PB82-192196

U.S. Department of Transportation

Federal Railroad Administration

Mechanics of Ballast Compaction

Volume 3: Field Test Results for Ballast Physical State Measurement

FRA/ORD-81/16.3
DOT-TSC-FRA-81-3, III

Final Report
March 1982

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FRA/ORD-81/16.3		PB82 192196

4. Title and Subtitle	
MECHANICS OF BALLAST COMPACTION Volume 3: Field Test Results for Ballast Physical State Measurement	5. Report Date March 1982 6. Performing Organization Code DTS-731
7. Author(s) C.M. Panuccio, T.S. Yoo and E.T. Selig	8. Performing Organization Report No. DOT-TSC-FRA-81-3,III
9. Performing Organization Name and Address Department of Civil Engineering* State University of New York at Buffalo Parker Engineering Building Buffalo NY 14214	10. Work Unit No. (TRAIS) RR219/R2309 11. Contract or Grant No. DOT-TSC-1115
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Railroad Administration Office of Research and Development Washington DC 20490	13. Type of Report and Period Covered Final Report Jan 76-Sep 79 14. Sponsoring Agency Code RRD-12

15. Supplementary Notes

*Under contract to: U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge MA 02142

16. Abstract

The important mechanical processes which influence the ballast physical state in track are tamping, crib and shoulder compaction and train traffic. Three methods of assessing physical state were used at four railroad sites to obtain needed data on the effect of these processes. The methods were: ballast density test, plate load test, and lateral tie push test. The available information from previous studies was also compiled and compared to the new information gathered in this study. The primary objective of this research was to evaluate the usefulness of crib and shoulder compaction in the maintenance of track. The research showed that the effects of tamping and compaction on ballast state depend significantly on the state existing prior to maintenance. For a track in service, tamping generally loosens the ballast. Crib and shoulder compaction primarily densifies the crib, but it also improves the ballast stiffness under the tie. Train traffic had the most influence on ballast physical state. After loosening from tamping, the ballast again reaches its stable physical state within 20 MGT of train traffic. Adding crib and shoulder compaction produced the same physical state as about 0.2 MGT traffic, and the effects of this compaction were not distinct from tamped-only track after about 2 MGT of traffic.

This report is Volume 3 of the Final Report on the subject contract.

17. Key Words	18. Distribution Statement
Ballast, compaction, properties, field tests, density, bearing test, lateral tie push test	DOCUMENT IS AVAILABLE TO THE U.S. PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	192	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This report describes and compares the ballast physical state test results obtained from field investigations on several track sites representing various track conditions, maintenance operations and traffic levels. The work is part of a contract to evaluate ballast compaction and recommend guidelines for using compaction to improve track performance.

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's Federal Railroad Administration, Office of Research. The Contract No. is 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. The outstanding cooperation of the Illinois Central Gulf Railroad, Southern Railways, and Canadian National Railways in permitting tests to be conducted on their track is gratefully acknowledged. Assistance of the Transportation Test Center in Pueblo, Colorado with the tests at the FAST track is also acknowledged. A majority of the field tests by SUNYAB and the related data reduction were conducted with the help of Hwang-Ming Chen, James I. Johnson, and Brian C. Dorwart, who were Graduate Research Assistants at SUNYAB.

METRIC CONVERSION FACTORS

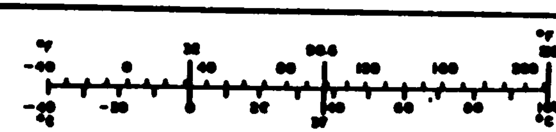
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ADDITIONAL CONVERSION FACTORS

To Convert

Units	Symbol	From	To	Multiply By	Symbol
length	in.	inches	millimeters	25.4	mm
	ft	feet	meters	0.305	m
area	sq in. (in.^{2})	square inches	square centimeters	6.45	cm^2
	sq ft (ft^2)	square feet	square meters	0.0929	m^2
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^2
volume	cu ft (ft^3)	cubic feet	cubic meters	0.03	m^3
density	lb/ft^3(pcf)	pounds per cubic feet	megagrams per cubic meter	0.016	Mg/m^3

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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).

B_k = Modified ballast bearing index value (B/Δ) in pci (kN/m^3).

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.

E = Compactive effort in ft-lb/cu ft ($m\text{-}kN/m^3$).

e = Void ratio.

E_m = Modified modulus of deformation in pci (kN/m^3).

E_r = The amount of elastic recovery expressed as a percent.

E_{rm} = Modified resilient modulus in pci (kN/m^3).

FAST = Facility for Accelerated Service Testing.

G_s = Specific gravity.

ICG = Illinois Central Gulf Railroad.

ISL = Initial static load or tie resistance at zero tie displacement in lb (N).

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.

N = Number of data points or symbol for Newtons.

P = Load in lb (N) at a given displacement level.

P_{peak} = Peak plate load in lb (N).

PLT = Plate load test.

R^2 = Coefficient of determination.

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.

USCS = Unified Soil Classification System.

UU = Undisturbed track condition.

Δ = Displacement in inches (mm).

Δ_p = Total or peak displacement per cycle in inches (mm).

Δ_r = Rebound displacement per cycle after complete unloading in inches (mm).

$\Delta\gamma$ = Density increment in pcf (Mg/m^3).

γ = Ballast density in pcf (Mg/m^3).

EXECUTIVE SUMMARY

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.

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.

1. INTRODUCTION

The railroad industry is currently concerned with the track system response following out-of-face track maintenance operations. The track system response has been categorized in terms of the changes in lateral track stability, in vertical track stiffness, and in track gage, surface, line and twist. Several factors which influence the track system response are: a) environmental conditions, b) magnitude of total train loading, c) physical state and type of ballast and subgrade, and d) type of track maintenance operation. The first three factors are interrelated for track in-service; however, the initial conditions established by the latter two factors are the most crucial. Accurate and reliable methods of measuring ballast physical state and its change from the initial conditions must be employed to properly relate track conditions to performance.

Presently, the two most common field methods of measurement related to track performance used by American and foreign agencies are single and panel-section lateral tie pull or push tests. Other available methods are track geometry measurement using instrumented cars, longitudinal tie push tests, plate load tests, ballast density measurements and track geometry surveying. A literature review (Ref. 1) indicated the three most promising methods for identifying the ballast physical state are the plate load test (PLT), single lateral tie push test (LTPT), and the in-situ ballast density test (BDT). SUNYAB's emphasis was placed upon developing apparatus for these methods which was rugged, portable, quickly set up, required a short amount of testing time, and retained a permanent record from each test.

This report will be concerned with field test results obtained from the plate load test, the lateral tie push test and the ballast density test. The first method measures vertical ballast stiffness and is a direct indicator of the changes in ballast physical state. The second method is only an indirect measure of physical state, but it is directly relevant to the lateral track buckling behavior. The third method directly measures the ballast physical state by determining the density or void ratio.

Available data were compiled on the PLT and LTPT from U.S. and foreign literature for different track maintenance operations and train loading conditions. These data will supplement tests performed by SUNYAB on the sites of several participating railroads. Since the BDT technique was only recently developed, density measurements will just be qualitatively compared with other published data.

For the PLT and LTPT, differences in test equipment, test procedures and the absolute magnitude of load resistances were identified with each source of data, and in particular with each test program and track structure. Thus, in order to establish the general trends for all data obtained for each test method, several data normalization techniques were devised to account for these differences for correlation purposes. The normalization procedures essentially yielded a dimensionless load ratio at a specific displacement level. The load ratio proportions load for a given track condition, i.e., a certain million gross tons (MGT) of traffic, to load at a common reference condition. The latter state appeared to be most suitably defined as that immediately following the track tamping-leveling-lining operation. The correlation would then involve establishing a relationship between the load ratio at a given displacement level and the MGT of traffic. Since the plate load test data is as limited as the ballast density measurements, the correlations will be emphasized for only the lateral tie push test results.

Evaluation of the LTPT correlations should indicate any apparent differences in trends caused by track maintenance operations, such as crib and shoulder ballast compaction. Thus, the correlation would serve a twofold purpose for the lateral tie push test. The first is identifying a reasonable magnitude of MGT following track maintenance which provides a stable track condition. The second would be the determination of an equivalent amount of MGT provided by crib and shoulder compaction after tamping. Where possible the trends implied from the other two ballast physical state tests will be used as additional supportive data to supplement the trends from the LTPT.

The track and test conditions existing on the sites for SUNYAB's field investigations are described in Section 2. The ballast density test, the plate load test, and the lateral tie push test data are summarized, compared, and evaluated in Sections 3, 4 and 5 respectively. A general summary of the findings of this report is provided in Section 6.

2. RAILROAD SITES FOR SUNYAB TESTS

The State University of New York at Buffalo (SUNYAB) conducted field tests on operating track utilizing the single lateral tie push test (LTPT), the plate load test (PLT), and the in-situ ballast density test (BDT). The railroad sites were: 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 2.1 and 2.2, respectively. The 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.

2.1 CANADIAN NATIONAL RAILWAYS

In 1976 CNR initiated a program to evaluate the effectiveness of tamping machines and ballast compactors available in North America. The CNR program mainly relied on lateral tie push tests as a measure of effectiveness. In July, 1976, with the cooperation of CNR, the ballast compaction study group at SUNYAB participated in the CNR field experiments, evaluating the laboratory-tested ballast density apparatus and procedures, and assessing the physical state changes in the ballast layer during maintenance.

Table 2.1. Track Conditions for SUNYAB Test Sites

Railroad	Track Classification	Maximum Speed (mph)	Annual Traffic (MGT)	Type of Track	Type of Rail	Ties: Type	Ties: Dimensions	Ties: Spacing
CNR	No. 2 mainline station yard	--	--	Tangent	78 ft bolted	wood (#1)	--	19½ in.
Southern	- -	--	20 to 30	Tangent	132 RE CWR	wood	8.6 ft. length	20 in.
ICG	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	19½ in.

Table 2.2. Test Conditions for SUNYAB Test Sites

Railroad	Test State	Ballast Type	Height of Tamping Raise (in.)	Compactor Vibration Time (sec)	Average No. of Ballast Physical State Tests: BDT Under Rail	BDT Center of Track	PLT Under Rail	PLT Center of Track	LTPT
CNR	Before Tamping	Nickel Slag			4	--	--	--	--
	Tamped Only		1-1/2		2	--	--	--	--
	Tamped-Compacted			3 to 4	4	--	--	--	--
					(All In-Crib Only)				
Southern	Tamped Only	Crushed Granite	--		4	--	--	--	--
	Tamped-Compacted			--	4	--	--	--	--
					(All In-Crib Only)				
ICG	Tamped Only	Limestone and Steel Slag	--		8	4	10	4	9
	Tamped-Compacted			3-1/2	8	4	10	4	10
	Tamped Pl: 5 MGT Traffic		1 to 1-1/2		16	8	6	5	21
					(Half of Tests In-Crib; Half of Tests Under Tie)				
FAST	After Track Construction; Before Traffic	a) Crushed Granite b) Crushed Limestone c) Crushed Traprock			8	4	--	--	--
	135 MGT	Only b) & c)			8	4	12	4	5
	Tamped Only	"	1 (b) 2 (c)		8	4	12	4	5
	0.1 MGT	"			8	4	12	4	5
					(Half of Tests In-Crib; Half of Tests Under Tie) (Total Number of Tests for Each Ballast Type)				

Total No. of Tests: BDT = 174, PLT = 135, LTPT = 70

The SUNYAB tests were conducted at the Belleville station yard near the No. 2 mainline between Toronto and Montreal. About 3000 ft (915m) of track was tamped, about 2/3 of which was compacted. A total of ten in-situ density measurements were made before tamping, after tamping, and after compaction, using a preliminary version of the ballast density apparatus. Measurements were conducted in the cribs, both inside and outside the rail. In addition to the in-situ density measurements, measurements were made of moisture content, gradation, and reference density.

The ballast at the test site was a nickel slag supplied by a mill at Sudbury, Ontario (Ref. 2). Figure 2.1 shows the gradation range of the ballast. It was determined from the sieve analyses of the ballast density samples. The ballast at the test site varied significantly in its gradation and appeared to have been completely fouled by intrusion of subgrade materials. The classification of the ballast samples taken for the density tests varied from GW to GP according to the USCS, and the percent finer than No. 4 sieve varied from 5.5 to 35.7%. The moisture content of the ballast ranged from 0.3 to 2.4%, depending on the amount of fines in the ballast layer. Table 2.3 lists typical index properties of the nickel ballast as determined by Gaskin and Raymond (Ref. 2). However, the gradation is not representative of the fouled ballast in the station yard.

2.2 SOUTHERN RAILWAY

The Southern Railway System (SR) has been active in evaluating the effectiveness of their maintenance work and had previously conducted a series of tie-push tests while using a Plasser compactor (Compactor

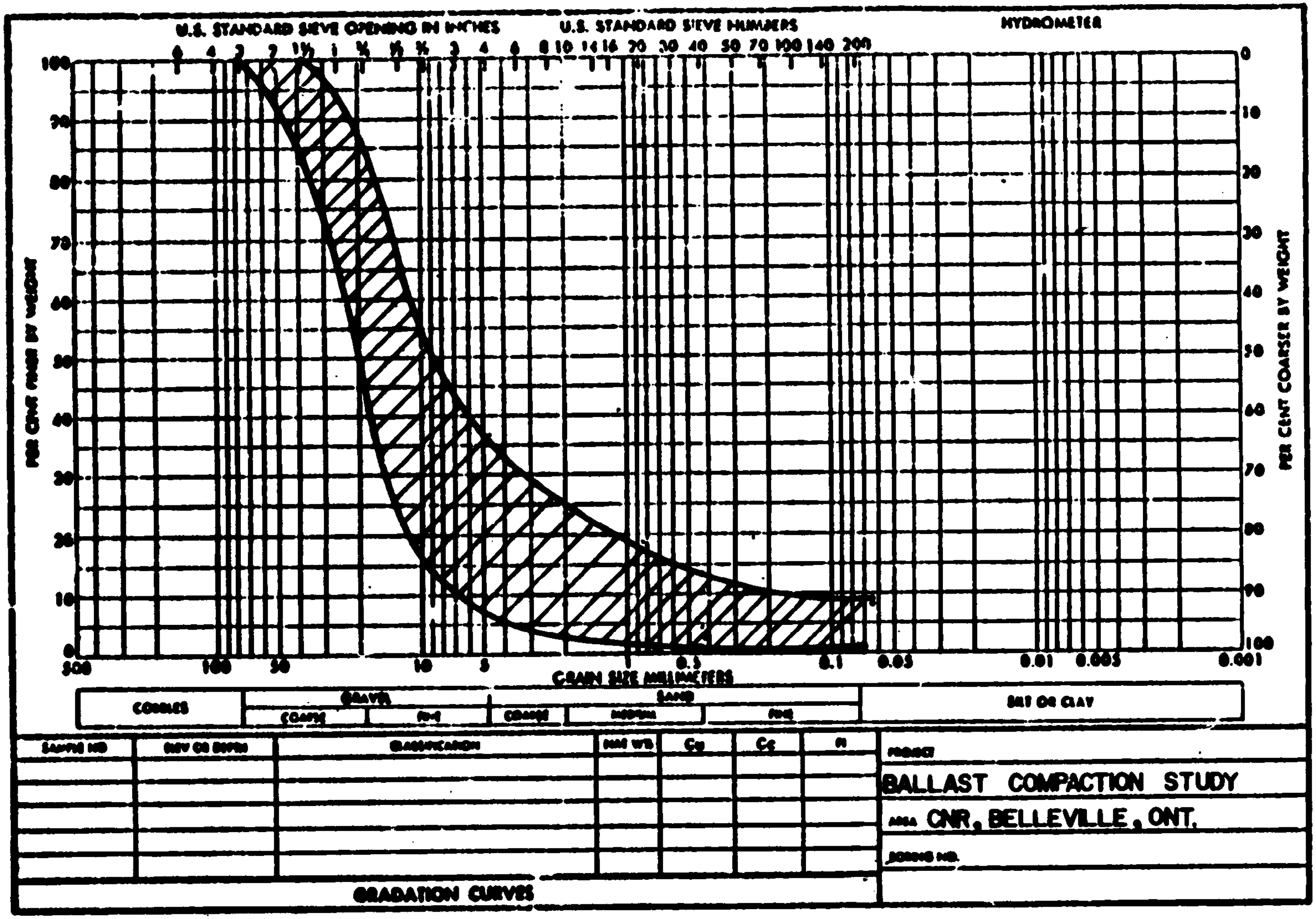


Figure 2.1. Gradation Distribution of Nickel Slag at the CNR Site

Table 2.3. Index Properties of Nickel Slag Ballast at CNR Site (Ref. 2)

Shape	Angular
Nominal Size, inches	1/4 - 2
Uniformity Coefficient, C_u	8.1
Concavity Coefficient, C_c	2.5
Unified Soil Classification	GW
Specific Gravity:	
Bulk	3.40
Apparent	3.42
Absorption (%)	0.25

VDM800R). The detailed results of their tests are reported in Ref. 3. In 1976, the SR leased a Tamper compactor for use in track maintenance on a 20 to 30 annual MGT mainline . With the cooperation of the SR, SUNYAB had a chance to conduct field tests during their maintenance work on the mainline on August 26 to 27, 1976, in Rockfish, Virginia, near Lynchburg.

The track was a single line of continuous welded rail (CWR) supported on crushed granite ballast. The ballast appeared to be quite uniformly graded, with little variation in its gradation over the entire test section (Fig. 2.2). The USCS classification indicates the ballast as GP.

A total of eight density measurements were performed in the crib. The test section was divided into tamped and tamped-compacted zones. Four tests were done in each test zone, using the improved version of ballast density apparatus. Also measured were in-situ ballast density, moisture content, gradation, void ratio, and reference density.

2.3 ILLINOIS CENTRAL GULF RAILROAD

As a part of the major track rehabilitation program (Refs. 4, 5), the Illinois Central Gulf conducted extensive ballast undercutting and cleaning work on about 200 miles of its mainline track between Effingham, Illinois, and Chicago, during the period of June to mid-November, 1976. The main objective of the work was to improve the existing ballast layer that had been fouled over an unknown period of time.

SUNYAB undertook two series of field tests to determine changes in the physical state of the ballast layer with the maintenance procedures,

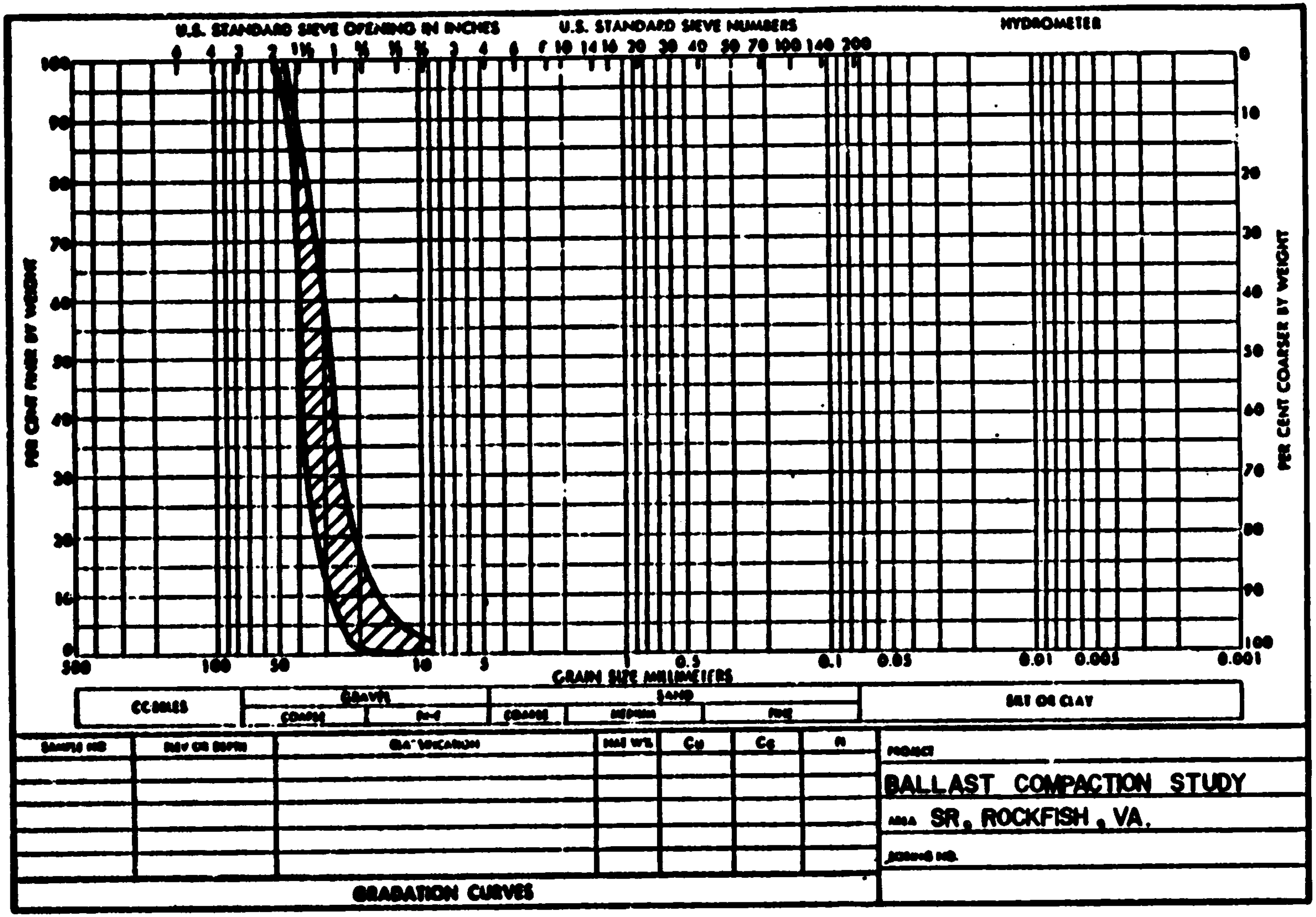


Figure 2.2. Gradation Distribution of Granite Ballast at the SR Site

and with traffic as well. The testing program consisted of in-situ ballast density, plate load resistance, and lateral tie push tests. The tests were conducted on the northbound line of the double track mainline connecting Chicago, Memphis, and New Orleans, located between Chebanse and Clifton, Illinois, about 20 miles south of Kankakee.

The first series of tests was conducted in November, 1976 on a tangent section of track. The track at the test site is an FRA class 5 track. The maximum train speed that ICG imposed on the track was 50 mph (80 km/hr) for freight trains, and 79 mph (126 km/hr) for passenger trains. The average traffic density was reportedly 23 MGT per year.

The track was constructed of 132 RE continuously welded rail (CWR) resting upon hardwood ties spaced from 20 to 22 in. (0.51 to 0.56 m) apart. The average tie dimensions were approximately 8 7/8 by 6 7/8 by 101 1/4 in. long (0.23 by 0.17 by 2.57 m). The shoulder width was approximately 12 in. (0.31 m) and the slope about 1:3 (vertical: horizontal).

The track maintenance operations performed prior to testing consisted of: 1) replacing deteriorated ties, 2) undercutting and cleaning ballast to a depth of 10 to 12 in. (0.25 to 0.31 m) underneath the tie, 3) reballasting with steel slag, 4) tamping, lining, and leveling the track, 5) filling the cribs and sweeping and shaping the shoulder with a ballast regulator, and finally, 6) crib and shoulder compaction. The last operation was accomplished with a Plasser and Theurer 800 VDM compactor with a 3 1/2 sec. vibration time.

The effects of crib and shoulder compaction on the ballast physical state were investigated by dividing 300 ft (91.4 m) of track into four equal test sections. Two sections, which included all track maintenance operations, were termed the tamped-compacted (TC) sections. The remaining two sections, which did not include the crib and shoulder compaction, were termed the tamped-uncompacted (TU) sections. A total of 24 density tests, 28 plate load tests, and 20 tie push tests were performed.

The ballast layer existing before the maintenance was reportedly in poor condition due to fouling that had taken place over many years. The thickness of the fouled ballast layer before the maintenance was reportedly about 12 to 15 in. (0.31 to 0.37 m), below the tie bottom. During the maintenance, the upper 10 to 12 in. (0.25 to 0.31 m) layer was undercut, and the cleaned ballast was redeposited onto the track between rails, mostly in the center area, after screening. The bottom 2 to 3 in. (51 to 76 mm) layer of fouled ballast remained untouched.

To supplement the loss of ballast and to accomodate track raise, new ballast was brought in and spread over the old cleaned ballast, mainly along the rails and the shoulder area.

The old existing ballast was limestone, for which the origin and supplier were not known. It was rather subangular, and appeared to be relatively hard. The freshly undercut and cleaned ballast was uniformly graded and was similar to the AREA No. 4 gradation, according to the sieve analysis results obtained in the density samples (Fig. 2.3).

The new ballast was blast furnace slag, which was supplied by the U.S. Steel Co. plant at Gary, Indiana. The new ballast was relatively round-shaped, and uniformly graded. The maximum particle size was 3 in. (76 mm) and the distribution appeared to fit the AREA No. 3 or No. 24 gradation

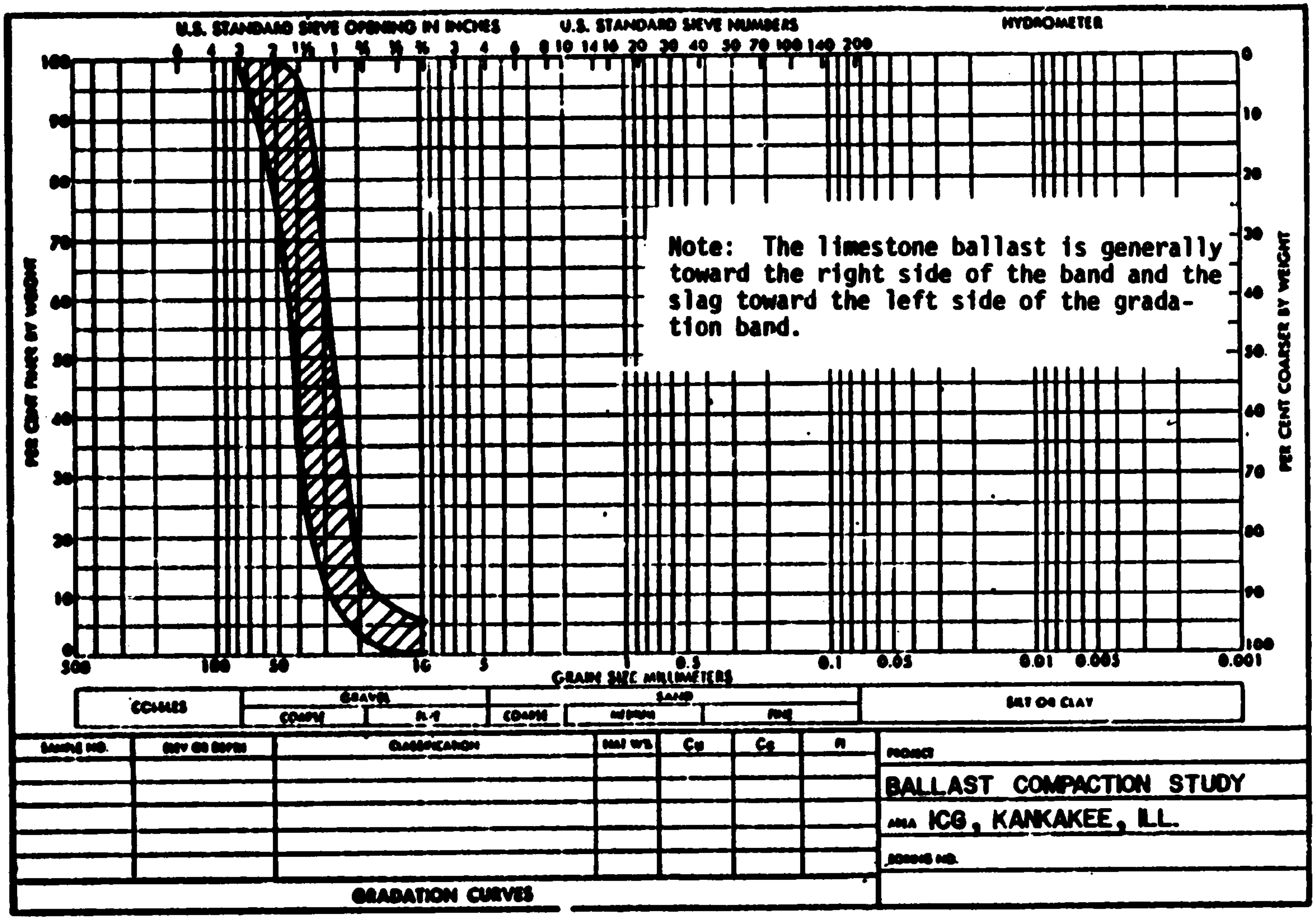


Figure 2.3. Gradation Distribution of Ballast at the ICG Site

(Fig. 2.3). However, the quality of the new ballast appeared to be so poor that severe breakdown or degradation was already noticed, even during maintenance, especially during compaction.

Figure 2.4 shows the two different ballast types. The characteristics of the old and new ballast were so different that special testing and care were necessary for proper evaluation of physical state of the ballast.

In June, 1977, the second series of tests was done after seven months to evaluate the effects of traffic on the physical state of ballast, and the long-term effects of the maintenance operation. The track, when revisited for the second series of tests, did not look in good condition, considering the fact that it was subjected to only a short period of traffic, i.e., about seven months since major maintenance. The whole track appeared to have experienced differential settlement, and at several spots in the vicinity of the test section the track seemed to be out of level. A number of ties were loosened from their fastening, or damaged or skewed. The tie spacing was also quite irregular; therefore, the amount of the ballast in the crib varied.

The ballast layer visually appeared to be quite dense. No significant fouling was noticed at the top surface of the ballast layer, except a very slight amount of coal particles that existed. However, it was later revealed during excavation of the density holes that the subgrade layer formed water pockets at several spots in the test section, and the infiltration of wet fine silty materials into the ballast from the subgrade was occurring.

Left: New Ballast (Blast Furnace Slag)

Right: Old Ballast (Limestone)

Figure 2.4. Two Different Types of Ballasts at the ICG Test Site

The degree of such fouling varied from one spot to another, but more fouling appeared in the center of the track where the limestone ballast was concentrated, and less around the rails where the slag ballast predominated. It is not known whether the degree of fouling is related to the type of ballast. However, the fact that limestone ballast particles tend to absorb and hold more moisture at the particle surface than slag particles may partially account for the difference.

A testing program identical to the first series was repeated at the same test location. Four test sections were again involved during the second series. One each was from the previously tamped-only and tamped-compacted sections. The other two test sections were located further north, about 300 ft away from the sections previously tested. These two sections were also tangent sections, about 66 ft (20 m) long each, which had been subjected to tamping and ballast compaction after the ballast cleaning, but which remained intact during the initial test series. The reason for selecting these other two sections was to eliminate any possible effects of track disturbance caused during the initial tests.

The original objective of this second test series was to investigate the effects of traffic on the ballast physical state for the TC and TU sections. According to local ICG track officials, track maintenance operations were apparently conducted earlier in March or April at the test site. The first was a track smoothing operation which consisted of tamping, lining, and leveling the track with a 1 to 1-1/2 in. (25.5 to 38.1 mm) raise. This was followed by a ballast regulator which was used to transfer shoulder ballast to the crib area outside of the rails. The shoulder was thus changed from 1:3 to 1:2 and a definite deficiency of crib ballast between the rails still existed.

The occurrence of this track smoothing operation would prohibit any possible determination of the long term effects from crib and shoulder compaction. Based upon the annual traffic density and the elapsed time from the tamping operation in March or April until the June tests, 5 MGT of accumulated traffic was estimated (Ref. 6). Because the tamping operation occurred, the second test series will be treated as a TU condition with the application of 5 MGT of traffic.

2.4 FACILITY FOR ACCELERATED SERVICE TESTING

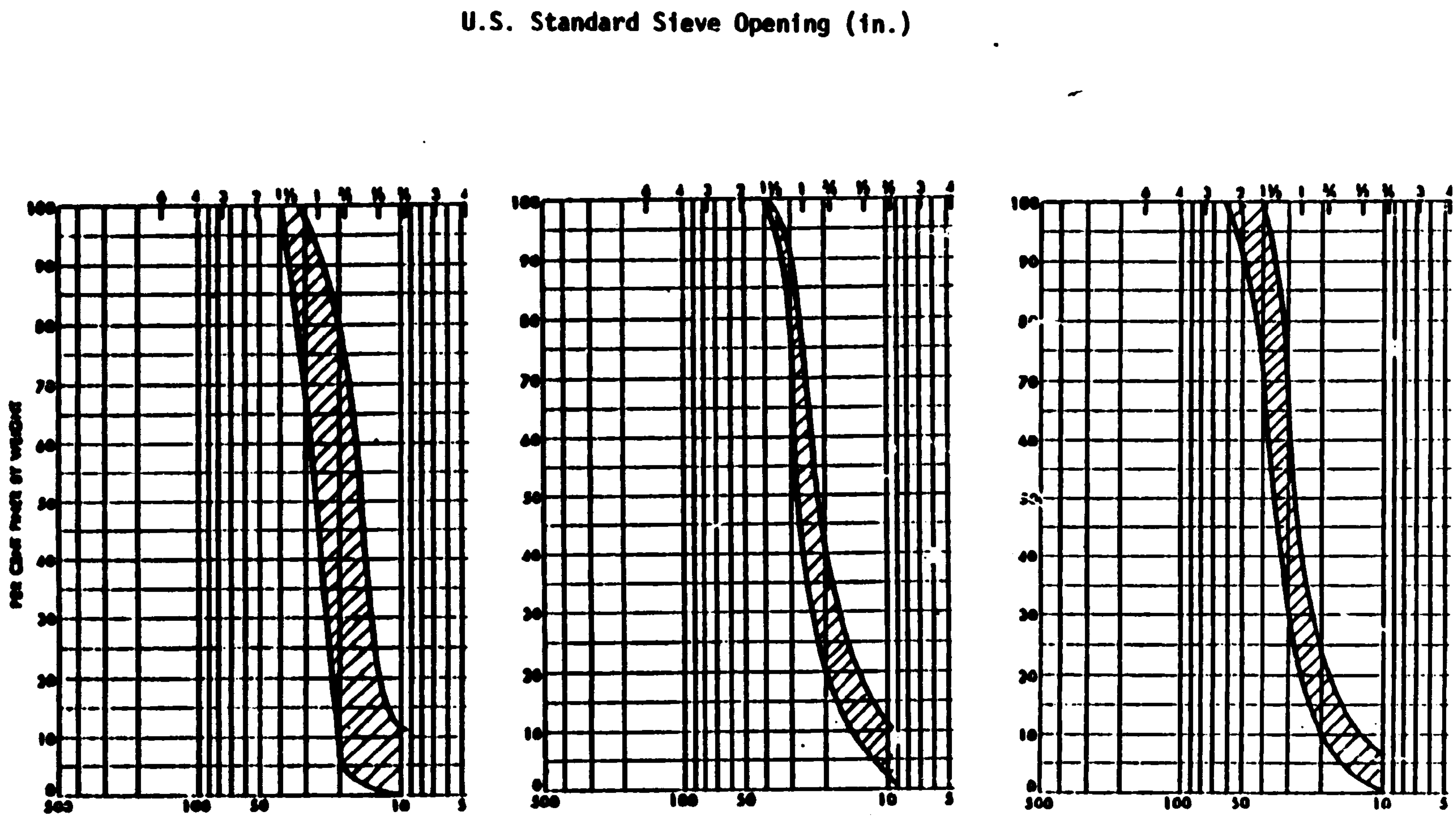
In conjunction with the ballast and subgrade instrumentation program (Ref. 7), an evaluation was made of the physical state of the ballast at the Department of Transportation FAST track near Pueblo, Colorado. The first series of tests was conducted in September, 1976, immediately after construction and before any traffic, to establish the initial track condition. The second series of tests was made in November, 1977, after the FAST track had been subjected to 134.6 MGT of traffic and various amounts of track maintenance work, to assess the effects of accumulated traffic and maintenance procedures involved.

The tests throughout all the series consisted of in-situ ballast density, ballast moisture content, ballast sieve analysis, void ratio determination, and reference density, as at the previous sites. During the supplemental series (after 134.6 MGT), one of the ties in each section used for the ballast density tests was removed and the ballast inspected for evaluation of ballast degradation and particle migration across the tie. In addition, plate load tests and lateral tie push tests were performed during the supplemental tests.

Three test sections of tangent track with different ballast types were involved during the first series of testing. These included granite (section 18A), limestone (section 20B), and traprock (section 20G, formerly $20E_2$). A total of 36 tests were performed on 3 different ballast types, with 12 tests for each ballast type. In each test section containing one type of ballast, 2 ties were removed for the density tests. At each tie, measurements were made both under the ties and in the crib areas.

The track structure was identical for the three ballast types. The shoulder slope and width remained relatively constant at 1:2 and 12 in. (0.31 m), respectively. The ballast depth was approximately 15 in. (0.38 m). The rail consisted of 136 RE jointed rail in 39 ft (11.9 m) lengths. The ties were hardwood with average dimensions of 6 7/8 in. (0.15 m) by 8-7/8 in. (0.23 m) by 101-1/2 in. (2.58 m) with an average tie spacing of 19-1/2 in. (0.50 m). Thus, the variables most likely to influence the test results for a given traffic condition are ballast type, gradation, and angularity.

The ballasts in the three test sections were uniformly graded and angular. They had similar grain size distributions, which were AREA No. 4 (Fig. 2.5), although the traprock ballast particles were slightly



a) Granite Ballast, Section 18A

b) Limestone Ballast, Section 20B

c) Traprock Ballast, Section 20G

Figure 2.5. Gradation Distribution of Ballast from FAST Track

larger, flakier and sharper-edged than the limestone and granite particles. Table 2.4 describes the index properties of the ballast, as reported in Ref. 8, and gives the source of the ballasts.

The objective of the supplemental tests in November, 1977 was to evaluate the effects of different ballast types and traffic conditions with the ballast physical state tests. The three different track conditions which existed for both limestone and traprock ballast test sections were: 1) undisturbed (UU) with 134.6 MGT of traffic since construction, 2) after maintenance tamping (TU) and 3) after an additional 0.1 MGT of traffic (AT). Thus, a total of 72 density tests, 96 plate load tests, and 30 lateral tie push tests were performed (Table 2.2). A tamping operation was believed to have been performed at approximately 16 MGT . However, adequate documentation was not available for confirmation. The value of 134.6 MGT of traffic for the UU condition will be used for comparisons in this report, since the observed trends are not expected to be significantly affected.

The track maintenance operation consisted of tamping, lining, and leveling with a Canron electromatic torsion beam tamper, model Mark I. The limestone received a 1 in. (25 mm) raise, and the traprock a 2 in. (51 mm) raise. All cribs were full prior to tamping; however, after tamping a ballast deficiency approximately equal to the height of track raise existed in the cribs. No additional maintenance operations followed the tamping.

The AT condition was achieved by the application of 0.1 MGT of traffic to the TU condition. A work train was utilized to accumulate the required tonnage by passing over the test sections at low speeds.

Table 2.4. Index Properties of the FAST Ballasts (Ref. 8)

Section	18A	20B	20G
Ballast Type	Crushed granite	Crushed limestone	Traprock (Crushed basalt)
Source	Cheyenne, Wyo.	McCook, Ill.	Reading, Pa.
Particle Index	14.2	12.2	16.4
Flakiness Index	20.8	9.4	22.7
Soundness	0.77	11.9	0.55
Los Angeles abrasion	18.8	25.7	13.2
Bulk G_s	2.67	2.65	2.94
Crushing value	18.4	19.3	13.1

At the start of the supplemental tests, i.e., after accumulation of 134.6 MGT traffic, the test sections involved visually appeared to be in good shape as far as track geometry is concerned, in spite of having been subjected to a traffic level equivalent to about 5 to 10 years in normal revenue service track. The ballast layer after the traffic was quite densely compacted both under the ties and in the crib. Some degree of ballast degradation by traffic was also evident, especially in the crib areas. The tie spacing was rather irregular at the beginning of the tests, and some ties were noticeably skewed. The ballast degradation observed in the crib areas was apparently due to such tie movement caused by traffic.

During the second series of tests, ballast fouling appeared in some cases at about 4 to 6 in. (102 to 152 mm) below the bottom of the ties. Probably, fine particles degraded from the ballast and migrated downward. In the case of the limestone ballast, the fine particle size varied widely from powdery fines to fine gravel-size chips, while the traprock section showed mostly chip-size particles. The fines in the limestone ballast layers were often well-packed into the voids around large ballast particles.

As expected, the tamping operation after the second series of tests appeared to have greatly disturbed and loosened the ballast packing in the crib areas. However, interestingly enough, the degree of disturbance of the ballast layer under the ties appeared to be minimal, especially in the limestone section. It appeared that the whole column of ballast layer beneath the ties around the rail areas was raised during tamping operations without disturbing the ballast structure. The center portion of ballast under the tie apparently remained unchanged, therefore creating a well-defined flat void under the tie in the center, as shown in Fig. 2.6. The gap between the tie bottom and the flat ballast surface in the center is about equal to the 1 in. (25 mm) raise during the tamping.

The above observation was not so apparent in the case of the traprock section where approximately a 2 in. (51 mm) raise was used. This is probably due to a lesser degree of interlocking and flakier ballast particles, along with the higher raise of tamping.

Figure 2.6. Photo Flat Void Under the Tie in the Center as Observed After Tamping, in Limestone Section 20B

3. IN-SITU BALLAST DENSITY TEST

Railroad ballast is a select granular material placed between the subgrade and the track structure, where it plays important roles in the overall track performance. Ballast behavior is significantly influenced by its in-situ physical state, in addition to its index properties such as particle size, shape, and angularity. However, the understanding of ballast performance in the track and the effect on ballast behavior of such factors as mechanical tamping and traffic is severely limited at the present time by the lack of information on the in-situ physical state of ballast. One important measurement of physical state is density. However, suitable techniques for ballast density measurement are not available, chiefly because of the characteristics of this material.

Typically, good ballast is noncohesive, granular material, the size of coarse aggregate, usually with relatively uniform gradation. Crushed granite, traprock, limestone, and slag are the most commonly used ballast materials in the United States. Although the particle size varies with different specifications, it generally falls within the range of 1/4 in. to 3 in. (6 to 76 mm). For these materials, existing standard field methods of density measurement, such as rubber balloon, sand cone, nuclear, oil replacement, block or cylinder sample, and various solidification methods are unsuitable, because these methods either cannot be used or are inadequate in precision and accuracy. A preliminary laboratory evaluation was made of potentially suitable methods of density measurement to assess them further and to determine those features that might be adaptable for use with ballast (Ref. 9). An approach employing water replacement in a lined hole was then selected for extensive evaluation. Based on the laboratory tests, a new apparatus was devised for measurement of ballast density, and test procedures were developed.

A series of field tests was subsequently conducted to evaluate the field application of test apparatus and procedures, after the laboratory tests had successfully demonstrated the validity of the measurement concepts and the suitability of the test techniques. In-situ ballast density was measured to assess the ballast physical state under a variety of track conditions at four different test sites.

Section 3 briefly discusses the development of the test apparatus and test procedures and presents the results of the field measurements of in-situ ballast density. The ballast density measurements are then evaluated in Section 3.2 to present an overall picture of ballast physical state and its changes with different track conditions. The effects of tamping, ballast compaction, and traffic were of particular interest.

3.1 SUNYAB Ballast Density Test

<u>Ballast Density Apparatus.</u> While the concept employed in this study for the measurement of in-situ ballast density remained the same throughout the research, the design of the apparatus as well as the measuring techniques underwent several changes and modifications.

Figure 3.1 shows the preliminary version of the apparatus which was used in the earlier stage of laboratory and field evaluation (Refs. 9, 10). It consisted of a surface ring and a support base plate. The surface ring is the major constituent of ballast density measurement apparatus, which serves as a guide for excavating the sample hole in the ballast and as lateral support for the upper portion of the membrane when water is placed in the lined hole.

The measurement technique using this preliminary ballast density device is illustrated schematically in Fig. 3.2. It is basically determination of the volume of sample removed by replacing water in the membrane-lined sample hole. Two different devices were used. One was a circular ring, 8 in. (203 mm) in diameter (Fig. 3.1a), and the other was an oval ring, 8 in. (203 mm) wide and 16 in. (406 mm) long (Fig. 3.1b). The height of both devices was 1-1/2 in. (38 mm) and the width was limited to 10 in. (254 mm) to permit tests within the width of a typical railroad tie-bearing area. The oval ring, having a larger cross-section area for the same width, was designed to provide a larger sample size than the circular one within the width constraint given. The lining used with this preliminary device was a very thin flexible plastic membrane.

After a series of laboratory tests which demonstrated the validity of the concepts and the potential of the techniques utilized (Ref. 9), the preliminary ballast density apparatus was evaluated for the field application. In July, 1976, with the cooperation of the Canadian National Railways (CNR), the first in-situ ballast density tests were performed on one of the CNR mail line tracks. Details of these tests are described in Ref. 10 and will be summarized in the subsequent section.

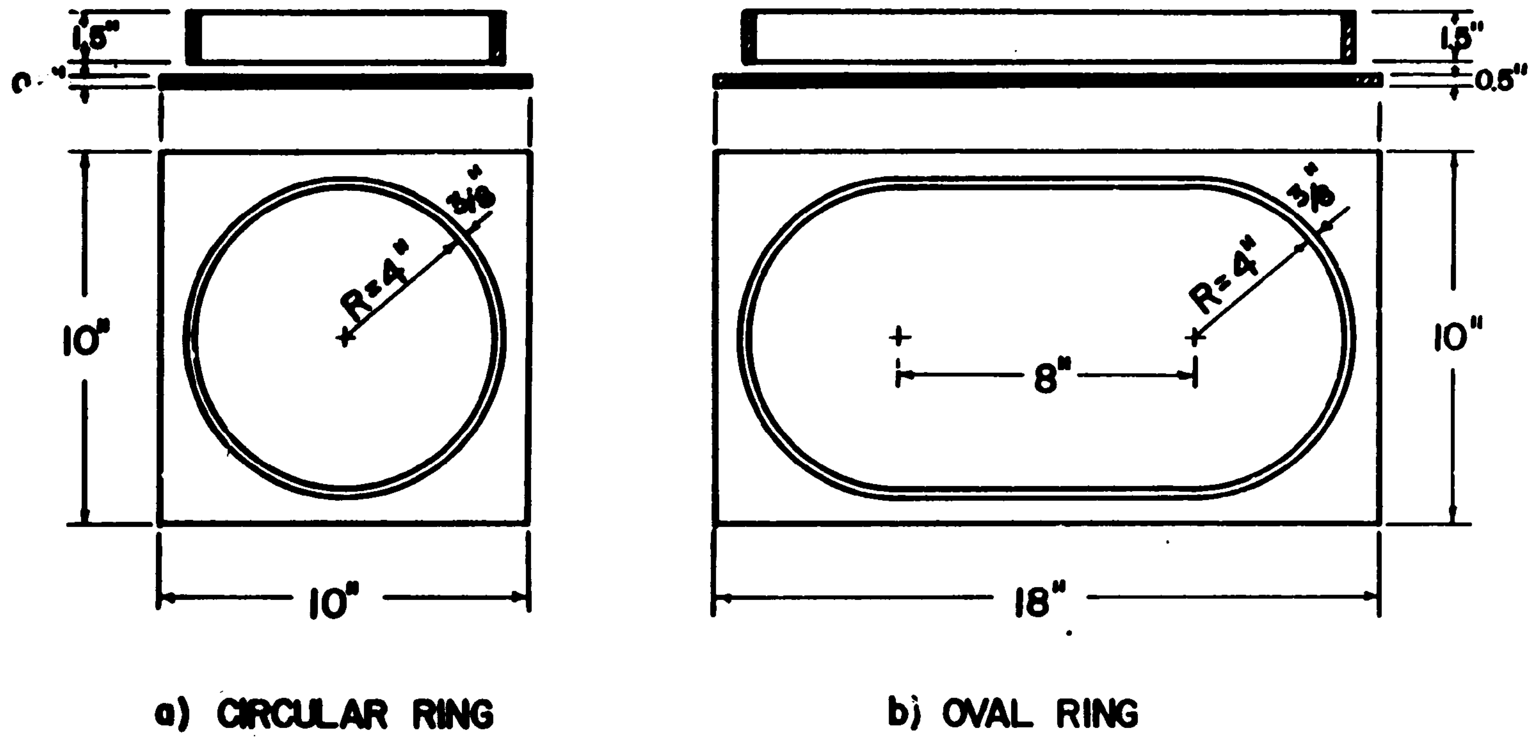


Figure 3.1. Preliminary Design of Ballast Density Apparatus

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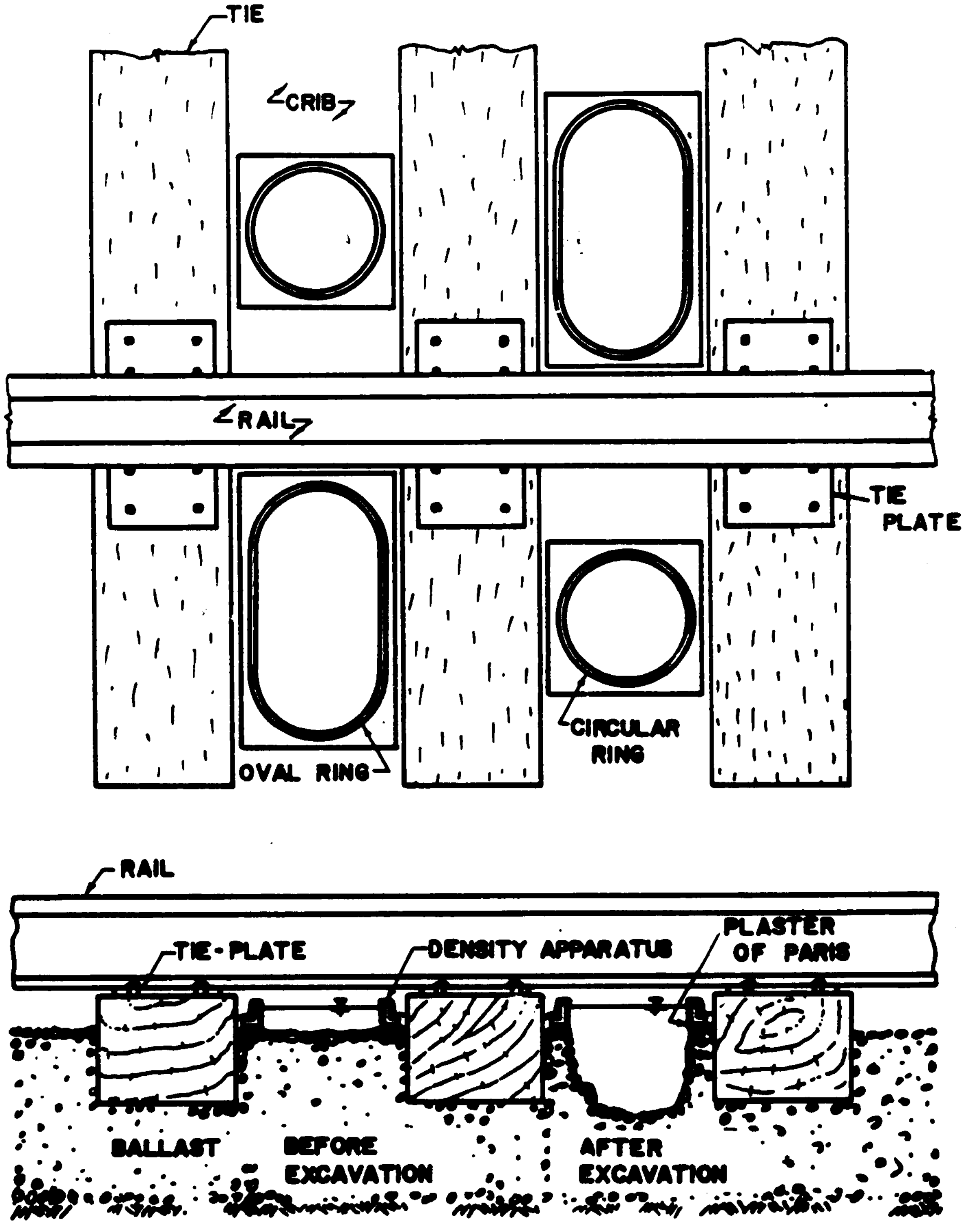


Figure 3.2. Schematic Illustration of In-situ Ballast Density Measurement Using the Preliminary Apparatus

Based on the initial field evaluation at the CNR site, the density device was completely redesigned to improve its performance (Ref. 11). The hole section areas remained about the same, but the ring height was increased substantially to 6 in. (152 mm) to provide sufficient water pressure to yield better conformation of the lining membrane to the ballast surface inside the measuring ring. The plastic membrane was also replaced with an extremely expandable latex rubber sheet of very high quality. A point gage was added to measure the distance from the top surface of the ring to the water surface inside the measuring ring to provide a more accurate determination of the volume of water in the hole. Figure 3.3 illustrates the schematic of the newly improved ballast density apparatus, and Fig. 3.4 shows the apparatus in operation.

The newly designed apparatus was further evaluated in the subsequent series of field tests at other railroad sites, including the Southern Railway System (Ref. 10), the Illinois Central Gulf Railroad (Ref. 12, 13), and the FAST track at the U.S. DOT Transportation Test Center in Pueblo, Colorado (Ref. 14, 15). In the course of this field work, which will be discussed later, the capability and adequacy of the field test apparatus have been well demonstrated, while the test procedures were continuously refined for faster operation and more accurate measurement.

Further improvements included use of plaster of paris to stabilize the loose ballast particles at the surface and to form a stable base for supporting the density ring, and replacement of a water measuring device. Application of a plaster of paris layer on the ballast surface was particularly successful in stabilizing loose ballast particles at the surface

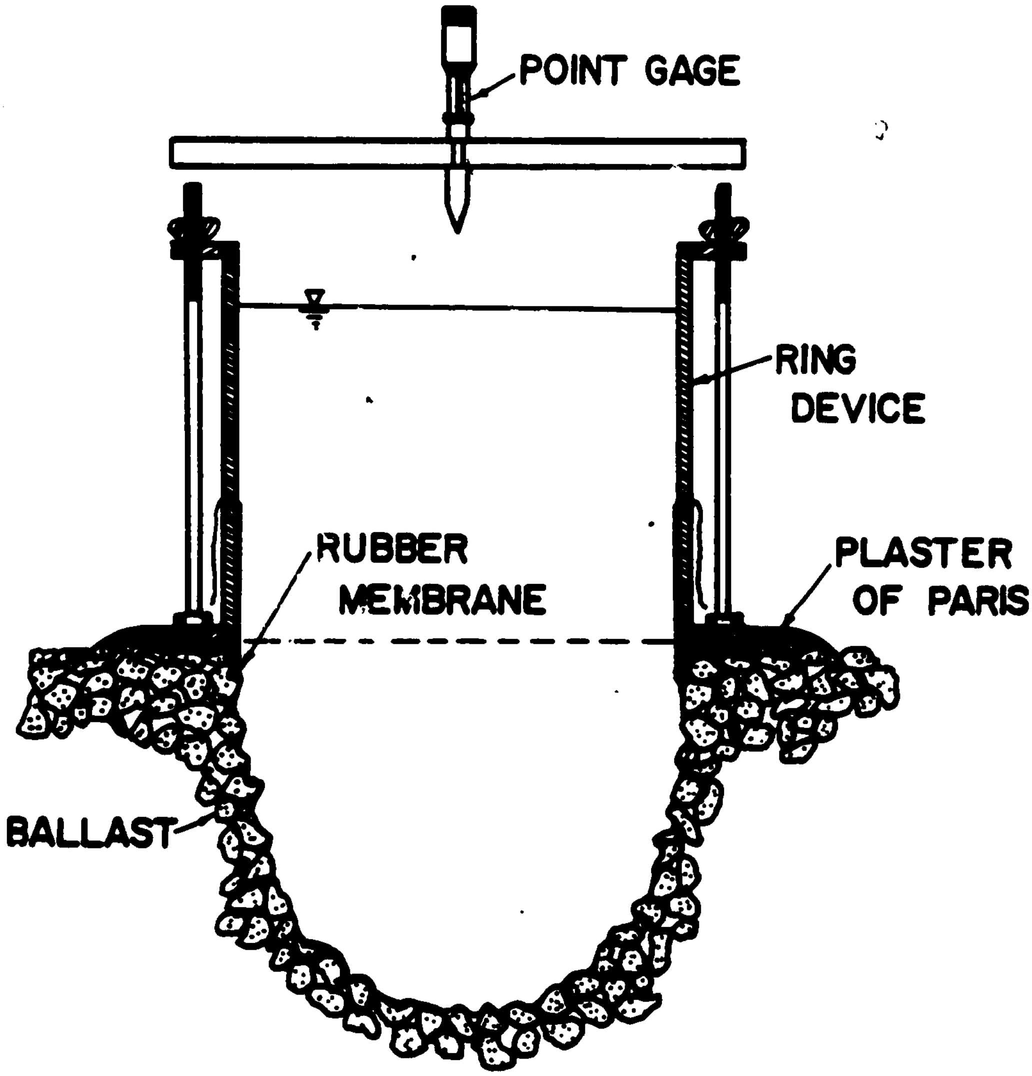


Figure 3.3. Schematic Diagram of Improved Ballast Density Apparatus

Figure 3.4. Ballast Density Apparatus in Operation

around the hole and providing a smooth area and shape for the ring device. Plastic templates with the same section area and shape as the density ring were usad to form the desired shape of the plaster of paris layer. Use of the electrical water-volume measuring device, equipped with pumps for mechanical water supply and return, made the tests much easier and faster. This was also used as an immersion container for laboratory measurement of the displaced volume of solid ballast particles used in the void ratio determination.

Reference 16 describes details of the final design of the ballast density apparatus that had gone through such modifications and refinements. Recommended test procedures using this final density apparatus for in-situ ballast density and void ratio determination (Ref. 11) are also described.

Reference Density Apparatus. Development of the reference density apparatus was originated from the laboratory sample preparation techniques which were used to create duplicate density states during ballast density apparatus evaluation. In the course of a series of laboratory studies to develop a reliable sample preparation method suitable for ballast materials and reproducible in a wide range of density states (Ref. 9), an approach of relating ballast density to compactive effort was applied to establish a reference density that could be used in assessing the amount of ballast compaction achieved in the field during track construction and maintenance operations.

The approach, used in the study and subsequently applied very successfully in the field experiments, was to calculate the ultimate density by extrapolation based on the assumption that the density-compactive effort curve has a hyperbolic shape as illustrated in Fig. 3.5.

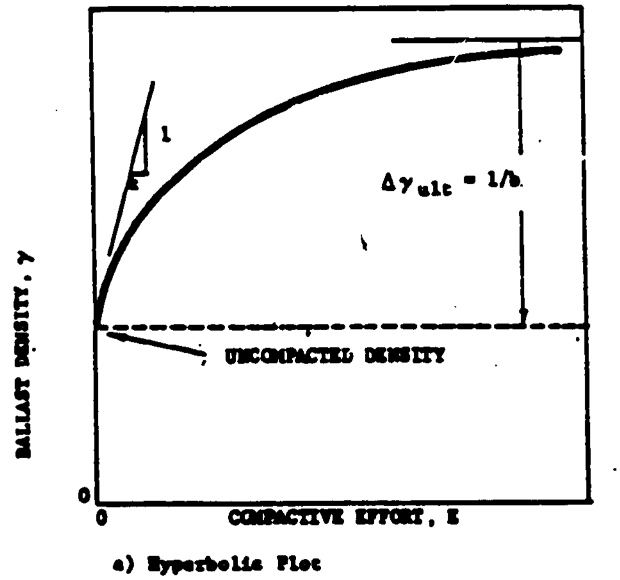


Figure 3.5. Representation of Relationship Between Density and Compactive Effort

Reference 16 describes details of the design of the ballast reference density test apparatus and procedures used throughout the field experiment.

CNR Tests. Table 3.1 lists a summary of the in-situ density test results. Reference 10 describes details of the test procedures used and the test results obtained. It is shown in the table that the in-situ measurement results at the CNR site were reasonably repeatable within the same track conditions. No appreciable difference was noticed in the crib densities between the inside and the outside of the rail and between the circular and oval rings.

Even though the small amount of data limits the certainty of various observations, the results indicate that the tamping operation may have slightly loosened the undisturbed ballast, but the crib compaction produced a density significantly greater than that of the undisturbed ballast (Fig. 3.6). It may sound surprising that the compactor-induced density exceeded that of the undisturbed track which has been long subjected to traffic. But it should be realized that the traffic-induced compaction is most likely to concentrate beneath ties, whereas these measurements were all in the crib.

The gradation characteristics of the density samples also reveal some interesting facts. The ballast from the undisturbed zone possessed a uniform gap gradation with an average of 15.5% finer than the No. 4 sieve. However, the gradation of the samples from the tamped zone represented a more well-graded situation, with a general reduction to 13.5% of percent of particles finer than the No. 4 sieve. Such losses of finer particles in the ballast layer is presumably due to particle segregation and migration of finer particles down toward the subgrade layer during tamping, especially with vibration.

Table 3.1. Summary of CNR Test Results

Track Condition	No. of Tests	Average Moisture Content, %	Average % Finer Than #4	Dry Density (pcf)		Void Ratio (e)*		Percent** Compaction, %	
				Mean	Range	Mean	Range	Mean	Range
Undisturbed Before Tamping	2	1.64	15.5	143.6	0.6	0.49	0.0	*** 93.9	-
After Tamping	2	0.63	13.5	143.1	0.3	0.50	0.02	93.5	0.2
After Compaction	4	1.04	18.6	146.2	1.3	0.48	0.03	95.5	0.8

* Computed Void Ratio Based on Specific Gravity, $G_s = 3.43$

** Ultimate Reference Density for Crushed Nickel Slag Ballast = 153.0 pcf

*** Reference Density Test on the Mixed Sample

Note: Reference Density Test Determined From Water Replacement Method

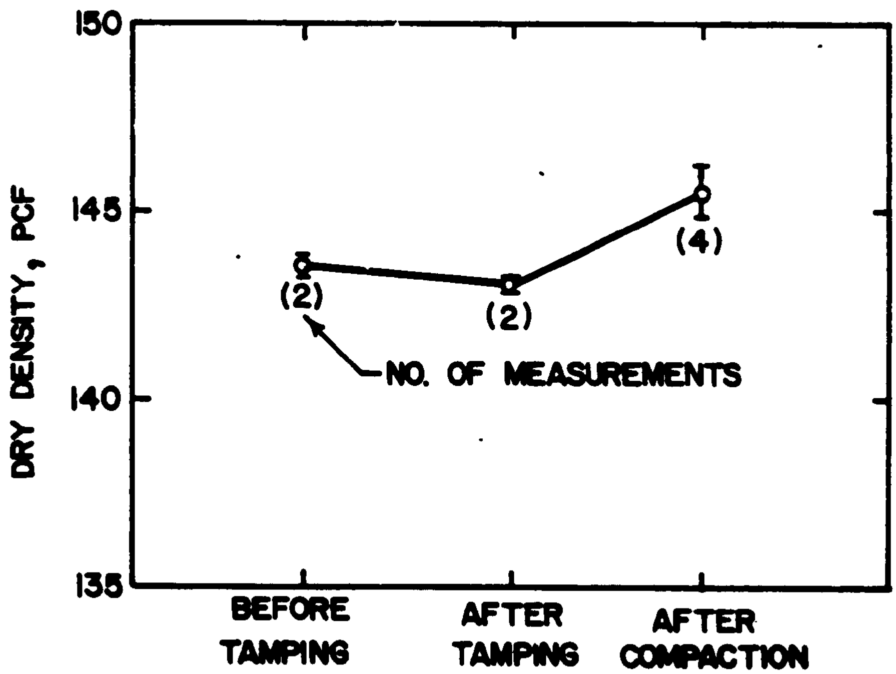


Figure 3.6. Changes in Average Ballast Density with Track Maintenance Procedures at the CNR Site

The average of 18.6% finer than the No. 4 sieve for the compacted ballast samples was significantly increased over that for both the undisturbed and tamped zones, indicating that a considerable amount of particle degradation or further mingling of ballast and subgrade materials might have occurred during the compaction process.

The moisture contents also showed similar trends to the above, which is another indicator of changes in the amount of finer particles, the major source of moisture retention, in the ballast layer.

Southern Railways Tests. Table 3.2 lists a summary of the test results obtained at the SR site. Details of the data can be found in Ref. 10. It is shown in the table that the results are very closely repeated for the tests under similar conditions, further confirming the success of the density measuring methods and procedures used in the study. It is evident that the circular and the oval ring worked equally well, and the size of samples appears to be sufficient for the aggregate sizes of ballast material.

In general, the SR results confirmed various observations made for the CNR tests, such as density increase with compaction and particle degradation accompanying compaction. However, one of the interesting observations in the SR data is the significant difference in ballast densities between the inside and outside of the rail (Fig. 3.7). This difference is greatly enhanced by compaction. The average dry density in the crib outside the rail was increased by about 30 pcf (0.48 Mg/m^3) with compaction of the tamped track, while there was only 2.7 pcf (0.04 Mg/m^3) increase on the inside of the rail.

Table 3.2. Summary of Southern Railways Test Results

Track Condition	Sample Location	No. of Tests	Average % Finer Than 1"	Dry Density (pcf) Mean	Dry Density (pcf) Range	Void Ratio (e) Mean	Void Ratio (e) Range	Percent Compaction Mean	Percent Compaction Range
After Tamping	Outside Rail	2	20.3	109.9	4.3	0.59	0.06	103.5 *	4.0
	Inside Rail	2	17.4	104.8	0.3	0.66	0.0	98.6	0.3
	Ave	4	18.8	107.3	2.3	0.63	0.03	101.1	2.2
After Compaction	Outside Rail	2	26.2	140.3	1.0	0.23	0.05	133.7 **	1.0
	Inside Rail	2	28.2	107.4	1.3	0.60	-	102.4 **	1.2
	Ave	4	27.2	123.8	1.2	0.42	0.05	118.1	1.1

* Ultimate Reference Density for Tamped Zone Sample of Crushed Granite = 106.2 pcf

** Ultimate Reference Density for Tamped and Compacted Zone Sample of Crushed Granite = 104.9 pcf

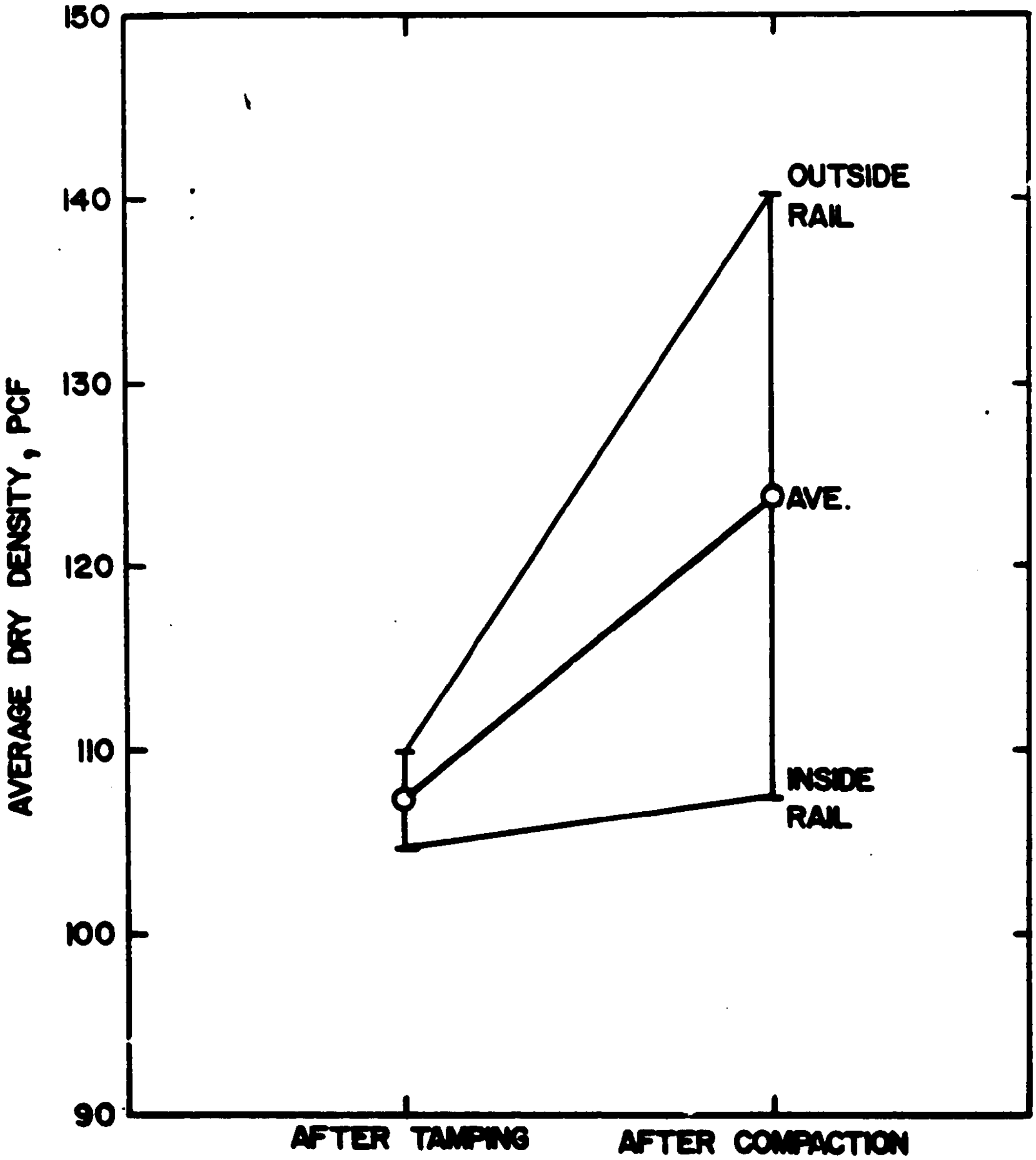


Figure 3.7. Changes in Ballast Density with Tamping and Ballast Compaction at the SR Site

ICG Initial Tests. Table 3.3 lists a summary of the test results obtained at the ICG site during the first series (initial tests). The measured in-situ ballast density varied significantly not only along the tie, but within the same test condition as well, due to different mixtures of ballasts. The scatter was sufficient, especially in the crib and at the center under the tie, so that no apparent trend is readily noticeable between different test conditions. However, the data still reveal some interesting facts (Fig. 3.8).

The densities measured under tie where the old, but cleaned, ballast was the main constituent clearly show density increase from tamping. In all cases, the ballast under the tie around the rail where tamping occurred was about 12 pcf (0.2 Mg/m^3) denser than in the center under the tie where the ballast was loosely deposited from the cleaning operation.

In the crib, the density values are quite scattered. There is also a significant difference between the outside and the inside of the rail, which can be explained by the material difference, i.e., the more the old ballast, the higher the measured density. That is the reason why the crib density at the center is much higher than near the rail. As to the effect of compaction, there again exists some evidence of density increase around the rail due to compaction. The density at the center portion of the track is higher in the crib than under the tie.

To eliminate the effects of having a mixture of two different types of ballast, two correction approaches were taken based on the percentage mixture of the two ballasts. One adjusts the specific gravity to a common value, and the other uses the reference density determined with the correct mixture of the ballasts. Details of these procedures are discussed in Ref. 12.

Table 3.3. Summary of Ballast Density Measurements at ICG During Initial Tests

Track Condition	Sampling Location		No. of Tests	Average Mixture, %		Measured Dry Density (pcf)		Corrected* Dry Density (pcf)		Void Ratio (e)		Percent Compaction**	
				Old Ballast	New Ballast	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Tamping Only	Crib	Outside	2	7.5	92.5	75.3	3.0	92.5	8.5	0.90	-	92.5	8.1
		Inside	2	33.5	66.5	78.6	0.2	91.4	2.2	0.86	-	90.7	2.6
		Center	2	100	-	96.2	0.2	96.2	0.2	0.60	-	96.2	0.2
	Under Tie	Outside	2	82	18	100.1	5.1	104.1	0.2	0.53	-	103.7	1.0
		Inside	2	95.5	4.5	99.8	5.9	100.8	4.9	0.54	-	100.7	5.0
		Center	2	98.5	1.5	84.6	0.8	84.9	1.3	0.77	-	84.9	1.3
Tamping and Compacted	Crib	Outside	2	15.5	84.5	80	1.6	96.3	5.7	0.76	-	96.4	5.5
		Inside	2	45.5	54.5	85.2	4.6	96.5	1.8	0.76	-	95.6	2.0
		Center	2	100	-	91.4	1.4	91.4	1.4	0.69	-	91.4	1.4
	Under Tie	Outside	2	82.5	17.5	98.2	5.5	101.5	4.0	0.56	-	101.7	2.6
		Inside	2	94	6	103.5	0.3	104.8	2.4	0.50	-	104.7	2.2
		Center	2	100	-	87.9	2.4	87.9	2.4	0.72	-	87.9	2.4

* Corrected Density with Bulk Specific Gravity

** Measured Dry Density Divided by Ultimate Reference Density

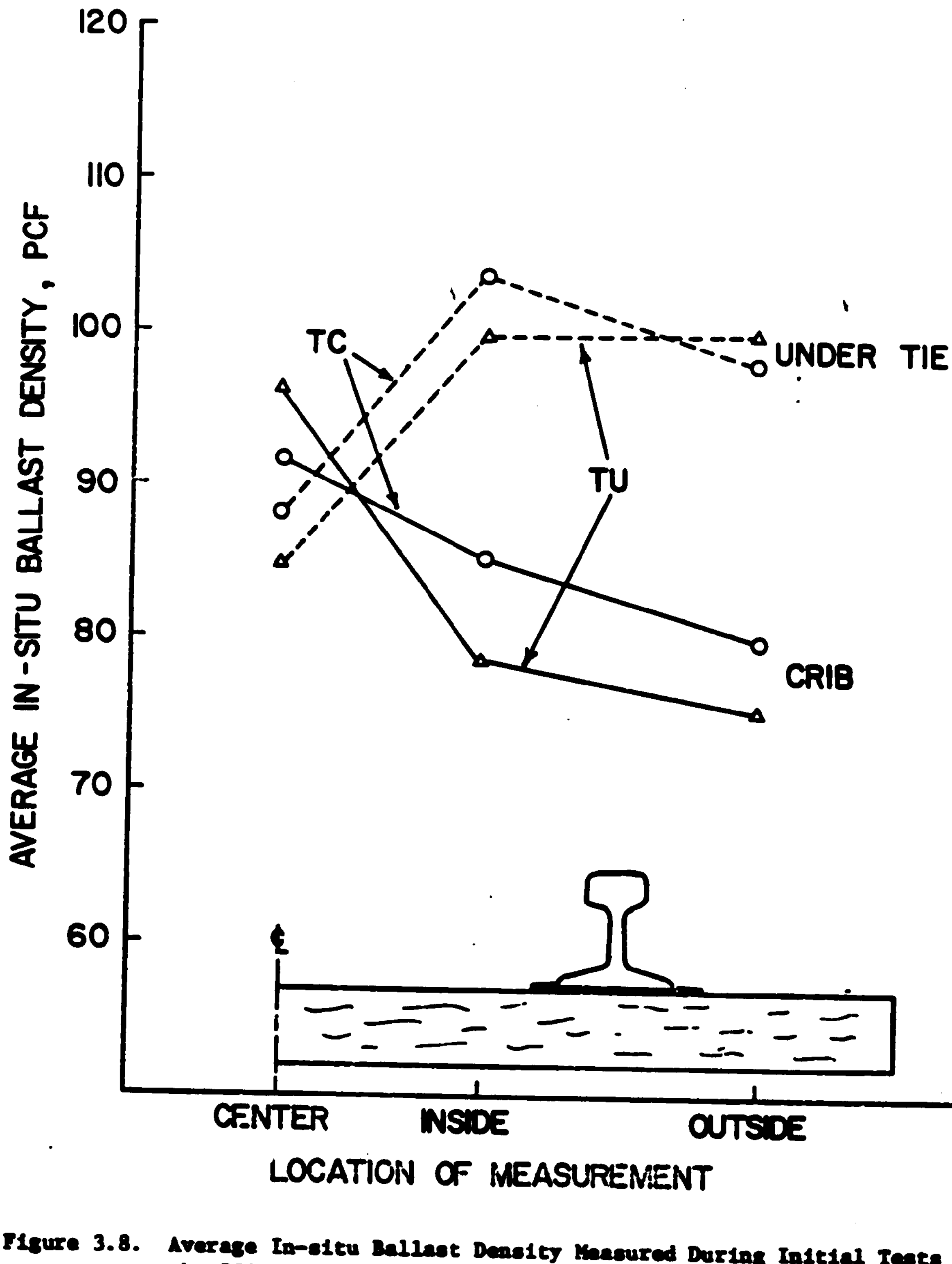


Figure 3.8. Average In-situ Ballast Density Measured During Initial Tests at the ICG Site

Table 3.3 also lists the densities corrected using the above procedures and the reference density for each sample interpolated from the linear relationship between the reference density and the mixture ratio. Also included is the percent computed from the prorated reference density based on the mix ratio.

Figures 3.9 and 3.10 show the results after the correction. Obviously, such correction did not change the distribution of the density under the tie, since the ballast under the tie was mostly the old ballast. However, significant changes were obtained in the crib density from the correction, as expected. The amount of scatter remained about the same. However, the trend shown by the corrected density became more reasonable, that is no significant difference in the crib density along the tie.

Unfortunately, the effects of tamping and compaction did not become more evident than before correction, which illustrates that the scatter was not only from the variation of the material types existing at the site, but also from the variation of the physical states from one sampling hole to another. The latter could be quite well expected, considering the nature of the maintenance involved, especially the way of removing and redepositing the ballast during undercutting and ballast cleaning.

ICG Follow-up Tests. Table 3.4 lists the corresponding measurements obtained during the follow-up tests. Detailed data can be found in Ref. 13. Figure 3.11 shows the corrected ballast density obtained during the follow-up tests.

The measured densities under the tie apparently show that the sections initially tamped and compacted (Sections 1, 5, and 6) achieved higher densities than the tamped-only section after traffic (Section 2). The difference is significant in the center of the tie and in the inside of the rail and appears to diminish in the outside of the rail.

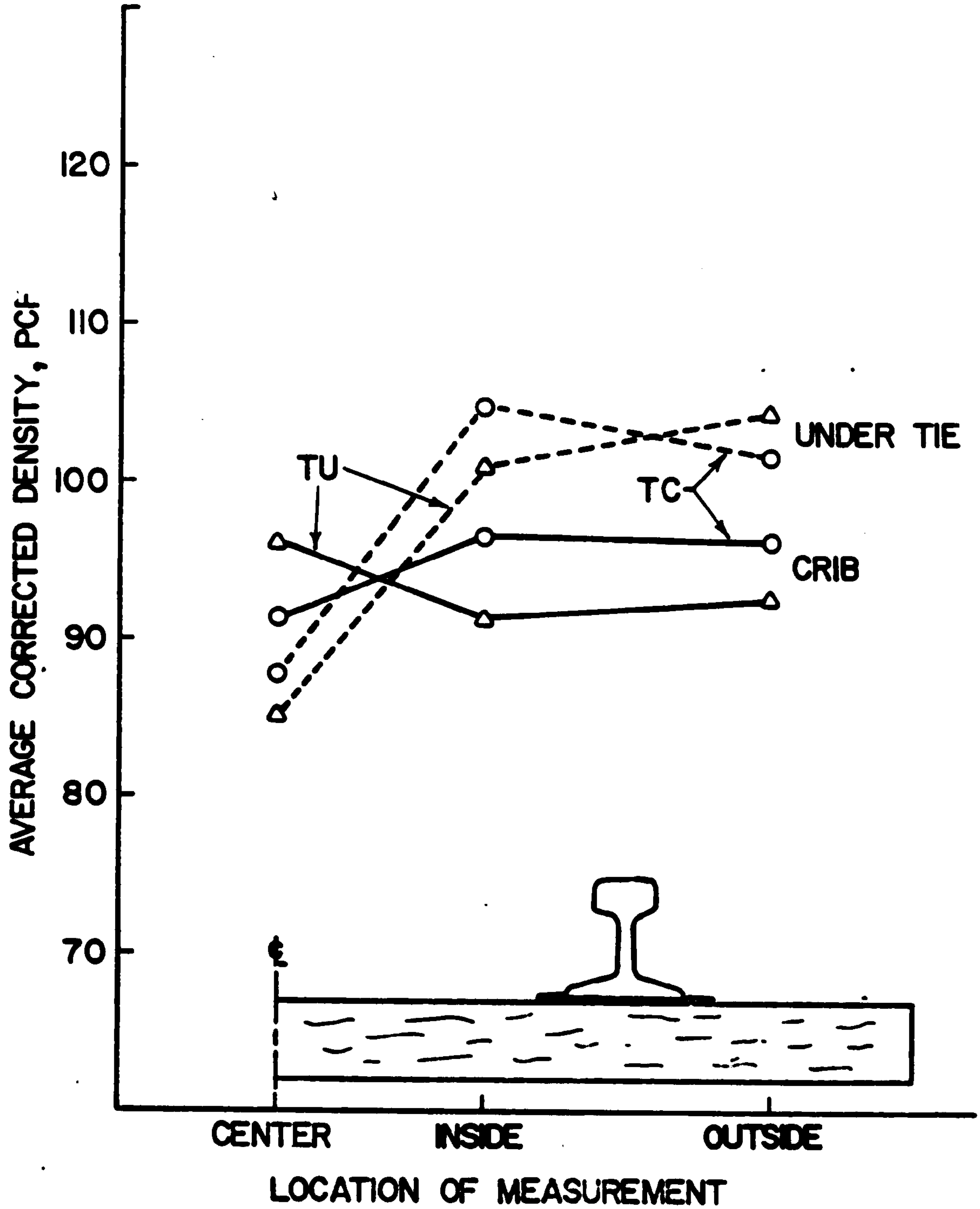


Figure 3.9. Average In-situ Ballast Density after Correction

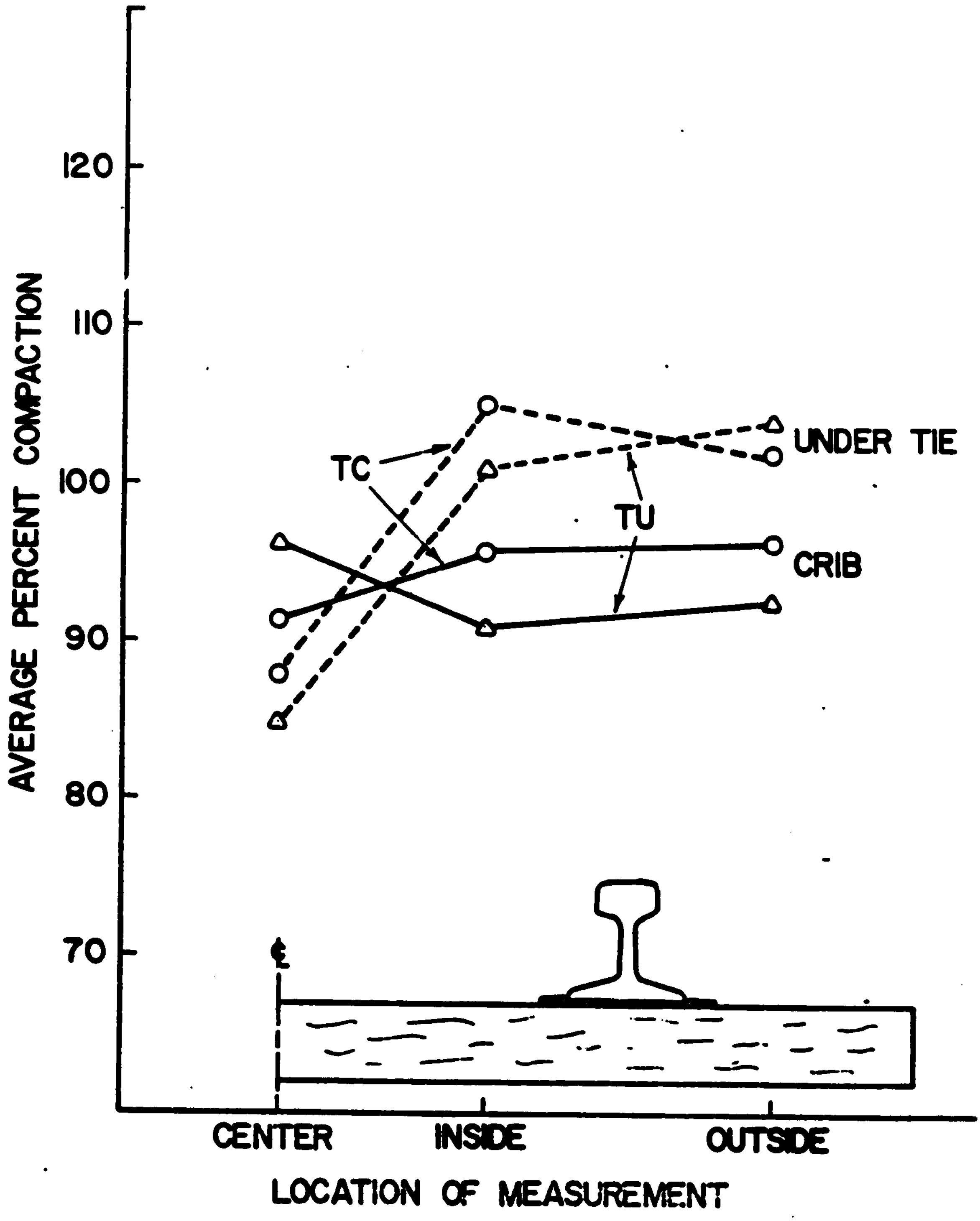


Figure 3.10. Percent Compaction Based on the Prorated Reference Ballast Density

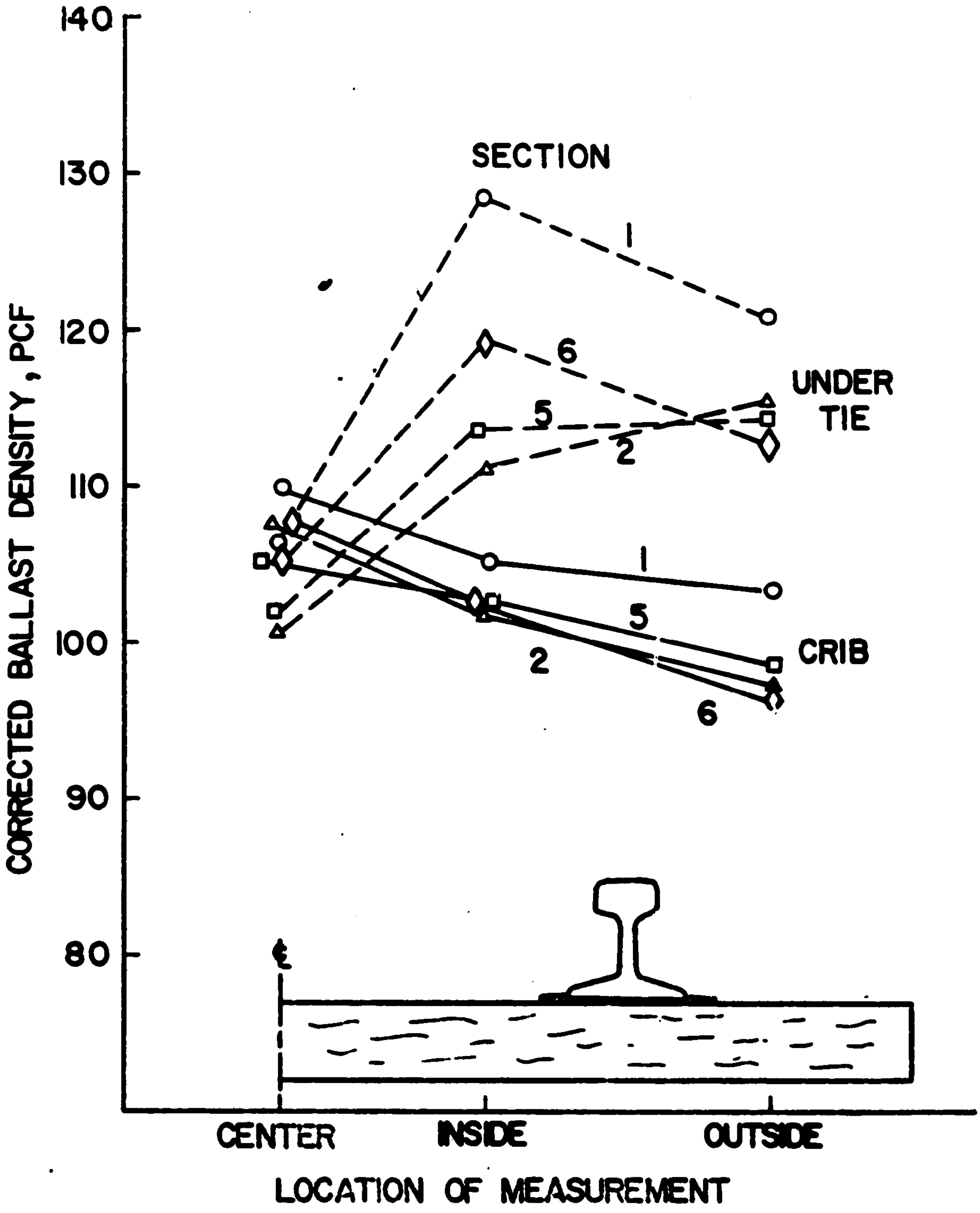


Figure 3.11. Corrected In-situ Ballast Density Measured During Follow-up Tests at the ICG Site

Table 3.4. Summary of Ballast Density Measurements During Follow-up Tests at ICG Site

Track Condition	Sampling Location		No. of Tests	Average ** Mixture, % Old Ballast	Average ** Mixture, % New Ballast	Measured Dry Density (pcf) Mean	Measured Dry Density (pcf) Range	Corrected Dry* Density (pcf) Mean	Corrected Dry* Density (pcf) Range	Void Ratio (e) Mean	Void Ratio (e) Range	Percent *** Compaction Mean	Percent *** Compaction Range
Tamping Only	Crib	Outside	1	9	91	80.2	-	97.3	-	0.76	-	97.1	-
		Inside	1	12	88	83.0	-	102.1	-	0.68	-	102.2	-
		Center	1	75	25	102.1	-	107.5	-	0.54	-	106.6	-
	Under Tie	Outside	1	35	65	98.5	-	115.4	-	0.47	-	114.6	-
		Inside	1	47	53	97.3	-	111.5	-	0.52	-	110.5	-
		Center	1	66	34	90.4	-	100.6	-	0.67	-	99.6	-
Tamping and Compacted	Crib	Outside	3	[illegible].3	90.7	81.2	6.0	99.2	6.7	0.72	0.12	99.2	6.7
		Inside	3	38	62	91.1	12.3	103.9	2.3	0.63	0.08	103.1	2.3
		Center	3	83	17	103.4	1.9	107.9	4.3	0.53	0.04	107.2	3.7
	Under Tie	Outside	3	47.7	52.3	103.9	11.4	116.0	7.2	0.45	0.10	114.9	7.1
		Inside	3	61	39	109.8	6.5	120.6	15.1	0.39	0.15	119.5	14.8
		Center	3	81.3	18.7	100.5	3.2	104.6	4.3	0.57	0.08	104.9	6.2

* Corrected Density with Bulk Specific Gravity

** Determined From Visual Classification

*** Measured Dry Density Divided by Ultimate Reference Density

Crib densities also show the same trend, but the difference is not as significant as under the tie. However, it is not so clear at this moment whether such differences are due to different initial conditions, because there is an unconfirmed report indicating that at least a portion of the test section was tamped sometime between the initial maintenance in 1976 and the follow-up tests in 1977.

In any event, the density distribution after traffic was generally similar to that observed before traffic. Ballast density under the tie was still higher around the rail than in the center of the tie, and the reverse trend was observed in the crib. The density under the tie was about 20 to 25 pcf (0.3 to 0.4 Mg/m^3) denser than in the crib around the rail, but about the same in the center.

Interestingly, the measured density is shown increasing from outside to inside of rail, both under the tie and in the crib. This may result from the fact that the ballast particles outside the rail do not have the confinement needed for compaction under traffic. The particles in this zone might just have flowed laterally toward the shoulder during vibrations and loading imposed by traffic.

Figure 3.12 shows the variation of the average corrected density when it is assumed that the average of Sections 1, 5, and 6 represents the initial track condition of tamped-compacted, and Section 2 the tamped-only condition. Even though the average values are not of statistical significance due to the few data points, they still show density differences between the sections assumed initially tamped-only, and tamped-compacted. The differences are quite significant (about 10 pcf or 0.16 Mg/m^3) inside the rail and in the center under tie, but not much (about 3 pcf or 0.05 Mg/m^3) outside of the rail. The crib densities are about the same between the two different

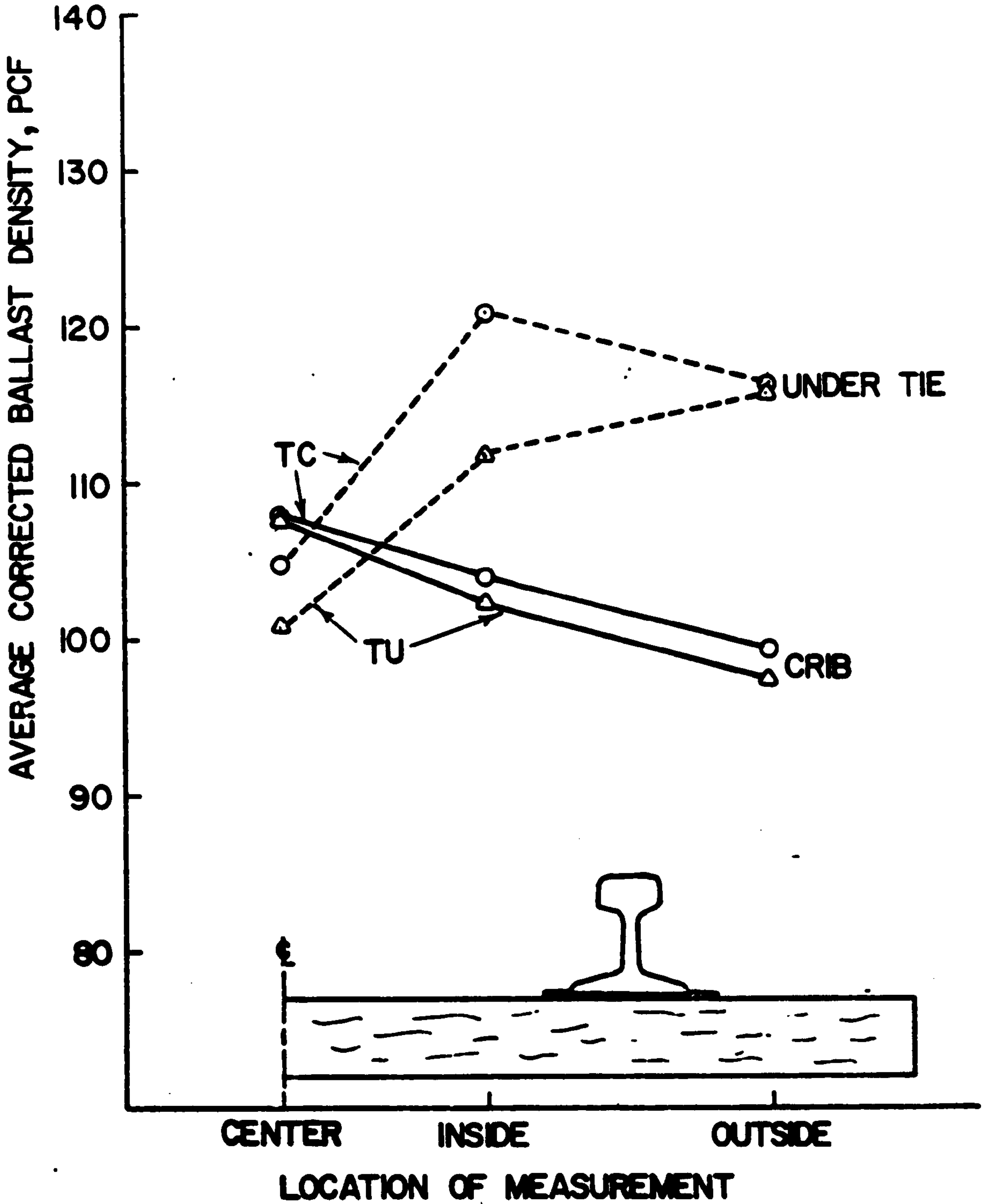


Figure 3.12. Average Corrected Ballast Density Measured during Follow-up Tests for Different Initial Conditions at the ICG Site

initial track conditions, but the tamped-compacted section shows slightly higher density than the tamped-uncompacted section.

Figures 3.13 and 3.14, show the results in terms of the void ratio and percent compaction, respectively. The same general trends are indicated by these methods of representation as by density, but without the influence of particle specific gravity.

FAST Initial Tests. Table 3.5 lists a summary of in-situ ballast density measurements obtained after tamping during construction. Density was measured both under the tie and in the crib, at locations inside the rail, outside the rail, and at the center of the tie. The tie locations were distributed over the test section involved so that representative sampling could be obtained. Details at test locations, test procedures, and test results as well are described in Ref. 14.

Figure 3.15 shows the changes of the average ballast density along the tie for different ballast types. It is shown that the distributions in the three ballasts were very consistent. The crib density was relatively uniform across the section. The density under the tie was almost the same inside and outside of the rail. The lowest density was in the center under the tie, the highest density was in the tamped zone beneath the tie, and the density in the crib lay between these two values in each ballast section. The difference in density under the tie between the center and the tamped zone was about 11 to 15 pcf (0.18 to 0.24 Mg/m^3). The above observations generally confirm the previous experience at ICG.

The differences in the magnitude of density among the three ballasts, shown in Fig. 3.15, it is at least partly a function of particle gradation

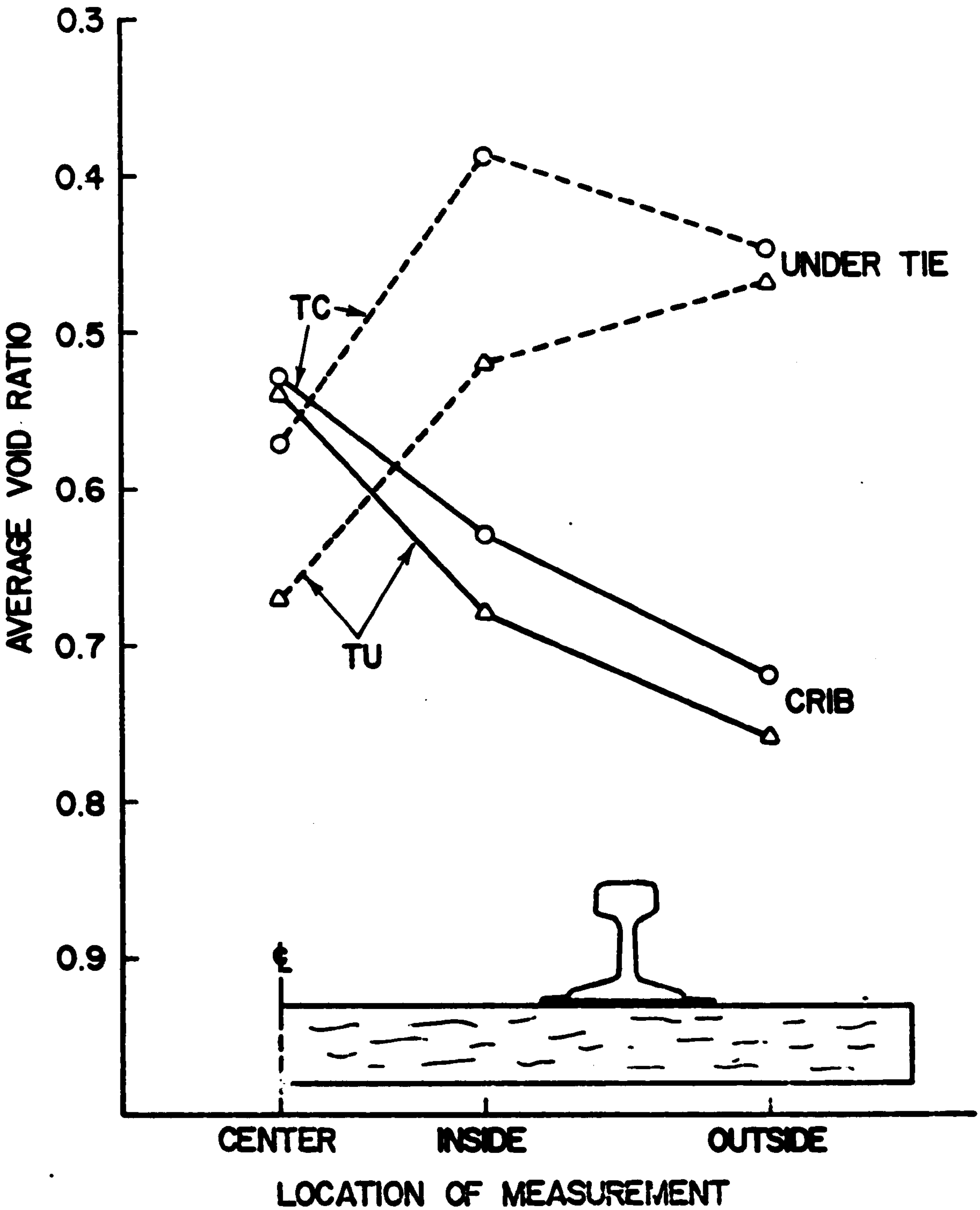


Figure 3.13. Average Void Ratio Obtained during Follow-up Tests for Different Initial Conditions at the ICG Site

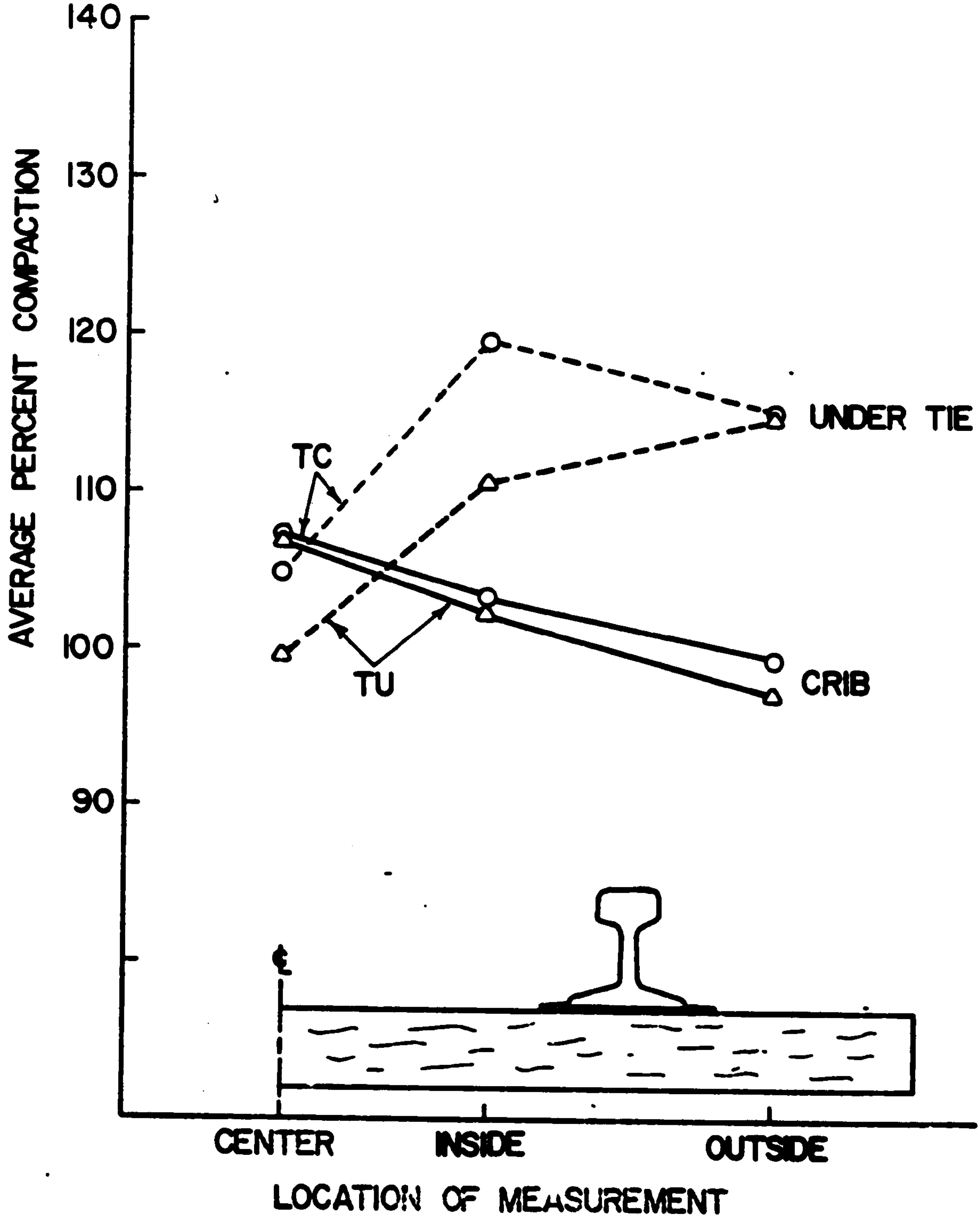


Figure 3.14. Average Percent Compaction Obtained during Follow-up Tests for Different Initial Conditions at the ICG Site

Table 3.5. Summary of In-Situ Ballast Density Measurement at FAST During Initial Tests

Section No.	Ballast Type	Sample Location		No. of Tests	Measured Dry Density (pcf)		Void Ratio (e)		Percent Compaction	
					Mean	Range	Mean	Range	Mean	Range
18A	Granite	Crib	Outside	2	99.2	9.5	0.69	0.15	97.2	-
			Inside	2	101.3	0.8	0.64	0.02	99.2	-
			Center	2	101	4.6	0.67	0.11	98.6	-
		Under Tie	Outside	2	107.7	4.5	0.59	0.08	105.5	-
			Inside	2	105.1	1.4	0.62	0.03	102.9	-
			Center	2	94.1	8.4	0.77	0.25	92.2	-
20B	Lime-stone	Crib	Outside	2	101.8	4.8	0.69	0.08	98.6	-
			Inside	2	106.3	2.4	0.60	0.04	102.9	-
			Center	2	104.9	7.3	0.62	0.09	101.5	-
		Under Tie	Outside	2	112.9	10.4	0.53	0.13	109.3	-
			Inside	2	112.5	7.0	0.51	0.10	108.9	-
			Center	2	98.0	-	0.76	-	94.9	-
20E	Traprock	Crib	Outside	2	111.2	6.4	0.66	0.10	100.8	-
			Inside	2	109.2	2.5	0.65	0.10	99.0	-
			Center	2	107.6	3.3	0.68	0.0	97.6	-
		Under Tie	Outside	2	118.7	6.6	0.53	0.09	107.6	-
			Inside	2	117.9	7.4	0.55	0.12	106.9	-
			Center	2	104.0	0.7	0.77	0.01	94.3	-

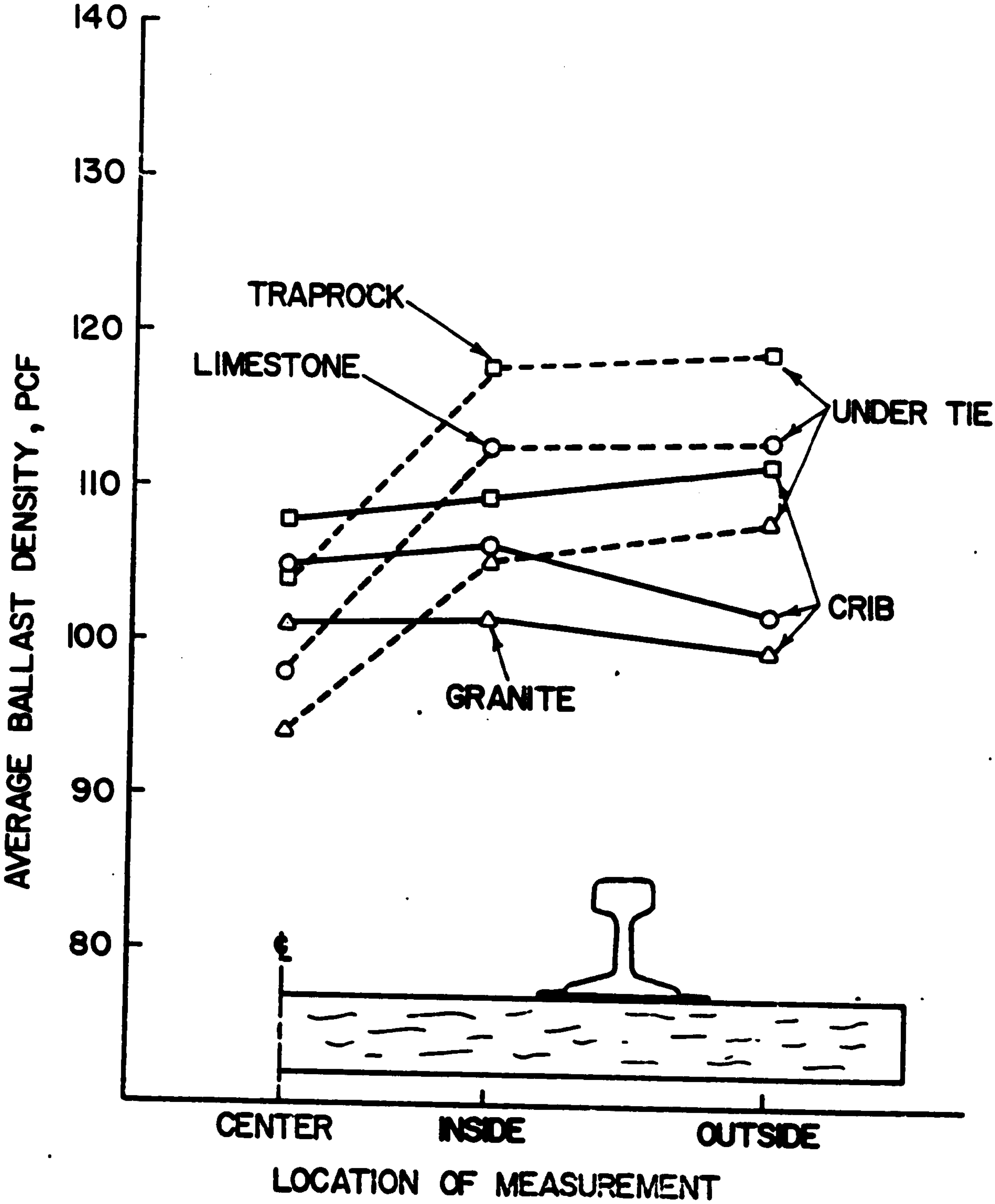


Figure 3.15. Variation of Ballast Density Along the Tie for Different Ballast Types, Initial Tests at FAST

and specific gravity. The effect of these parameters is shown removed in Fig. 3.16, which plots the results in terms of void ratio and percent compaction.

FAST Supplemental Tests. Table 3.6 summarizes the results obtained during the supplemental tests at FAST. Details of test results are described in Ref.-15.

Figures 3.17 to 3.19 illustrate the distributions of the average ballast density in the crib and under the tie for the two different ballast sections. The density distribution along the tie after 134.6 MGT of traffic (Fig. 3.17) showed, in general, very similar trends to those observed previously at FAST and ICG as well, i.e., the higher under-tie density in the rail area than in the center, and about the same crib densities along the tie. However, the magnitude of the density differences between in the rail area and in center, and between in the crib and under the tie were reduced. In fact, in the case of the limestone section, the in-situ ballast density throughout the section appeared to be very uniform regardless of location in the crib or under the tie.

As expected, tamping showed the most significant effects in the crib around the rail where the insertion of tamping feet occurred (Fig. 3.18). The density decrease was very significant in the limestone, about 16 pcf (0.26 Mg/m^3) decrease from after traffic, and moderate in the traprock, about 3.5 pcf (0.06 Mg/m^3) decrease. Tamping caused little change in both the crib density and the under-tie density in the center of the tie. Tamping caused a considerable scatter in density distributions from one spot to another in the traprock section. For unknown reasons, the ballast density was consistently lower inside the rail than outside the rail for both the crib and under-tie densities.

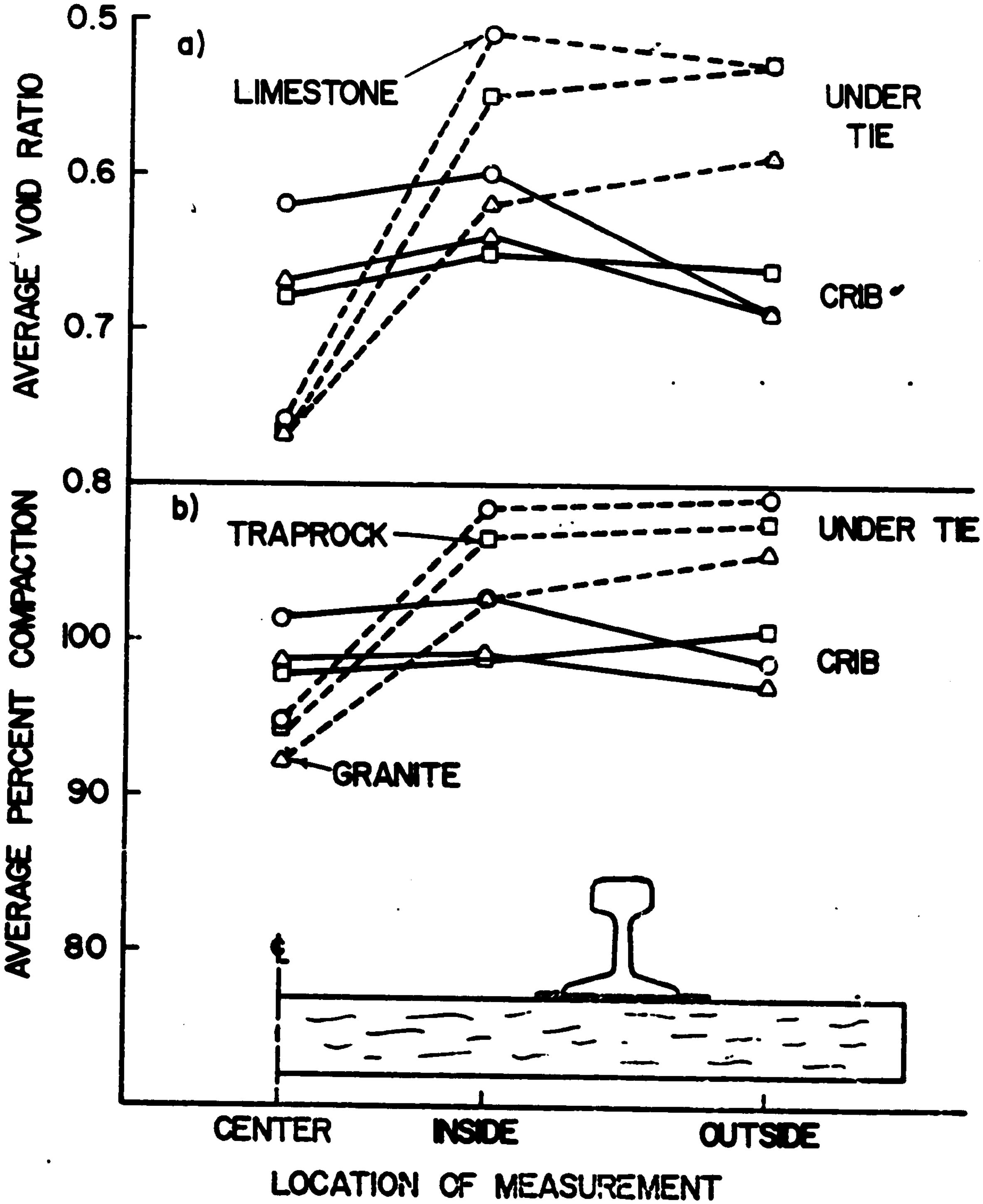


Figure 3.16. Variation of Void Ratio and Percent Compaction Along the Tie for Different Ballast Types, Initial Tests at FAST

Table 3.6a. Summary of In-Situ Ballast Density Measurement During Supplemental Tests in Section 20B at FAST

Track Conditions	Sample Locations		No. of Tests	Measured Dry Density (pcf)		Void Ratio (e)		Percent * Compaction	
				Mean	Range	Mean	Range	Mean	Range
After 134.6 MGT (UU)	Crib	Outside	2	113.1	1.8	0.50	0.04	109.5	-
		Inside	2	112.6	0.5	0.52	0.01	109.0	-
		Center	2	112.2	0.7	0.53	0.0	107.7	-
	Under Tie	Outside	2	114.0	0.8	0.50	0.0	110.4	-
		Inside	2	114.8	2.2	0.48	0.03	111.1	-
		Center	2	109.7	0.1	0.55	0.0	106.2	-
Tamped (TU)	Crib	Outside	2	98.9	0.8	0.73	0.04	95.7	-
		Inside	2	94.3	4.0	0.82	0.08	91.3	-
		Center	2	110.6	4.3	0.55	0.09	107.0	-
	Under Tie	Outside	2	114.4	0.4	0.49	0.0	110.8	-
		Inside	2	113.7	2.3	0.50	0.03	110.1	-
		Center	2	107.6	1.8	0.57	0.03	104.2	-
0.1 MGT of Additional Traffic After Tamping (AT)	Crib	Outside	2	112.5	2.0	0.51	0.03	108.9	-
		Inside	2	108.5	5.7	0.58	0.08	105.1	-
		Center	2	112.3	9.2	0.52	0.11	108.7	-
	Under Tie	Outside	2	112.1	3.9	0.52	0.04	108.6	-
		Inside	2	112.4	5.0	0.52	0.06	108.8	-
		Center	2	106.4	4.7	0.61	0.06	103.0	-

* Ultimate Reference Density for Limestone (LS) = 103.3 pcf Determined from Water Replacement Method (Ref. 9)

Table 3.6b. Summary of In-Situ Ballast Density Measurement During Supplemental Tests in Section 20G at FAST

Track Condition	Sample Locations		No. of Tests	Measured Dry Density (pcf)		Void Ratio (e)		Percent * Compaction	
				Mean	Range	Mean	Range	Mean	Range
After 134.6 MGT (UU)	Crib	Outside	2	117.3	8.11	0.60	0.16	106.3	-
		Inside	2	119.2	7.9	0.53	0.16	108.0	-
		Center	2	118.2	4.3	0.52	0.10	107.2	-
	Under Tie	Outside	2	126.6	2.1	0.46	0.02	114.7	-
		Inside	2	127.8	0.7	0.45	0.01	115.8	-
		Center	2	117.1	4.8	0.57	0.07	106.2	-
Tamped (TU)	Crib	Outside	2	119.2	3.7	0.55	0.05	108.0	-
		Inside	2	112.5	2.2	0.63	0.05	102.0	-
		Center	2	117.9	4.3	0.55	0.07	106.9	-
	Under Tie	Outside	2	125.8	4.9	0.47	0.06	114.0	-
		Inside	2	113.7	8.3	0.62	0.12	103.1	-
		Center	2	114.6	2.8	0.62	0.07	103.9	-
0.1 MGT of Additional Traffic After Tamping (AT)	Crib	Outside	2	118.5	11.7	0.55	0.12	107.4	-
		Inside	2	107.7	5.3	0.70	0.09	97.6	-
		Center	2	120.1	2.9	0.52	0.03	108.9	-
	Under Tie	Outside	2	124.7	10.5	0.48	0.12	113.1	-
		Inside	2	114.5	10.2	0.61	0.19	103.8	-
		Center	2	115.3	0.4	0.58	0.0	104.6	-

* Ultimate Reference Density For Traprock (TR) = 110.3 pcf Determined from Water Replacement Method (Ref. 9)

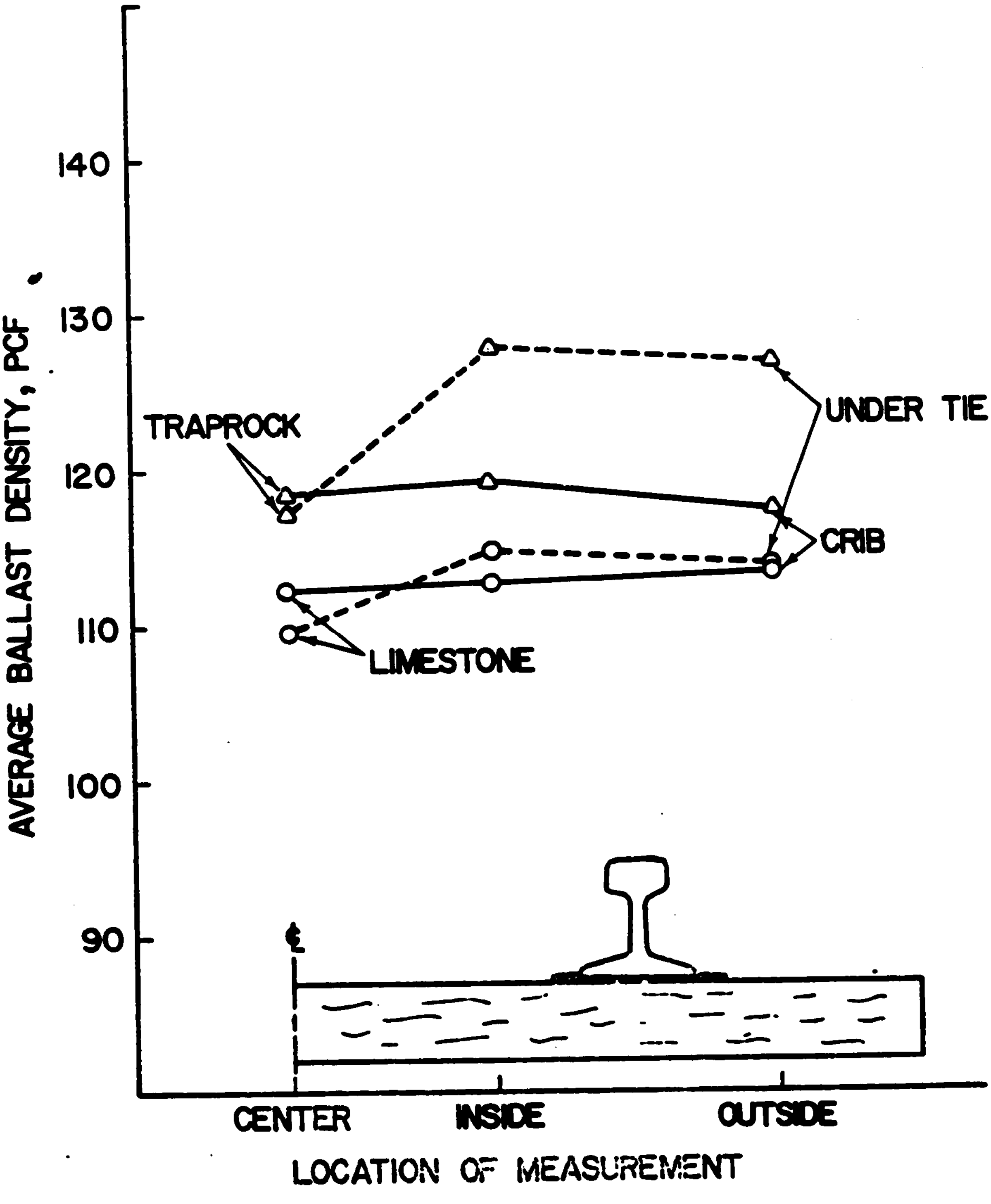


Figure 3.17. Distribution of Ballast Density Along the Tie for Different Ballast Types, After 135 MGT, FAST

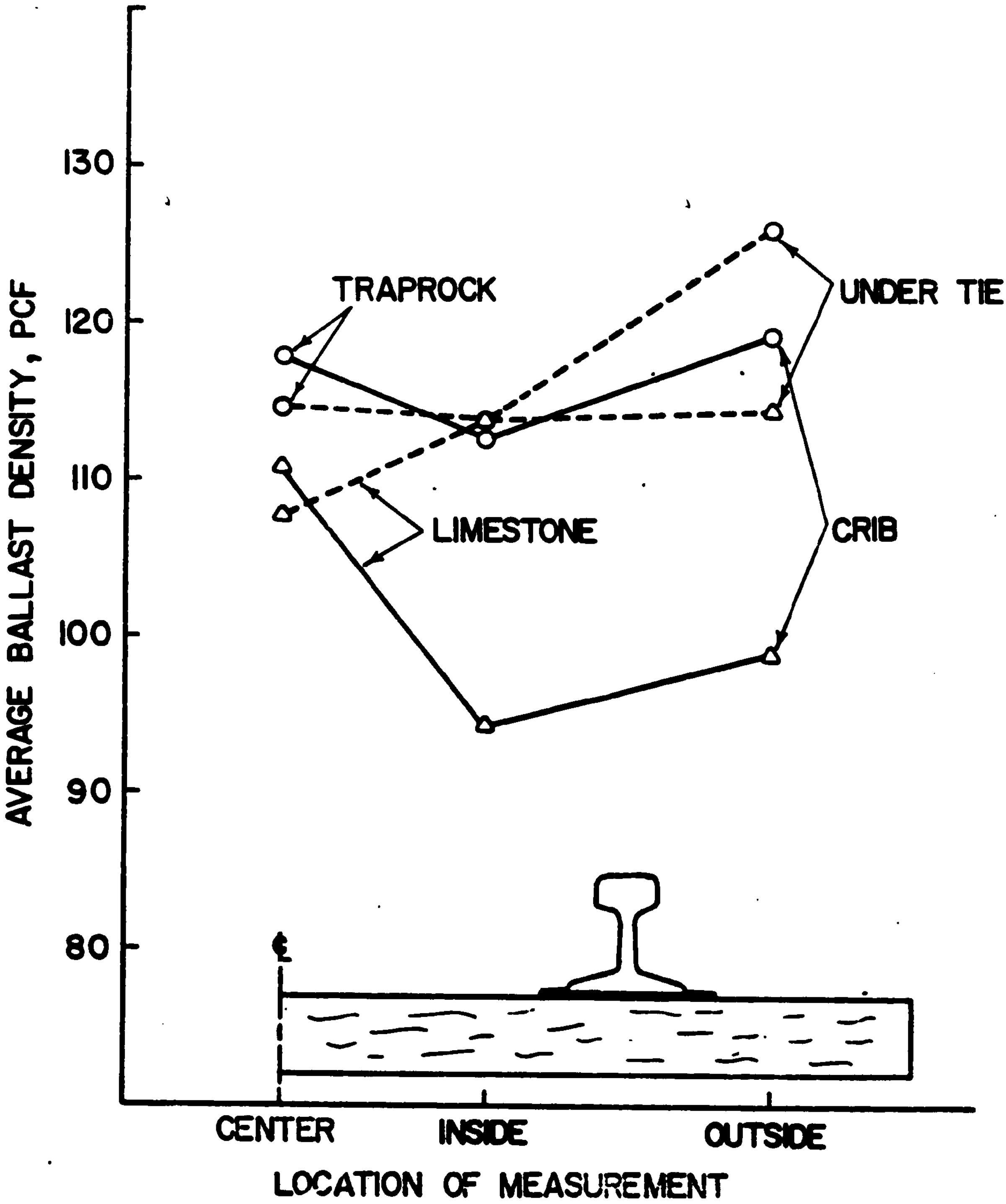


Figure 3.18. Distribution of Ballast Density Along the Tie for Different Ballast Types, After Maintenance Tamping, FAST

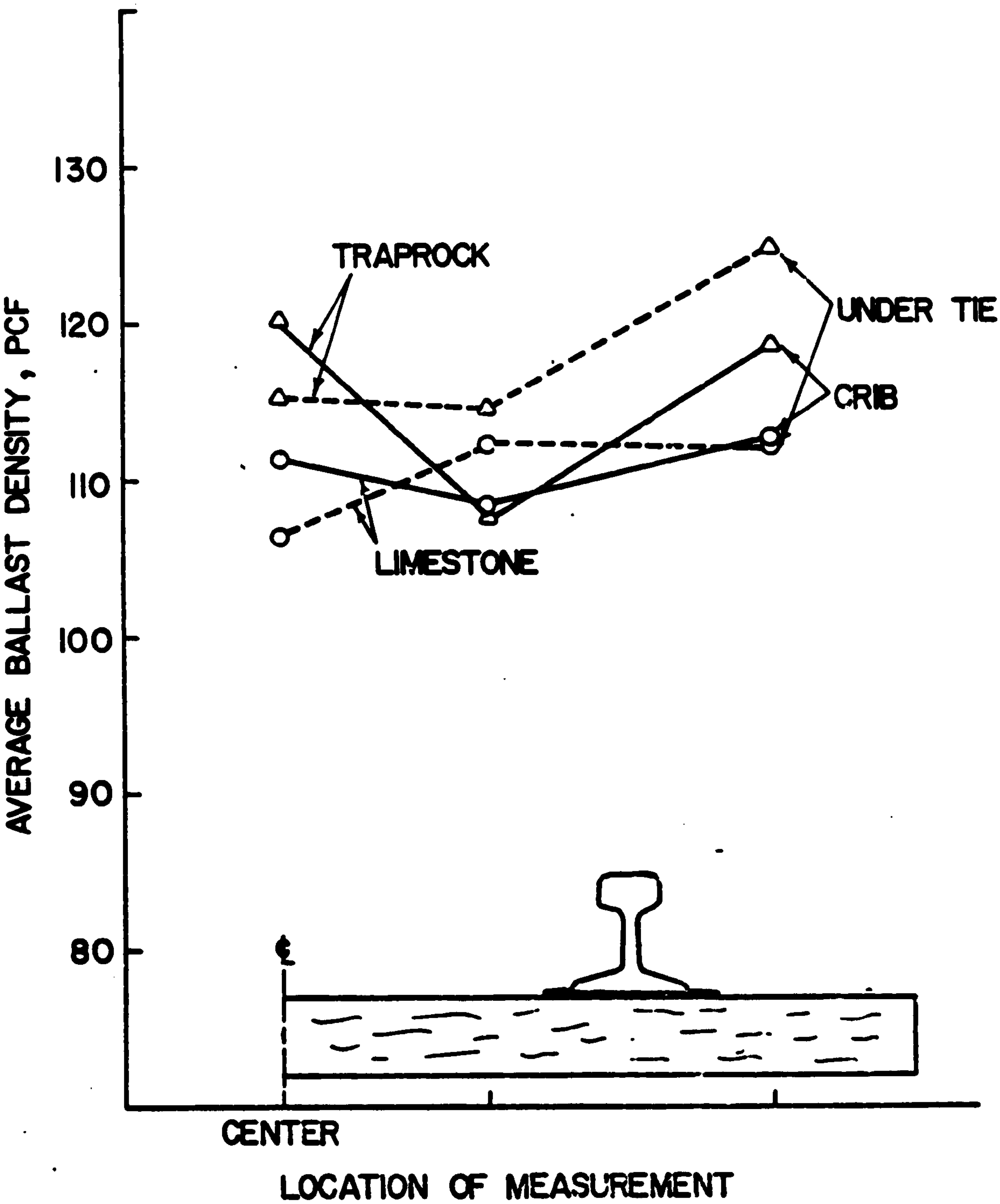


Figure 3.19. Distribution of Ballast Density Along the Tie for Different Ballast Types, After Additional 0.1 MGT, FAST

The effect of additional traffic of 0.1 MGT following tamping is inconclusive at the moment (Fig. 3.19). In the limestone section, the under-tie density appeared to have decreased, while the crib density almost returned to the same level as that after 134.6 MGT. In the traprock section, the 0.1 MGT traffic showed very little effect on the under-tie density and rather erratic trends in the crib density.

FAST Ballast Gradation. Figures 3.20 to 3.27 summarize the gradation test results of the ballast samples obtained throughout all the tests at FAST. For each ballast, average gradation at different track locations, i.e., under the tie and in the crib, and in the rail area and in the center of the track, are shown for the four different track conditions tested.

Regardless of ballast type, it is shown that the ballast gradation under the tie did not change at all with different track conditions, i.e., from the time of initial construction to 134.6 MGT and again to tamping. However, the ballast gradation in the crib is shown to have changed, but not significantly.

In the rail area, both sections showed almost the same ballast gradations in the crib and under tie after the initial tamping and after 134.6 MGT. However, with the tamping operation performed during the supplemental tests, the limestone section seems to have lost some fine particles in the crib area due to downward migration, while the traprock section lost a lot. The under-tie gradation remained about the same in both sections.

In the center of the track, both sections had about the same gradation in the crib and under the tie after the initial tamping; however, more fines appeared in the crib area after 134.6 MGT of traffic than under tie. It illustrates that a significant portion of ballast degradation during

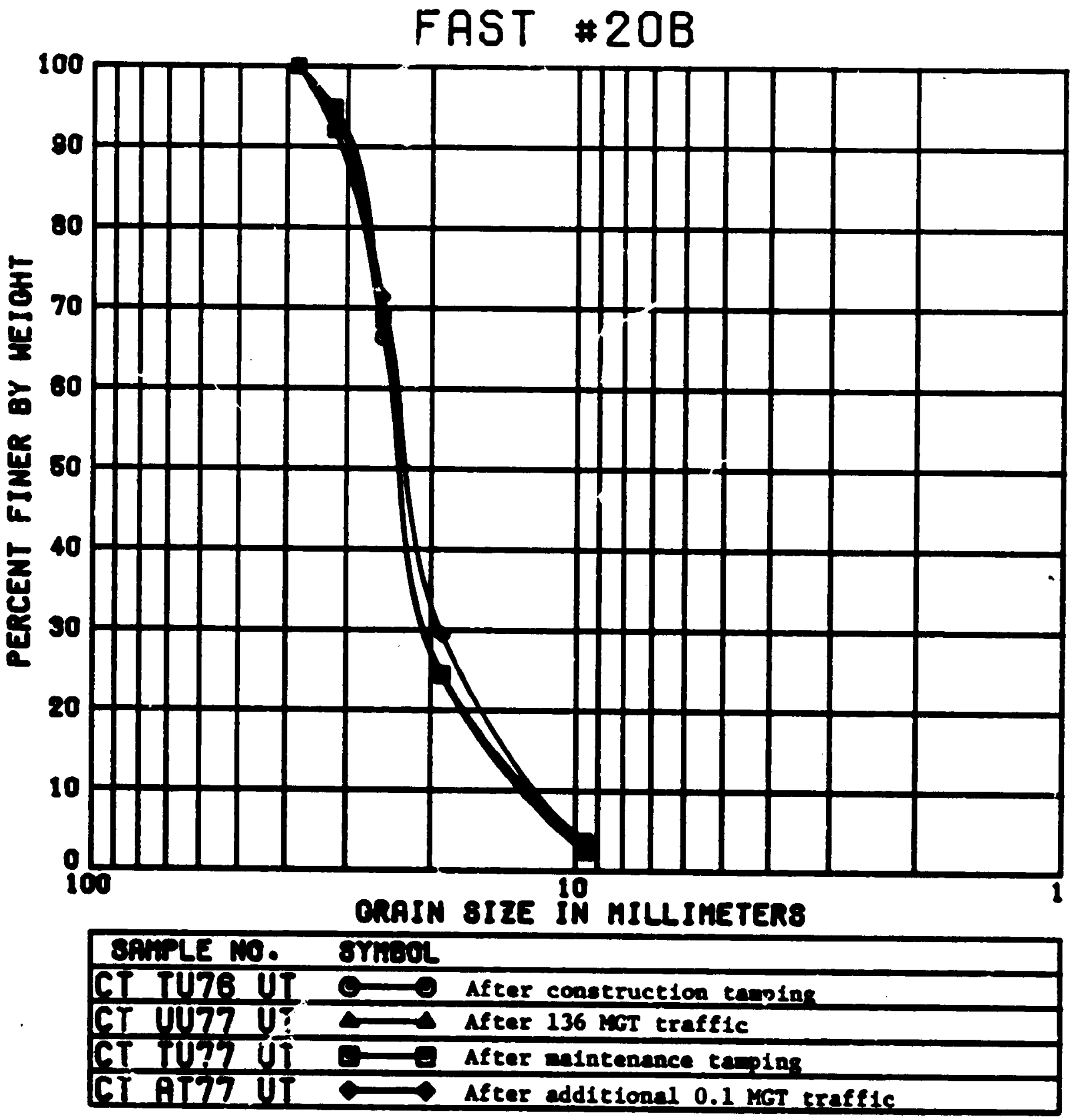


Figure 3.20. Changes in Ballast Gradation with Track Conditions, Under the Tie in the Center of Track, Limestone Section, FAST

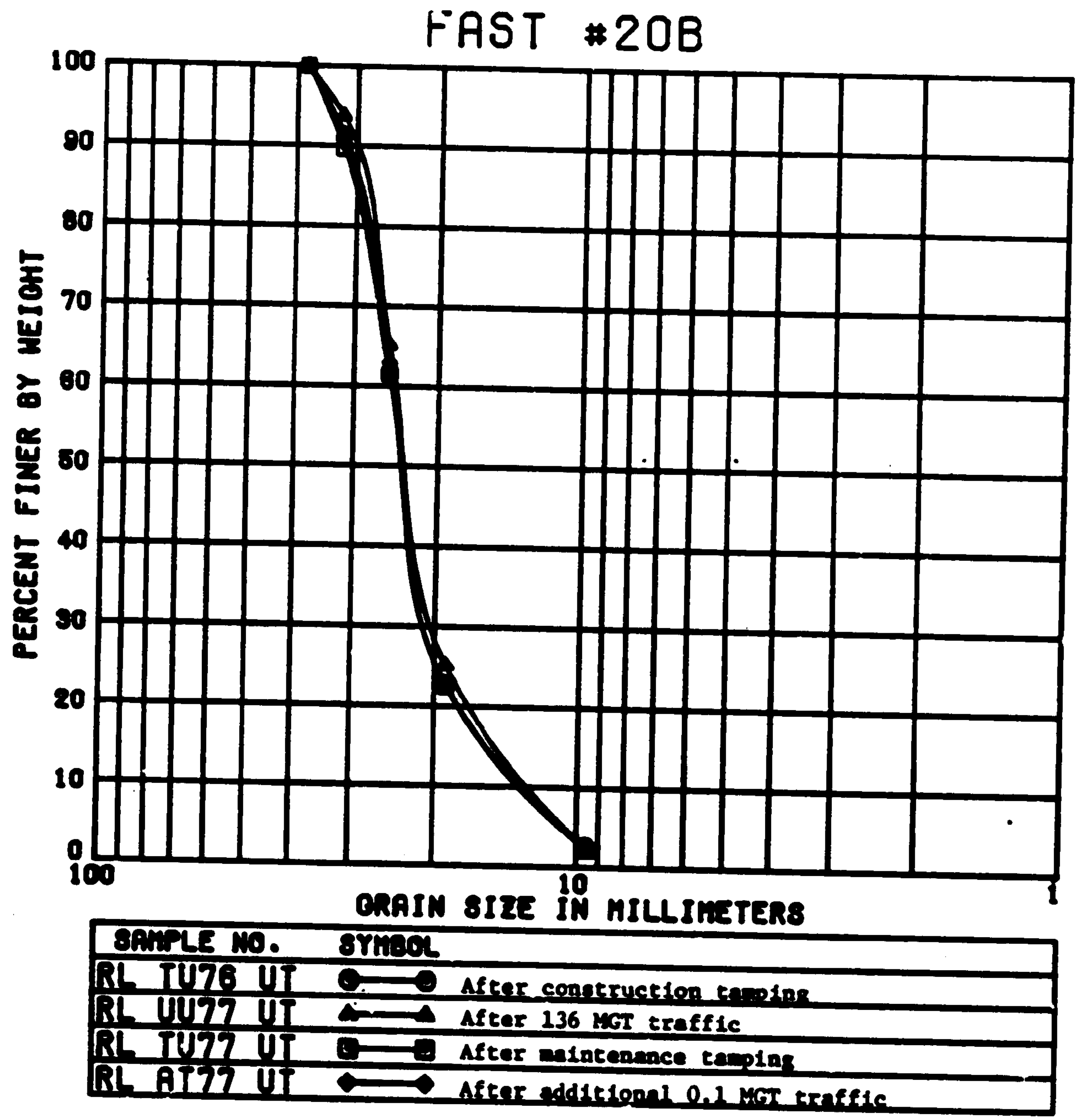


Figure 3.21. Changes in Ballast Gradation with Track Conditions, Under the Tie in the Rail Areas, Limestone Section, FAST

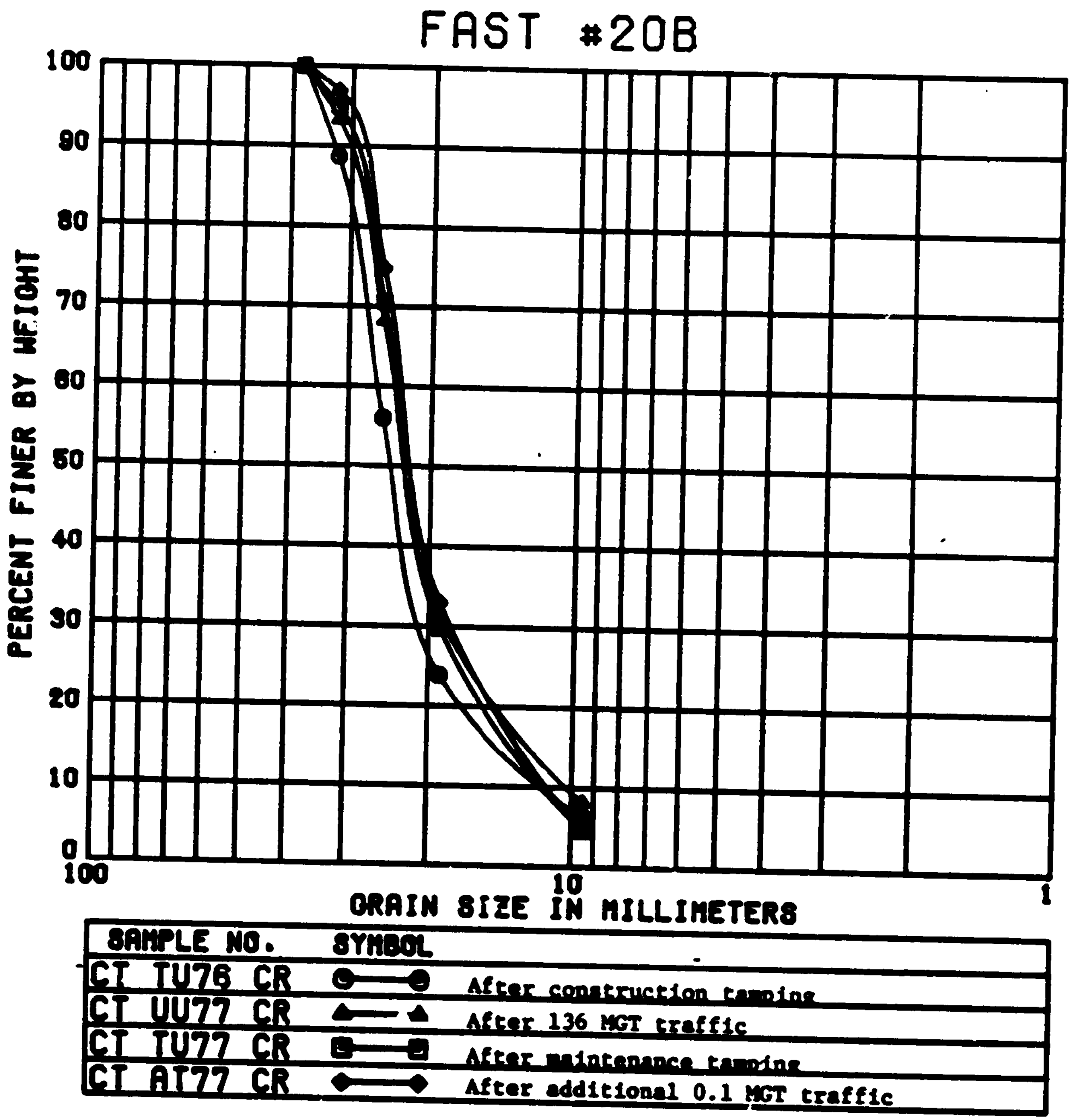


Figure 3.22. Changes in Ballast Gradation with Track Conditions, Under the Tie in the Crib in the Center of Track, Limestone Section, FAST

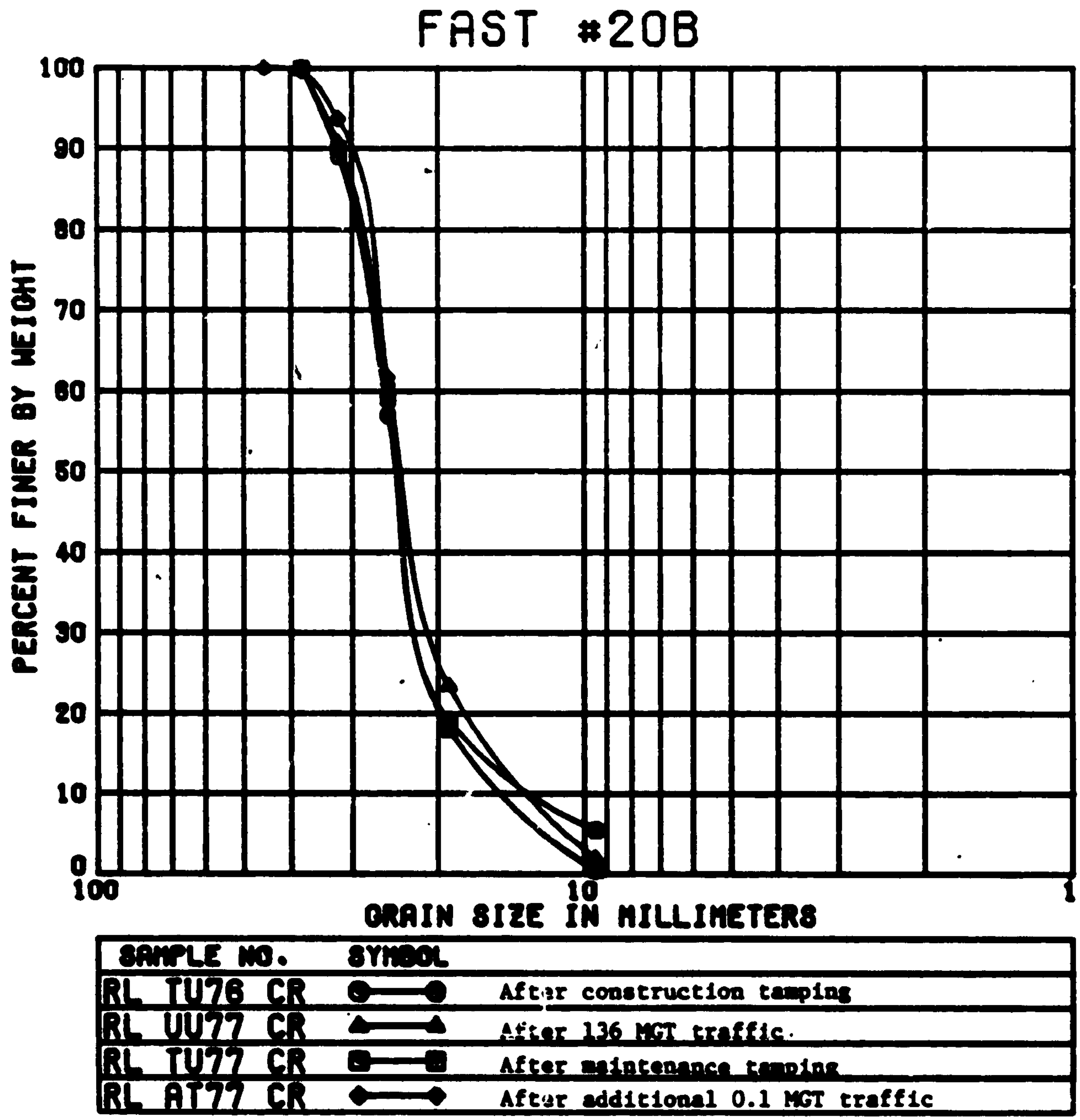
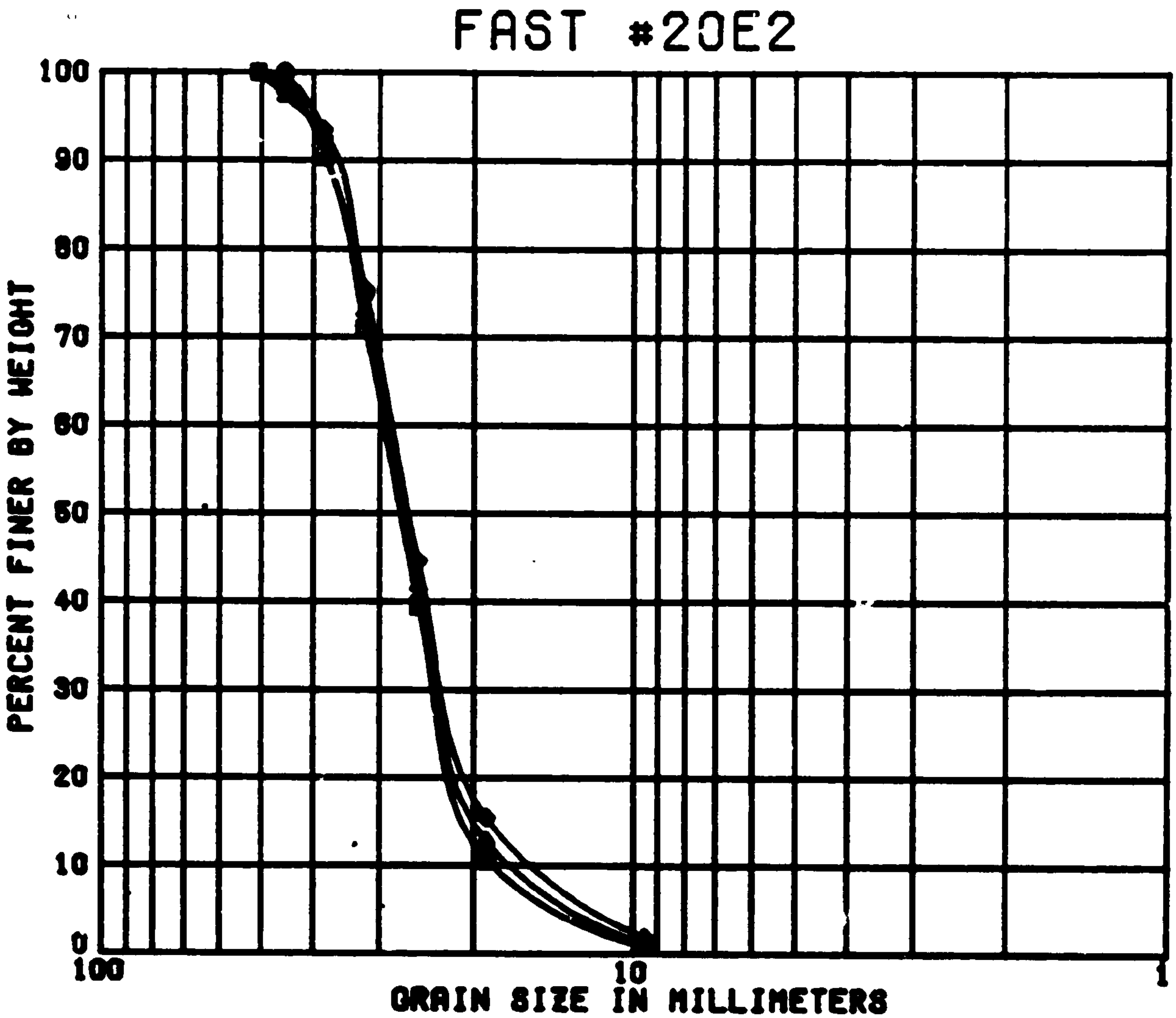


Figure 3.23. Changes in Ballast Gradation with Track Conditions, Under the Tie in the Crib in the Rail Areas, Limestone Section, FAST



SAMPLE NO.	SYMBOL	
CT TU76 UT	●—●	After construction tamping
CT UU77 UT	▲—▲	After 136 MGT traffic
CT TU77 UT	■—■	After maintenance tamping
CT AT77 UT	◆—◆	After 0.1 MGT traffic

Figure 3.24. Changes in Ballast Gradation with Track Conditions, Under the Tie in the Center of Track, Traprock Section, FAST

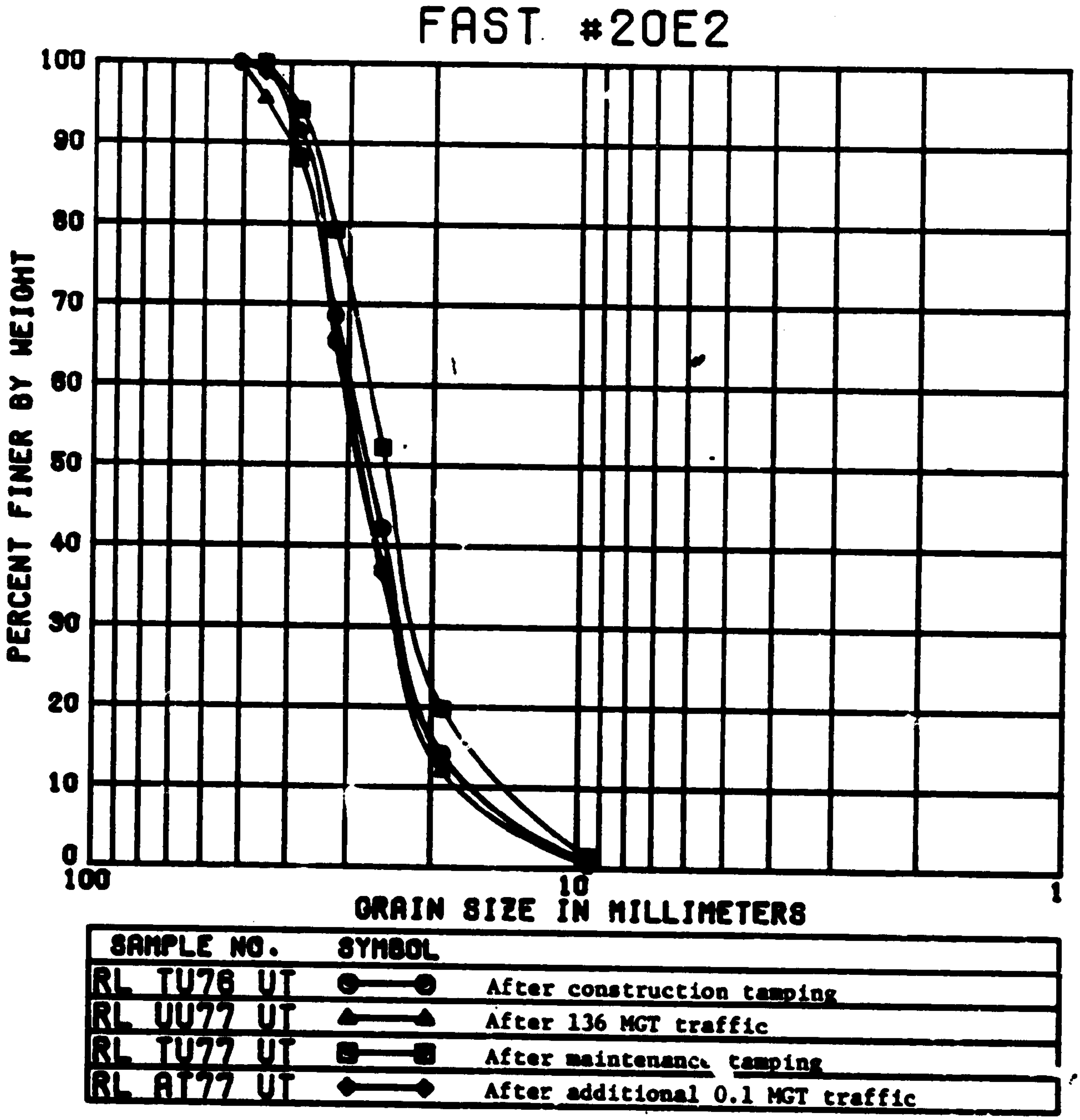


Figure 3.25. Changes in Ballast Gradation with Track Conditions, Under the Tie in the Rail Areas, Traprock Section, FAST

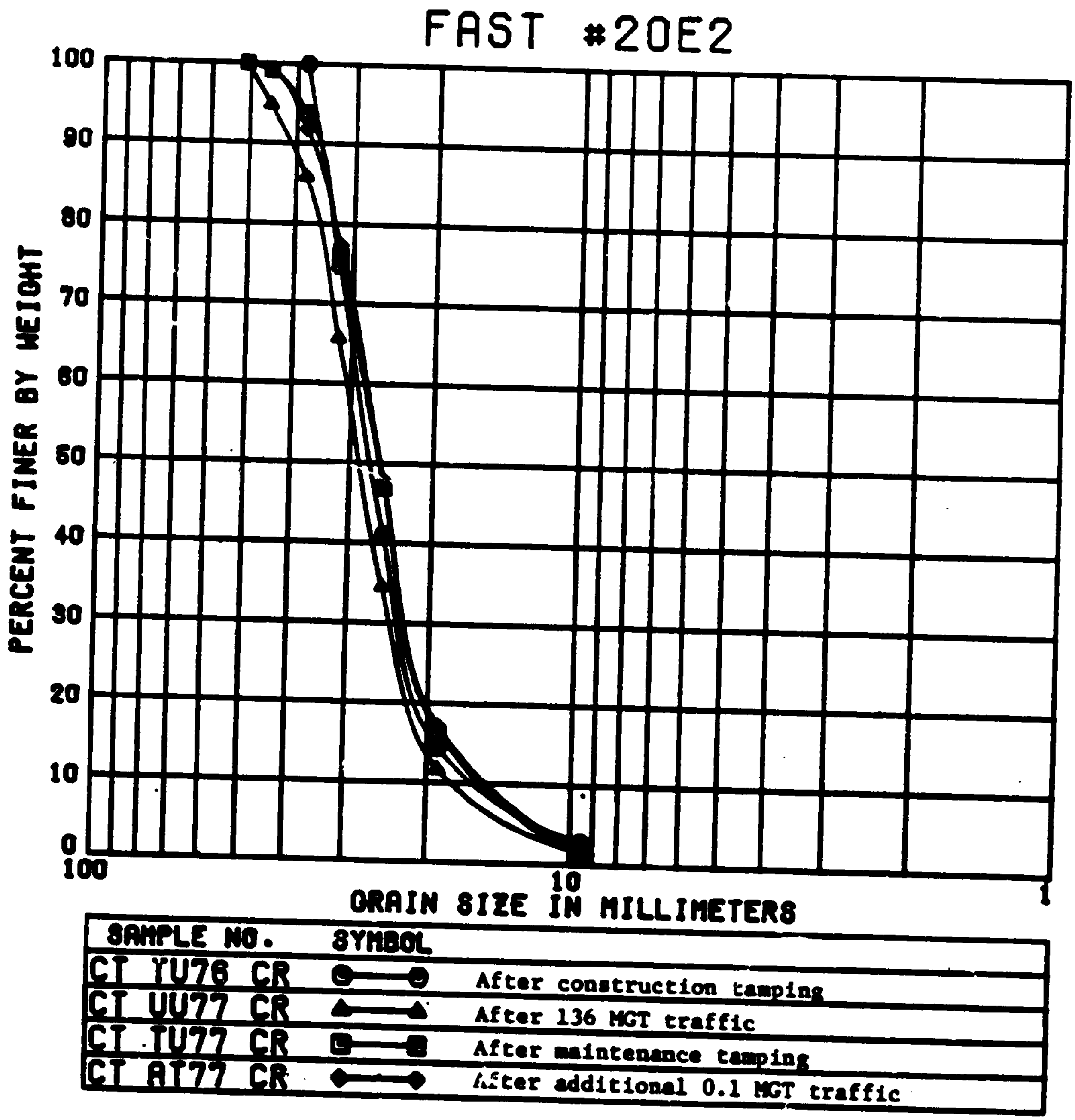


Figure 3.26. Changes in Ballast Gradation with Track Conditions, Under the Tie in the Crib in the Center of Track, Traprock Section, FAST

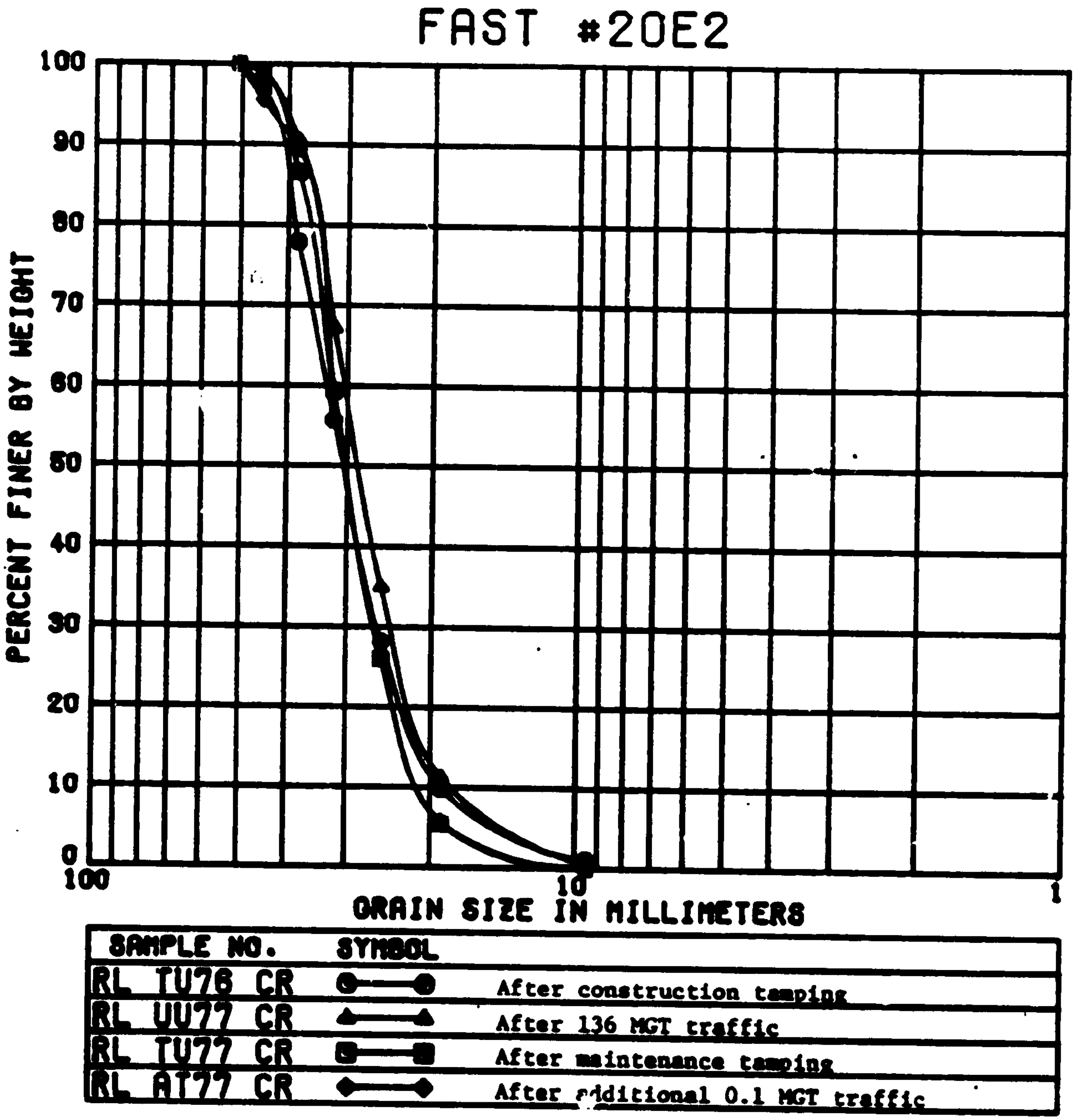


Figure 3.27. Changes in Ballast Gradation with Track Conditions, in the Crib in the Rail Areas, Traprock Section, FAST

traffic occurs in the crib between the ties, possibly due to the longitudinal movement of ties. Again, since the center portion of the track is not disturbed during tamping, the ballast gradation remained about the same between in the crib and under the tie, and before and after the tamping performed during the supplemental tests.

3.2 ASSESSMENT

In the preceding sections, in-situ ballast density measurements at different test sites have been presented along with description of the test apparatus and procedures used, test background, and field conditions. This section summarizes the results to present aspects of ballast physical state based on the ballast density measurements.

Throughout the study, four typical track conditions were tested. They are 1) after initial tamping during new construction or complete ballast undercutting, 2) after compaction immediately following tamping, 3) after accumulation of traffic, and 4) after maintenance tamping. For each of these track conditions, changes in the measured ballast density and its distribution along the tie are examined as well as the ballast gradation changes to assess the effects on the ballast physical state of important track parameters such as ballast type, tamping, ballast compaction, and traffic.

Initial Tamping. 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. Figure 3.28a summarizes qualitatively the measurements after such tamping at the two sites. The results generally indicated similar ballast density distributions along the tie at both test sites, even though the two sites

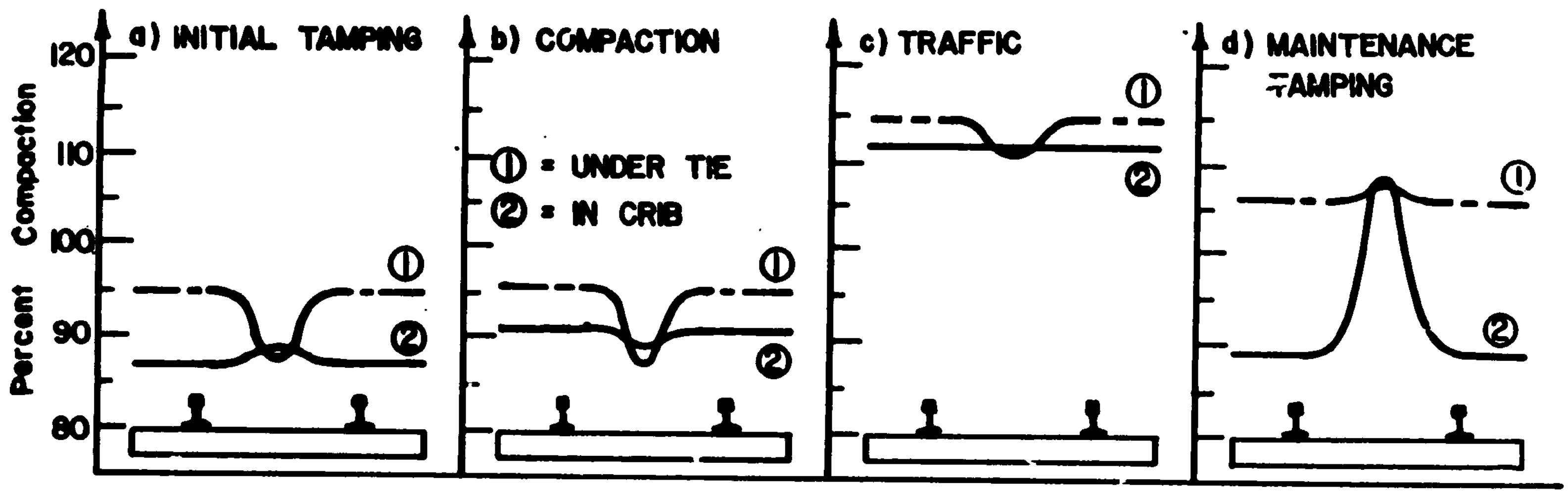


Figure 3.28. Schematic Illust:ation of Ballast Density Profiles under Different Track Condit'ons

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. For the same track condition, the ballast density under the tie varied significantly along the tie, and it was much denser in the rail area than in the center.

In the center, the under-tie density and the crib density were about the same, but in the rail area the density was much higher under the tie than in the crib. It was about 11 to 15 pcf (0.18 to 0.24 Mg/m^3) higher at FAST, and 9 to 12 pcf (0.14 to 0.19 Mg/m^3) 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, along with the confinement provided by the tie bottom and the squeezing action.

Crib and Shoulder Compaction. It is a widely accepted conviction that crib and shoulder compaction reduce the adverse loosening effects of ballast tamping and enhance the process of restoration of track stability by ballast density increase. However, it has not been completely understood how crib and shoulder compaction change the ballast physical state and how much ballast compaction contributes to restoration of track stability.

Figure 3.29 summarizes the results from ICG regarding ballast density changes with crib and shoulder compaction. Changes in average void ratio with ballast compaction at different locations in the ballast layer are to

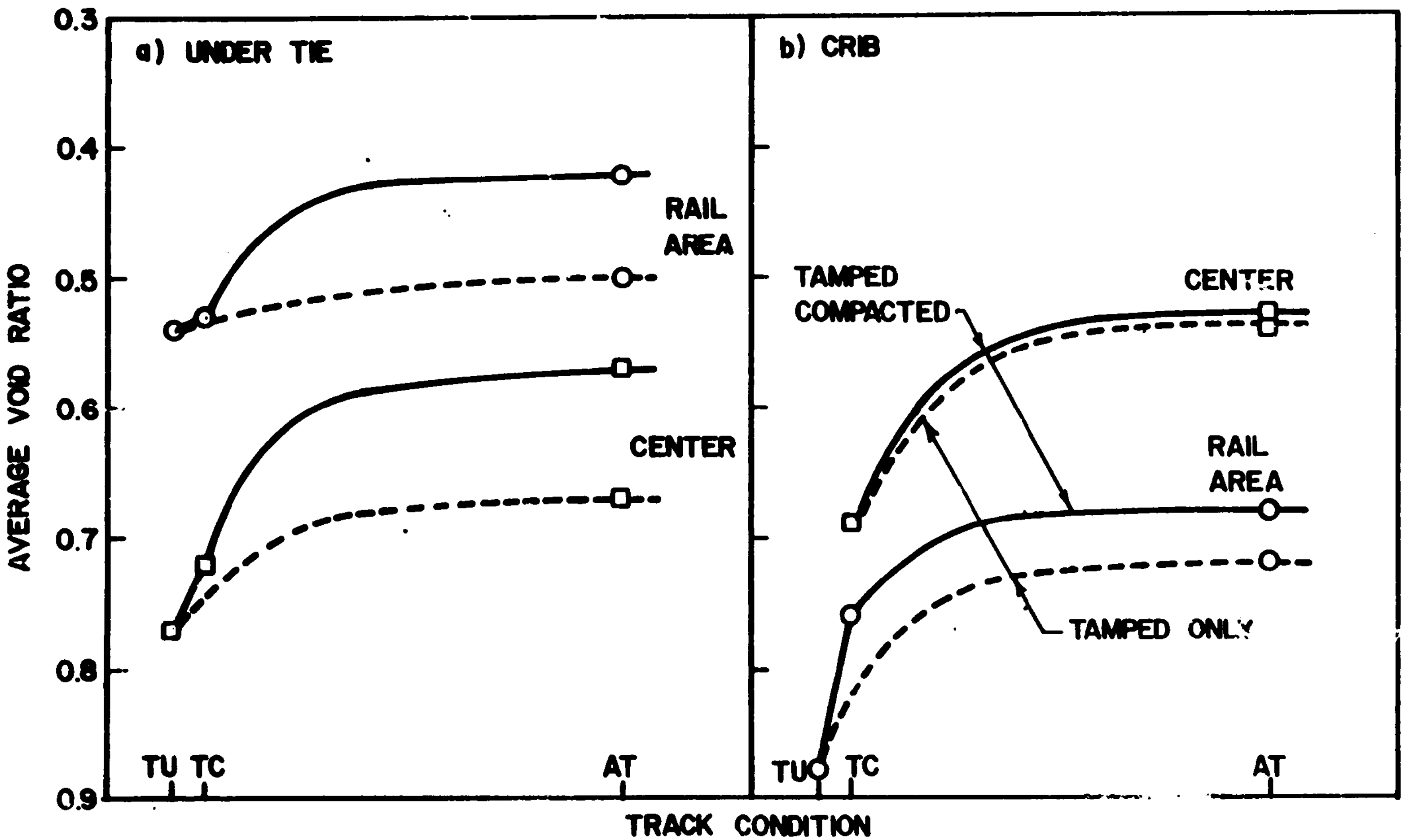


Figure 3.29. Effect of Crib and Shoulder Compaction on the Ballast Density, ICG

those obtained under the tamped-only condition. In addition, the long-term effects of the ballast compaction are also illustrated with measurements assumed to be obtained after at least 10 MGT of traffic, which is a significant amount of traffic.

Comparison of the measurements obtained from the tamped-only (TU) and the tamped and compacted (TC) conditions generally indicate ballast density increases in the ballast layer, 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 ballast compaction occurred. As shown in the figure, 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. Similar observations have been reported by CNR in a field study on the changes in the ballast bearing capacity with different track conditions (Ref. 17).

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. 18) observed 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 differed among different sites, presumable due to different track conditions and compaction procedures. There was about a 2% increase over the density achieved after tamping at the CNR site, and about 4% and 17% at the ICG and SR sites, respectively.

Figure 3.28b 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. 19) asserted from a series of field tests at a Canadian Northern 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 that the same degree of track stability restoration will be achieved during compaction.

Accumulation of Traffic. Summarizing the measurements at FAST, Fig. 3.30 illustrates ballast compaction changes with accumulation of traffic. Ballast densities at different locations of track 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. Even though the data do not provide sufficient information on the exact patterns of compaction growth for different

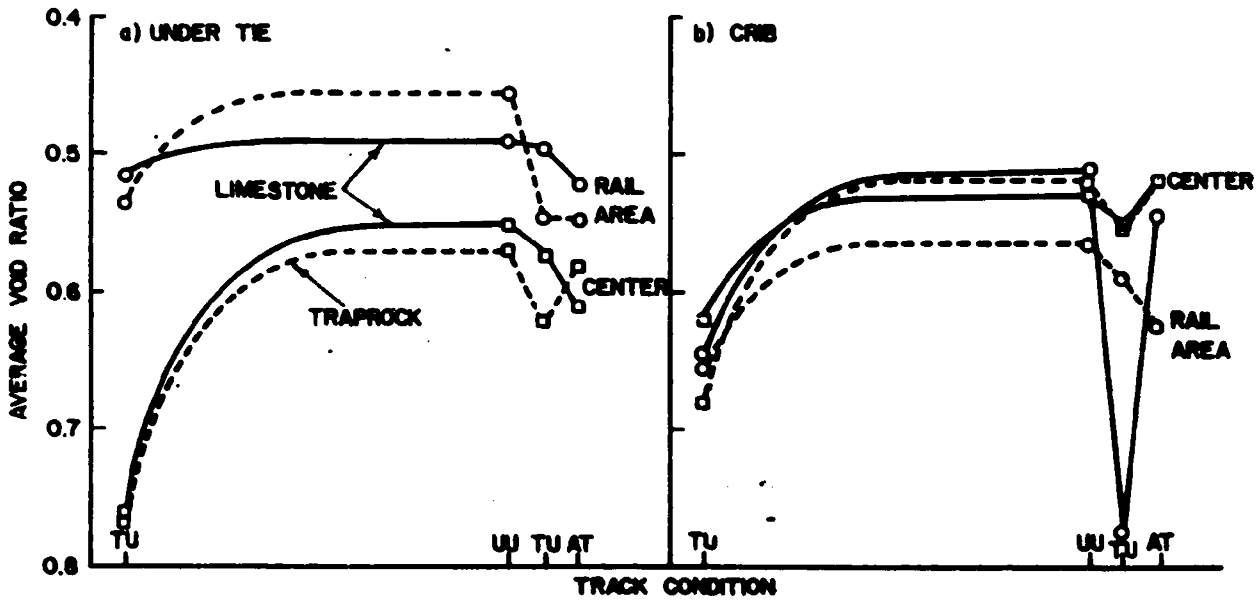


Figure 3.30. Changes in Ballast Compaction with Traffic and Maintenance, FAST

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

The two different ballasts having similar particles shape and gradation 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. 3.28c). 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 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 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.

Maintenance Tamping. Effects of maintenance tamping on the ballast density change can also be examined from Fig. 3.30. 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 the location of the 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 3.28d 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 conditions. For example, less than 1% density decrease from the undisturbed track condition was noticed at the CNR site, while more than 14% 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 those after initial tamping. One of the possible reasons for such a significant decrease in the limestone might be that the degraded particles, sometimes in powdery form, generally tend to form bonding between large ballast particles, therefore leaving large voids intact after removal of tamping feet.

Ballast Gradation Changes. Gradation change in the ballast layer also illustrates another important aspect of ballast physical state. Ballast degradation reflected by gradation changes could very well indicate ballast performance under different track conditions. Figure 3.31a shows variation of percent finer than No. 4 sieve as presented in the ballast density samples taken at the CNR site under different test conditions. It illustrates significant reduction of fines with tamping, and regaining with ballast compaction.

Loss of fine particles in the ballast during tamping is obviously due to particle segregation and downward migration of the fines. The regain of fines with ballast compaction was in this particular case mainly due to intermingling of ballast and subgrade materials. The loss of fines during tamping is directly related to the subsequent moisture content decrease, because the fines are the major source of water retention in the ballast layer (Fig. 3.31b).

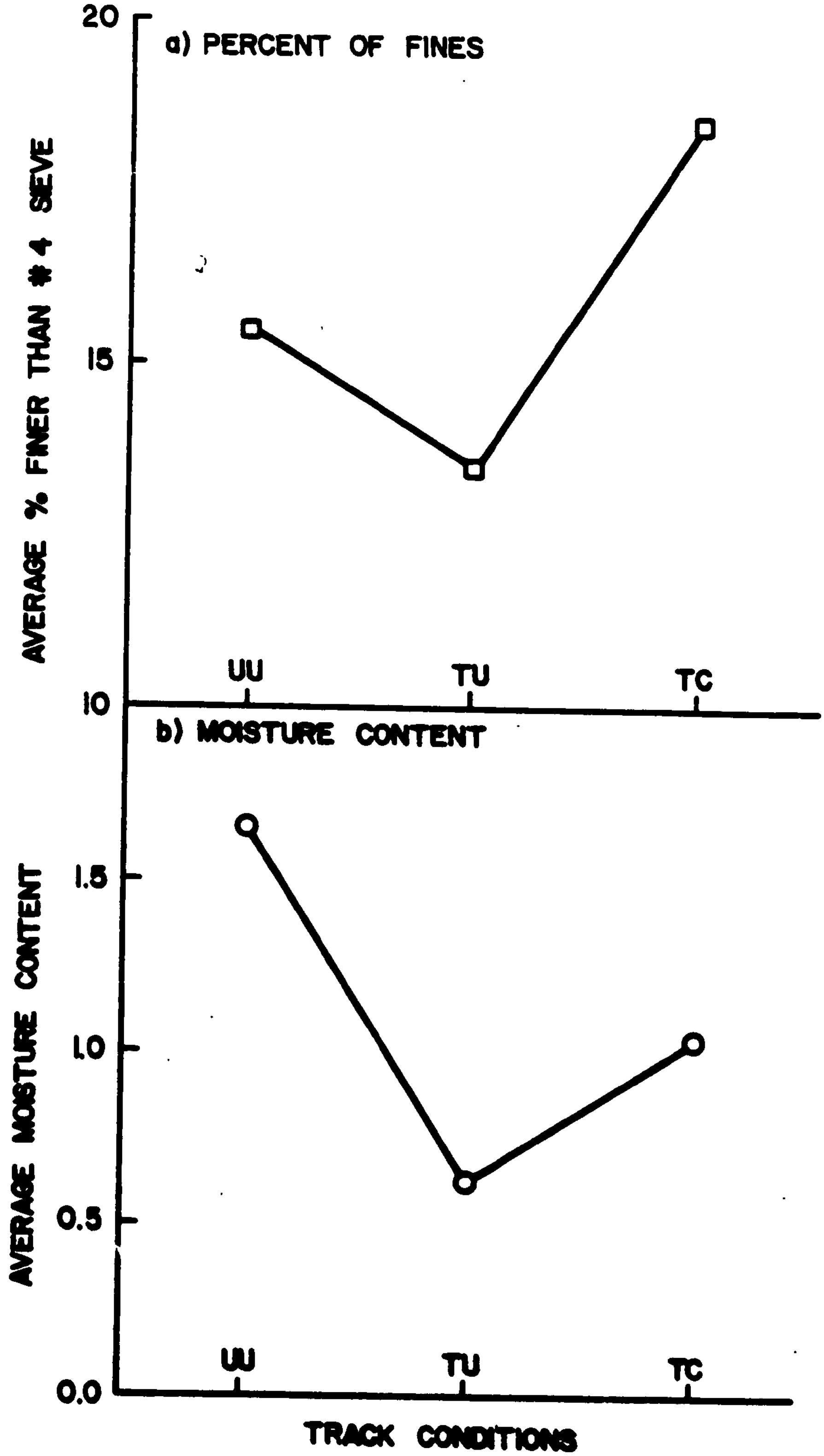


Figure 3.31. Changes in Percent Fines and Moisture Content in the Ballast Layer with Track Conditions, CMR

4. PLATE L ‹D TEST

This chapter will initially discuss SUNYAB's plate load test field apparatus and procedure. Several strength and deformation indices were employed to evaluate the changes in the ballast physical state. The important findings and general trends obtained from field investigations with SUNYAB's field plate load test apparatus will be compared to available results from other investigations. Additional details of the test results are described in a summary report by Panuccio and Dorwart (Ref. 20) and in individual field test reports (Ref. 21, 22, and 23).

4.1 SUNYAB PLATE LOAD TEST

The field plate load tests in this study are an extension and adaptation of equipment and procedures established in laboratory investigations by Wayne (Ref. 24) and Cioklo (Ref. 25). A discussion of the factors affecting the in-situ plate load resistance can be obtained from these references.

The current PLT apparatus (Fig. 4.1) essentially remained unchanged from the original laboratory design. Detailed specifications for the individual components of the apparatus are described by Selig, et al. (Ref.1).

The main refinement was a method to accurately measure the average plate displacement. The key element developed for the deformation system is a slotted steel cylinder, termed the displacement reference block. This block allows displacement measurements to be recorded directly at the centroidal axis of the plate.

The basic field test procedure has undergone only slight changes from that developed in the laboratory. Improvements with respect to testing

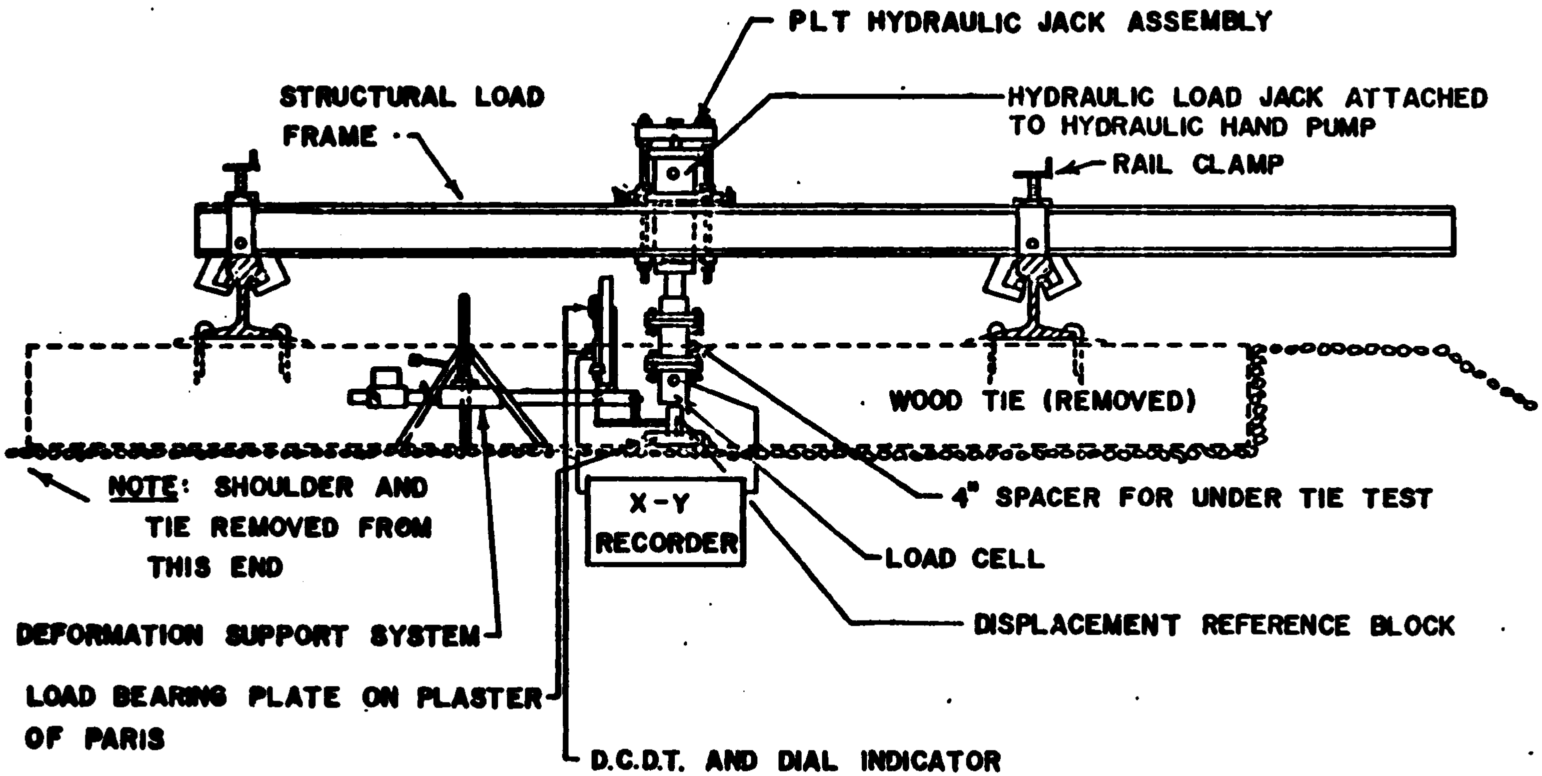


Figure 4.1. Assembled Plate Load Test Apparatus

efficiency and the deformation measuring system are described in a detailed test procedure by Selig, et al., (Ref. 1). A brief description of the procedure used is as follows:

1. For tests on the tie bearing area, remove all the ballast in both adjacent cribs. Remove spikes, tie plates, and rail anchors, and then carefully remove the test tie. For tests in the crib, remove only the spikes from both adjacent ties.
2. Select the center of spots to be tested in the crib and under the ties.
3. Place the 5-in. (127-mm) diameter load bearing plate on a plaster of paris seat and level the plate.
4. Place the PLT structural load frame on the rails in a position straddling the plate.
5. Insert the hydraulic load jack assembly in the PLT frame over the test plate.
6. Place the displacement reference block on the load bearing plate.
7. Set up the deformation support system on a level and firm foundation.
8. Apply a load to the plate at a constant deformation rate of about 0.25 in./min (6.35 mm/min) until 0.3 in. (7.6 mm) of displacement is reached and then unload the plate to zero load.
9. Perform additional cycles of plate loading to the same peak load as the first.

Approximately 20 minutes is required to complete a test with five load-unload cycles on one plate.

Load and displacement readings are manually recorded at zero and peak displacements, and after complete unloading for each cycle. Mechanical gages used to obtain these values of load and displacement were a calibrated hydraulic pressure gage and a dial indicator, respectively. In addition, commercially available electronic transducers were used to continuously record the load-displacement curves on the X-Y recorder.

The data reduction process involved proportioning the loads and displacements from the recorded field curves with known calibration signals. For the first cycle, loads were determined at 0.1, 0.2, and 0.3 in. (2.5, 5.1, and 7.6 mm) vertical plate displacement. For all subsequent loading cycles, only peak load and the peak and rebound displacements were determined from the curves.

The strength and deformation indices obtained from the load-displacement curves which were used to analyze the PLT data are as follows:

1. Ballast bearing index, $B = \frac{P}{A}$. (4.1)

2. Modified ballast bearing index, $B_k = \frac{B}{\Delta}$. (4.2)

3. Average modified ballast bearing index =

$$\text{Average } B_k = \frac{(B_k)_{0.1} + (B_k)_{0.2} + (B_k)_{0.3}}{3} . \quad (4.3)$$

4. Modified modulus of deformation,

$$E_m = \frac{P_{peak}}{A\,\Delta_p} . \quad (4.4)$$

5. Modified resilient modulus,

$$E_{rm} = \frac{P_{peak}}{A(\Delta_p - \Delta_r)} \quad . \qquad (4.5)$$

6. Percent elastic recovery,

$$E_r = \frac{(\Delta_p - \Delta_r)}{\Delta_p} \times 100 = \frac{E_m}{E_{rm}} \times 100 \quad . \qquad (4.6)$$

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 plate in square inches = 19.63 in.^{2} (0.0127 m^2) ,

Δ = 0.1, 0.2, and 0.3 in. (2.5, 5.1 and 7.6 mm) displacement,

P_{peak} = peak plate load in lb (N),

Δ_p = total deformation per cycle in inches (mm),

Δ_r = rebound deformation during unloading in inches (mm).

The B and B_k values are computed for the first cycle only, while E_m , E_{rm} and E_r values are computed for all cycles. Since the plate area is a constant, the B and B_k values yield identical trends at a given deformation level though the magnitude and units of values are different. The average B_k value represents an average stiffness response of the entire load-displacement curve as determined by Wayne (Ref. 24). The B_k at 0.3 in. (7.6 mm) displacement and first cycle E_m values are also equal by definition.

The results obtained from the ICG and FAST test sites will be discussed in the following sections. The B values will be compared only at 0.2 in. (5.1 mm) displacement. The general trends have been shown to be similar to those for the other B values and for the average B_k value (Refs. 21, 22, and 23). Inside rail and outside rail test locations are averaged and defined as the "under the rail" location results. In the figures, these values are shown symmetrically about the center of the track.

Values of ε_m, ε_{rm}, and percent ε_r were examined by Panuccio and Dorwart (Ref. 20) for the ICG and FAST test series. These indices were not found to be useful in establishing meaningful relationships and, thus, will not be discussed in this report.

Illinois Central Gulf. The first series of PLT's which occurred in November 1976 was analyzed and discussed by Panuccio (Ref. 21). A second trip followed in June 1977 for a continued study of the ICG track system. These results were analyzed and discussed by Dorwart and Panuccio (Ref.22). The track maintenance operations, the track loading history, and a description of the track system have been summarized in Section 2. However, some further discussion is warranted at this point.

The track loading history after undercutting, tamping, and crib and shoulder compaction in November 1976 is assumed to have consisted of: 1) approximately 9 MGT of traffic, 2) then a second tamping operation (March or April, 1977), and 3) finally, approximately 5 MGT more of traffic (Refs. 22 and 6). The trafficked ballast under the rail for both the crib and under-tie zones were probably disturbed by the second tamping operation. The ballast stiffness in these zones at the time of tamping may have been similar to those values obtained in November, 1976. Thus, it is assumed that the physical state changes can be attributed to only 5 MGT of the 14 accumulated MGT of traffic. However, this situation is not necessarily valid for the center of track. Note that depressions in the center of the track from a track raise during tamping were observed for both trips (Refs. 21 and 22). Since tamping might possibly loosen the ballast in this zone, the actual amount of applied traffic is uncertain. However, for the purpose of convenience and consistency of data presentation, 5 MGT of traffic will also be assumed for the center of track.

The field load-displacement curves are represented by ballast bearing index (B) as a function of displacement for under the rail (Fig. 4.2) and center of track (Fig.4.3). Each individual curve is identified for the under-tie and in-crib locations and for specific track maintenance operations and traffic loading. These average curves illustrate the general differences in ballast behavior for the given conditions for ICG. The principal reasons for including these curves, however, are to illustrate the similarity in trends for the three displacement levels and to show the general shape of the PLT load-displacement relationship.

The ballast strength profiles (Fig. 4.4) for the ICG track system are constructed from the B values at 0.2 in. (5.1 mm) displacement in Figs. 4.2 and 4.3. 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

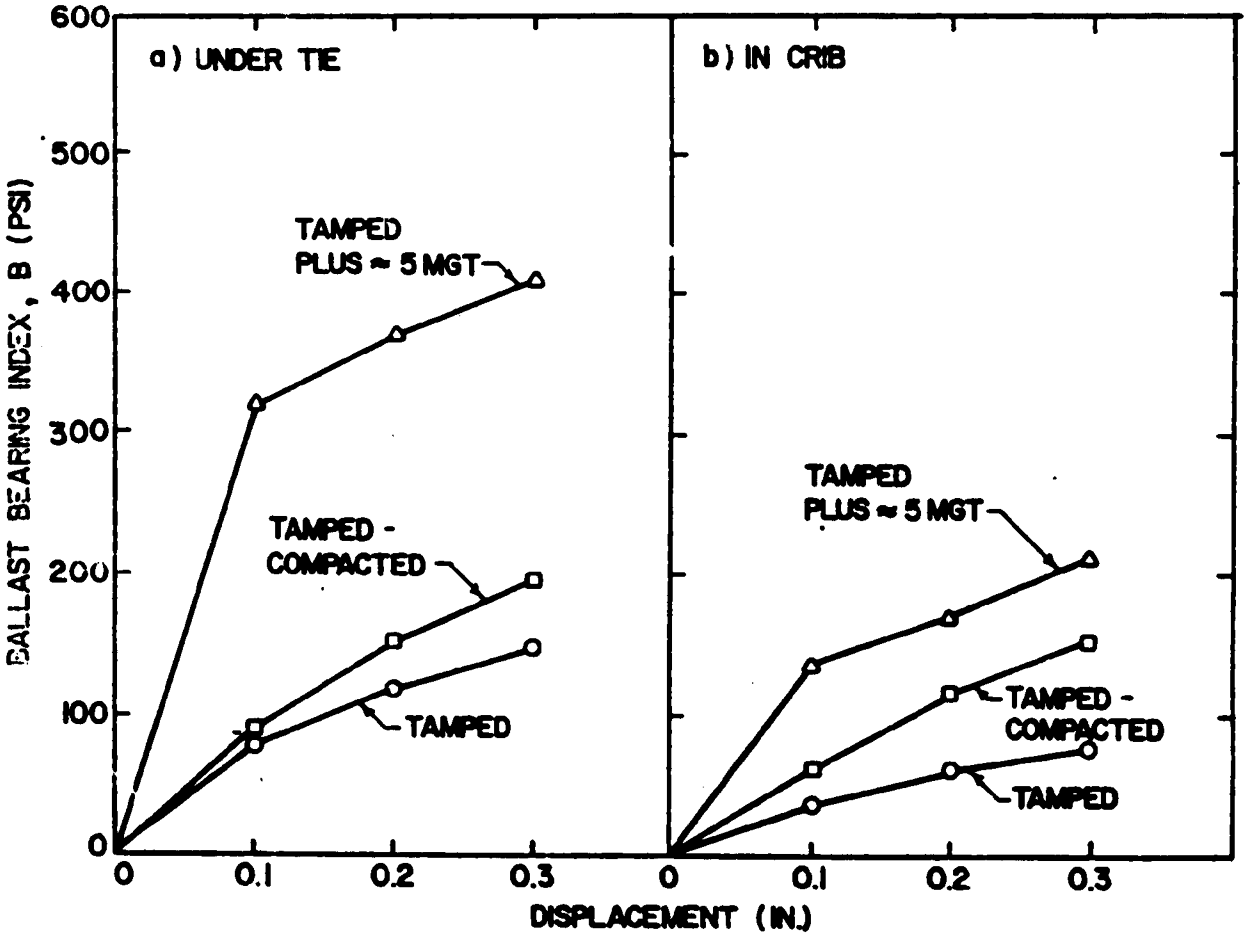


Figure 4.2. Plate Resistance Under the Rail at the ICG Site for Limestone and Steel Slag Ballast

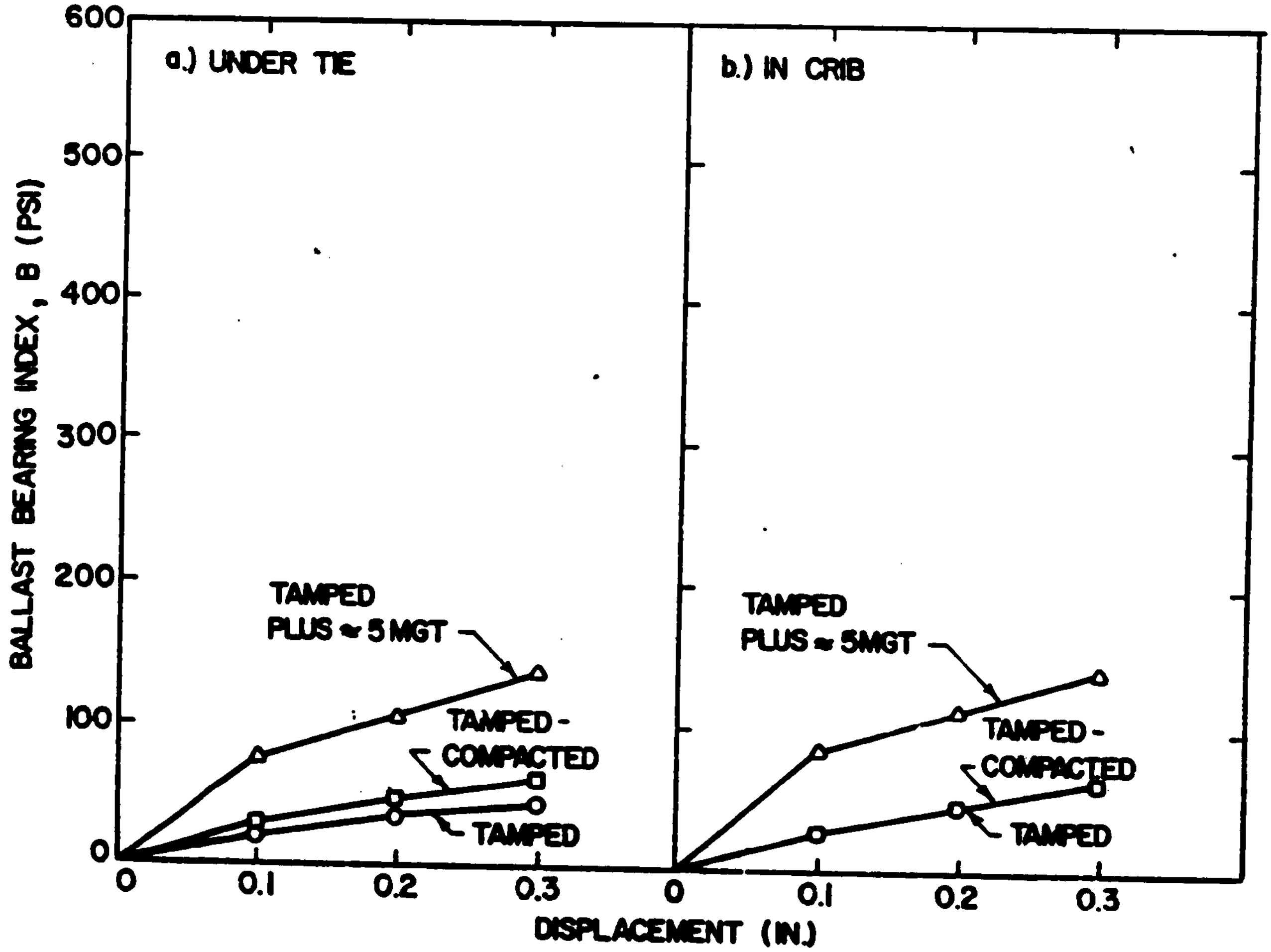


Figure 4.3. Plate Resistance in the Center of the Track at the ICG Site for Limestone and Steel Slag Ballast

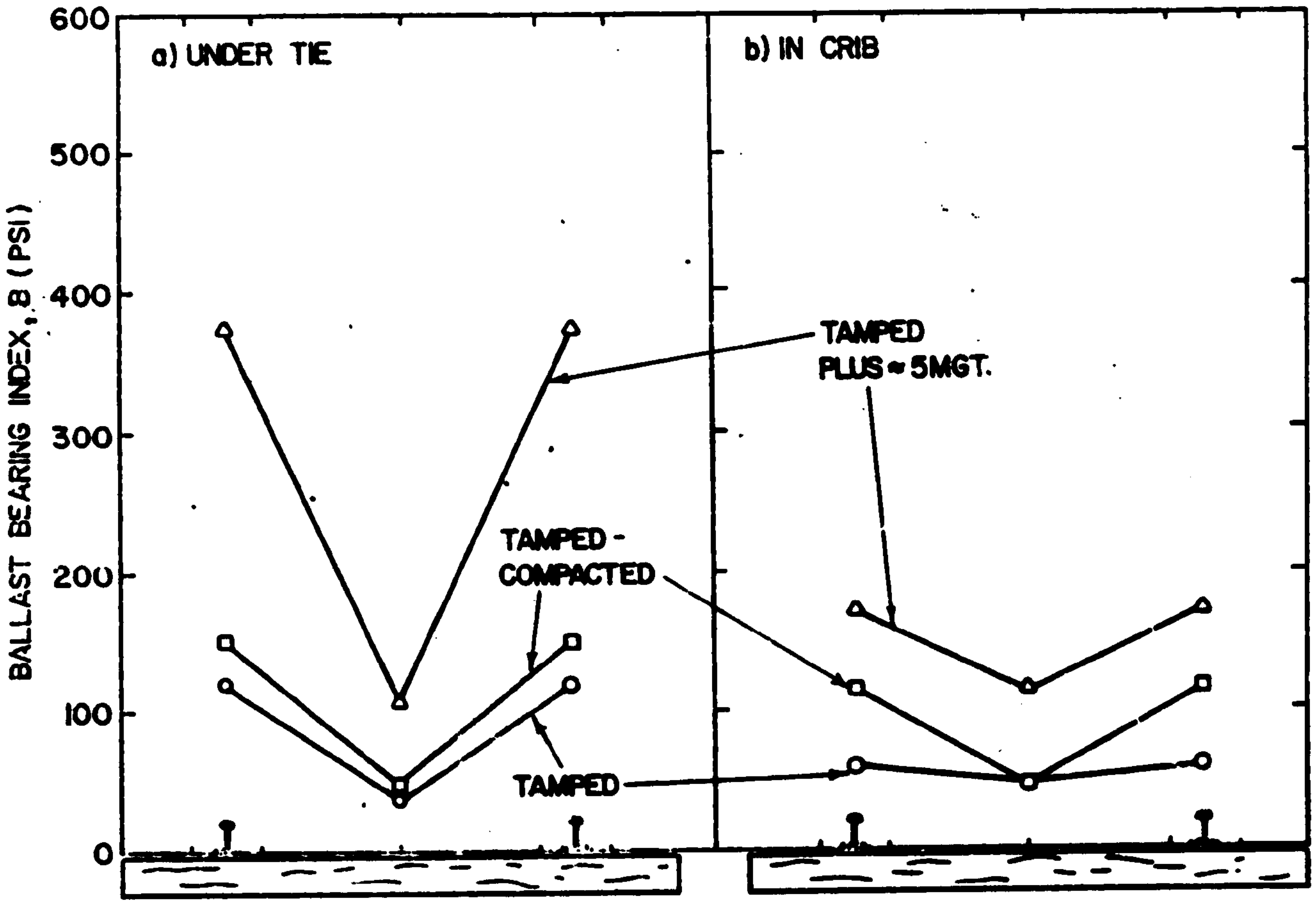


Figure 4.4. PLT Strength Profile at 0.2 in. (5.1 mm) Plate Displacement for ICG Limestone and Steel Slag Ballast

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 and 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.

FAST Test. Dorwart and Panuccio (Ref. 23) analyzed the FAST plate load tests which occurred in November, 1977. The test parameters and track system are described in Section 2 along with track maintenance operations.

The same effect on the center of track values of ballast bearing index (B) resulting from tamping an undisturbed, trafficked track bed prevailed at the FAST tie site as it did at the ICG site. For both the limestone and traprock ballasts a depression approximately equal to the track raise existed under the center of the tie for the tamped-uncompacted (TU) condition and after 0.1 MGT of traffic (AT). The center of track B values are not expected to yield the same increases in strength as those occurring under the rail. Since the depression prevents ballast-tie contact in the center of the track, the strength in that location is not necessarily a good indicator of the changes in ballast physical state with various track conditions.

The profile of limestone ballast results (Fig. 4.5) illustrates increasing ballast strength after tamping with the application of traffic. The effect is apparent both under the tie and in the crib with the under-tie values being greater in magnitude.

The center of track location for both under the tie and in the crib increases in strength with traffic. The under-tie location in particular

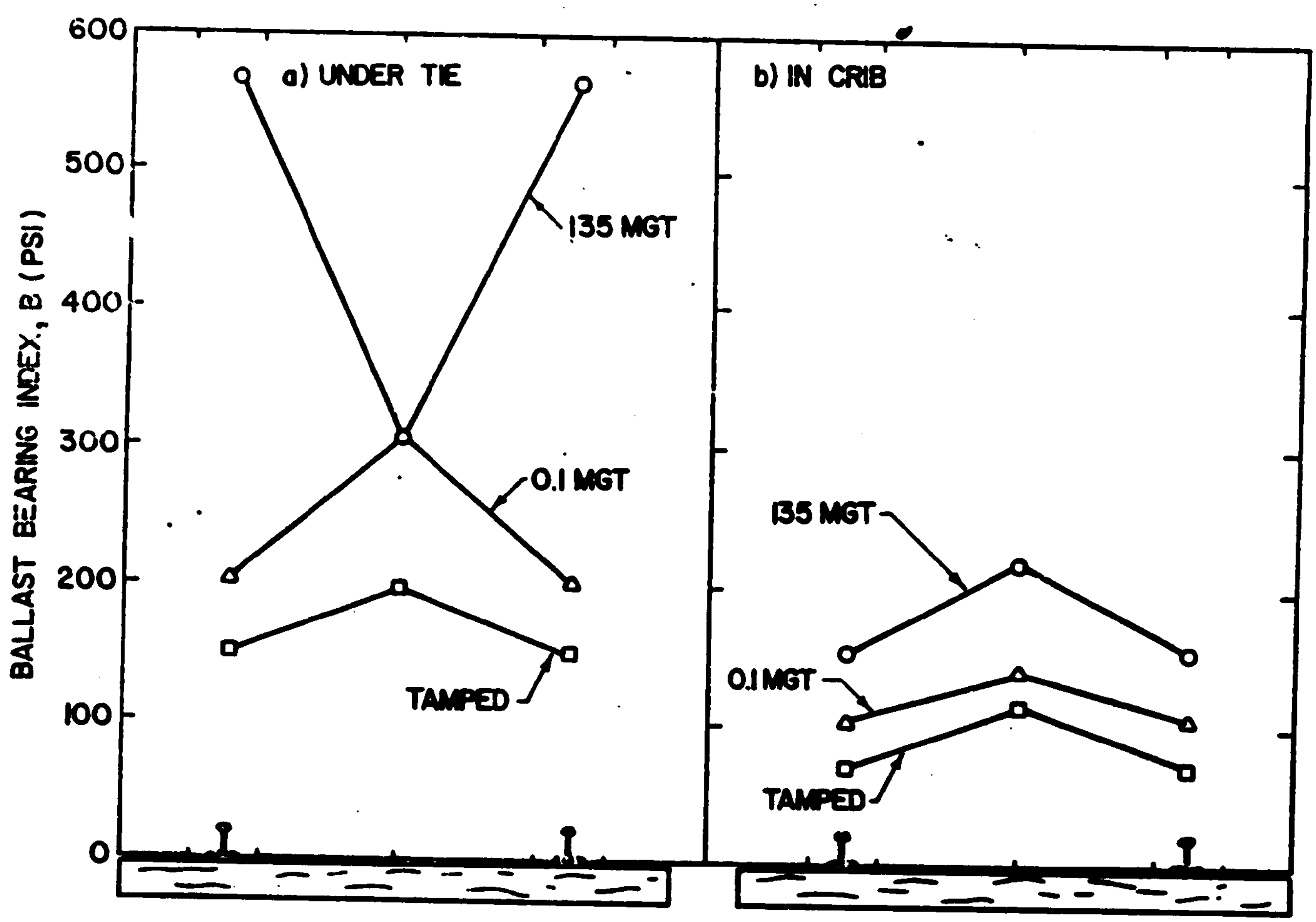


Figure 4.5. PLT Strength Profiles at 0.2 in. (5.1 mm) Plate Displacement for FAST Limestone Ballast

increases to the same value as the undisturbed value with the application of 0.1 MGT of traffic. The corresponding crib value increased by 22% with 0.1 MGT of traffic or 64% of the undisturbed value.

The under 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% from the tamped-only condition with the application of 0.1 MGT of traffic and 115% with 135 MGT of traffic.

The traprock strength (Fig. 4.6) increases with traffic, however, the curves for both under the tie and in the crib are markedly different from the limestone curves. Except for the tamped-only condition, the under-rail values both under the tie and in the crib are generally greater than the corresponding center of track values for traprock than for limestone. Another notable feature for traprock is that the in-crib strength after the application of 0.1 MGT of traffic is the same as the undisturbed crib strength at all locations.

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, as previously indicated, increase after the application of 0.1 MGT of traffic to values equal to the undisturbed condition.

Summary. A summary of the SUNYAB PLT results under the rail is presented in Fig. 4.7. The B value at 0.2 in. (5.1 mm) displacement under the rail is chosen for comparison since this value is representative of the

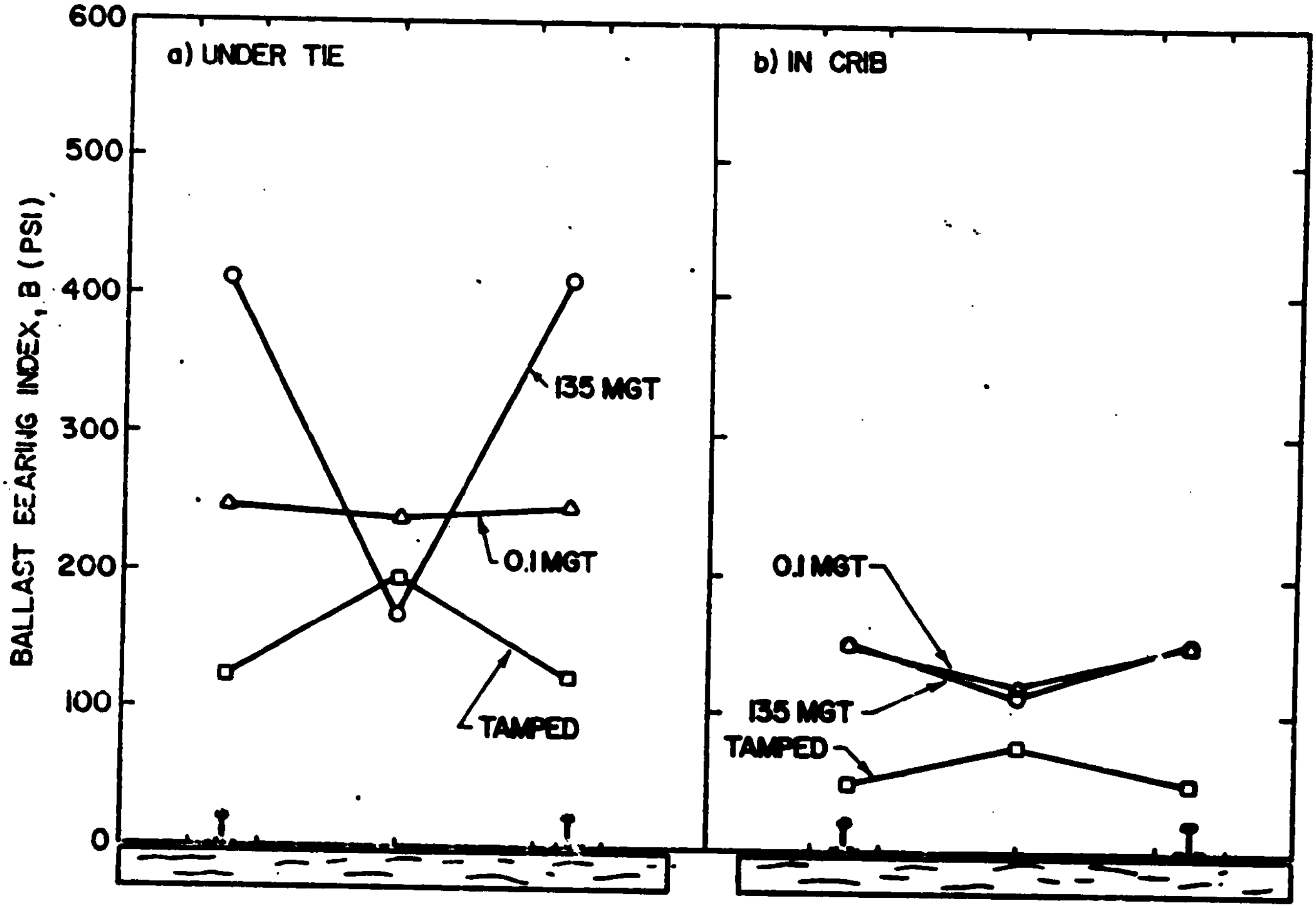


Figure 4.6. PLT Strength Profiles at 0.2 in. (5.1 mm) Plate Displacement for FAST Traprock Ballast

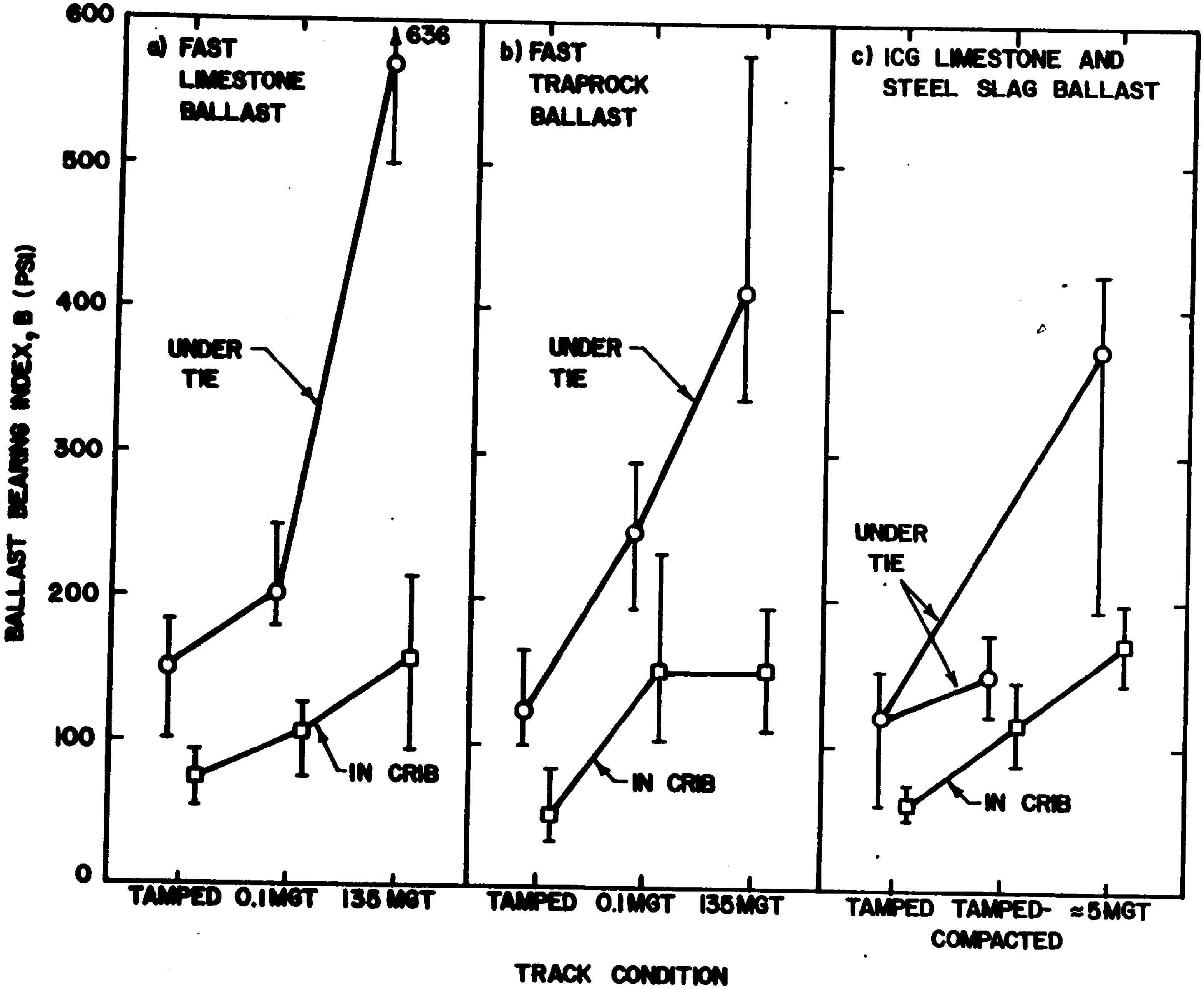


Figure 4.7. Summary of ICG and FAST PLT at 0.2 in. (5.1 mm) Displacement Under the Rail

ballast strength relationships for different ballast types and various track conditions. Included in this figure are the maximum and minimum values of B for each average point.

The center of track 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 for the 5 MGT condition at ICG as well as for the tamped-only and 0.1 MGT traffic conditions at FAST. The trends associated for the center of track values are valid for each particular track system, however, comparisons between track systems is not justified. Therefore, these results are not considered in this summary.

The most pronounced feature displayed in Fig. 4.7 is the increase in the under-rail, under-tie B values with increasing traffic. 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 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 conditon at FAST. For the 5 MGT traffic conditon 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. Note that the ICG strength at 5 MGT of traffic is also between the FAST 0.1 and 135 MGT of traffic values.

The amount of data scatter is greatest after the condition of most traffic. The PLT, however, appears to be a sensitive test for an evaluation of the changes associated with different ballast types, maintenance operations, and train traffic conditons. Also, correlation of the under-rail values would provide the most reliable trends.

4.2 PREVIOUS STUDIES

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. Peckover (Ref. 26) of the Canadian National Railway (CNR) and Prause (Ref. 27) are the only known sources of reported plate load test results.

The test results obtained by Prause (Ref. 27) will not be considered in the present study due to different track and test conditions. The tests were performed using an 8-in. (0.203 m) diameter plate with a plaster of paris seating material placed upon granite ballast. The track consisted of concrete ties which were loaded with 20 to 25 MGT of traffic. In general, the plate displacements for the under-the-rail tests were less than 0.1 in. (2.5 mm), which is insufficient for a comparison with SUNYAB data. Also, the larger plate diameter produces different strength index values than SUNYAB's 5-in. (0.127-m)-diameter plate (Ref. 24).

Peckover (Ref. 26) 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. The CNR tests had the following differences:

1. Instead of plaster of paris, the bearing plate was seated in pea gravel having the same minerology and particle shape as the in-situ ballast.
2. A 250 lb (1113 N) seating load was applied by a hydraulic jack, and this load plus the associated deformation may or may not have been included as part of the load-displacement results.
3. The location of the measured plate displacement was not reported.

These three factors will each have some effect upon the reported results. First, Wayne (Ref. 24) has determined that pea gravel produces slightly lower plate resistance values than plaster of paris for the loose ballast density state. Second, if the seating load is not included, it will not properly reflect the ballast behavior, especially for the loose density state results. As for the third factor, the displacement measuring system should be located such that plate rotation or track system displacements do not influence the recorded ballast load-displacement response. The effects of the latter two factors on the CNR results is unknown and the differences in seating material for all density states has not quantitatively been established. Nevertheless, the test results obtained by Peckover (Ref. 26) will presently be considered representative.

The plate load tests in Ref. 26 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 track bed was replaced with a new crushed rock ballast and a new slag ballast. Full crib ballast conditions are assumed to exist at the time of testing. The ballast gradations and particle shapes were not reported.

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 Matissa and Jackson ballast compactors were used. A vibration time was not specified for either machine. A third compaction machine was also used, but was mounted with shoulder vibration plates only. The results obtained with this third machine will not be discussed because of this difference.

A ballast undercutting operation was also performed with a Kershaw under-cutter. The in-situ ballast was removed and replaced at one test site with a new crushed rock ballast and at another test site with a new slag ballast. Since a Kershaw machine was used, the depth of cut is assumed to be approximately 6 in. (0.15 m) below the base of the tie (Ref. 28). This factor will be considered in the data analysis. Sections of both undercut sites were compacted. However, it is assumed that this track first received tamping, and possibly surfacing and lining, after reballasting and prior to compaction.

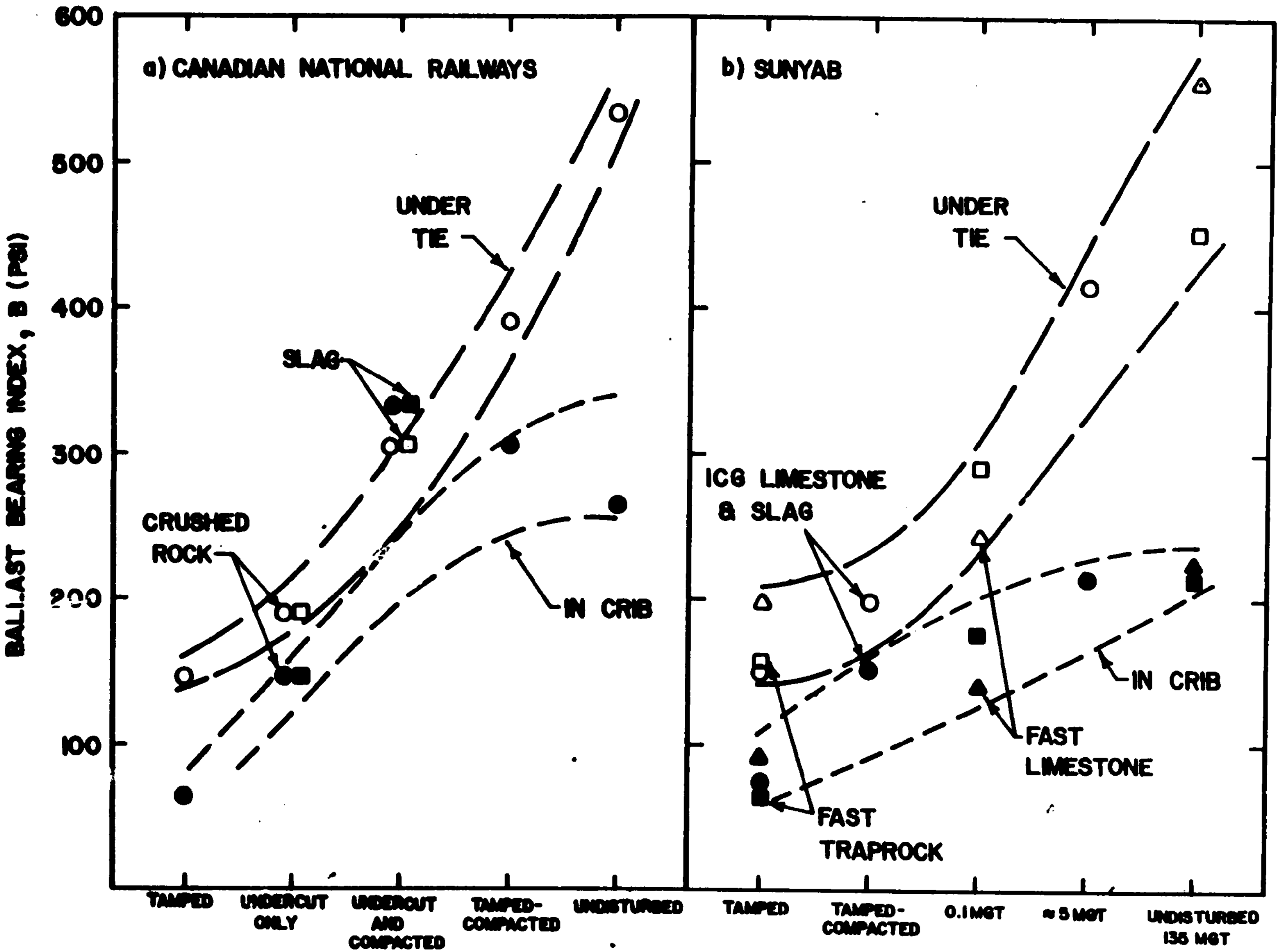


Figure 4.8. Ballast Bearing Index at 0.3 in. (7.6 mm) Plate Displacement under the Rail for Various Track Conditions

The final test condition investigated was on an "undisturbed" ballast. The amount of train traffic loading for this condition was not reported. The lack of sufficient information prohibited any attempt to reasonably estimate this traffic condition.

The test results reported by Peckover (Ref. 26) were in the form of ballast bearing index (B) values at 0.3 in. (7.6 mm) displacement. The PLT's 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. For each track condition investigated, four plate load tests were conducted for each test location.

The average ballast bearing index values are graphically illustrated in Fig. 4.8a for the various track conditions. Peckover indicates a large variation in these test results. Note that the abscissa is not a defined scale and is intended for comparative purposes only. 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 4.8a indicates that the tamped-uncompacted condition (TU), which includes surfacing and lining, produces the lowest B values both in the crib and under the tie for the crushed rock ballast. These values are approximately 25 percent of the respective undisturbed (UU) 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. 4.8a. 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 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 the data in the present form, this situation cannot be resolved.

When crib and shoulder compaction is 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.

4.3 ESTIMATE OF COMPACTION EFFECT

Insufficient quantities of under-rail plate load test data limits the establishment of clearly defined plate resistance trends with track maintenance operations and train traffic loading. The only available source of information to supplement SUNYAB's data was supplied by Peckover (Ref. 26) for the CNR. This data is also limited by the lack of plate resistance values at intermediate traffic levels for the tamped-uncompacted and tamped-compacted conditions. Thus, the differences for these two track conditions, as well as differences in ballast type and the effectiveness of different ballast crib and shoulder compaction equipment, cannot easily be quantified.

A correlation for the under-rail plate load test data with traffic can at best yield only approximate general trends. An evaluation of the absolute magnitudes of plate resistance will be as reliable as any data normalization techniques which may be attempted. Several data normalization approaches have been considered as possible methods of more adequately representing the plate resistance trends. These will not be elaborated upon here, but are discussed by Panuccio and Dorwart (Ref. 20).

An attempt will be made in order to determine an equivalent amount of train traffic on a tamped-only track which is initially offered by ballast crib and shoulder compaction. Any attempt to define a reasonable MGT of traffic which provides a stable or "undisturbed" track condition will be a guess at best. Also, the amount of traffic at which plate resistance cannot be differentiated for either track condition is presently indeterminate due to the lack of available data. Thus, the equivalent traffic estimate, as implied by the plate load test, is the only value comparable to the other ballast physical state test results.

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. 4.8b along with CNR's data in Fig. 4.8a. This figure displays two particularly interesting features. First for the undisturbed condition (UU), the under-tie and in-crib B values are of comparable order of magnitude for CNR and SUNYAB. Note, however, that the average under-tie B values for each ballast type at FAST only represents two of the six tests conducted and are probably much lower than the actual average, since the high plate loads prohibited the tests to be performed to 0.3 in. (7.6 mm) deformation. A similar situation also existed for the 5 MGT condition at ICG. 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. 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 difference is as unexplainable for the TC comparison as it was for the TU to TC comparison for the CNR data sets.

Due to the nature of SUNYAB's data, an approximate equivalent traffic estimate for the TC condition can be obtained. 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.

5. LATERAL TIE PUSH TEST

This chapter will briefly discuss SUNYAB's lateral tie push test field apparatus and test procedure. In order to evaluate the changes in the ballast physical state with track maintenance operations and traffic, the lateral tie resistance at certain displacement levels were obtained from the recorded load-displacement curves. A summary of the general trends for SUNYAB's field investigation are presented in the following sections. Further details of these LTPT test results can be obtained in Refs. 29, 30, and 31. Available United States and foreign data were compiled and compared to SUNYAB's results, and the combined data thoroughly assessed. Several techniques were devised to correlate the LTPT data in order to establish the general lateral tie resistance trends with applied traffic. Panuccio and Dorwart (Ref. 20) provide additional details on the LTPT correlation.

5.1 SUNYAB LATERAL TIE PUSH TEST

The field LTPT's in this study are primarily an extension and adaptation of equipment and procedures established by Ciolko's laboratory investigation (Ref. 25). The test apparatus and procedures will be briefly discussed here in order to familiarize the reader with SUNYAB's method. A thorough description and evaluation of factors affecting lateral tie resistance are adequately covered by Ciolko (Ref. 25). These factors have been accounted for in the test data analysis of each field investigation.

The field test apparatus has been refined several times since the original laboratory design. The main emphasis concentrated upon increasing the reaction load capacity of the structural frame. Each iteration of increasing the structural capacity of the frame for the anticipated lateral loads proved satisfactory for each field trip. That is, for the first ICG trip (Ref. 29), the second ICG trip (Ref. 30), and the FAST trip (Ref. 31), the frame load capacities of 950, 2,000 and 10,000 lb (4.23, 8.9 and 44.5 KN), respectively, were adequate. However, with the advantage of increased frame stiffness, which subsequently increased the weight, the advantages of lightness and portability had to be sacrificed.

The final design of the LTPT apparatus, which includes the instrumentation package, is shown schematically in Fig. 5.1. Detailed specifications of the individual components of the apparatus can be obtained from Selig, et al. (Ref. 1). The key element illustrated in Fig. 5.1, which was a critical design feature throughout the evolution of the LTPT apparatus, was the location of the load applying and measuring system at the centroidal axis of the tie. This method comes close to measuring actual lateral tie resistance, since the location is nearly coincident with the resultant ballast forces acting upon the tie.

The field test procedure was adjusted in accordance with apparatus modifications. These changes were designed primarily to improve testing efficiency. The basic format of the test performed for each field investigation remained essentially unchanged. The detailed test procedure associated with the LTPT apparatus is also contained in Selig, et al. (Ref. 1). However, a brief description of the test procedures used is as follows:

1. Remove the spikes, tie plates, and rail anchors.
2. Align the load frame over the centerline axis of the tie and attach it to the rails.
3. Align and attach the deformation system to the tie.
4. Locate the load system at the centroidal axis of the tie.

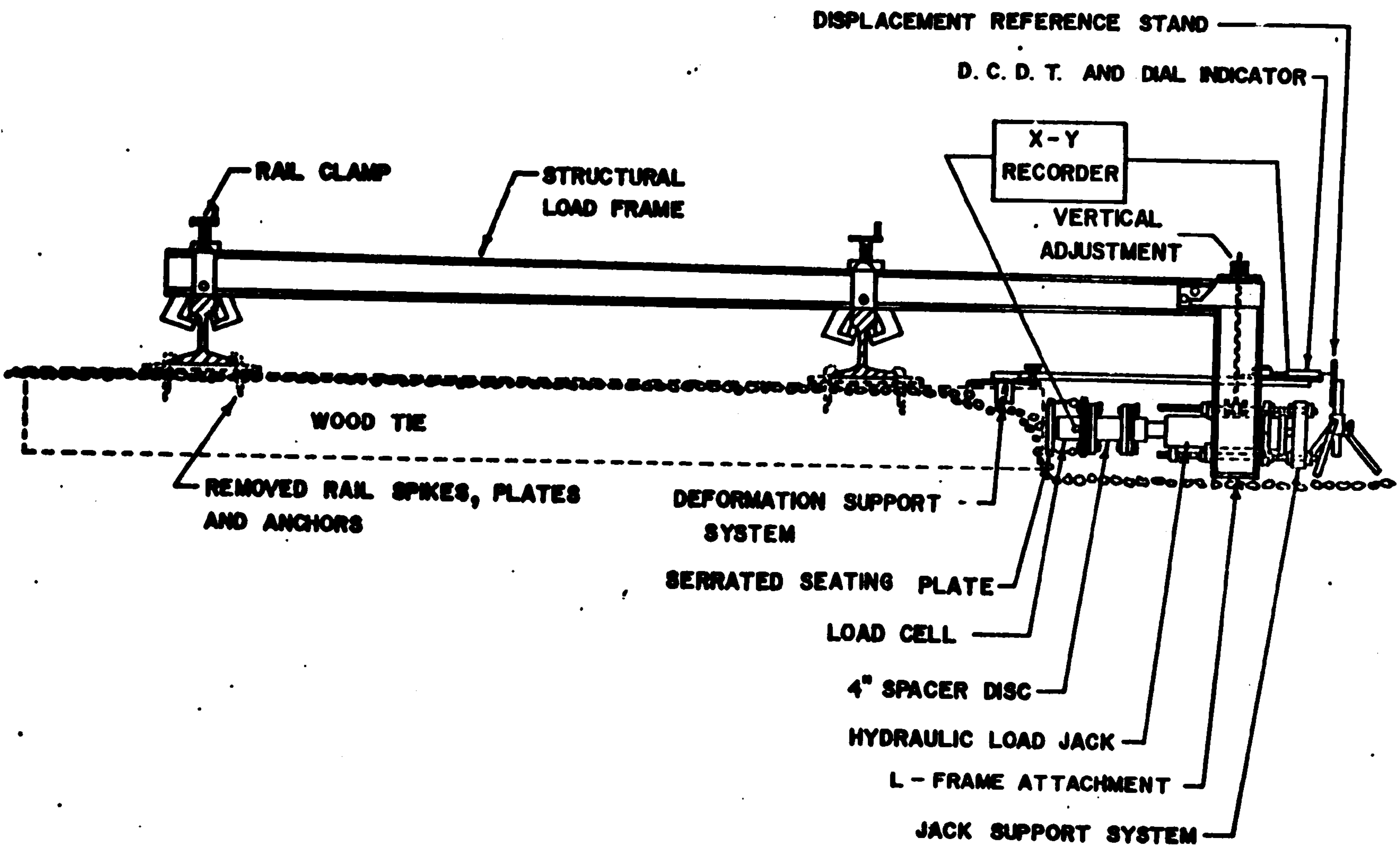


Figure 5.1. Assembled Lateral Tie Push Test Apparatus (Ref. 1)

5. Apply load at a constant rate of 0.25 in. (6.35 mm) per minute until 0.25 in. (6.35 mm) displacement is reached.

6. Reduce the load on the tie to zero.

7. Repeat the procedure for a second cycle.

The total time required per test was approximately 20 minutes.

Load-displacement readings were manually recorded at the start of displacement, at peak displacement, and after complete unloading (i.e., rebound) for each cycle. The instrumentation package is the same as that used for the plate load tests.

The data reduction process involved proportioning the loads and displacements from the recorded field curves with respect to known calibration signals. Each individual test cycle curve was reduced to determine the load values at zero or initial static load (ISL), 0.0393, 0.0787, 0.157, and 0.25 in. (1, 2, 4 and 6.35 mm) displacement. Also computed was a rebound deformation index,

$$E_r = \frac{\Delta_p - \Delta_r}{\Delta_p} \times 100 , \qquad (5.1)$$

in which E_r = the amount of elastic recovery of the tie expressed as a percent, and Δ_p and Δ_r = peak and rebound displacements, respectively. The results obtained on the ICG and FAST test sites will be discussed in the following sections.

<u>Illinois Central Gulf Tests</u>. For the initial series of tests at ICG, ten ties were selected for testing in the tamped-compacted (TC) section, while nine ties were selected in the tamped-uncompacted (TU) section. The details of this test series can be obtained from Panuccio (Ref. 29);

however, the important findings will be presented in this report.

The average load-displacement curves for each loading cycle of the TU and TC sections are illustrated in Fig. 5.2a. The second cycle of the tie loading involved reloading the tie after completion of the first cycle. An important feature displayed in the curves is that additional cycles of loading produced essentially the same lateral resistance as the first cycle for each test condition. This trend is consistent with test results obtained by SUNYAB staff for the two remaining field studies (Refs. 30 and 31). Since the second cycle lateral resistance does not provide much additional information, the second cycle test will not be further elaborated upon in this report.

The effect of crib and shoulder compaction upon increasing the lateral tie resistance is clearly demonstrated in Fig. 5.2a. The first cycle loads for the TC section were consistently 26% greater than the first cycle loads for the TU section at all displacement levels except the initial static load. The initial static load values for TC and TU were comparable for both cycles of loading.

Crib and shoulder compaction appeared to increase the percent elastic recovery (E_r) slightly (Ref. 29). The percent E_r also increased slightly with increasing cycles of loading for both the TU and TC conditions. In general, the average E_r values were within the range of 17 to 31 percent.

Two relationships were found not to exist for either test condition. The load at 0.25 in. (6.35 mm) displacement did not correlate with percent E_r for any cycle of loading, and the initial static load (ISL), or load

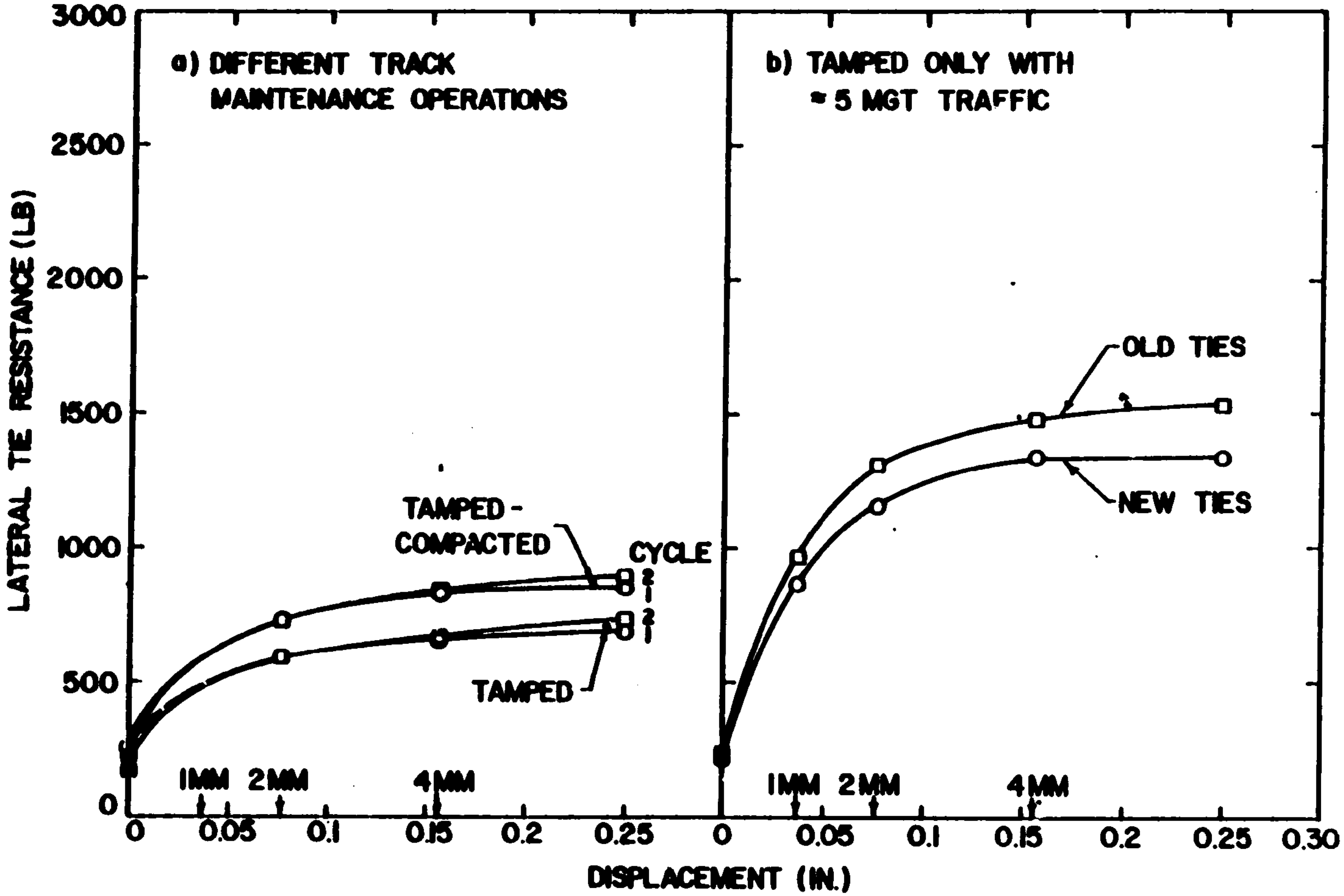


Figure 5.2. LTPT Load-Displacement Curves for ICG Limestone and Steel Slag Ballast

at zero displacement, was not a function of the ballast-tie contact area. For the second test series at ICG, which is considered a tamped-uncompacted condition with 5 MGT applied traffic, a total of 21 ties were tested. Also, eleven of the ties were classified as old, and ten ties as new, based upon visual inspection.

The average first cycle load-displacement curves (Fig. 5.2b) illustrate the effects of tie age and traffic on lateral tie resistance. The lateral resistance for old ties is generally 12% greater than for new ties at all displacement levels, except zero. In this case, the initial static load values were approximately equal. A higher lateral resistance seemed to be indicated for older ties, but a greater amount of scatter existed for the older ties than for the new ties at all displacement levels.

The general shape of the average load-displacement curves for the old and new ties (Fig. 5.2b) is the same as those obtained for the TC and TU conditions (Fig. 5.2a). However, the first cycle lateral resistance for both the old and new ties, i.e., the TU condition with 5 MGT of traffic, is approximately twice that obtained for the TU condition alone at all displacment levels except zero.

The percent elastic recovery (E_r) is more consistent and slightly greater for the old ties then for the new ties (Ref. 4). The average E_r values for all ties were generally within the range of 19 to 37% for 5 MGT of traffic. These results are slightly greater than the E_r values obtained from the TU condition.

For the second test series, the load at 0.25 in. (6.35 mm) displacement did not correlate with percent E_r. Also, the lateral resistance at all displacement levels and percent E_r were not a function of either the base area of the tie or the total ballast-tie contact area.

FAST Tests. Lateral tie resistance was investigated for three track conditions: 1) 135 MGT applied traffic (UU) condition, 2) tamped only (TU condition), and 3) 0.1 MGT applied traffic (AT condition). Five lateral tie push tests were performed for each ballast type at a given track condition. A detailed discussion of the lateral tie push tests at the FAST track can be obtained from Dorwart and Panuccio (Ref. 31). The most significant results are represented by the first cycle load-displacement curves for the limestone (Fig. 5.3a) and traprock (Fig. 5.3b). The change in lateral tie resistance for the various traffic conditons is clearly illustrated.

The data analysis for the FAST tests involved: 1) comparisons of limestone to traprock for a particular track conditon, and 2) comparisons of different track conditions for a particular ballast type. For each comparison the percent lateral resistance change was determined at the four displacement levels: 0.0394, 0.0787, 0.157, and 0.25 in. (1, 2, 4 and 6.35 mm). Relatively consistent percentages were obtained for all four displacement levels. Thus, the four values were averaged in presenting the general trends. The initial static load (ISL) values, on the other hand, did not demonstrate the same consistency, so they will not be considered in this discussion, other than to note that they were comparable for both ballast types (Fig. 5.3).

The traprock and limestone results are compared in Fig. 5.3. The first cycle average loads were 15% greater for traprock than for limestone in the TU condition, but the traprock was 15% lower than the limestone for the AT condition, and 6% lower for the UU condition. The loads for the UU condition are comparable for both ballast types. Also, loads for the TU and AT conditions are 25 and 38%, respectively, of the UU condition for lime-

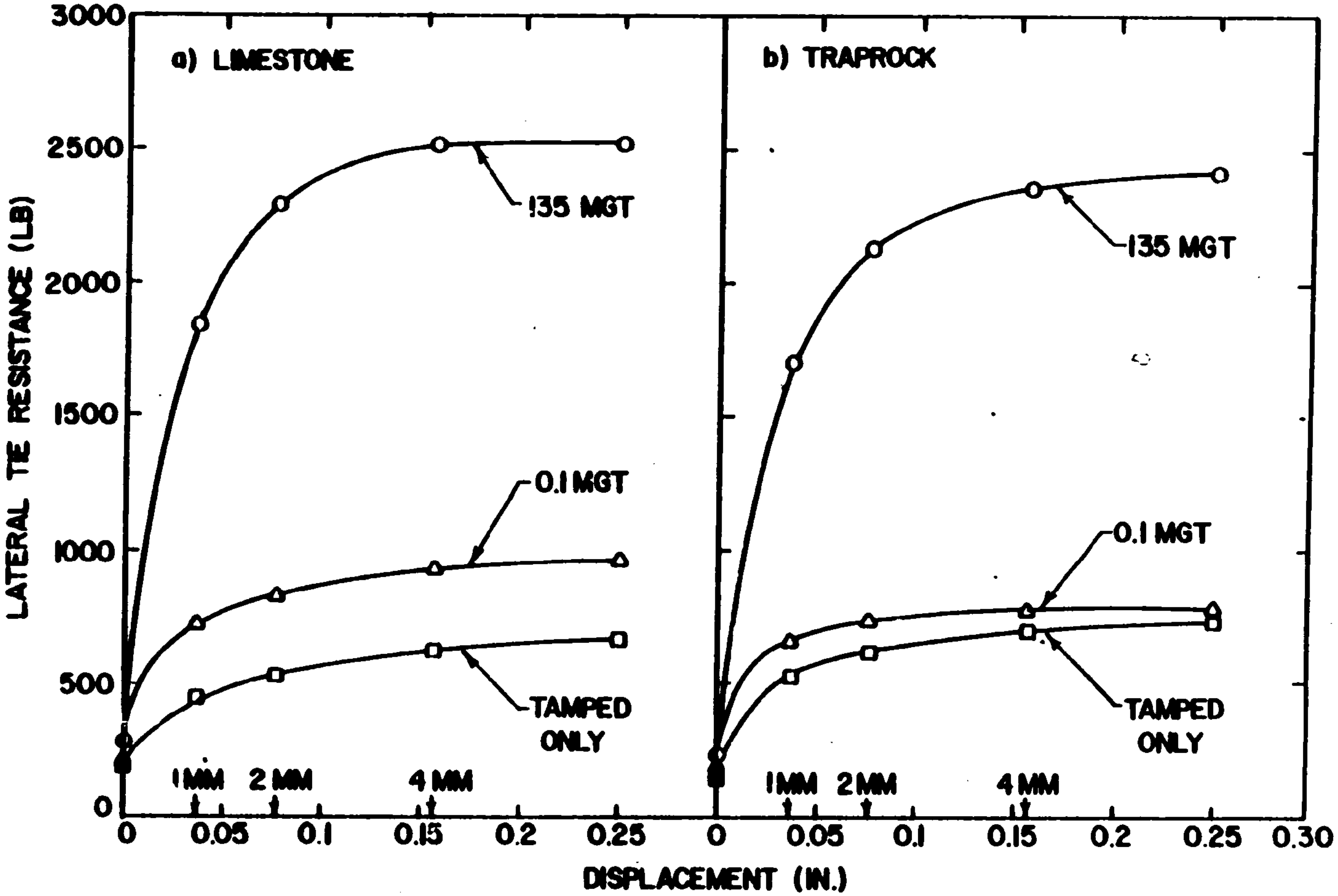


Figure 5.3. LTPT Load-Displacement Curves at FAST for Various Track Conditions

stone, and 30 and 35%, respectively, of the UU condition for traprock. For both ballasts, the application of 0.1 MGT of traffic following the tamping operation measurably increases the lateral tie resistance. Although limestone has a slightly lower lateral resistance than traprock after tamping, the limestone ballast attains a greater resistance at a more rapid rate with the application of 0.1 MGT of traffic.

Generally, all first and second cycle percent elastic recovery (E_r) values for both ballast types were between 10 and 30% for the three different track conditions (Ref. 31). The second cycle E_r values were slightly greater than the first cycle for each track condition. Traprock and limestone yielded comparable values of E_r. However, a definite relationship of E_r with amount of traffic could not be established.

No correlation existed between the first and second cycle peak loads and the percent E_r for either ballast type. Based upon the ICG findings, a relationship between load or percent E_r and ballast-tie contact area was not attempted.

Summary. A summary of the SUNYAB LTPT results for the ICG and FAST sites is presented in Fig. 5.4. The tie type, dimensions, and spacings, as well as the amount of track raise for the tamping operation (TU condition) were approximately equal for both sites. The deficiency of crib ballast due to the tamping raise may, however, exhibit a slight influence on the magnitudes of lateral tie resistance. Load values from 0.0394 to 0.25 in. (1 to 6.35 mm) displacement levels consistently demonstrate the same percent changes in tie resistance with different track maintenance operations and train traffic. The average load value at 2 mm displacement was chosen for comparison, since that displacement level best represents the general trends.

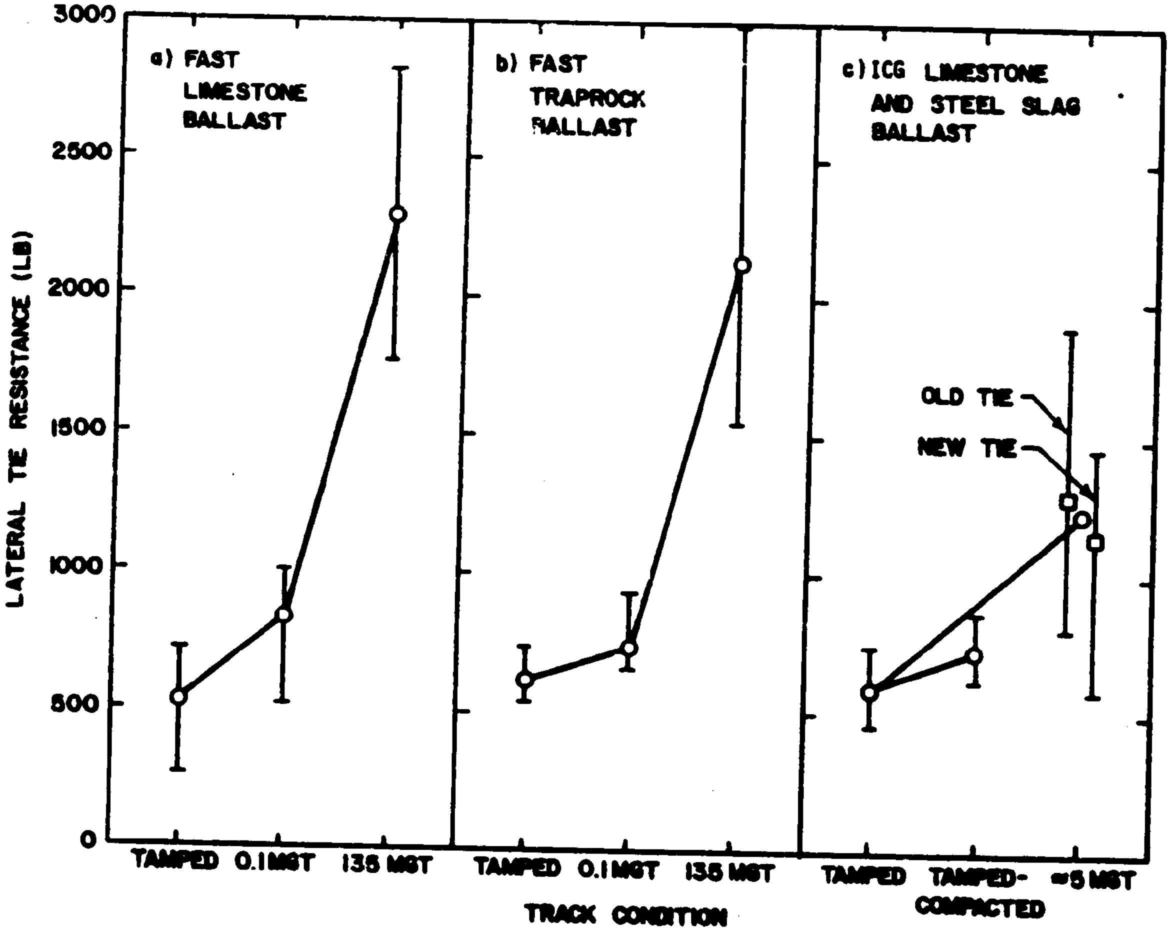


Figure 5.4. Summary of ICG and FAST LTPT at 0.0787 in. (2 mm) Displacement

In Fig. 5.4, with each average load value are the maximum and minimum values, which are rough indicators of the amount of data scatter. The scatter appears to increase with increasing train loading.

Several other results are evident in Fig. 5.4 with the most notable being the large increase in lateral tie resistance with traffic for both test sites. A similarity in tie resistance obtained by the tamping only (TU) operation for the three ballast types can also be seen, and implies that the lateral tie resistance at ICG was not affected by the pre-tamping track maintenance operations, such as undercutting. The value of tie resistance after crib and shoulder compaction (TC) at the ICG site is shown to be comparable to the 0.1 MGT of traffic condition at the FAST site, and the 5 MGT tie resistance at ICG lies between the 0.1 and 135 MGT values at the FAST site.

Generally,the LTPT appears to be sensitive to differences in ballast types, tie condition, and track maintenance operations, and yields fairly reproducible results considering the varied histories of each track system. The correlation trends can most satisfactorily be developed by utilizing the lateral tie resistance at 0.0787 or 0.157 in. (2 or 4 mm) displacement levels.

Several other indices compared for each test series with no significant trends developing were percent elastic recovery, cycles of loading, and ballast-tie contact area. The initial load (ISL) was also evaluated and presently determined not to be useful as an indicator of the changes in lateral tie resistance with traffic.

5.2 PREVIOUS STUDIES

United States. The only previous U. S. field lateral tie push (pull) test results on individual ties were reported by Cunney, et al (Ref. 3) from ENSCO, which will herein be referred to as ENSCO. This testing was carried out under Federal Railroad Administration sponsorship. The purpose of this study was to utilize the LTPT as a means of evaluating the effect of accelerated ballast consolidation on lateral track stability. The ballast crib and shoulder vibratory compaction machine used was a Plasser-American CPM 800 owned by FRA.

The tests were conducted on the sites of five commercial railroads: the Southern Railway Company, Boston and Maine Corporation, Penn Central Transportation Company, St. Louis and Southwestern Railway Company, and Missouri Pacific Railroad Company. The test sites of these railroads were in regionally different locations; however, the track structures were similar. The important track and test conditions were carefully documented and are presented in Tables 5.1 and 5.2 respectively.

In general, the ties were hardwood with average dimensions of 7 in. (0.178 m) by 8.5 in. (0.2.6 m) by 8.5 ft (2.59 m), with an average tie spacing of 20 in. (0.508 m). The ties were visually classified as old or new. All ties, including the old, are assumed to be in relatively good condition at the time of testing, since each track is a freight line with a high operating speed and is heavily loaded yearly with a high MGT. The average track raise was approximately 2 in. (51 mm). Either 3 or 5 second vibration time was used with the crib and shoulder compactor for the selected test sections. The ballast type was primarily a crushed granite except for Penn Central, which was a crushed limestone, and each ballast was AREA gradation number 4. The cribs are assumed full, since a ballast

Table 5.1. LTPT Track Conditions For All Railroads

Railroad	Track Classification	Max. Speed (mph)	Annual Traffic (MGT)	Ties: Type	Ties: Dimensions	Ties: Spacing	Ballast Type (AREA Gradation)
United States							
Southern #1 (Ref. 3)	Freight Class #4	60	25	New (1973) Oak	7 in. x 8 in. x 8.5 ft	20 in.	Crushed Granite (#4)
Boston & Maine (Ref. 3)	Freight Class #4	50	19	Old & New (1972) Hard Wood	7 in. x 8 in. x 8.5 ft	21 in.	Crushed Granite (#4)
Penn Central (Ref. 3)	Freight Class #5	70	40	Old (1966) New (1973)	7 in. x 9 in. x 8.5 ft	20 in.	Crushed Limestone (#4)
St. Louis & Southwestern (Ref. 3)	Freight Class #5	70	41	Old New (1973)	7 in. x 9 in. x 9.0 ft	20 in.	Crushed Granite (#4)
Missouri-Pacific (Ref. 3)	Freight Class #4	50	18	New (1973) Oak	7 in. x 9 in. x 8.5 ft	19.5 in.	Crushed Granite (#4)
Penn Central (Ref. 3)	Freight Class #4	50	15	Yellow Pine	6 in. x 8 in. x 8.5 ft	21 in.	Crushed Granite with Fines
Southern #2 (Ref. 3, 32)	Freight Class #4	60	≈10-20+	Old New (1974) Oak	7 in. x 8 in. x 8.5 ft	20 in.	Crushed Granite (#4)
Foreign							
C.N.R. (Ref. 33)	-	-	≈14*	Wood	6 in. x 8 in. x 7.75 ft 7 in. x 9 in. x 7.75 ft	-	Crushed Stone
Austria (Wenel) (Ref. 34)	1st order	100	≈8**	B-58 Concrete	-	-	Gravel

+ Assumed
* Estimated bases upon 1.2 MGT/1 Month
** Estimated based upon 1.3 MGT/2 Months

Table 5.2. LTPT Test Conditions For All Railroads

Railroad	Date Tested	Test Load (MGT)	Type Track Degree, (Super elevation)	Type Rail	Tamping Raise (in)	Compactor Vibration Time (Sec)	No. Ties Tested
United States							
Southern #1 (Ref. 3)	July, Aug. 1973	0, 0.5, 1.5	Tangent Curved (2.2°, 5 in.)	CWR 132	2→3	5	20/Section
Boston & Maine (Ref. 3)	Aug., Sept. 1973	0, 1, 2	Tangent Curved (1°.35', 1 in.)	CWR 112	1→2	3	20/Section
			Curved (2°, 1-3/8 in.)	Bolted 132			
Penn Central (Ref. 3)	Aug. 1973	0, 0.5, 1.7	Curved (0° 30', 0.25 in.)	CWR 140	2	5	20/Section
			Tangent			3	
St. Louis & Southwestern (Ref. 3)	Nov. 1973	0, 0.75, 2.0	Tangent	CWR 112	1.5	5	20/Section
Missouri-Pacific (Ref. 3)	Dec. 1973, Jan. 1974	0, 0.75, 2.0	Curved (- -) Tangent	CWR 119	2→3	3	20/Section
Penn. Central (Ref. 3)	Oct. 1973	Undisturbed		CWR 140	-	-	2
Southern #2 (Ref. 3, 32)	June-Aug. 1974	0.032, 0.065, 0.16, 0.26, 0.68, 0.71, 1.62, 1.68	Tangent	CWR 132	2→3	3	16/Section
Foreign							
C.N.R. (Ref. 33)	July-Aug. 1974	0, 0.3, 0.6, 1.2, Undisturbed	Tangent	132	-	-	20/Track Condition
Austria (Wanel) (Ref. 34)	Nov. 1971	0.01, 0.045, 0.09, 1.3, Undisturbed	Tangent	118	-	-	20/Section

sweeping operation was performed prior to crib and shoulder compaction. The dimensions of shoulder width and shoulder slope were not reported for any of the sites.

A section of track at each site was divided into four test sections. Two sections were tamped-only and the remaining two sections were tamped followed by crib and shoulder compaction. Ties were tested in tangent track at each site and on curved track at four of the sites. For the test sites with both track geometries, a tamped-only and a tamped-compacted test section were provided. The LTPT was performed on 20 ties in each test section after the initial track maintenance operations and after selected intervals of applied train traffic.

Two different types of field apparatus were reported to have been used in the ENSCO study to measure lateral tie resistance. The initial tests for all five railroads used the equipment schematically illustrated in Fig. 5.5. Load and displacement level were recorded manually from pressure gage and dial indicator readings. The tests were apparently performed at a constant but not necessarily a consistent deformation rate. Penn Central later used ENSCO's system, which included slight modifications, in order to obtain accurate values of lateral tie resistance for an undisturbed track condition. However, tests were performed only on two ties. Therefore, they will not be considered further.

Southern Railway also fabricated a tie pull test apparatus (Fig. 5.6) with the intent of supplementing the data obtained from ENSCO's initial test series. This apparatus is distinctly different from ENSCO'S earlier version in that the load applying system is located parallel to the top of the tie and not 4 to 5 in. (0.1 to 0.13 m) above the top of the tie. Also, a continuous load-displacement record for each test

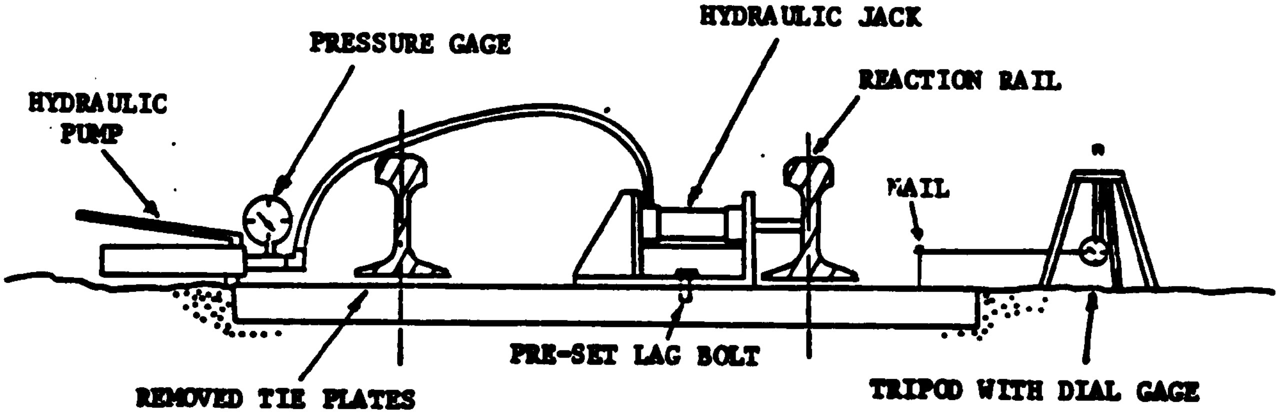


Figure 5.5. Lateral Tie Push Test Apparatus Used by ENSCO (Ref. 3) and Similar to CNR (Ref. 33)

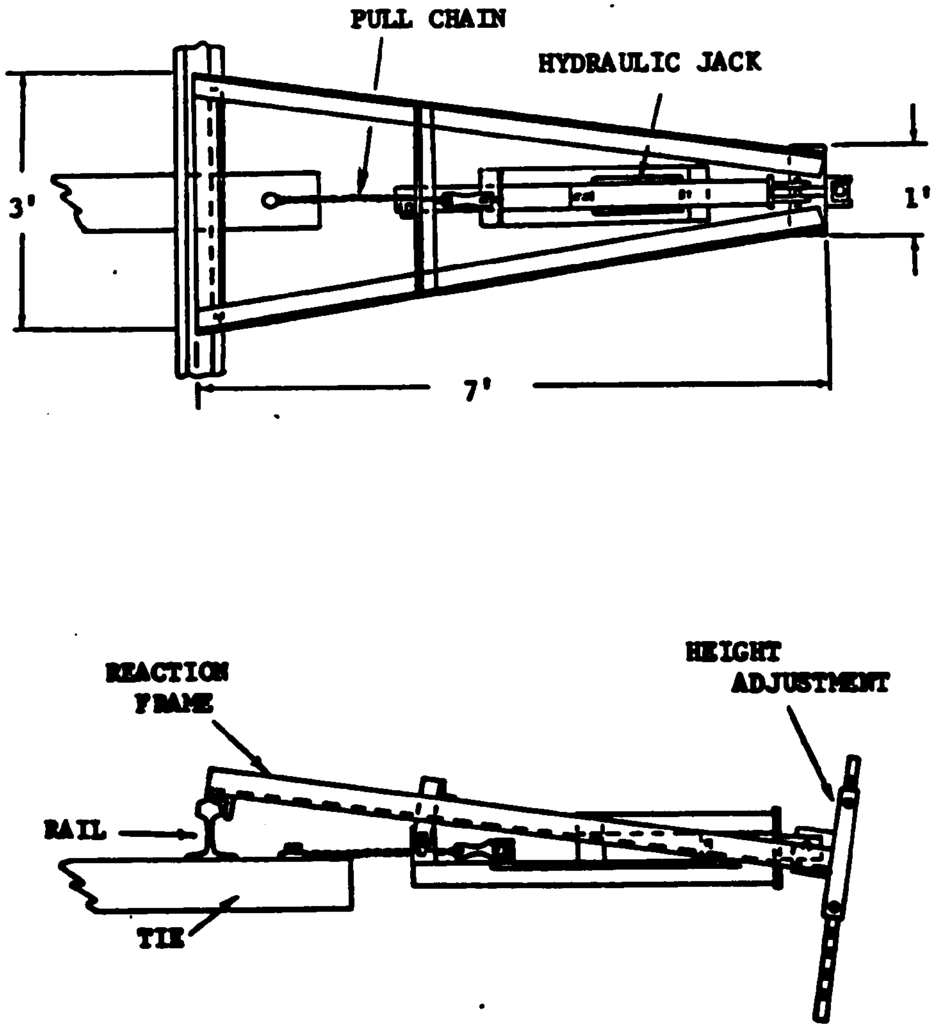


Figure 5.6. Lateral Tie Pull Test Apparatus Used by Southern #2 (Ref. 32)

was obtained with electronic transducers being used in conjunction with mechanical gages. This is a significant improvement in field data recording techniques, since the previous method is quite susceptible to errors. These errors might include synchronized recording of the load and displacement readings, insufficient resolution of gages, and difficulty in identifying the intercept of the load-displacement curves. For these reasons, the test results obtained with this apparatus will be discussed separately and treated as Southern set number 2. The initial tests conducted by ENSCO on the Southern line will thus be defined as Southern set number 1.

Southern also tested different ties at each increment of traffic, whereas the initial ENSCO test series apparently retested the same ties. The differences in lateral tie resistance of old and new ties with track maintenance practices and subsequent traffic was an additional feature considered by Southern test number 2.

ENSCO (Ref. 3) tabulated lateral tie resistance values at 0.0787 and 0.157 in. (2 and 4 mm) displacement levels for the initial test series. The data was subdivided according to tamped-only and tamped-compacted conditions, type of track, and amount of applied traffic to the test section on each of the five participating railroads. Included were four "representative" values of tie resistance for the twenty ties tested per section. A large degree of scatter was contained within these four values. These "representative" values were averaged and are listed in Appendix B of Ref. 20. Some of the load values at 0.157 in. (4 mm) displacement were noted to have been obtained by extrapolation.

Also, ENSCO included a statistical analysis of the the lateral tie resistance data on the tangent track of Southern test number 1 and on the Boston and Maine test. Values from 9 to 20 new ties were used to compute an average value. This data apparently originated from the same data as the "representative" values previously discussed for the initial test series. Thus, the statistical data is expected to yield a more realistic estimate of the actual average lateral tie resistance than the average of the "representative" values. Both data sets for the two railroads are compared in Fig. 5.7. The statistical data average is generally 80 lb (356 N) less at 0.0787 in. (2 mm) and 170 lb (757 N) less at 0.157 in. (4 mm) displacement than the "representative" average values. Since the statistical data encompasses a larger set of tie resistance values, only this data will be utilized for the Southern test number 1, and for Boston and Maine railroad.

Two additional points of ENSCO's initial test series for the five participating railroads need to be elaborated upon. First, ENSCO computed the average lateral tie resistance values for the tamped-only and tamped-compacted conditions at 0.0787 in. (2 mm) displacement and zero applied traffic condition. Each average value was obtained by combining all the original test results from the tangent and curved track test sections for all five railroads. These average values, which should be the same as statistical averages, were slightly lower than the average computed from the "representative" test values. It was previously indicated that the Southern test number 1 and the Boston and Maine "representative" averages were slightly higher than their respective statistical averages. However, the difference in the "representative" and statistical averages for these two data sets is greater than the difference for all the five

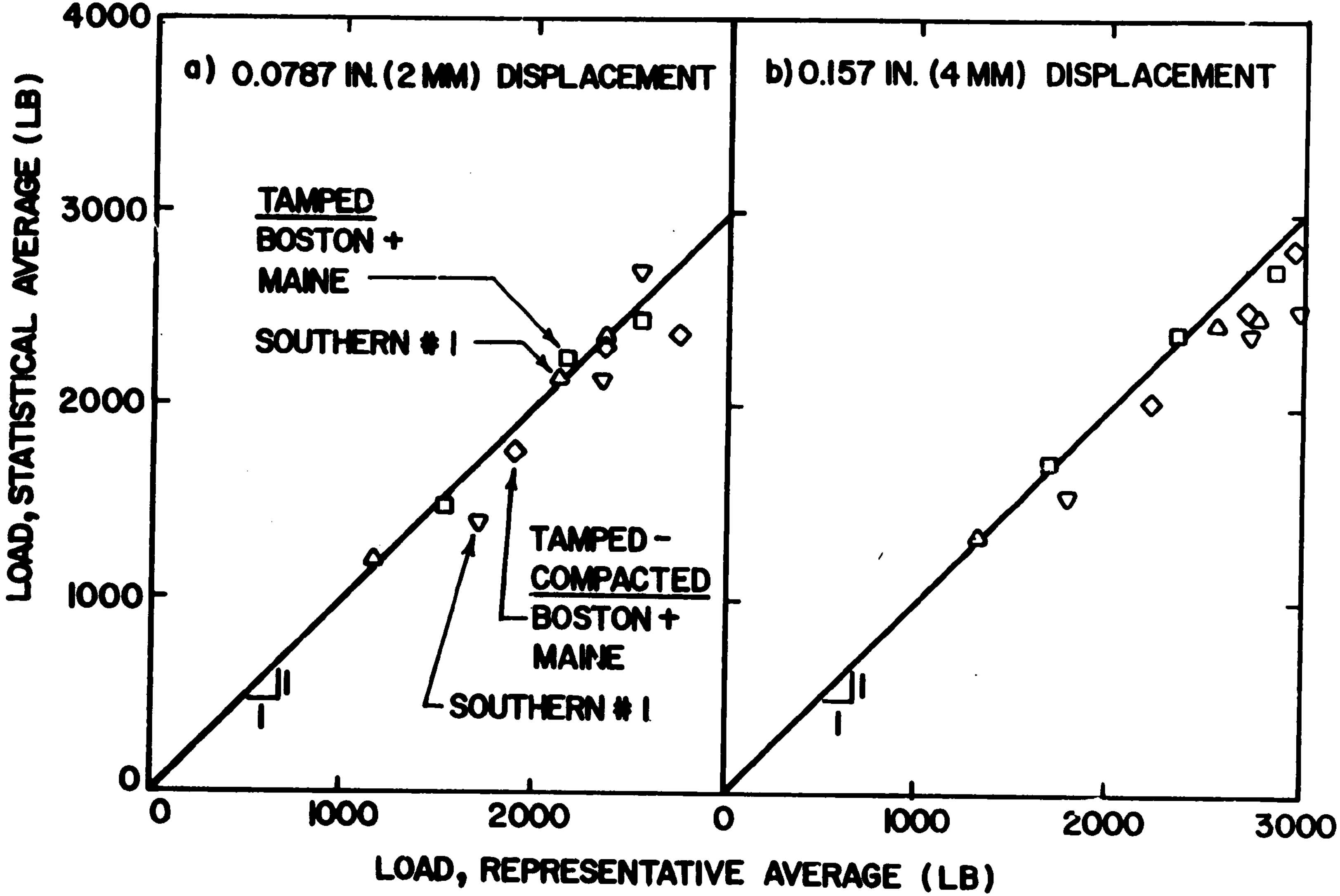


Figure 5.7. Comparison of Statistical and Representative Average LTPT Results on U.S. Tangent Track for Different Track Conditions

railroads combined. This implies that the "representative" average values for the three remaining railroads are probably much closer to their respective statistical averages than the Southern test number 1 and the Boston and Maine data. Thus, the Penn Central, St. Louis and Southwestern, and Missouri Pacific "representative" average values are probably realistic estimates of each of these railroad's average lateral tie resistances at 0.0787 in. (2 mm) displacement and zero MGT traffic condition. The "representative" average values at 0.157 in. (4 mm) displacement and other trafficked conditions on tangent and curved track data will have to be assumed as realistic averages.

The second point to be considered is tie age, which is only a subjective interpretation of the tie condition. ENSCO states that the LTPT statistical data on Southern number 1 was for new ties only in new ballast. These values were low compared to the other results. However, with the exception of Penn Central, and Boston and Maine, all LTPT's apparently were performed on new ties, i.e., 1 to 1-1/2 year age in service, and yielded comparable values. Also, ENSCO does not quantitatively differentiate between the old and new tie lateral resistances. Thus, for the initial test series, all data will be considered without distinguishing initial tie age.

The lateral tie resistances at 0.157 in. (4 mm) displacement will be presented, since Panuccio and Dorwart (Ref. 20) have shown the values at 0.0787 in. (2 mm) exhibit similar trends.

The changes in lateral tie resistance at 0.157 in. (4 mm) displacement from a tamped and uncompacted state are illustrated in Fig. 5.8a for tangent track and in Fig. 5.8b for curved track. In general, tie resistance increases with applied traffic for both types of track. However, large

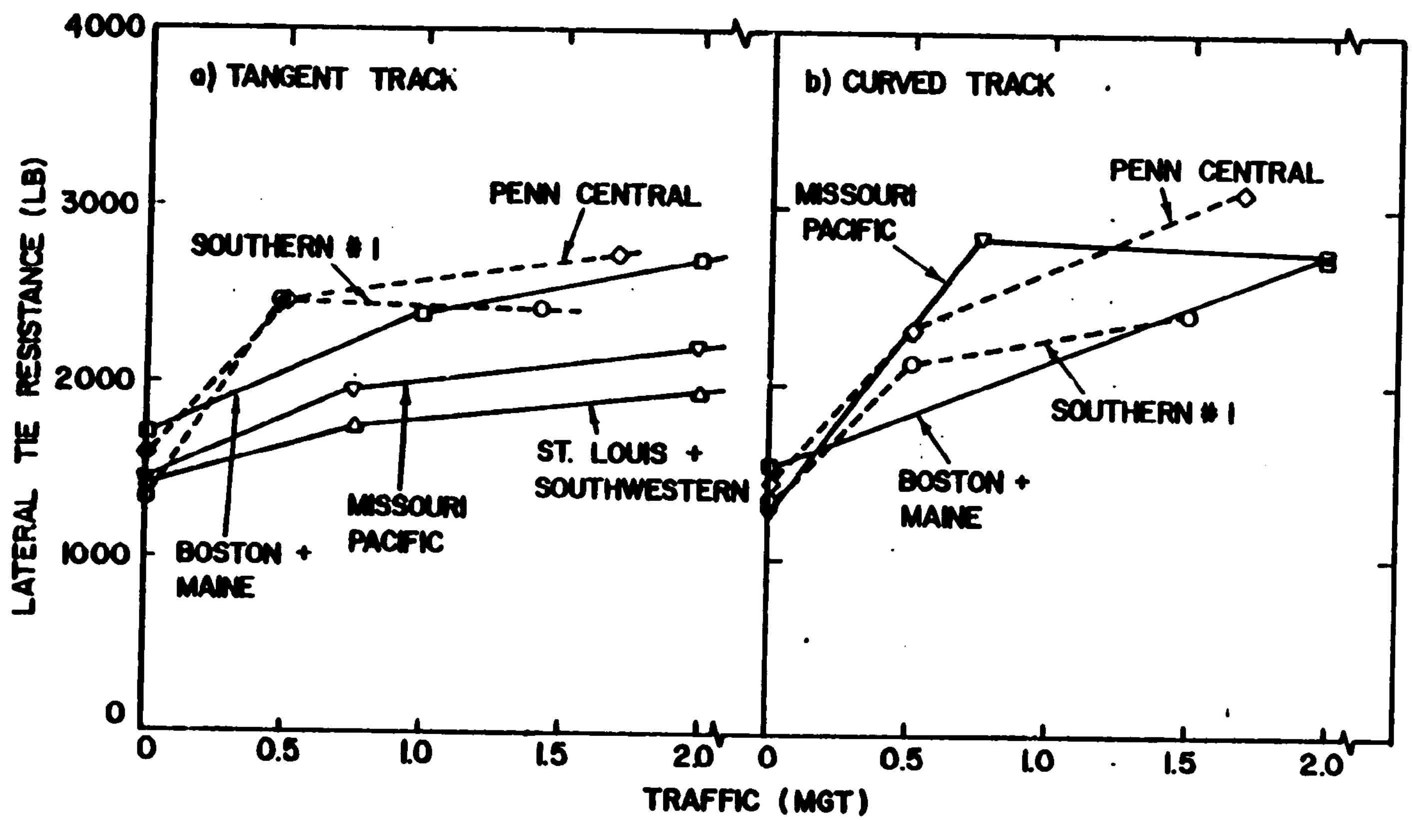


Figure 5.8. U.S. (EMSCO) LTPT results at 0.157 in. (4 mm) Displacement for the Tamped-Uncompacted Condition on Different Types of Track

differences in values are evident for the similar track structures. Penn Central tests were noted to have been performed on a mixture of old and new ties in a crushed limestone trackbed. These results are comparable to those of the other four railroads with new ties and a crushed granite ballast. Also, the effect of a reported wet ballast condition existing on the sites at 1.7 MGT for Penn Central and 2 MGT for Missouri Pacific and St. Louis and Southwestern does not appear to appreciably change the tie resistance trend with traffic.

A comparison of lateral tie resistance values immediately after tamping demonstrates nearly identical results for tangent and curved track. Note that ENSCO did not stipulate the direction in which the ties were displaced on the curves. The lateral resistance trends with traffic on curved track fall within the same ranges as those on tangent track. The only significant difference occurred on the curved track for the Missouri Pacific Railroad which yielded some of the highest reported values. The reported 5 in. (0.127 m) superelevation on the Southern number 1 track was the greatest. These results did not indicate that lateral resistance was higher on curved track than on tangent track. Thus, considering the present quantity of data, it is inconclusive to state that curved track would yield higher lateral tie resistance than tangent track after tamping and after applied train traffic.

The effect on lateral tie resistance of crib and shoulder compaction following the tamping operation is illustrated in Fig. 5.9a for tangent track and Fig. 5.9b for curved track. In general, lateral resistance increases up to approximately 1 MGT of traffic and then appears to level off with increasing traffic loading. The observations stated for the tamped-uncompacted condition are also present and consistent for the

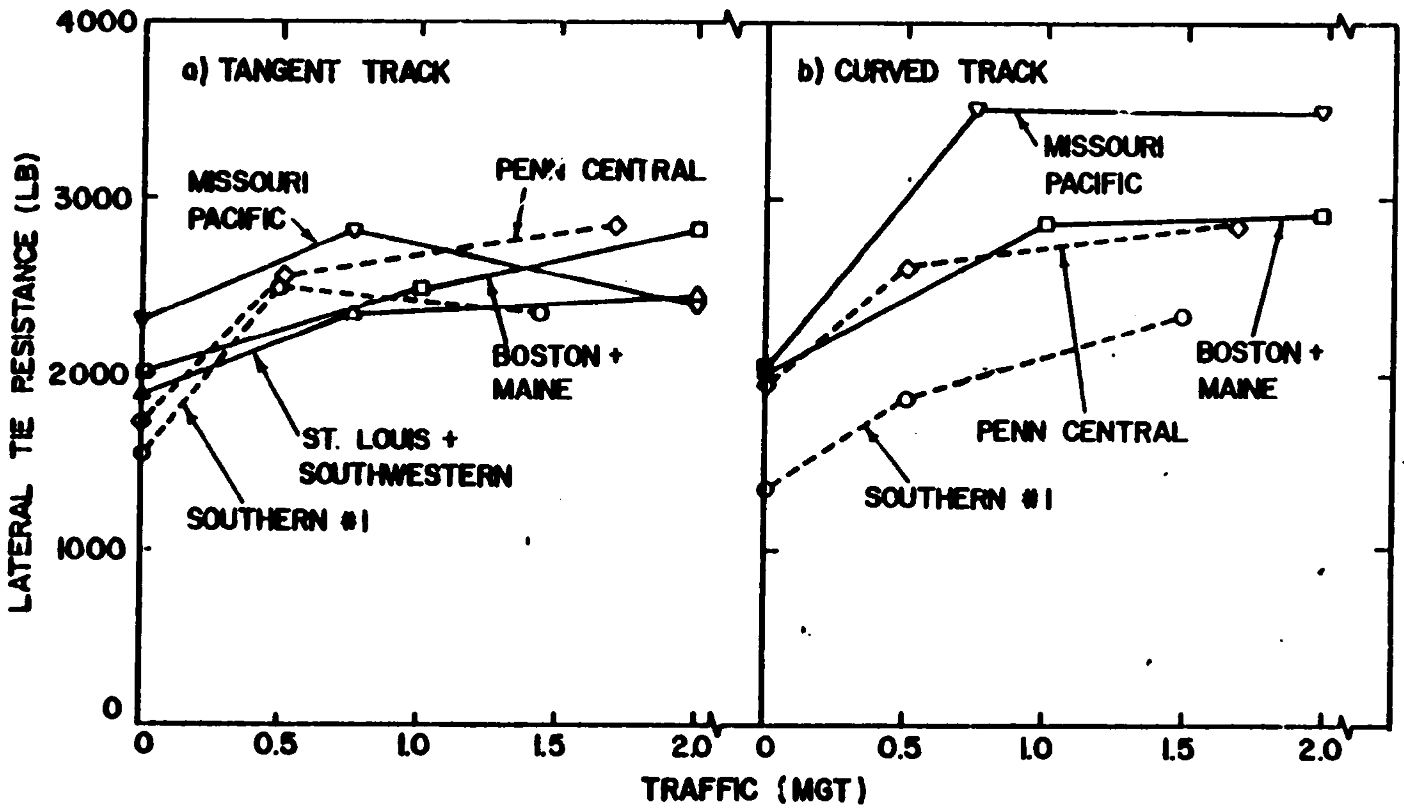


Figure 5.9. U.S. (ENSCO) LTPT Results at 0.157 in. (4 mm) Displacement for the Tamped-Compacted Condition on Different Types of Track

tamped-compacted condition. The application of crib and shoulder compaction to a tamped-only track initially increased the lateral resistance by 400 to 500 lb (1780 to 2225 N). This trend is consistent for both types of track. The lateral resistances are generally the same order of magnitude for the tamped-uncompacted and for the tamped-compacted conditions on both the tangent and on curved track as 2 MGT traffic is approached. An exception is the Missouri Pacific data on curved track.

Southern Railway (Ref. 32) conducted a followup series of lateral tie push tests to further verify the effects of crib and shoulder compaction. As previously mentioned, the apparatus and instrumentation package were more sophisticated than those utilized in the initial test series. The second Southern tests were performed on two sites with crushed granite ballast. Lateral reistance was investigated for tangent track only. However, the results with track maintenance operations and subsequent train traffic were analyzed separately for old and new ties.

The increase in lateral tie resistance at 0.157 in. (4 mm) displacement with traffic is evident for both the tamped-uncompacted condition (Fig.5.10a) and the tamped-compacted condition (Fig. 5.10b). Both track conditions did not have tie resistance values exactly at zero MGT traffic, but were reported for 0.032 and 0.065 MGT. Since these values were close to zero MGT, the initial values for the tamped-uncompacted and tamped-compacted conditions could reasonably be estimated by a linear extrapolation.

Figure 5.10 clearly illustrates that old ties have a higher lateral resistance than new ties. The result of the initial test series, that crib and shoulder compaction following tamping increased lateral tie resistance, was also obtained by Southern number 2. At approximately 0.7 MGT of traffic, Southern reported a high amount of rainfall on the two test sites. Thus,

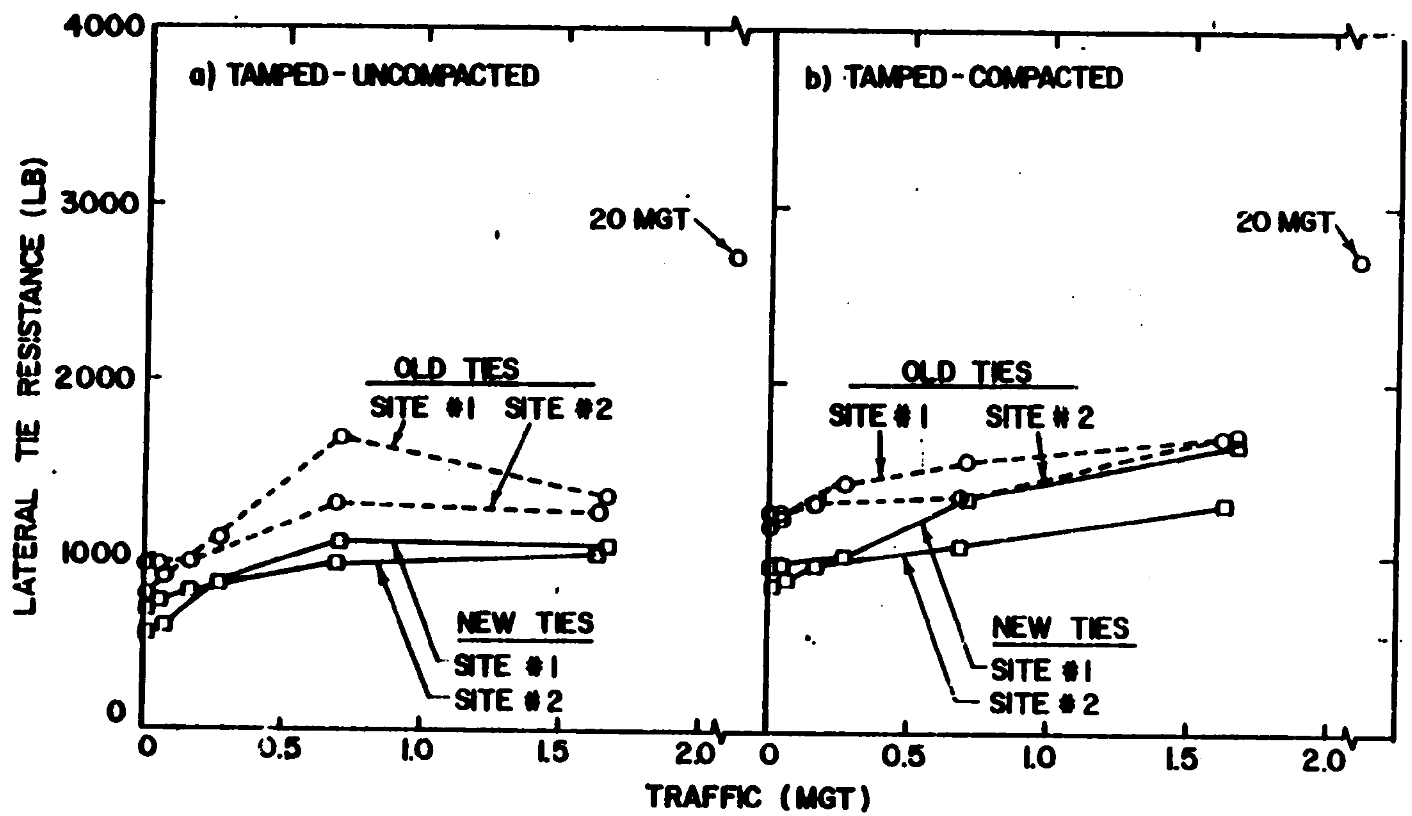


Figure 5.10. Southern #2 LTPT Results on Tangent Track at 0.157 in. (4 mm) Displacement for Different Track Conditions

any influence of lubricating the ballast particles and subsequently reducing the lateral resistance should have an apparent and most pronounced effect at 0.7 MGT for both track conditions. However, this influence appears relatively small since these test results follow the establishing trends.

Southern also performed 34 tests on an undisturbed track in order to obtain a "stable" lateral tie resistance. This value is significantly greater than all the other reported results. A 20 MGT traffic condition was assumed as a reasonable estimate of applied train loading although the track classification was not reported for this track. This is based upon a yearly traffic of 10 to 20 MGT and one to two years from the previous tamping operation. The 20 MGT value of lateral resistance in Fig. 5.10 is an average for both TU and TC track conditions since, as will be shown later in this report, the effect of crib and shoulder compaction is not expected to remain after the amount of traffic.

A comparison of the Southern number 2 data with the general trends obtained from ENSCO's initial test series reveals an exceptionally significant finding. That is, the apparatus used on the Southern number 2 tests produced much lower lateral tie resistance values. Since the track structures were similar for all the tests, the differences in results can most reasonably be accounted for by the difference in test apparatus and method of recording the field data.

<u>Non U.S. Railroads</u>. Other railroads, especially European, have been concerned with the problem of lateral track stability as long as U.S. railroads. European employing of the single lateral tie push test as a means of evaluating the relative degree of track stability precedes usage on U.S. railroads. This test apparently originated at the time that ballast crib and shoulder compaction machines were introduced onto

the European market. The tie push test was utilized in an attempt to quantify the benefits obtained from ballast compactors, as a part of normal track maintenance program. These benefits were intended primarily as a) the restoring of a portion of the lateral track stability lost due to ballast disturbance during the tamping, lining and leveling operation, and b) increasing the time between major track maintenance cycles. The only advantage, which has been substantiated with experimental studies, is that the crib and shoulder compactor used immediately after tamping produces a higher lateral resistance of individual ties (Ref. 34, 35, 36 and 37). However, only limited European data are available on the changes in tamped-compacted and tamped-uncompacted conditions with train traffic.

The Austrian Wesel station tests, which are reported by the Plasser and Theurer testing division (Ref. 34) and also by Reissberger (Ref. 35 and 36), provided the only usable European information compatable with the objectives of this study. However, the Wesel tests contain several parameters which were not investigated in the United States tests. The important factors include: a) type B-58 concrete ties, b) heaped shoulder ballast, and c) a gravel ballast which did not have a specified shape or mineralogical type. The amount of track raise during tamping was not reported and it is uncertain if the cribs were full of ballast for the tests. Also, the ballast shoulder dimensions and tie spacing were not reported.

Although the tie push test apparatus used (Fig. 5.11) was similar to that used by ENSCO in the initial U. S. test series (Fig. 5.5), the test did contain two distinctly different features. The first was that the test was load-controlled and not displacement-controlled. The second was mounting the deformation recording system on the test tie and using the

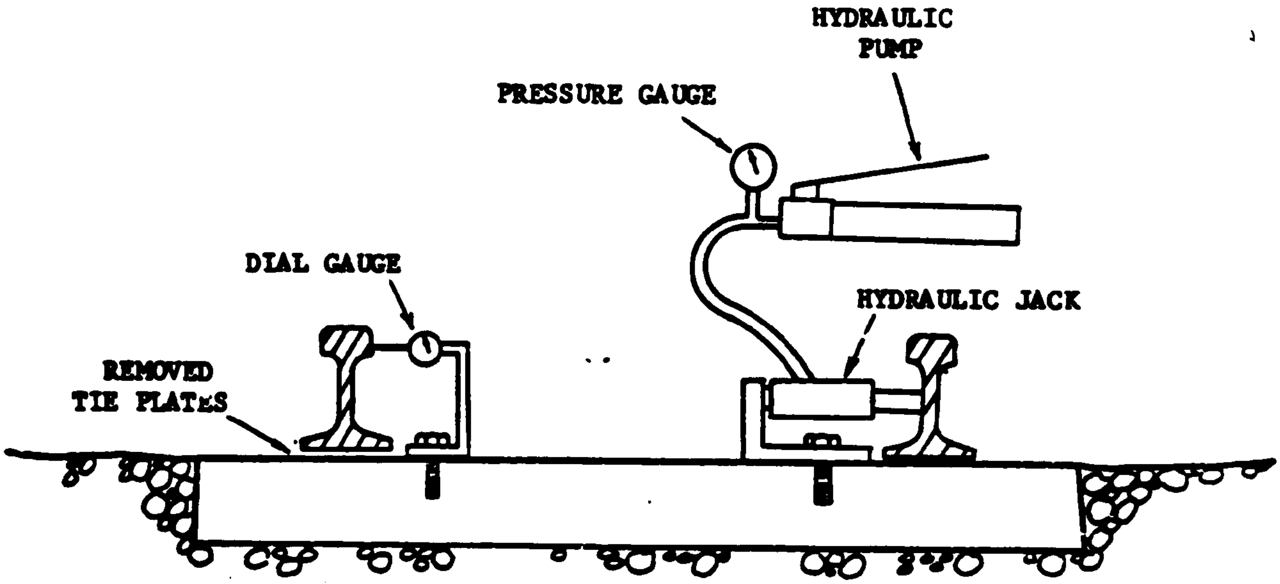


Figure 5.11. Plasser and Theurer Lateral Tie Push Test Apparatus Used for Austrian Wesel Station Tests (Ref. 36)

rail as a stable reference location. This rail is subject to unaccountable movements from the rest of the track structure during testing. In this test program, the same ties were not retested with traffic. An undisturbed lateral tie resistance was reported. However, the amount of traffic could not reasonably be estimated. The evaluation and comparison of the Wesel test results to all other reported values will be treated in general terms, since the influence of the previously mentioned factors is uncertain.

The average lateral tie resistance values on tangent track for the tamped-uncompacted condition and tamped-compacted condition are illustrated in Fig. 5.12. The compaction was done with a Plasser-Theurer model VDM 800 U ballast compactor. Two trends which exist for this data as with the U. S. data are: a) crib and shoulder compaction initially increases lateral tie resistance, and b) lateral tie resistance increases with applied traffic from the physical states established by both initial track conditions. The second trend is not as pronounced as in the U.S. data since the lateral resistance at 1.3 MGT is only slightly higher than the initial values or after a slight amount of traffic, i.e., 0.09 MGT. The reasons for such a trend have not clearly been defined. Note that the lateral resistances at 1.3 MGT are equal for both track conditions.

The only other source of available foreign data was provided by Trask (Ref. 33) of the Canadian National Railway (CNR). The test apparatus (Fig. 5.5) and procedure were similar to those used by ENSCO. A crushed rock ballast was tested on a tangent section of track. The test ties were wood and primarily 8 in. by 6 in. by 93 in. (0.2 m by 0.15 m by 2.36 m), which was smaller than ties tested by ENSCO. The ballast compactor used was a Plasser and Theurer model CPM 800-R. The amount of track raise, tie spacing, and shoulder dimensions were not reported.

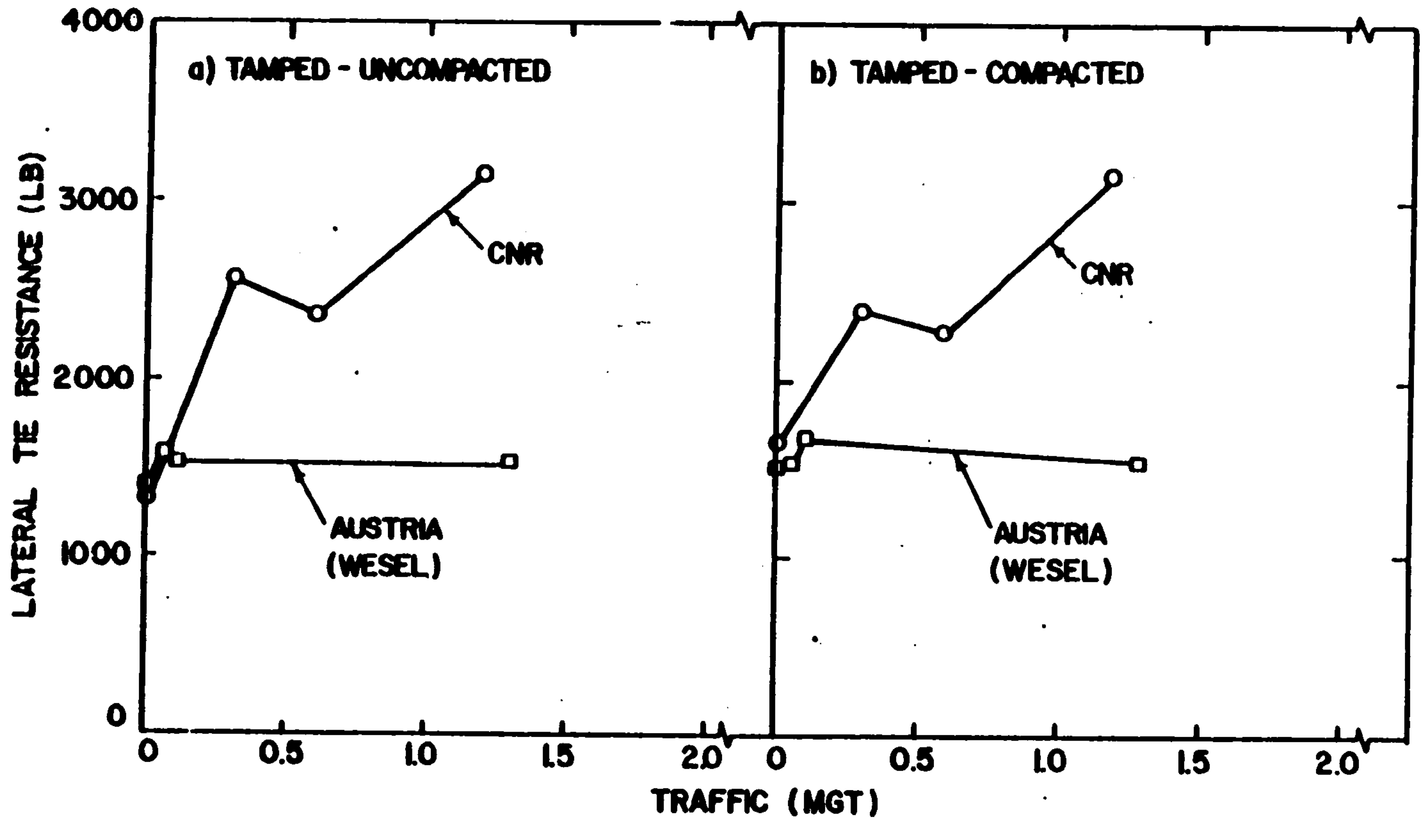


Figure 5.12. Foreign LTPT Results on Tangent Track at 0.157 in. (4 mm) Displacement for Different Track Maintenance Conditions

The lateral tie resistance was obtained by averaging twenty ties for each traffic level and for each track condition. Different ties were tested within each group for each traffic loading condition. The CNR results are presented in Fig. 5.12 along with the Austrian Wesel station results. The general trends of increasing lateral tie resistance with traffic and with crib and shoulder compaction is also demonstrated by the CNR data. As with the Wesel tests, the CNR results at 1.2 MGT are the same for the tamped-uncompacted and the tamped-compacted conditions.

The lateral tie resistance values from these foreign tests will be compared to the United States data in the following section.

Summary. The lateral tie push (pull) test results from available American and foreign literature were compiled and presented in the preceding sections. The results from SUNYAB's testing programs on the ICG and FAST sites were discussed in Section 5.1 and are illustrated in Fig. 5.13 in a form compatable with the other reported test values.

The average lateral tie resistance trends at 0.157 in. (4 mm) displacement for the United States, foreign and SUNYAB data are shown in Fig. 5.14a for the tamped-uncompacted condition and in Fig. 5.14b for the tamped-compacted condition. The track structures were similar in all cases except for the Austrian Wesel tests. Note that the trends for SUNYAB have been estimated with the available data.

In general, lateral tie resistance rapidly increases with the application of a limited amount of traffic after track maintenance operations and then, at approximately 0.5 to 1.0 MGT of traffic, the rate of increase is significantly reduced. Crib and shoulder compaction initially increases the tie resistance of a tamped-only track. However, the Southern number 2 data and the intial test series for the U.S. ENSCO data indicate that

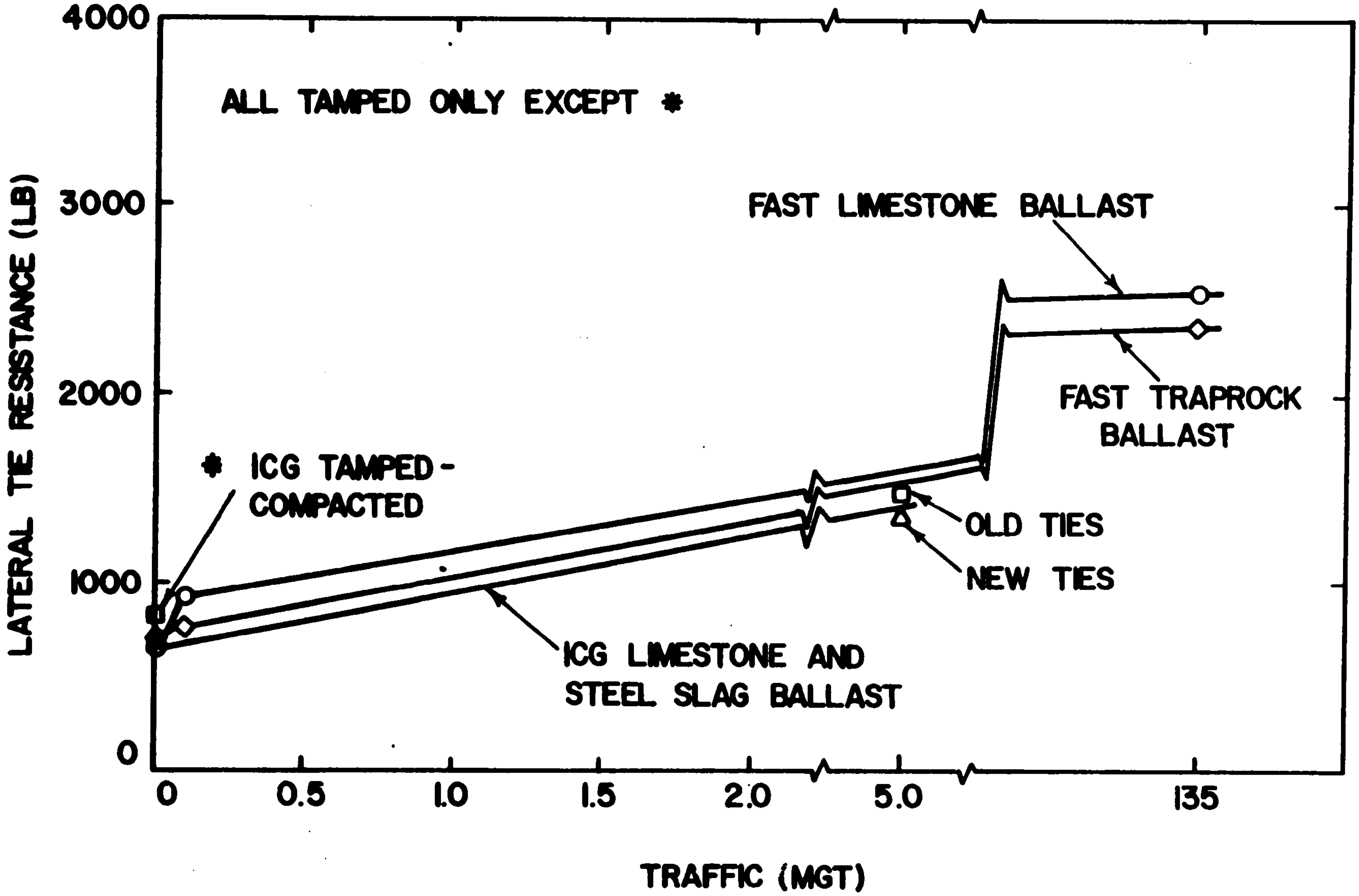


Figure 5.13. SUNYAB LTPT Results on Tangent Track at 0.157 in. (4 mm) Displacement for Various Track Conditions

this initial increase in tie resistance due to compaction is almost entirely retained by the ties for up to 2 MGT of traffic. The CNR and Austrian data demonstrate that the lateral resistance approaches the same value for both track conditions after the application of a limited amount of traffic. Although the Austrian tests were not performed in conditions similar to U.S. tests, the CNR tests were in fact very much the same. Although the CNR trends are greater than the average U.S. data above 0.5 MGT on tangent track, the values are comparable to the trends established on the individual railroads, i.e., Southern number 1 and Penn Central (Fig. 5.8a and 5.9a). Thus it is difficult to determine at which amount of traffic that crib and shoulder compaction no longer have an effect upon lateral resistance. The possibility of factors influencing the test results will be investigated next.

The effect of rain upon lubricating the ballast particles and subsequently reducing tie resistance has been considered in the evaluation of the ENSCO and Southern number 2 tests. This factor was determined to have a small effect on the tie resistance, since the general trends did not appear to be affected.

The differences in test apparatus and test procedures were considered next. The lateral tie resistances immediately after track maintenance operations, i.e., zero MGT, in Fig. 5.14 are nearly the same for the ENSCO, CNR and Austrian tests, which utilized similar equipment, while the Southern number 2 and SUNYAB tests yield much lower results using different apparatus.

SUNYAB's load apparatus, which is located at the centroidal axis of the tie end, is close to the line of action of the ballast resisting forces acting upon the tie. This would provide the closest measure of the actual lateral tie resistance and thus can be used as a reference point. SUNYAB's

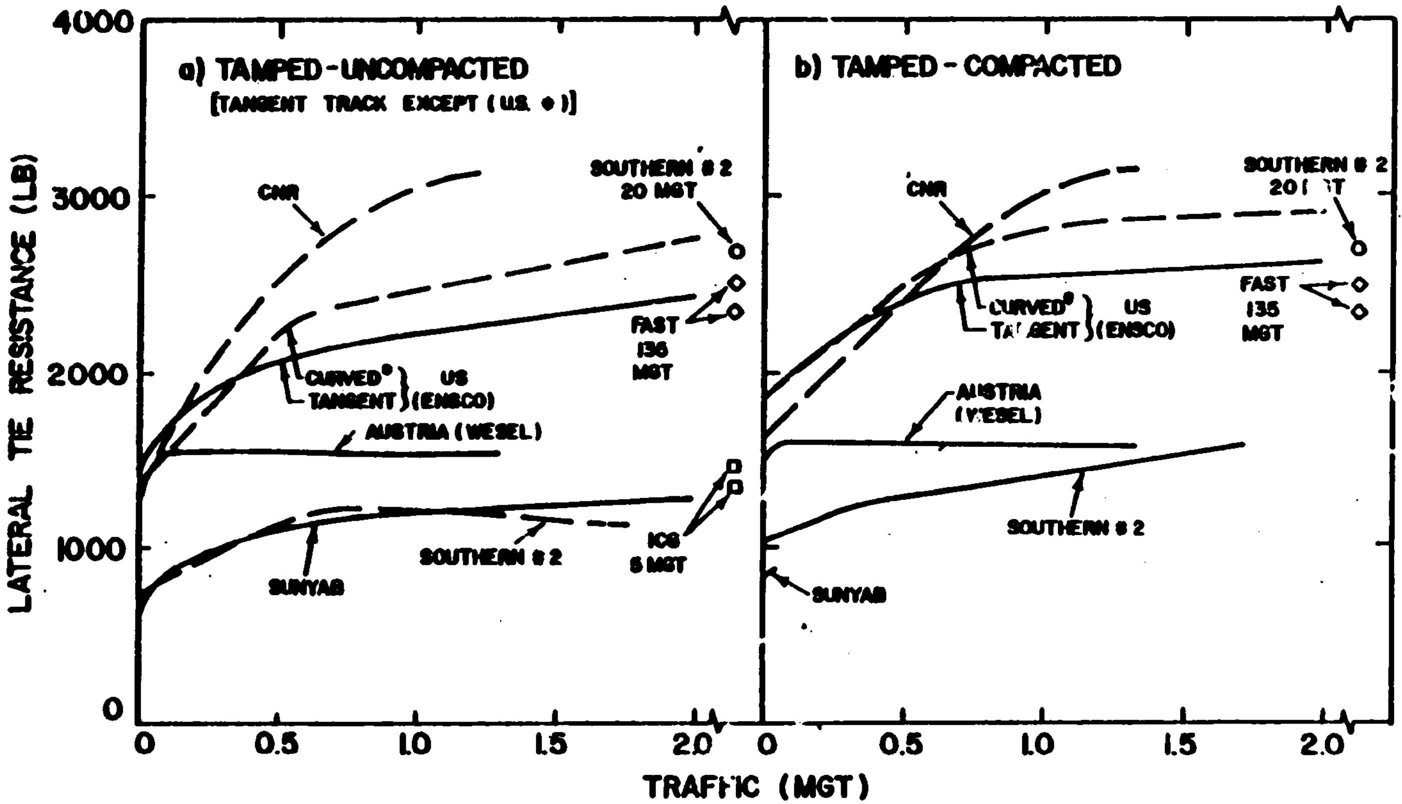


Figure 5.14. Summary of LTPT Trends for All Data at 0.157 in. (4 mm) Displacement for Different Track Maintenance Operations and for Different Types of Track

data also indicates that for the tamped-only condition, the lateral resistance is nearly the same for three different ballast types tested (Fig. 5.13).

The effect of the location of the load applying and measuring system on lateral tie resistance at zero MGT traffic is more clearly illustrated in Fig. 5.15 for all the U.S. data having similar track structures. As the location of the applied load moves upward from the centroidal axis of the tie end to the web of the rail, the lateral resistance increases. The Southern #2 data for the tamped-only condition is comparable to SUNYAB's data; however, ENSCO's values are nearly twice as great. This data does indicate that the measured lateral tie resistance is highly dependent upon the type of apparatus used, let alone the methods of recording data, testing procedure, or the sophistication of the instrumentation used. Field test data can be more easily evaluated if standard test apparatus are utilized, i.e., similar to SUNYAB's. This at least would reduce the amount of data scatter for given site conditions and provide a means for comparison between different sites such that the factors influencing the test results might more easily be identified.

5.3 DATA INTERPRETATION APPROACH

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, the present study cannot 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

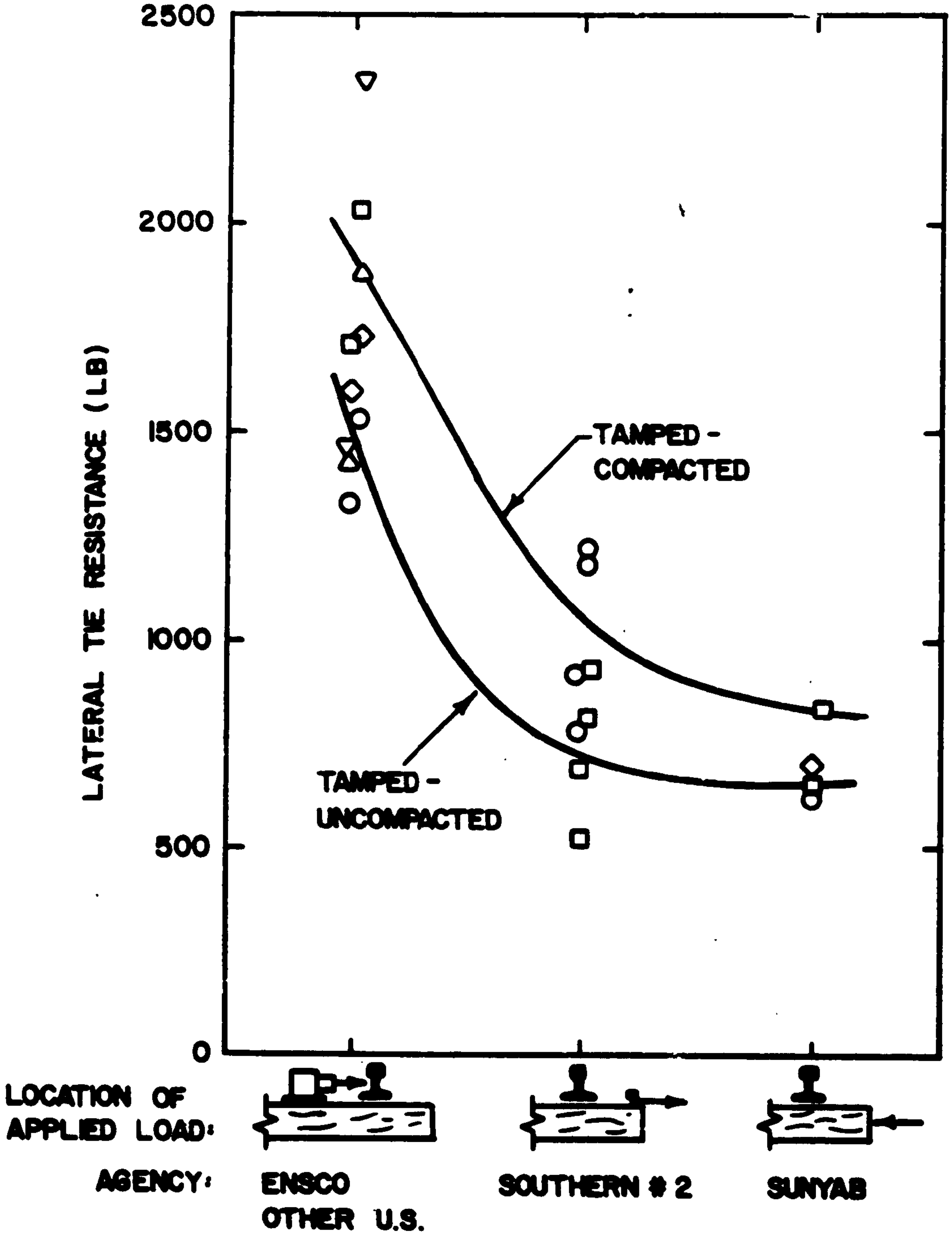


Figure 5.15. Comparison of LTPT Results at 0.157 in. (4 mm) Displacement with Location of Load Applying System on U.S. Tangent Track at Zero MGT Traffic

dynamic forces. Thus clearly, the seleciton of the most suitable ballast type or ballast compactor is not possible.

With the quality and quantity of available LTPT data, an attempt to put the data from various sources in comparable form in order to correlate the results should be undertaken in order to establish the general trends. Such a correlation would focus upon the following three basic questions for tie resistance of an individual tie:

1. What amount of train traffic on a tamped-only track is crib and shoulder compaction after the tamping operation equivalent to?
2. What amount of traffic is required such that the effect of crib and shoulder compaction can no longer be differentiated from a tamped-only track?
3. What amount of traffic is required in order to achieve a stable track condition?

Two normalization techniques were developed which, to the best extent possible, would eliminate errors due to:

1) different types of compaction equipment,
2) different loading rates between testing procedures,
3) inherent instrument errors in the different sets of testing apparatus, and
4) different ballast moisture conditions.

These techniques were not expected to totally eliminate effects from tests on different ballast types or bed geometry.

The first normalization technique employed utilizes the average load at a given displacement level for tests conducted in the tamped and uncompacted condition. This test essentially becomes a reference condition as established by SUNYAB's data for all other tests conducted at a given site, providing that the ballast type remains the same. The dimensionless ratio used to express these results has been termed the load ratio (LR) and is defined as:

$$LR = L/L_o \text{ ,} \qquad (5.2)$$

in which L = tie resistance at a given displacement level for a specific track condition, and L_o = tie resistance at the same displacement level as L, but for the tamped-uncompacted condition with zero applied traffic. The L value may be either a tamped-only condition with applied traffic or a tamped-compacted condition with or without applied traffic. In the former case at zero MGT, $L = L_o$ and $LR = 1$. This normalization technique is expected to answer the first question.

The second normalization technique utilized will attempt to answer the second question. It involves a dimensionless ratio, termed the compaction ratio (CR), defined as:

$$CR = C/U \text{ ,} \qquad (5.3)$$

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.

The preceding ratios have been computed with respect to the tamped-uncompacted condition rather than an undisturbed or highly trafficked condition. This is based upon the fact that SUNYAB's data for the tamped-uncompacted condition at zero MGT produces nearly identical lateral tie resistances for different ballast types. Also, the applied traffic required to achieve a stable track condition or a stable lateral resistance for an individual tie has not been clearly established. This basically sets the format for finding a solution to the third question.

The trends in Fig. 5.14 for lateral tie resistance with applied traffic are generally hyperbolic in shape. Since the load ratio (LR) is computed with a constant value, i.e., L_0 , in the denominator, then the shape of the LR curves will also be hyperbolic. Thus, a transformed hyperbolic fitting technique for the LR - MGT curves can be 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. 38) and for granular soils (Ref. 39). The linear form of the hyperbolic equation is:

$$= a + b\ (MGT), \qquad (5.4)$$

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

$$LR_{ult} = 1/b\ . \qquad (5.5)$$

The three approaches previously described appear to be the most suitable in achieving the three stated objectives. The United States (ENSCO), Southern number 2 and SUNYAB's data will be the most critically evaluated due to the similarity in track structures and train loading conditions. The data from CNR and Austria Wesel station will be compared to the results obtained from all the U.S. data.

5.4 TAMPED-UNCOMPACTED CONDITION

The individual load ratio values computed for each railroad are contained in Ref. 20. The results, to be presented herein, were more easily computed from the summary curves for the tamped-uncompacted condition (see Fig. 5.14a).

The Southern number 2 data will be considered first since it is the only data set which clearly differentiates between old and new ties. The LR trend with traffic shown in Fig. 5.16a for the tamped-uncompacted condition reveals the important finding that tie age does not influence the LR trend for tests conducted on the same section of track. For each test site, old and new ties produced essentially the same LR values with traffic.

This implies that results from ENSCO's initial test series would produce the same trend if lateral resistance were separated for old and new ties. Thus, the individual or combined LR results would be similar.

The differences in LR values between sites, shown in Fig. 5.16a, presently cannot be explained. Because LR does not appear to be affected by tie age, the four data sets for Southern number 2 will thus be combired to present the general trend.

The LR trends for all data are summarized in Fig. 5.17a. This normalization technique proves to be worthwhile because all the United States data are confined to a narrow range. Panuccio and Dorwart (Ref. 20) have shown that 0.0787 and 0.157 in. (2 and 4 mm) displacements also yield nearly identical trends. A comparison with Fig. 5.14a shows that correlation with the LR method is at least partially effective in reducing the amount of data scatter between test apparatus and procedures used in the different test programs.

The foreign LR trends are similar to the U.S. data in the range from zero to 0.25 MGT, but deviate from the U.S. trends after 0.25 MGT. The

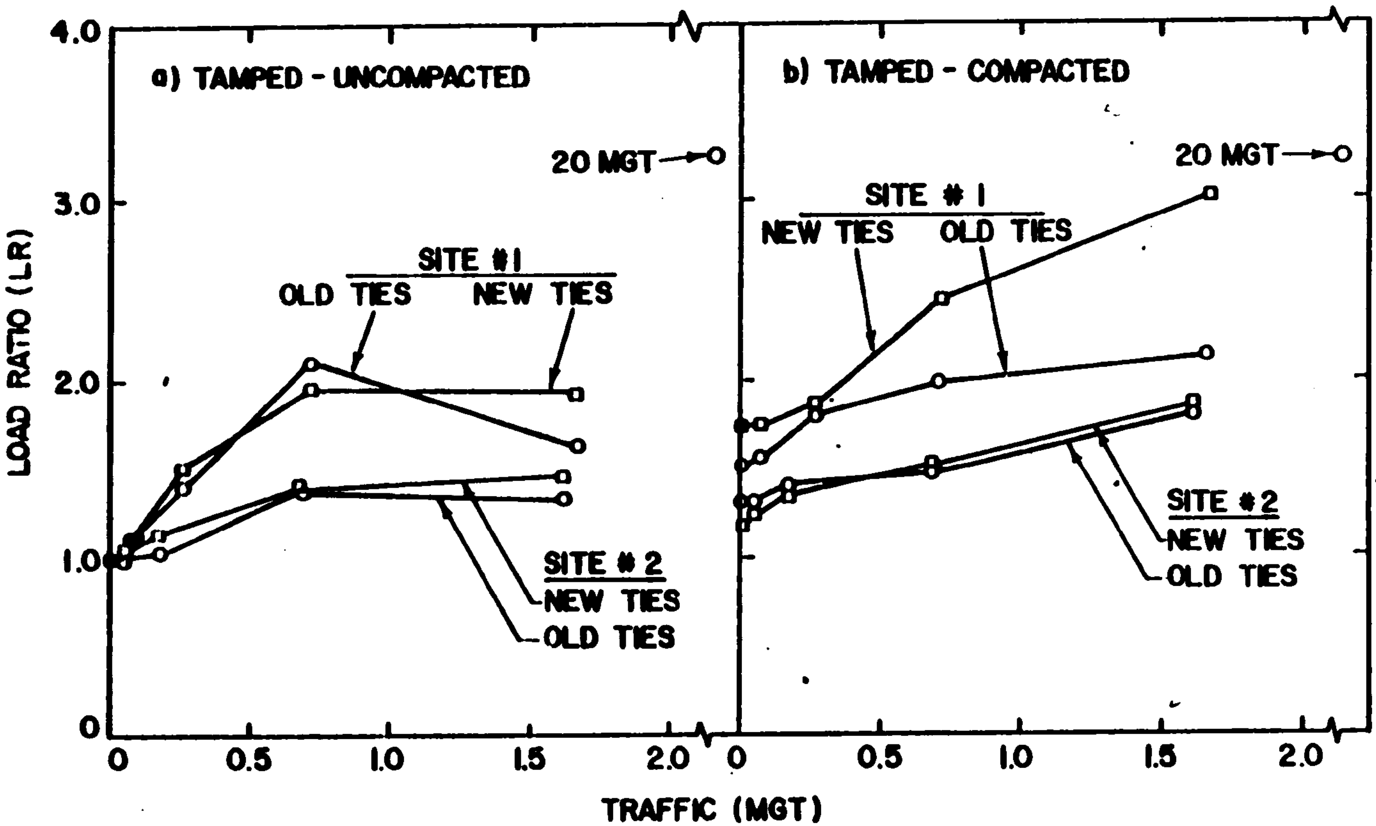


Figure 5.16. Load Ratio at 0.157 in. (4 mm) Displacement for Southern #2 Data

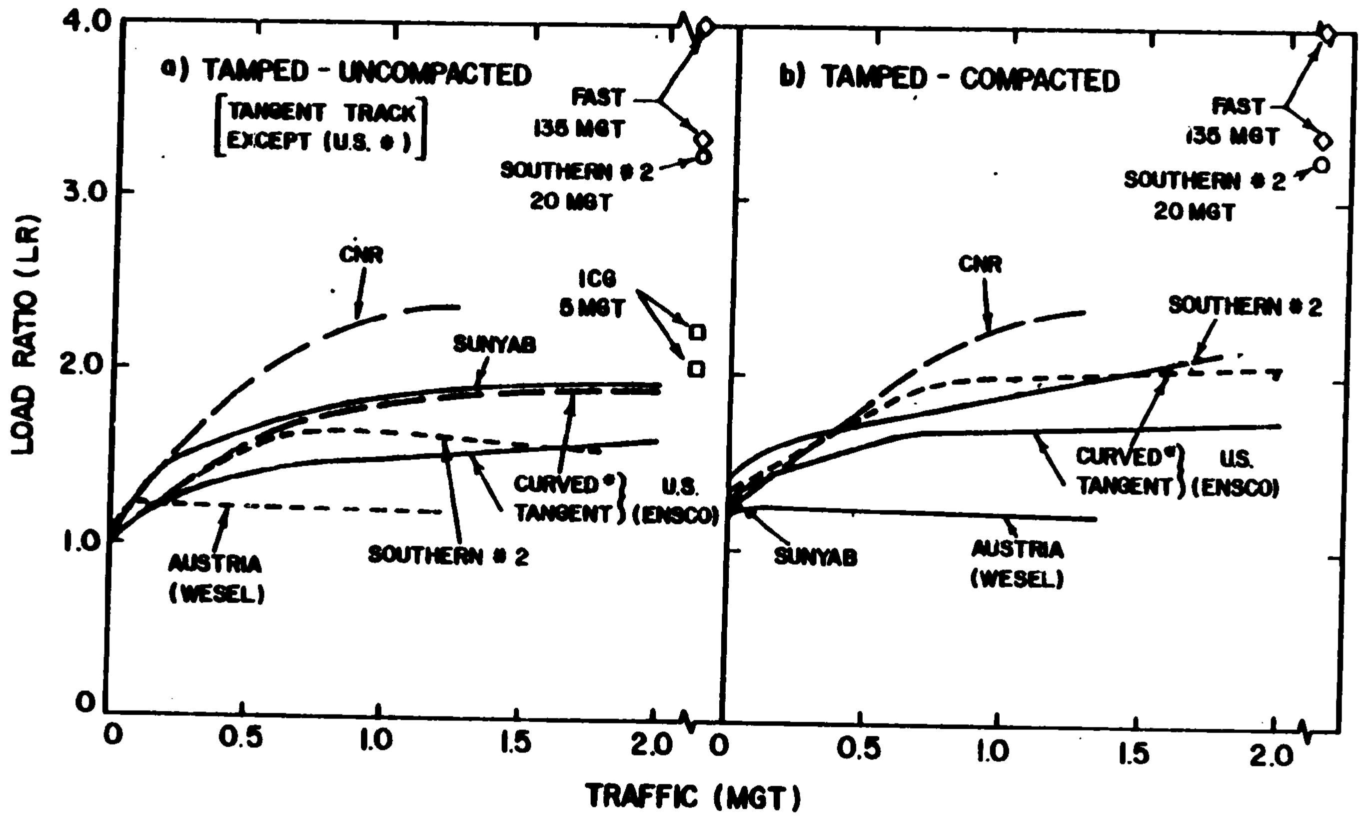


Figure 5.17. Summary of LTPT Load Ratio Trends at 0.157 in. (4 mm) Displacement for All Data

Austrian data is explainable due to the vastly different test conditions. However, the CNR data may be influenced by other factors such as ballast type.

Also shown in Fig. 5.17a are the SUNYAB and Southern number 2 LR values at the higher traffic loadings. These values are significantly larger than the LR values at 2.0 MGT and indicate that the lateral tie resistance continually increases with traffic loading although the rate may be diminished.

The transformed hyperbolic fitting equations of the LR-MGT trends for each data set in Fig. 5.17a are presented in Table 5.3 The coefficient of determination, R^2, ranged from 0.93 to 1.0 for all the equations. This indicates a very good fit between the original data points and the linear regression equations. The number of data points used for an individual data set was the lowest for CNR and Austria at 4 , while 10 to 21 points were used for an individual U.S. data set. By combining all the U.S. data, 37 to 46 data points were used for 0.157 in. (4 mm) displacement.

The ultimate load ratio was also computed for each data set in Table 5.3. Ref. 20 indicates that values for each particular data set show good agreement for both 0.0787 and 0.157 in. (2 and 4 mm) displacement levels. The average ultimate LR value for all U.S. data is the same as that for SUNYAB's data. This is expected since SUNYAB's data contains the highest MGT values, which would strongly influence the fit for the linear regression equation. The Southern number 2 value at 20 MGT is the only other data point greater than 2.0 MGT. Note, that when the 20 MGT value is extracted from the Southern number 2 data, the equation is almost exactly

Table 5.3. Equations for 0.157 in. (4 mm) Displacement from Hyperbolic Fitting Technique for all Railroads

$$MGT/LR = a + b\,(MGT)$$

Railroad	Maximum MGT	Tamped-Uncompacted a	Tamped-Uncompacted b	Tamped-Uncompacted R^2/N	Tamped-Uncompacted LR_{ult}	Tamped-Compacted a	Tamped-Compacted b	Tamped-Compacted R^2/N	Tamped-Compacted LR_{ult}
United States (ENSCO)									
a) Tangent	2.0	0.008	0.638	0.983/15	1.57	(-) 0.0005	0.561	0.99/15	1.78
b) Curved	2.0	0.012	0.498	0.98/11	2.0	0.021	0.432	0.93/12	2.31
Southern #2	1.7	0.011	0.624	0.963/20	1.60	0.022	0.464	0.931/20	2.16
	10	0.16	0.315	0.911/21	3.17	0.096	0.309	0.965/21	3.24
	20	0.172	0.303	0.974/21	3.3	0.102	0.304	0.991/21	3.29
	50	0.175	0.303	0.996/21	3.3	0.104	0.304	0.999/21	3.29
SUNTAB	135	0.249	0.272	0.989/10	3.68	-	-	-	-
All U.S. Tangent	5	0.068	0.509	0.951/43	1.96	-	-	-	-
	20	0.199	0.323	0.935/44	3.10	0.14	0.309	0.971/37	3.24
	135	0.257	0.272	0.99/46	3.68	0.179	0.272	0.991/39	3.68
CNR	1.2	0.029	0.419	0.97/4	2.39	0.035	0.418	0.96/4	2.39
Austrian (Wesel)	1.3	0.0	0.826	1/4	1.21	(-) 0.002	0.828	1/4	1.21

R^2 = Coefficient of Determination

N = Number of Data Points

the same as that of ENSCO's tangent track at 0.157 in. (4 mm) displacement (see Table 5.3).

The Austrian and CNR equations produce exactly the same trends with respect to the U.S. data in Table 5.3 as they did in Fig. 5.17a. Thus, this data will not be further elaborated upon.

The key question is the selection of a reasonable value of traffic which is respresentative of a stable track condition for the lateral resistance of a single tie. The lack of sufficient quantities of data above 2.0 MGT of traffic makes the determination of a specific value difficult, and so at best is only approximated. From Table 5.3, the Southern number 2 data indicates that 20 MGT yields an LR value comparable to that of SUNYAB's at 135 MGT. Note, however, that this 20 MGT traffic value was not a reported value, but was estimated for the undisturbed condition. The hyperbolic fitting technique was iterated several times with assumed values of traffic for the undisturbed condition. The result was that the slopes of the regression lines and subsequently the ultimate LR values were nearly equal for assumed traffic loads in the range of 10 to 50 MGT (see Table 5.3). Thus, 20 MGT and LR = 3.3 appear to be a reasonable estimates of a stable traffic condition for an individual tie at 0.157 in. (4 mm) displacement.

5.5 TAMPED-COMPACTED CONDITION

The load ratio values for the tamped-compacted condition were computed from the summary curves in Fig. 5.14b for each data set. The individual values for each railroad are tabulated in Ref. 20.

As previously stated in the tamped-uncompacted section, the Southern number 2 load ratio trends are essentially the same for old and new ties at a given site. This is also confirmed for the tamped-compacted condition at site number 2, (Fig. 5.16b). The site number 1 curves are reasonably close from zero to 0.26 MGT, however, the curves deviate at the larger traffic loadings. This may partially be explained by the initially low lateral resistance for the tamped-uncompacted condition at site number 1. In order to establish the general trend, all the tamped-compacted data will be combined.

The LR trends for all the data are summarized in Fig. 5.17b. The resulting trends and observations for the tamped-compacted condition are similar to those for the tamped-uncompacted condition, except that the magnitudes of the LR values are slightly greater. Note that points at zero and 135 MGT are shown in Fig. 5.17b for SUNYAB data since intermediate values were not obtained.

Using Fig. 5.17 or also Fig. 5.14, an estimate of the amount of traffic on a tamped-only track equivalent to the effect of crib and shoulder compaction can be obtained. This is easily accomplished by first obtaining the load ratio (Fig. 5.17b) or lateral tie resistance (Fig. 5.14b) for the tamped-compacted condition immediately after tamping, i.e., zero MGT, and then finding the equivalent traffic from the tamped-uncompacted trends (Figs. 5.17a and 5.14a) for the same corresponding values. This is based upon the average values and does not statistically consider the amount of data scatter.

The results listed in Table 5.4 indicate that 0.0787 and 0.157 in. (2 and 4 mm) displacement levels produced comparable MGT estimates for each

Table 5.4. Equivalent Traffic Estimates for Crib and Shoulder Compaction from a Tamped Only Track

Railroad	Equivalent Traffic (MGT) Displacement 0.079 in. (2 mm)	0.157 in. (4 mm)	Annual Traffic (MGT)	Equivalent * No. Days Traffic
U. S. (ENSCO)				
·Tangent	0.30	0.25	28.6	3 → 4
·Curved	0.23	0.27		
Southern #2 (Old & New Ties)	-	0.35	≃20	6 → 7
SUNYAB	0.06	0.08		
·ICG	-	-	23	1 → 2
·FAST	-	-	135	< 1
Austria (Wesel)	0.08	0.06	8	3 → 4
CNR	0.18	0.10	14	2 → 4
Average →	0.17	0.19	-	3 → 4
Average without Wesel →	0.19	0.21	-	3 → 4

* Based Upon Equal MGT/Day Loading Condition

Reported Values (Ref. 3)				
U. S. (ENSCO) [Tangent & Curved]	0.40	0.44	18 - 40	–
Southern #2				
·New Ties	-	0.45	–	–
·Old Ties	-	0.43 (see Fig. 5.19)	–	–

particular data set. ENSCO's initial test series on tangent and curved track were similar with an average equivalent traffic of approximately 0.26 MGT. Considering that the average annual traffic for these five railroads is 28.6 MGT, then crib and shoulder consolidation would essentially produce the same results as 3 or 4 days of train traffic. This assumes an equal amount of train traffic each day.

The Southern number 2 data yielded the highest equivalent traffic at 0.35 MGT and SUNYAB's data was the lowest with 0.07 MGT as an average. SUNYAB's data indicates that approximately 1 day of train traffic on a tamped-only track is equivalent to the effect of crib and shoulder compaction.

The test data from CNR and Austria yield equivalent traffic values comparable to SUNYAB's. Although the Austrian Wesel station tests used concrete ties, the results were approximately equal to SUNYAB's.

In general, as implied by the single lateral tie push test, the average equivalent train loading achieved by crib and shoulder compaction after the tamping operation is approximately 0.17 to 0.19 MGT for all railroads. This amounts to 3 to 4 days traffic on a tamped-only track.

The transformed hyperbolic fitting technique was also performed on the tamped-compacted condition (Table 5.3). The computed ultimate load ratio values are slightly higher than the tamped-uncompacted values only for the U.S. ENSCO data. The CNR, Austrian, Southern number 2 and overall average for all U.S. data yield the same ultimate LR values for both track conditions. The 20 MGT traffic and LR of 3.3 also appear to represent a stable track condition for the tamped-compacted results.

The second normalization technique used for the tamped-compacted condition is the compaction ration (CR). This ratio will attempt to define the amount of traffic at which the long term effect of crib and shoulder compaction no longer exists when compared to tamped-only track with traffic. This point will be defined as the point at which the tamped-compacted values of lateral resistance are within 5 percent of the tamped-uncompacted values. The 5 percent was arbitrarily selected but appears reasonable since this is approximately equal to the standard deviation of the two track conditions for the statistical analysis performed on the Southern number 1 and Boston and Maine data sets (see Appendix B of Ref. 20). The CR approach was determined to be a simpler method of analyzing the data than by using the lateral tie resistance curves for the two track conditions (Fig. 5.14).

The CR trends for all U.S. data on tangent track are shown in Fig. 5.18a. The Southern number 2 set supplied more data at 0.157 in. (4 mm) displacement; however, the general trend changed considerably at 1.65 MGT. By including this data, it is implied that the initial increase in lateral tie resistance at zero MGT due to crib and shoulder compaction is approximately constant and retained up to at least 2.0 MGT. The Southern #2 data indicates that the effect of train traffic on a tamped-only condition can be superimposed upon the initial tamped-compacted condition, i.e, the effect is additive. In actuality, crib and shoulder compaction initially defines a different ballast physical state than the tamped-only condition, and the respective responses with traffic for both should approach the same steady state condition. With the exception of the 1.65 MGT data, the Southern number 2 data does follow the expected trends.

From Fig. 5.18a, 2.0 MGT of traffic appears to be a reasonable estimate

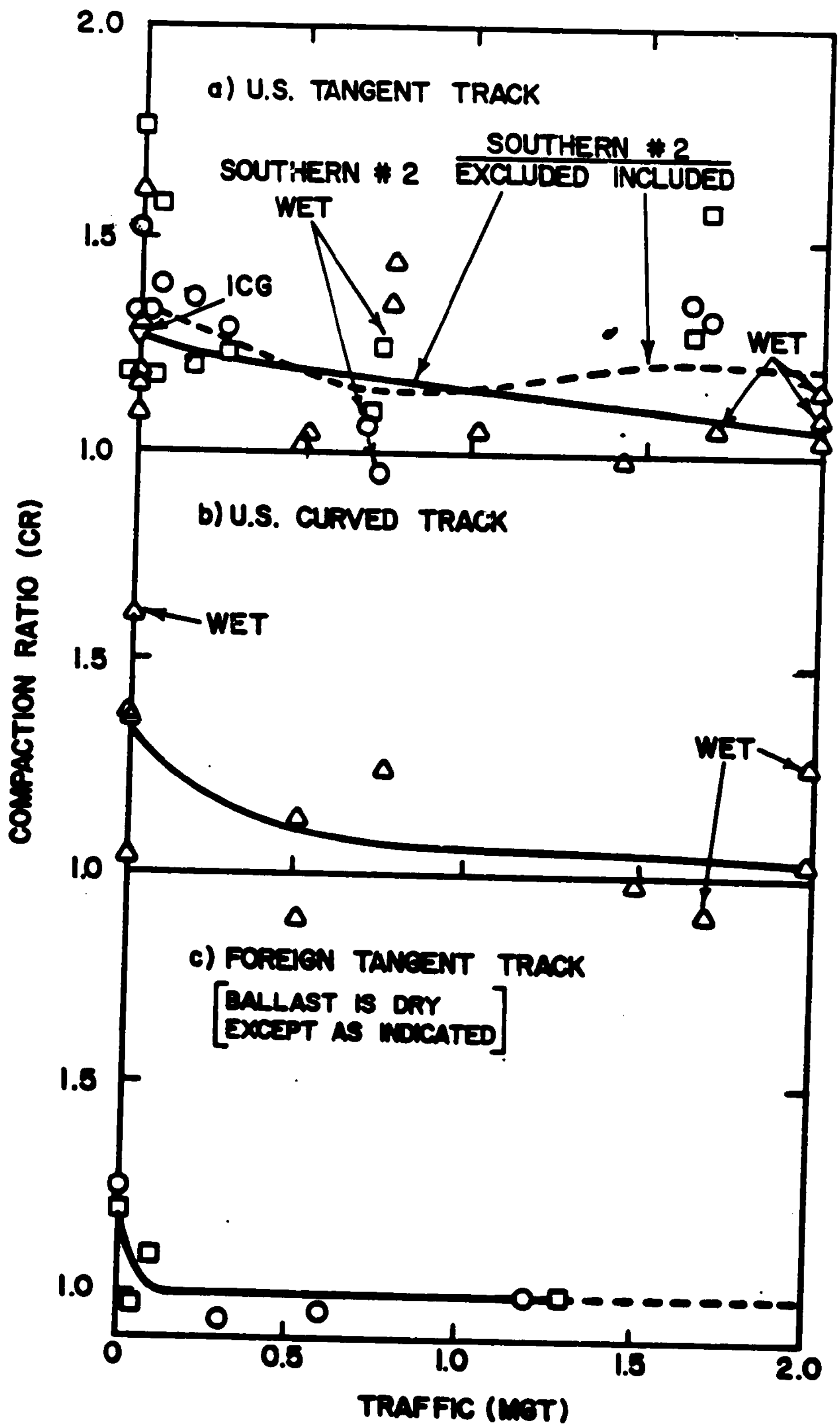


Figure 5.18. Summary of LTPT Compaction Ratio at 0.157 in. (4 mm) Displacement for all Data

at which the effects of crib and shoulder compaction can no longer be differentiated from a tamped-only condition on tangent track. Any effect of ballast wetness during the time of testing should be accounted for by the compaction ratio, since the amount of data scatter in Fig. 5.18a is not different for the wet and dry cases. The CR trends for U.S. curved track (Fig. 5.18b) produce the same results as U.S. tangent track.

The compaction ratio trends for foreign data on a tangent track (Fig. 5.18c) showed a termination of the effects of crib and shoulder compaction at less than 0.25 MGT. This is significantly less than the 2.0 MGT of traffic indicated by the U.S. data, which presently cannot be explained. The ORE (Ref. 37) results from eight European railway administrations for the past 15 years indicate that the effects of crib and shoulder compaction are concluded after a traffic loading of 1.5 to 2.5 MGT. This result is compatable with the findings of U.S. data in this study, even though the track structures are different.

5.6 ASSESSMENT

The individual lateral tie push test results for the tamped-uncompacted and tamped-compacted conditions with applied train traffic have been discussed and evaluated for all available United States, SUNYAB and foreign data. The track structures were similar for all the railroads except the Austrian Wesel station tests.

The greatest variation in results between sites was obtained from ENSCO's initial test series 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 a second test series performed by Southern Railways 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, which represent extreme differences of index properties for common ballast types. However, the large difference in the lateral tie resistances obtained by ENSCO and SUNYAB can primarily be attributed to the locations of the load applying and measuring systems.

In addition to the limited quantities of data and the associated data scatter, the analysis is further complicated when the results obtained by utilizing different apparatus significantly influence the LTPT values. This presents an additional difficulty in assessing and isolating the differences in the more important factors which are of prime concern. These factors include differences in height of track raise, in ballast type, in ballast moisture conditions, and in vibration time or other characteristics of ballast crib and shoulder compactors. For the present study, these factors were considered not to be statistically important enough to influence the tie resistance trends. Thus, if further studies are to be conducted on the lateral tie resistance of individual ties, a standard LTPT apparatus and test procedure should be utilized.

In general, lateral tie resistance increased with the application of train traffic. 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 on ICG produced almost the same percent increase. This result was consistent for both 0.0787 and 0.157 in. (2 and 4 mm) displacement levels on tangent and curved track

(Ref. 20). 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 for Southern number 2 and 135 MGT for FAST, were significantly greater than the values at low amount of traffic. At FAST, the ballast bed underneath the tie was observed to have a smooth appearance and appeared to cause only slight indentations on the base of the tie. The ballast shoulder appeared to be in a loose condition. The base and shoulder resistance was probably a small portion of the total lateral resistance per tie. Thus, the crib ballast is apparently the principal component of tie lateral resistance. 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 plausable 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.

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.

The LR approach provided a reasonable method of relating the tie resistance values in a form such that the data were more directly comparable. The LR trends with traffic were similar for both displacement levels and for both tangent and curved track for all U.S. data. Using a transformed hyperbolic fitting technique to the LR-MGT relationships, 20 MGT of traffic was determined to be a reasonable estimate of a "stable" or undisturbed track condition.

The 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. A value of 2 MGT appeared to be a reasonable estimate for all U.S. data and is consistent with ORE 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 conditions at the time of testing. Note that a statistical analysis performed by ENSCO (Ref. 3) on Southern number 1 and Boston and Maine data indicated a lower value of 0.5 and 1 to 2 MGT of traffic, respectively, on tangent track as having relatively no effect from ballast compaction. The 2.0 MGT estimate may be a conservative estimate in comparison to the Southern number 1 and Boston and Maine values. These values are considered reliable since "representative" average values were available for analysis and not all the original test data.

The final factor to be determined was 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. 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.

The equivalent traffic estimates are lower than the values reported by ENSCO (Ref. 3) and Southern number 2 (Ref. 32) for their respective average trends. This discrepancy is largely due to the method of interpreting the trends. ENSCO and Southern number 2 assumed that a linear relationship exists between lateral tie resistance values and amounts of traffic, whereas this study used a best-fitting curve through the data points, which is a more reasonable approach.

ENSCO reported the average values of equivalent traffic for tangent and curved track of 0.40 and 0.44 MGT at 0.0787 and 0.157 in. (2 and 4 mm) displacements, respectively. These values were obtained by the linear interpolation technique as shown in Fig. 5.19a, along with SUNYAB's interpretation of ENSCO's data. By fitting a reasonable curve through each set of data points, the resulting average equivalent traffic values are 0.24 and 0.28 MGT for 0.0787 and 0.157 in (2 and 4 mm) displacement, respectively. These values are nearly one-half of ENSCO's estimate and are close to the estimates obtained in this study using ENSCO's data (Table 5.4).

Southern number 2 reported an equivalent traffic value of 0.45 MGT for new ties only at 0.157 in (4 mm) displacement. A value of 0.33 MGT is obtained from using a best-fitting curve to Southern number 2 data (Fig. 5.19b). For old ties, this value is 0.36 MGT. The old and new tie average is reasonably close to the 0.35 MGT value listed in Table 5.4. Actually,

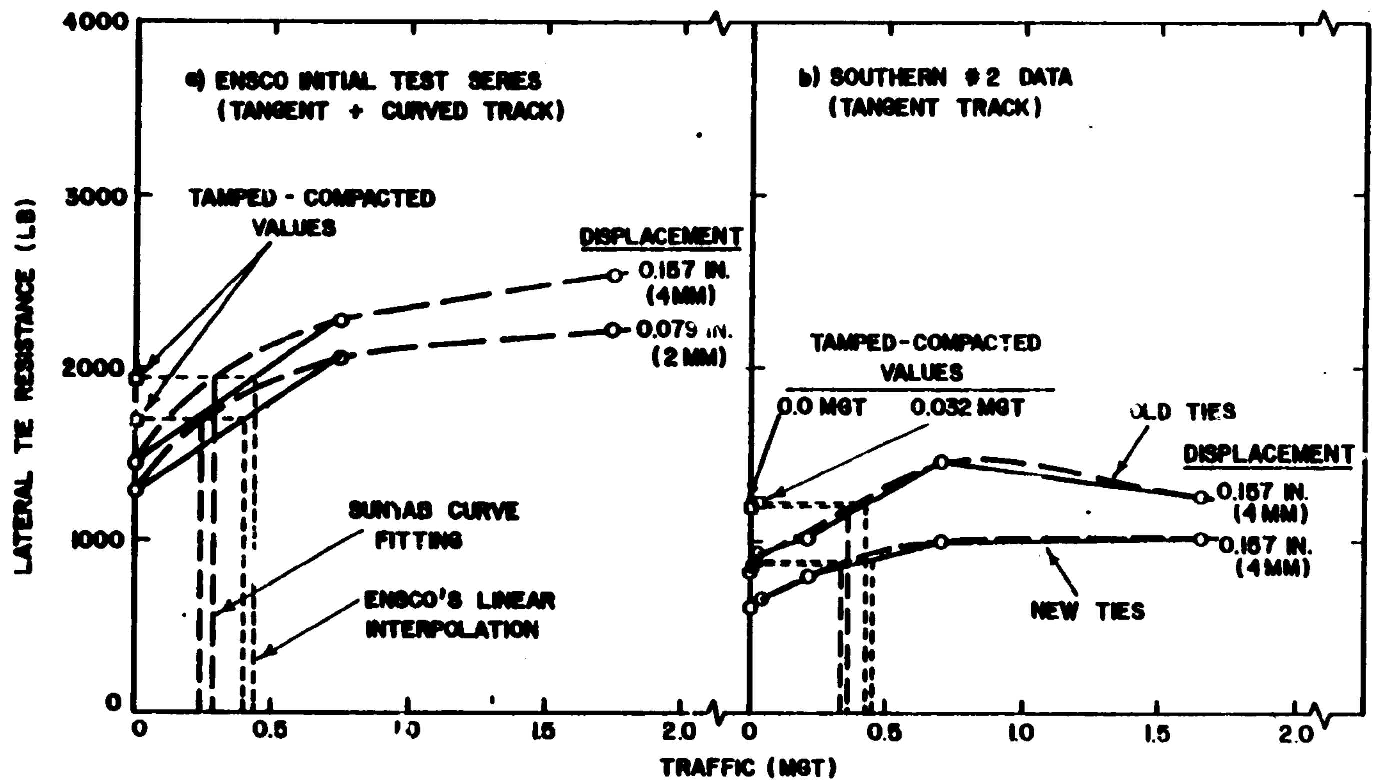


Figure 5.19. Comparison of Crib and Shoulder Compaction Equivalent Traffic Estimates from Tamped-Uncompacted Condition

the Southern number 2 estimate would have been closer to 0.35 MGT if the tamped-compacted trends were extrapolated to zero MGT and that value was used instead of the one at 0.032 MGT.

Southern number 2 does present an interesting approach, based upon statistics, toward the determination of the equivalent amount of traffic that crib and shoulder compaction offers. This has been termed the minimum advantage (Ref. 32). Instead of using the average tamped-only lateral tie resistance trend to determine the equivalent amount of traffic, the trend is generally defined as the average plus the second standard deviation. Also, the tamped-compacted value of lateral tie resistance at zero MGT is generally defined as the average minus the second standard deviation. However, using this method, the equivalent traffic estimate will be significantly lower.

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 is considered highly reliable, but lacks 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.

6. SUMMARY AND RECOMMENDATIONS

The objective of this project was to evaluate the changes in the ballast physical state for both a tamped-only (TU) track and a tamped-compacted (TC) track with applied train traffic by utilizing the lateral tie push (pull) test (LTPT) on a single tie, the in-situ ballast density test (BDT), and the plate load test (PLT). These tests are good indicators of the changes in ballast physical state. The test results were reliable and reproducible. In a relative sense, the BDT, LTPT, and PLT each produced consistent results for limestone, traprock, and mixtures of limestone and steel slag ballasts for the TU state at zero MGT traffic and with applied traffic. This same consistency was demonstrated for the TC state at zero MGT traffic in the limestone and steel slag ballast mixture. Test data were compiled and evaluated from available United States and foreign sources and compared with SUNYAB data. The main conclusions for this study, as implied from the BDT, PLT, and LTPT, are as follows.

<u>Ballast Density Test.</u> The newly developed ballast density measuring method has successfully demonstrated its potential as a useful tool for determining the in-situ ballast physical state. The techniques, which evolved out of various improvements, 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 track conditions. They constitute a significant enhancement of knowledge toward a better understanding of track response and its relationship to track performance.

Effects of various important parameters influencing the ballast physical states and subsequent track performance have been assessed, and the following important findings are concluded:

1) In-situ ballast physical state, as determined in terms of ballast density, is significantly affected by track history, including traffic, track maintenance procedures, and track conditions existing prior to maintenance.

2) 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 under tie in the rail area, but the same tamping performed during track maintenance after traffic will inevitably disturb and loosen the ballast layer that has been compacted over a period of traffic.

3) Ballast density increase from crib and shoulder ballast compaction is quite evident in the crib in the rail area, but the effect of crib compaction on the ballast layer under the tie is very limited.

4) The long-term effect of ballast compaction is not conclusive at this moment, mainly because of insufficient data.

5) Traffic appears to be the biggest source of ballast compaction. With accumulation of traffic, density throughout the ballast layer will increase with gradual rearrangement of ballast particles to a relatively dense and stable structure.

6) Ballast type does not appear to be a significant factor influencing in-situ ballast physical state and its changes with traffic history. Instead, particle properties such as toughness, hardness, particle gradation and texture seem to play more important roles than type of ballast.

Plate Load Test. The following conclusions were drawn from the plate load test results:

1. A comparison of the CNR and SUNYAB bearing index B values, located in the crib and under the tie near the rail, showed good agreement for the tamped-only condition at zero MGT and the undisturbed track condition.
2. Test results for the tamped-compacted condition at zero MGT were different between the CNR and SUNYAB data, which discrepancy has not been explained.
3. The ballast bearing index B value trends with MGT of traffic could not be established. However, SUNYAB data indicates that the amount of traffic equivalent to the benefits of crib and shoulder compaction is similar to that estimated from the LTPT correlation.

Lateral Tie Push Test. The following are the conclusions from the lateral tie push tests:

1. The two normalization techniques used to establish the lateral tie resistance trends with traffic provided a useful means of comparing the test data from several different test programs which utilize different test apparatus, and can be used for immediate evaluation

of field test results following the tamping operation.

2. A reasonable estimate of train loading after disturbance to reach a "stable" ballast condition is 20 MGT of traffic.
3. An estimate of the amount of traffic to produce the same benefits as crib and shoulder compaction used immediately after tamping is 0.17 to 0.19 MGT, or 3 to 4 days of average daily traffic.
4. The effects of crib and shoulder compaction cannot be distinguished from the tamped-only track condition after approximately 2.0 MGT of traffic.

The lack of sufficient quantities of available PLT and LTPT data in the 2 to 20 MGT range prohibits the establishment of clearly defined trends for the TU and TC conditions with applied traffic. Also, effects of differences such as in ballast type, amount of track raise, characteristics of ballast crib and shoulder compactors, and track structures, cannot be thoroughly evaluated. Further study is strongly recommended with due consideration given to the preceding factors, as well as taking the following factors into account:

1. Maintaining, to the best extent possible, controlled test conditions on several different sites.
2. Providing adequate documentation of the track structures, train traffic loading history, track maintenance history, and environmental conditions.
3. Using standardized BDT, PLT, and LTPT apparatus and test procedures, i.e., similar to SUNYAB.

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APPENDIX A

REPORT OF NEW TECHNOLOGY

The work performed under this contract has provided important new insights into the effects of tamping, vibratory compaction, and traffic on the physical state of ballast in track. Specifically, the research showed that tamping generally loosens ballast, that crib and shoulder compactors primarily densify the ballast around the tie, and that traffic provides the greatest amount of compaction of any of the mechanical processes found in the field. These findings were achieved through field investigations using the ballast density test, plate load test and lateral tie push test methods developed under this contract.

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