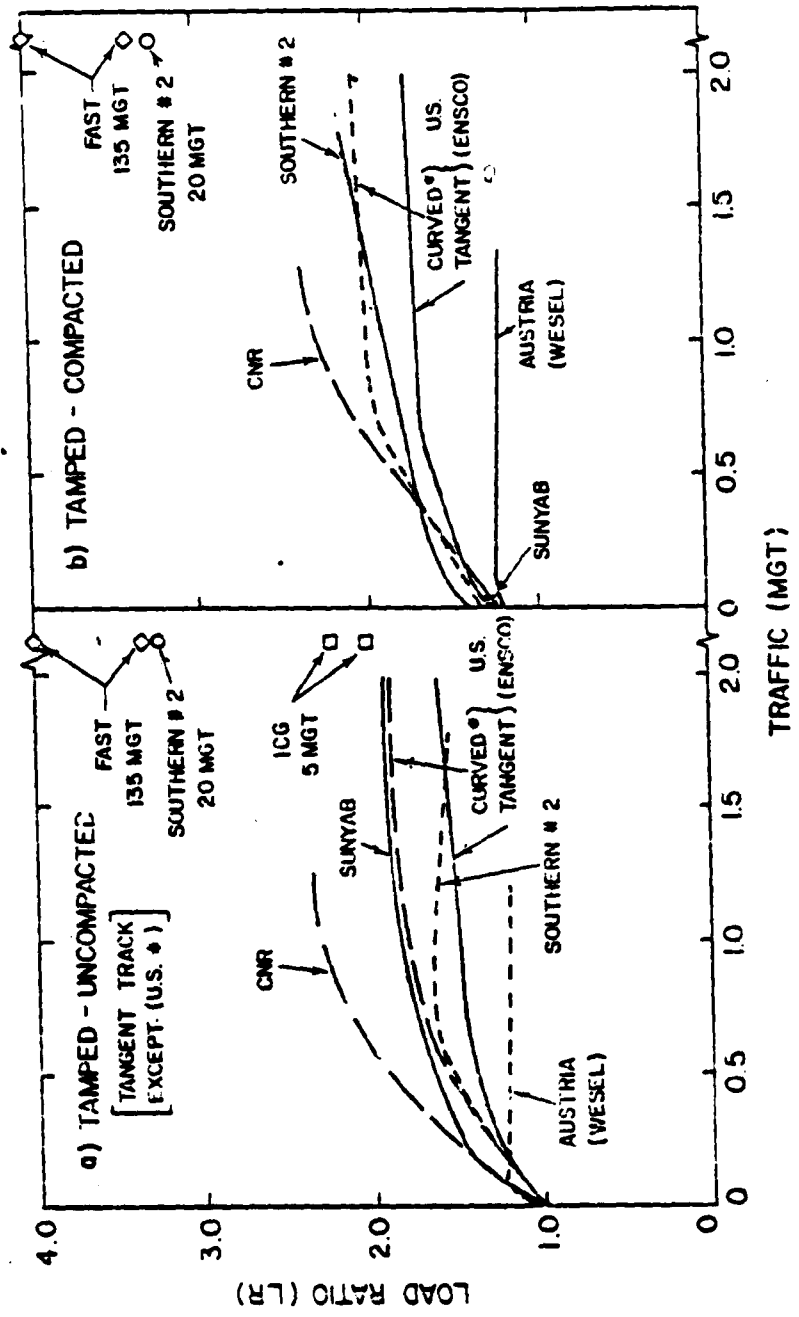


Figure 3.16. Summary of LTFT Load Ratio Trends at 0.157 in. (4 mm) Displacement for All Data

Using the transformed hyperbolic fitting technique, 20 MGT of traffic was determined to be a reasonable estimate of a "stable" or undisturbed track condition.

The compaction ratio (CR) approach appeared to be an adequate means of determining the amount of traffic required such that the effect of crib and shoulder compaction can no longer be distinguished from a tamped-only track. This dimensionless ratio is defined as:

$$CR = C/U \quad , \quad (3.5)$$

in which C = tie resistance at a given displacement level and at a certain amount of traffic for the tamped-compacted condition, and U = tie resistance at the same displacement level and amount of applied traffic as C, but for the tamped-uncompacted condition.

A value of 2 MGT appeared to be a reasonable, conservative estimate for all U.S. data (Fig. 3.17) and is consistent with ORE (Ref. 25) findings for European railroads. This result was similar for both displacement levels and for both tangent and curved track. Also, the CR approach is apparently not affected by ballast moisture (wet or dry) conditions at the time of testing (Ref. 5).

An overall evaluation of the lateral tie push test results indicates a definite deficiency of field data suitable for a comprehensive evaluation of the factors affecting the ballast physical state. SUNYAB's data are considered highly reliable, but lack the tie resistance values at intermediate levels of traffic to clearly define the trends for tamped-only and tamped-compacted conditions. Additional data would establish, as implied by the tie push test, whether the ballast crib and shoulder compactor is worthwhile as an integral part of a normal track maintenance program.

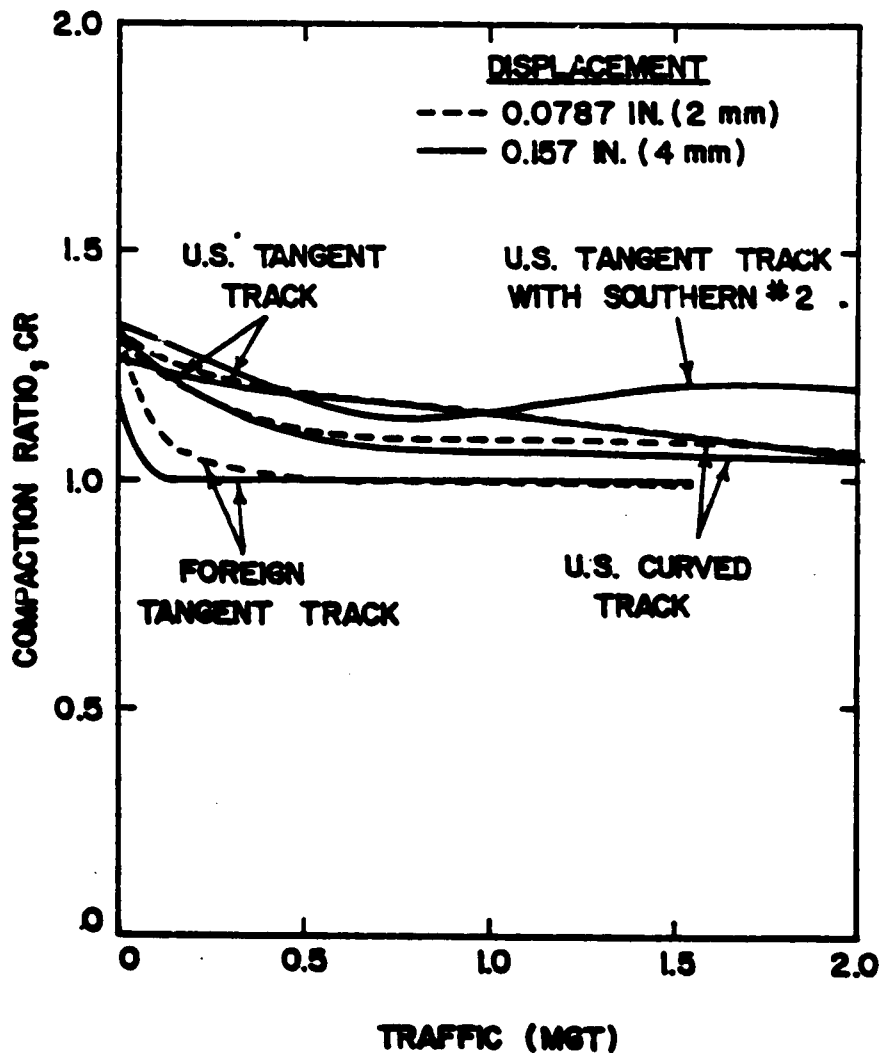


Figure 3.17. Summary of the Lateral Tie Push Test Compaction Ratio Trends for all Data

Cross-correlations of lateral tie resistance and plate load resistance values for the tamped-compacted condition and the tamped-uncompacted condition with traffic were attempted, but provided no definitive trends.



#### 4. SUMMARY AND CONCLUSIONS

The purpose of this study is to evaluate the benefits of ballast compaction with crib and shoulder compaction machines, and to determine to the extent possible the most effective compaction procedures. However, early in the study it was concluded that these objectives could not be achieved without considering the influence of the accompanying maintenance operations and previous traffic history. The reason is that the track maintenance operations have a significant influence on the ballast physical state and hence on the degree of effect of compaction and traffic on changes in the physical state and in the resulting track performance and service. Therefore, in this study were examined the effects of such maintenance operations as undercutting, tamping-surfacing-lining, and crib and shoulder compaction.

A brief review of the economic factors involved in track maintenance was also made. The cost factors vary widely with the particular situation and so it was not possible to provide a general economic assessment of the benefits of crib and shoulder compaction. Instead, the study has concentrated on determining the effect of crib and shoulder compaction on ballast physical state in comparison with the effects of maintenance and traffic. The economic evaluation is best done by the railroad users by applying their own cost information to the observed effects presented in this report.

The most significant accomplishments of this study are:

1. Development of recommended standard tests for measuring the physical state of ballast in-situ.
2. The use of these measurements in the field to quantitatively evaluate the effects of crib and shoulder compaction on ballast

physical state compared to the effects of maintenance and traffic.

3. Instrumentation of the FAST track to observe the contribution to the dynamic and long-term deformation of track from the ballast, subballast, and su!grade.

This chapter will summarize the results of this study. However, the FAST instrumentation results will be omitted since these will be included in a separate summary report.

#### 4.1 BALLAST PHYSICAL STATE METHODS

Both because of the nature of ballast material and the variability of field conditions, measuring the ballast physical state in-situ is very difficult. However, a direct quantitative measurement is essential to progress, for example, to sort out conflicting opinions as to the cause and effect of maintenance operations, to determine the degree to which the maximum compaction benefits are being achieved, and to determine the relative contributions of compaction to track performance. After an examination of the type of information needed and a consideration of previous experience with ballast physical state measurements, it was concluded that the most useful measurements would involve ballast density, plate bearing resistance, and lateral resistance of ballast to pushing individual ties.

There has been little success in the past in measuring ballast density in-situ. No standard methods exist. The only useful data in the past were obtained with nuclear probes at fixed locations which measured changes at those locations after probe installation. The nuclear method thus was not suitable to meet the requirements of this program. In this present study, a ballast density test (BDT) method was developed and successfully applied in the field and in the laboratory.

Limited use has been made of plate bearing tests on ballast in the past. However, the use of small bearing plates was found to be very promising. Therefore, techniques were evaluated and apparatus and procedures developed for a ballast plate load test (PLT) that were suitable for field and laboratory use.

The resistance of ballast to the lateral displacement of an unfastened, unloaded tie is the only test relating to ballast physical state that has been used to any significant extent in the past. However, this is an indirect measurement of compaction compared to the ballast density test and plate load test. The procedures and apparatus that have been used in the past have varied widely and these differences have a significant effect on the results. However the lateral tie push test (LTPT) is sensitive to the effects of maintenance, traffic and compaction. As part of this project, a study was made to determine the factors that influence the magnitude of the ballast resistance determined with this test. The results showed that the correlation between track performance and the lateral tie resistance was not a simple one because the way in which the ballast conditions influence the resistance is different than in track under train traffic.

Based on a study of alternative methods of measuring the lateral tie resistance and after initial laboratory and field experience with these methods, recommended apparatus and procedures were established for standardizing the LTPT.

The three physical state tests (BMT, PLT, and LTPT) have been developed to the point where they can be used in practice to supplement other observations on track performance such as track geometry measurements and maintenance experience. Subsequent sections of this chapter will describe some of the findings obtained by application of these measurements at track sites

in the field and in controlled laboratory experiments.

#### 4.2 EFFECTS OF MAINTENANCE OPERATIONS

As might be expected, no evidence was found that the tamping operation has any significant effect on the subballast and subgrade performance. However, the influence of traffic was felt even down into the subgrade. Cyclic loading from the succession of train axles caused cumulative vertical strains which produced a contribution to settlement from the subgrade as well as from the ballast and subballast layers.

No subballast and subgrade measurements were available in tests in which crib and shoulder compaction was involved. However, based on experience with compaction as well as the observations associated with tamping, no significant effects on the subballast and subgrade behavior from surface crib and shoulder compaction with available machines is expected.

Newly deposited ballast conditions occur with such maintenance operations as undercutting, sledding, and new construction. The ballast density is usually lowest for these conditions. As a result, the density is usually higher in the tamped zone under the tie than in the crib. Under the center of the tie, the ballast will be as loose as in the crib.

The primary effect of the crib and shoulder compactor is in the crib at the locations of application of the compacting plates (near the rail). When a crib and shoulder compactor is used following tamping of newly deposited ballast, the ballast density in the crib near the rail increases significantly. A small increase may also occur under the tie near the rail.

Traffic significantly increases the amount of compaction in the crib and under the tie after tamping and crib and shoulder compaction. Traffic-induced compaction under the tie is greater than with tamping and crib and shoulder compaction. The increment caused by traffic can even be greater in the crib. A valuable objective of further research would be to find out

how to produce traffic-induced level of compaction as part of the maintenance operation so that the track will be stable before the application of traffic rather than be stabilized by traffic.

Traffic degrades track by creating permanent settlements which is generally manifested by irregularities in surface and line. However, at the same time, the ballast is compacted by the action of traffic and its properties will be improved unless the ballast degrades by mechanical breakdown or pumping from infiltration of fines and moisture. Thus periodically maintenance tamping is required as part of the process of reestablishing surface and line. This tamping loosens the ballast from its state after traffic. The amount of disturbance is directly related to the amount of the raise. The greater the raise, the lower the ballast density becomes. The density of the tamped zones in the crib will be reduced the most, particularly for small raises.

The research results show that crib and shoulder compaction increases the plate bearing resistance both under the tie and in the crib compared to the effects of tamping only. The percentage of bearing resistance increase, of course, is greatest in the crib tamping zone. The bearing resistance increase under the tie may be a result of greater ballast confinement from crib compaction rather than the change in physical state of the ballast under the tie.

Crib and shoulder compaction was also observed to consistently increase the lateral tie resistance compared with the resistance following tamping only. However, the percentage increase measured with the LTPT is believed to be much greater than the corresponding increase in track lateral resistance which would develop under train load with the ties fastened to the rail.

#### 4.3 EFFECTS OF COMPACTOR VARIABLES

The information gathered in this study on the effects of vibratory crib and shoulder compactors has been obtained with a variety of machines operating under different conditions. Since the effects of the vibration parameters on the amount of compaction are interrelated, the application of conclusions from one particular test with a particular machine to another set of conditions must be done with considerable caution. Available information did not permit the establishment of any clear guidelines as to the optimum operating conditions for crib and shoulder compactors. No comprehensive test program was found which adequately considers the vibratory compactor variables and their interrelationships on the effectiveness of compaction, particularly as a function of other influencing parameters like the ballast conditions.

In spite of the above limitations, however, this study has permitted the identification of the principal machine variables and some indication of their role. A summary of this information as it pertains to compaction with vibrating surface contacting elements is as follows:

1. Static Contact Pressure

Up to some maximum pressure, an increase in pressure will increase the amount of compaction during vibration.

2. Generated Dynamic Force

The generated dynamic force should be distinguished from the dynamic force applied to the ballast. The difference in the two forces is primarily a function of the inertial resistance of the compaction elements. The generated force is created by the machine and usually can be defined. However, the contact force will vary with the ballast conditions and is therefore difficult to define and measure. It is expected that for a given frequency,

increasing the generated dynamic force will increase the amount of compaction up to some limit. The effects of the dynamic force must be considered in relation to the static pressure or force, because an applied dynamic force greater than the static force means that the compaction plate will lose contact with the ballast during part of the cycle. This permits the introduction of the impact mechanism in compaction compared to the situation where the plate is always in contact with the ballast.

### 3. Vibration Time

In practice, vibration times at each particular ballast location have ranged from two to twelve seconds. Increasing vibration time can either increase or decrease the amount of compaction, but increasing time on the order of seconds in the range of about zero to five seconds should continually increase the amount of compaction.

### 4. Vibration Frequency

The relationship between the vibration frequency and amount of compaction is not clear from available data. This observation is expected because frequency affects the amount of compaction in several ways which may be conflicting. For example, frequency affects the magnitude of the applied force, frequency affects the degree of particle vibration, and frequency affects the number of cycles of loading applied at a particular location.

### 5. Geometry and Size of Compactor Plate

This variable will certainly affect the compaction results, if only because the contact pressures will vary with these parameters for the same static and dynamic forces. However, no information was found to select these parameters.

## 4.4 BENEFITS OF BALLAST COMPACTION

One of the accepted benefits of crib and shoulder compaction of ballast is to reduce the slow order time for traffic because of the reduced

lateral stability after tamping. The results suggest that the compaction process provides the equivalent of 0.2 million gross ton (MGT) of train traffic in stabilizing the track. Thus immediate operation of trains at the speed otherwise permitted after 0.2 MGT of slow orders could be initiated immediately. Low traffic density lines might benefit more than higher density lines since the period of time for slow orders would be much longer on the low density lines.

Slow orders should be more critical in maintenance operations involving undercutting and ballast replacement because the ballast bed will generally be much looser. Normally, the compaction process follows the final tamping-surfacing-lining operation with fully ballasted cribs. However, consideration should be given to compaction before the cribs are filled in order to provide a greater depth of penetration of the compaction effect into the ballast below the bottom of tie. The benefits of this approach might be particularly useful for the reballasted track. Test results have shown that the lateral tie resistance is greater when compaction is done on a fully ballasted crib than on a partially filled crib. To conclude from this that compaction is most effective using full cribs may be misleading because in the LIPT measurements, a substantial part of the lateral resistance comes from the crib when the tie is unloaded. However, the bottom of the tie provides a much greater proportion of the resistance for loaded ties under train traffic. Possibly the benefits of compaction would be increased by a sequence which first provides compaction with low cribs followed by crib filling and a second application of compaction. Further studies are needed to evaluate this possibility.

Another important application of crib and shoulder compaction is in conjunction with spot maintenance where loosening of the ballast has occurred around only some of the ties. The use of crib and shoulder compaction will



reduce the physical state difference in the ballast between the disturbed cribs and the undisturbed cribs.

By far the most significant benefit of using crib and shoulder compactors that has been expressed by railroad users is associated with maintenance that must be done during hot weather. For a variety of reasons, track maintenance involving tamping may be impossible to defer until a sufficiently cool period. In such cases, immediate stabilization is a very important safeguard that even slow order traffic cannot provide. Economically, the benefits of crib and shoulder compaction would be greatest if a substantial lengthening of the maintenance life of the track were to result. This would occur either if the rate of settlement were reduced by compaction or the uniformity of settlement were improved by compaction. Unfortunately, the available field information is not adequate to confirm this benefit, although intuition suggests that it must be true to a certain extent.

In general, the results of this study suggest that:

- 1) The addition of crib and shoulder compaction to the maintenance operation is beneficial,
- 2) Crib and shoulder compaction with existing machines and procedures does not restore the ballast to the same degree of stability that is provided by traffic, and
- 3) The full potential of compaction of ballast including the optimal use of the vibratory compaction parameters has not yet been reached.

## 5. RECOMMENDATIONS FOR FURTHER STUDIES

As a result of this study on the mechanics of ballast compaction, several areas requiring further research have been identified. These areas are expected to supplement or extend the existing knowledge and general trends established by this present program, or are topics related to this study but not investigated due to time limitations. The subject areas recommended for further study, which have not been ranked in order of importance, are as follows:

1. Develop a track performance index which can be used to realistically evaluate the cost effectiveness of alternative compaction procedures for given rated levels of track performance.
2. Use analytical track models which predict the elastic and inelastic behavior of the ballast and subgrade together with property tests on ballast samples compacted to various degrees, to establish a maintenance life prediction method representing the affect of ballast compaction.
3. Correlate lateral tie push (pull) test results for unfastened and unloaded individual ties with lateral track stiffness measurements, both with and without vertical load. Study further and in more detail the factors influencing lateral resistance of ties. More accurate data could be generated as inputs for lateral track stability models for thermal loadings and for dynamic lateral wheel loading experienced during traffic. The factors considered might include: a) different ballast types, gradations, hardnesses, and particle shapes, b) effects of water, cementation, frost, fouled ballast with different plasticities of the fine fraction, c) various shoulder widths and slopes, d) different heights of super-elevated ties, and e) tie type, shape, hardness, and age.
4. Conduct further controlled field studies on various track sites to establish the trends with train traffic determined with the ballast density test, the plate

load test, and the lateral tie push test trends for tamped-only and tamped-compacted conditions. Adequate documentation of the track conditions, maintenance and traffic history, and the existing environmental factors during testing period are a necessity.

5. Conduct experiments to more precisely identify the influence of the controlling parameters in tamping and vibratory ballast compaction. Factors to consider for the tamping operation include the number of tamping insertions, heights of track raise, the depth of tamping tool insertion, and tamping force and frequency. For the ballast crib and shoulder compactor the factors might include the vibration time, the static down pressures, applied dynamic force, frequency, displacement amplitude, and the number of compaction passes. Also included should be a study of the compaction process, such as compaction of the crib ballast in layers, i.e., first on a semi-filled crib and then on a reballasted full crib; and investigating the effects of using only crib plates or only shoulder plates, as well as the combination of the two.
6. Continue the laboratory study of the changes in the ballast physical state and the amount of compaction achieved with a single crib compaction plate over a range of frequencies and vibration times. Several other factors to consider are: plate size and shape, constant stroke amplitude versus constant load amplitude, fouled or wet ballast, different ballast materials possessing different particle shapes and gradations, and the use of a subballast and/or subgrade as a supporting material.
7. Investigate the differences in track behavior for tamped-only and tamped-compacted conditions with traffic at the instrumented ballast test sections at FAST. The effects of ballast type, ballast depth, tie spacing, tie type, and the amount of track raise should be taken into consideration.

## REFERENCES

1. Ward, E.J., "Technology and Reviving the Railroads," Technology Review, July-August, 1976.
2. Raymond, G.P., Gaskin, P.N., and Svec, O., "Selection and Performance of Railroad Ballast," Symposium on Railroad Track Mechanics, Princeton University, Princeton, New Jersey, April, 1975.
3. Selig, E.T., Yoo, T.S. and Panuccio, C.M., Mechanics of Ballast Compaction, Volume 1: Technical Review of Ballast Compaction and Related Topics, Final Report, State University of New York at Buffalo, Contract No. DOT/TSC/1115, Submitted to Transportation Systems Center, U.S. DOT, Cambridge, Massachusetts, September, 1980.
4. Selig, E.T., Yoo, T.S. and Panuccio, C.M., Mechanics of Ballast Compaction, Volume 2: Field Methods for Ballast Physical State Measurement, Final Report, SUNYAB, Contract No. DOT/TSC/1115, Submitted to Transportation Systems Center, U.S. DOT, Cambridge, Mass., September, 1980.
5. Panuccio, C.M., Yoo, T.S. and Selig, E.T., Mechanics of Ballast Compaction, Volume 3: Field Test Results for Ballast Physical State Measurement, Final Report, SUNYAB, Contract No. DOT/TSC/1115, Submitted to Transportation Systems Center, U.S. DOT, Cambridge, Mass., September, 1980.
6. Panuccio, C.M., McMahon, D.R. and Selig, E.T., Mechanics of Ballast Compaction, Volume 4: Laboratory Investigation of the Effects of Simulated Field Compaction Mechanisms, Final Report, SUNYAB, Contract No. DOT/TSC/1115, Submitted to Transportation Systems Center, U.S. DOT, Cambridge, Mass., September, 1980.
7. Selig, E.T., Yoo, T.S., Adegoke, C.W. and Stewart, H.E., "Status Report - Ballast Experiments, Intermediate (175 MGT) Substructure Stress and Strain Data," Interim Report, FRA/TTC/Dr-10(IR), Prepared for FAST Program, Transportation Test Center, Pueblo, Colorado, Submitted September, 1979.
8. Selig, E.T., Yoo, T.S., Adegoke, C.W. and Stewart, H.E., "Status Report - Ballast Experiments, Intermediate (175 MGT) Substructure Stress and Strain Data," Interim Report, FRA/TTC/Dr-10(IR), Prepared for FAST Program, Transportation Test Center, Pueblo, Colo., Submitted Sept., 1979.
9. Adegoke, C.W., "Elastic and Inelastic Deformation Response of Track Structures Under Train Loads," Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Civil Engineering at SUNYAB, December, 1978.
10. National Slag Association, "Processed Blast Furnace Slag," AIA File No. 3D3, Washington, D.C., June, 1966.
11. Thompson, M.R., "FAST Ballast and Subgrade Materials Evaluation," Ballast and Foundation Materials Research Program, Dept. of Civil Engineering, University of Illinois at Urbana-Champaign, Interim Report to USDOT, FRA Contract No. FRA/ORD-77/32, December, 1977.

12. Plasser, "Technical Description of the Consolidating Machine VDM 800 U,"  
Manufacturer's Literature.
13. Panuccio, C.M., "Trip to Canadian National Railway Site," Internal Report,  
Department of Civil Engineering, SUNYAB, June-July, 1976.
14. Office for Research and Experiments of the International Union of Railways,  
"Optimum Adaptation of the Conventional Track to Future Traffic: Study  
of the Change in the Track Level as a Function of the Traffic and of the  
Track Components," ORE Question D117, Report No. 2, UTRECHT, April, 1973.
15. Plasser and Theurer, Manufacturer's Literature on Track Maintenance Equip-  
ment Specifications.
16. McMahon, D.R., "Visit to DOT-FAST Site in Pueblo, Colorado, with SUNYAB Staff  
for Field Tests," November, 1977.
17. Cunney, E.G., May, J.T., and Jones, H.N., "The Effects of Accelerated Ballast  
Consolidation," ENSCO, Inc., et al., prepared for USDOT, Federal Railroad  
Administration, Office of Research and Development, Contract DOT-FRA-54174,  
March, 1977.
18. Plasser Information, "Consolidating Machines," Manufacturer's Literature.
19. Canron (Tamper and Matisa), Manufacturer's Literature on Track Maintenance  
Equipment Specifications.
20. Peckover, F.L., "Ballast Compaction Tests," Interdepartmental Correspondence  
for Canadian National Railways, File E5510-9, Montreal, Canada, October, 1970.
21. Birman, F. and Cabos, P., "Determining of the Increase in Ballast Density Under  
Traffic by Means of the Gamma Absorption Method," Bulletin of the Interna-  
tional Railway Congress Association, March, 1967, pp. 229-249.
22. Hardy, R.M., "Stress Distribution in Track Structures," Proceedings of the  
AREA, Vol. 69, Bulletin 614, June-July, 1968, pp. 924-940.
23. Powell, M.C., "The Effect of the VDM 800 Crib Consolidator on the Value of  
Lateral Ballast Resistance," British Railways Engineering Research Division,  
Technical Note No. L18, July, 1970, 3 pgs.
24. ORE, "Einfluss Verschiedener Massnahmen auf den Querverschiebewiderstand des  
Unbelasteten Gleises," Report DT 44/D117/D, UTRECHT, Office for Research and  
Experiments of the International Union of Railways, May, 1976.
25. Office for Research and Experiments of the International Union of Railways,  
"Optimum Adaptation of the Conventional Track to Future Traffic: A Study  
of Factors Influencing the Resistance to Transverse Displacement of Unloaded  
Track," ORE Question D 117, Report No. 8, UTRECHT, October, 1976.
26. Reisberger, K.H., "Evaluation and Measurement of Ballast Consolidation by Use  
of Compacting Machines," Presentation, Washington, D.C., March 29, 1973.

27. Hay, W.W., Peterson, H.C., Plutkin, D.E., and Bakas, P.T., "Lateral Stability of Ballast," Ballast and Foundation Materials Research Program, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Technical Report to USDOT, FRA, Report No. FRA/ORD-77/61, September, 1977.
28. Southern Railway Company, Research and Tests Laboratory, "The Effects of Ballast Consolidation on Continuous Welded Track," Alexandria, Virginia, July 7, 1975.
29. Trask, E.R., "Ballast Compaction Tests," Report to Railway Maintenance Officer, File #5510-13, Canadian National Railways, Montreal, Canada, August, 1974.
30. Plasser and Theurer Testing Division, "Report on Measurement of Resistance to Transverse Displacement in an Operational Track with the Object of Determining the Effect of Intertie Compactification," November 19, 1971, (Translation).
31. Konder, R.L., "Hyperbolic Stress-Strain Response: Cohesive Soils," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 89, No. SM1, pp. 115-143, 1963.
32. Duncan, J.M. and Chang, C.Y., "Nonlinear Analysis of Stress and Strain in Soils," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 96, No. SM5, pp. 1629-1653, September, 1970.

## APPENDIX A

### SUMMARIES: VOLUMES 1, 2, 3, AND 4

This report provides a technical review of literature concerning ballast compaction and ballast-related factors influencing track performance.

The performance of railroad track systems is a function of the characteristics and the complex interactions of the track system components under traffic and environmentally-induced stresses. Descriptions of the track components are presented in the report, including the rails, ties and fasteners, and in particular, the ballast, subballast and subgrade. Also, the relationships which exist between the track system components and track performance have been discussed. The ballast and subgrade behavior were shown to have a significant effect on the performance of the track in-service.

Recently developed analytical track models have been described with particular emphasis concentrated on the representation of the ballast and subgrade materials. However, the reliability of these models for predicting track performance was not established. The primary reason is the lack of corroboration with field data. Available field measurements or criteria that are indicators of track performance are track stiffness, track geometry, safety, ride quality, and maintenance effort. However, each individual item is not sufficient for proper representation of the overall track system performance.

Ballast materials possess different particle physical and chemical properties. Many laboratory index property tests, such as those for abrasion resistance, absorption, shape and soundness, are currently utilized to quantify and categorize the relative merits of these different ballast types. The applicable test standards and ballast specifications limits have been cited and the basic test procedures, as well as the factors influencing the test results, have been discussed. However, at present, a proven method for rating ballast using these index properties does not exist.

The stress-strain behavior of ballast-sized materials may be determined from laboratory tests. The conventional static and dynamic test apparatus and procedures, as well as the factors affecting the test results, have been discussed and assessed with respect to use with ballast materials. The cyclic or repeated load triaxial test appears to be particularly suitable for determining the ballast stress-strain and strength properties. Laboratory test data need to be correlated with in-situ data representing these properties. An evaluation of the available field methods indicates that the plate bearing test is best suited for this purpose.

The strength and compressibility characteristics of ballast are directly related to the relative degree of compaction of ballast within the track structure. Methods used in geotechnical engineering practice for measuring and specifying compaction are reviewed. However, it was shown that these methods have limited application for ballast materials. Furthermore, no quantitative ballast compaction specifications are available and measurement of the degree of ballast compaction is rarely done. However, an in-situ ballast density test, a small plate load test, and a single lateral tie push test on an unloaded tie have been identified as potential means of representing the ballast physical state.

The rate of change in the ballast physical state within the track structure caused by train traffic loading and environmental conditions is highly dependent upon the initial state achieved from the track maintenance operations. Ideally, an "undisturbed" ballast trackbed after considerable traffic is the most desirable condition from a stability viewpoint. The reason is that the subsequent correction of track geometry defects during maintenance by ballast tamping disturbs the stable condition created by traffic. Therefore, the effect that present track maintenance processes have upon changing the ballast



physical state should be studied. To aid in understanding these effects, the principal types of track maintenance equipment and the associated field procedures in current use have been described.

The ballast state produced by the tamping, leveling and lining operations, and the more recent ballast crib and shoulder compaction process after tamping are discussed in relation to their expected effect on track performance under traffic following maintenance. Lateral resistance of either single tie or tie panel sections is the most frequently used method for measuring track performance related to ballast conditions. However, alternative methods, including track geometry changes, track or ballast stiffness, and ballast density have also been used. Supporting evidence obtained with these methods and published opinion indicate that mechanical ballast compaction following the tamping operations should be beneficial. The degree and nature of the benefit was not clearly established, however.

The amount that the ballast is compacted with present crib and shoulder compactors is a complex function not only of the initial ballast physical state, but also the compactor characteristics including static force, generated dynamic force, vibration frequency, and duration of vibration. However, sufficient information is not available to determine the effects of these factors on ballast compaction. Therefore, laboratory and field investigations are required to find the most effective means of obtaining the desired physical state of ballast.

The economic aspects of track maintenance are briefly discussed to provide a basis for assessing the cost-effectiveness of ballast compaction. This subject was shown to be complex and require further study.

The practices and principles of geotechnical engineering provide direct and valuable input into understanding the behavior of the ballast, subballast and subgrade materials under the imposed loading environment. However, the lack of

field measurements and the incomplete development of both laboratory property tests and computer track design models require further research in order to establish the needed understanding of ballast properties and their relation to track performance.

SUMMARY  
Volume 2

A review of the state-of-the-art of ballast revealed the need for suitable methods to measure ballast compaction. After considering possible alternatives, three methods were selected for study. The first determines in-place density. The second determines plate bearing resistance, which is a measure of the stiffness and strength of ballast. The third determines lateral tie resistance to displacement. This is an indirect measure of both physical state and compaction, but it is the only one of the three methods that has been used in the past to any significant extent.

A study of ballast density measurement methods was undertaken in the laboratory with the primary purposes of developing 1) methods that are suitable for application to ballast materials, both in the laboratory and in the field, and 2) methods of determining reference densities that could be used in assessing the amount of ballast compaction achieved in the field during track construction and maintenance operations. A technique employing the water-replacement concept was selected as the most feasible approach for ballast density determination. This method involves measuring the volume of an excavated hole in the ballast bed by lining the hole with a membrane and determining the volume of water required to fill the hole. A series of density measurements employing this method was performed to establish appropriate testing procedures and to determine the most suitable dimensions and volume of the excavated hole. Various devices were considered for applying the compactive effort to the samples for determination of reference densities. The best approach involved the use of a rubber-tipped impact hammer applied to the surface of ballast placed in layers in a steel mold.

The successful development of a ballast density measurement method is a noteworthy achievement of this study. With careful attention to test techniques

and use of special apparatus, consistent test results can be obtained and differences in ballast density can be detected. The study showed that the sample boundary conditions have a major effect on the magnitude of the calculated density. Thus, the weight of a ballast sample compacted into a container, divided by the container volume, will not be an accurate indication of the sample density. Boundary corrections must be applied to get the correct density. Furthermore, the study showed that values of density obtained with one method of measurement will probably not be comparable with values using another method.

Research was undertaken to assess the usefulness of plate load tests for ballast physical state measurement, and to develop procedures for the tests. Various types of seating materials and different plate sizes and shapes were investigated. The effects of repeated loading and ballast layer depth were explored. Finally, the influence of using wet or dry ballast was considered.

The recommended test uses a vertically-loaded 5-in.-diameter circular plate seated on the ballast surface using gypsum plaster. The most useful parameter found to represent the load-deflection results from the test is the load per unit plate area per unit deformation. This is determined by measuring the load required to settle the plate, an amount ranging from 0.1 to 0.3 in.

A test involving lateral displacement of individual ties or tie panel sections has been widely used as a measure of lateral resistance of track. Several investigators have also used this test as a means of evaluating the effectiveness of ballast tamping and compaction operations. In this study, the factors influencing the test results were investigated to assess the usefulness of the test for these purposes, and to determine the most suitable apparatus and procedures for field use.

The recommended test procedure requires pushing the tie from the centroid of the end face, rather than from the top as is sometimes done. The lateral resistance was shown to be highly sensitive to ballast type, tie condition, and especially the depth of crib and shoulder ballast. The results indicated that correlation between lateral resistance measured in the single tie test and track lateral resistance is complicated and must take into account the effect of the rails, the interaction between adjacent ties, and the train vertical loading, if present.

SUMMARY  
Volume 3

The three most promising methods for identifying the physical state of ballast were determined to be the plate load test (PLT), the lateral tie push test (LTPT) with single ties, and the ballast density test (BDT). The plate load test determines the pressure on the ballast surface from a 5-in.-diameter plate which is required to produce a specified amount of surface deflection, usually 0.1 to 0.3 in. The resulting parameter, termed ballast bearing index, is a measure of the ballast stiffness. The lateral tie push test determines the force to push a tie up to 0.25 in. horizontally when the tie is unfastened from the rail. This gives indirect measurement of ballast physical state but it is directly related to the amount of lateral restraint to the track provided by the ballast. The ballast density test determines the weight of ballast particles per unit volume of ballast structure. This is a direct measure of the degree of compactness of the ballast.

Apparatus and procedures were developed for performing each of these tests in the field. Measurements were then made on existing track to investigate the effects of tamping, crib and shoulder compaction, and traffic on the ballast physical state. The four sites at which the field tests were conducted were: 1) Canadian National Railways in Belleville, Ontario, 2) Southern Railways site near Lynchburg, Virginia, 3) Illinois Central Gulf (ICG) site near Kankakee, Illinois, and 4) the Department of Transportation Facility for Accelerated Service Testing (FAST) in Pueblo, Colorado. Available data from U.S. and foreign literature for different track maintenance operations and train loading conditions were correlated with this new data.

The field measurements showed that the ballast physical state is significantly affected by train traffic, track maintenance procedures, and track conditions existing prior to maintenance. Tamping may densify or may loosen the ballast layer depending on the type and nature of tamping operation, track conditions, and location of the ballast layer. Typically, tamping during initial construction may increase ballast density and stiffness under the tie near the rail, but the same tamping performed during track maintenance after traffic will disturb and loosen the ballast layer that has been compacted by traffic. Ballast density and stiffness increase from crib and shoulder ballast compaction was quite evident in the crib near the rail, but the effect of crib compaction on the ballast under the tie was very limited. The long-term effect of this ballast compaction was not conclusive, however, because of insufficient data. Traffic appeared to be the biggest source of ballast compaction.

The ballast density test was shown to be a useful tool for determining the in-situ ballast physical state. The techniques, which were improved through the field experience, have proven suitable for railroad application, and the measurements are considered reliable. The density test results presented in this report provide important and needed information which will improve the understanding of track performance.

The lateral tie push test results indicated that, after disturbance from maintenance operations, a reasonable estimate of train loading required to reestablish a "stable" ballast condition is 20 million gross tons (MGT) of traffic. The amount of traffic to produce the same benefits as crib and shoulder compaction when used immediately after tamping is about 0.2 MGT, or 3 to 4 days of average daily traffic. The effects of crib and

shoulder compaction following tamping could not be distinguished from the tamped-only track condition after approximately 2.0 MGT of traffic.

The plate load test ballast bearing index trends with traffic could not be established. However, the amount of traffic equivalent to the benefits of crib and shoulder compaction appeared similar to that estimated from the LTPT correlation. <sup>2</sup>

Insufficient data in the 2 to 20 MGT range prohibits the establishment of clearly defined trends with applied traffic. Also, effects of differences in ballast type, amount of track raise, characteristics of ballast crib and shoulder compactors, and track structure cannot be thoroughly evaluated. Further study of these factors is strongly recommended. In such studies, adequate information on the track structure, traffic loading history, track maintenance history, and environmental conditions is important. In addition, standardized BDT, PLT, and LTPT apparatus and test procedures are needed because the measured values are sensitive to the apparatus and procedures.



SUMMARY  
Volume 4

The first part of this report describes an investigation of tamping and compaction of ballast using laboratory-simulated field conditions. A track bed was constructed in the laboratory and tie tamping and compaction operations were performed in order to examine the effects on the resulting physical state of the ballast. The ballast physical state was measured using the three in-situ tests developed at SUNYAB. These were the plate load test (PLT), which measures vertical ballast stiffness, the ballast density test (BDT), and the lateral tie push test (LTPT), which measures the resistance offered by the ballast to an individual tie displaced laterally. In general, tamping machinery is used for track maintenance work, while ties are manually tamped only for spot work. However, all of the tie tamping in this project was performed manually, because mechanical tamping equipment could not be used in the laboratory.

Simulation of a railroad track ballast bed that has been conditioned by traffic, but which has not been recently subjected to maintenance operations, was attempted in the laboratory by filling a large test box with a 12-in.- (0.305-m-) thick layer of limestone ballast and compacting it with a vibratory plate compactor. An increase in ballast density of about 12 pcf from the loose state was observed after only 25 to 50 passes with the vibratory compactor. Most of the ballast bearing stiffness increase occurred within approximately 500 passes of the vibratory plate compactor. The laboratory ballast density and stiffness values after 1000 compactor passes compared favorably well with field test results for a track bed after long periods of traffic.

Several lateral tie push tests were performed when a standard railroad tie was placed on the compacted bed with no crib or shoulder, and the effects

of various weights placed on the tie were evaluated. Tests were also performed for a semi-filled crib, a full crib, and a full crib with a surcharge load. The ballast shoulder section was subsequently formed and lateral tie push tests were performed on a compacted base, as well as a loose base resulting from various amounts of tamping raises. These ballast physical state test results were also compared with previous reported data.

The lateral resistance of an individual tie after manual tie tamping was not affected by the height of the tamping raise for a full, loose ballast crib and shoulder condition. The lateral tie resistance increased nearly linearly as the amount of ballast in the cribs increased. Even when the cribs were over-filled, the tie resistance continued to increase in a similar fashion. Thus, the crib component of resistance is a significant contributor to the total lateral resistance of an unloaded tie. For ties of various weights placed on a compacted base with no crib or shoulder ballast, the lateral tie resistance was approximately equal to one-half of the tie weight.

The field lateral tie resistance forces from the LTPT were generally greater than the laboratory forces for the tamped-only condition by 50 to 150 lb (223 to 668 N). The laboratory PLT and EDT results, however, compared very favorably to the field test results for the tamped-only condition. Thus, representative field track conditions appear to have been reproduced in the laboratory.

The second part of the report describes an investigation of the factors influencing ballast compaction with surface vibrating plates. This series of tests with a single oscillating plate on the ballast surface was intended to simulate a typical compaction element from a crib and shoulder compactor. To accomplish this, a single, flat, steel plate having dimensions comparable

to those for ballast compactors was fabricated and attached to a cyclic load actuator. The plate was first loaded statically. Then an alternating load was applied at a low enough frequency to eliminate vibration. The load-displacement response was recorded for a loose, crushed limestone ballast in small test boxes under controlled loading conditions. The effects of the following factors on the compaction of ballast were investigated: 1) magnitude of static load, 2) magnitude of cyclic load, 3) ballast depth, 4) cycles of loading, 5) frequency, and 6) lateral boundary effects. In addition, BDT and PLT tests were performed on the compacted zone after the required number of loading cycles was achieved. These two physical state tests permit a comparison with field experience.

The cumulative cyclic deformation (settlement) of the plate increased as the ratio of cyclic to static load was increased for a given static load. The cumulative cyclic deformation also increased as the static load increased for a constant ratio of cyclic to static load. The ballast density increased by only about 3 pcf from the loose state after application of 300 load cycles. The final density state appeared to be independent of the loading conditions. The plate bearing stiffness value at a given deformation increased as the static load was increased for a given ratio of cyclic to static load. Similarly, as the ratio of cyclic to static load was increased for a given static load, the bearing stiffness increased. When the sample ballast depth was decreased, both the static deformation and the cumulative cyclic deformation decreased. When the lateral boundary constraints of the box were removed by using a larger box, the deformations increased for a given set of loading conditions, but the amount of compaction was essentially unchanged. Within the frequency range of 0.1 to 2 Hz, the ballast physical state resulting from compaction with the oscillating plate was essentially independent of frequency.

The physical state for the loose ballast condition in the lab prior to compaction with the oscillating plate was comparable to the observed physical state in the field under two conditions. These conditions were under the center of the tie after reballasting and in the crib near the rail after tamping. However, the ballast stiffness in the crib after crib compaction in the field was much greater than that achieved in any of the lab tests. The conclusion was drawn that the vibration effects from the high frequency used in the field contributed significantly to the amount of compaction achieved by an oscillating plate.

## APPENDIX B

### REPORT OF NEW TECHNOLOGY

The work performed under this contract has led to significant new technology, improvement of existing technology, and new insights into the behavior of ballast in track. Apparatus and procedures were developed for three field test methods to measure compaction or its effects on ballast behavior. The influence of maintenance tamping, crib and shoulder compaction, and traffic on the physical state of ballast were assessed and a better understanding of these processes was achieved. Laboratory tests showed the significant effect of crib and shoulder conditions on resistance of ties to lateral displacement, and also showed the influence of some of the parameters influencing compaction with surface vibrating plates.

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