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WOOD TIE TRACK RESISTANCE CHARACTERIZATION AND CORRELATIONS STUDY

Office of Research and
Development
Washington, D.C. 20590

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13. ABSTRACT (Maximum 200 words)

The work presented here is part of a major program to evaluate lateral buckling of continuous welded rail (CWR) tracks. The program to develop the technical information to support safety guidelines and specifications for track buckling prevention is being directed by the Volpe National Transportation Systems Center in support of the Federal Railroad Administration.

This report presents the results of an extensive field test and evaluation study conducted to characterize the track lateral and longitudinal resistance behavior. More than 1400 tests were conducted to measure the lateral resistance for the purpose of isolating the effects of ballast type and consolidation, crib depth, shoulder width, track curvature, and loading methodology and rate. The contribution of each of these factors is quantified and discussed. The relationship between peak and limiting lateral resistance has been evaluated, and recommendations for the required test sample size are made. Data from tests performed with the Single Tie Push Test (STPT) fixture were correlated with the data from the Track Lateral Pull Tests (TLPT).

This report also presents the results of pilot field tests conducted to measure the track longitudinal resistance. The influences of rail anchoring, ballast consolidation, and crib depth were measured, and their effects are quantified.

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Lateral Resistance, Longitudinal Resistance, Track Lateral Stability, Field Tests, Single Tie Push Test

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PREFACE

This report presents the results of a comprehensive field test and data analysis program conducted to characterize the track lateral and longitudinal resistances. The work was performed under Contract No. DTRS-57-87-C-00063, which was awarded by the Volpe National Transportation Systems Center (VNTSC). The work was conducted by Foster-Miller and VNTSC, and was sponsored by the Federal Railroad Administration (FRA), U.S. Department of Transportation. The sponsor of the research program at the FRA is Mr. William R. Paxton, and the VNTSC program manager was Dr. Andrew Kish.

The support of Foster-Miller personnel including Mr. Douglas Thomson, for revision of this document, and Mr. Adam Purple, for review of this document, is gratefully acknowledged.

The field test program was conducted at the Transportation Test Center (TTC), managed by the Association of American Railroads (AAR), and on the revenue service lines of the Chessie System, now the CSX Transportation (CSXT). Single tie push tests (STPTs) and track lateral pull tests (TLPTs) were performed at TTC during numerous site visits between July 1985 and April 1989. Track characterization tests were performed also at the CSXT sites between July 1985 and July 1987. The longitudinal resistance tests were performed at TTC during March 1988. The support of numerous TTC personnel, under the direction of Mr. Dave Read, and numerous CSXT personnel, under the direction of Mr. Bruce Dunseth, is gratefully acknowledged.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2 = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2 = 0.09 square meter (m$_2$)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (1)
1 pint (pt) = 0.47 liter (1)
1 quart (qt) = 0.96 liter (1)
1 gallon (gal) = 3.8 liters (1)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yeards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliters (ml) = 0.03 fluid ounce (fl oz)
1 liter (1) = 2.1 pints (pt)
1 liter (1) = 1.06 quarts (qt)
1 liter (1) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES 0 1 2 3 4 5 6 7 8 9 10
CENTIMETERS 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

LIST OF SYMBOLS AND ABBREVIATIONS

ATSF - Atchison, Topeka, and Sante Fe
BRC - Ballast Resistance Characterization
C - Consolidated
CSR - Crib and shoulder ballast removed
E3TA - Every third tie anchored
EOTA - Every other tie anchored
ETA - Every tie anchored
F - Lateral resistance
f_0 - Constant longitudinal resistance
F_a, F_b, F_c - Peak lateral resistance for random ties
FAST - Facility for Accelerated Service Testing
FC - Full crib
FCS - Full crib and shoulder ballast
F_L - Limit resistance
F_m - Average peak resistance for a cell
F_o - Average peak resistance of three random ties
F_P - Peak resistance
HC - Half crib
HTL - High Tonnage Loop
k_f - Longitudinal stiffness
MGT - Million gross tons
NS - Norfolk Southern
SR - Shoulder ballast removed
STPT - Single tie push test
T - Tamped
TLPT - Track lateral pull test
TTC - Transportation Test Center
W_P - Lateral dsplacement at peak resistance
W_L - Lateral displacement at limit resistance

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EXECUTIVE SUMMARY

The Volpe National Transportation Systems Center (VNTSC) is providing technical support to the Federal Railroad Administration (FRA) in the development of technical information to support performance-based safety standards for continuous welded rail (CWR). A major problem with CWR is lateral buckling under high thermal and vehicle loads. The track lateral and longitudinal resistances are two important parameters that can control lateral stability. An investigation of these parameters has been completed by VNTSC. The investigation involved data analysis, hardware development and field testing at the Transportation Test Center (TTC) and the Chessie System, now the CSXT. Field tests for track lateral resistance were carried out in three phases from 1985 to 1989. In all, 1,377 single tie push tests (STPT) and 40 track lateral pull tests (TLPT) have been compiled into a database report. This database is the foundation for this correlation study.

This report presents correlations between the STPT and TLPT to validate the performance of the STPT device. The effects of track consolidation by traffic on lateral resistance, the influence of different ballast types, and the respective contributions from crib, shoulder and bottom ballast to overall track lateral resistance are quantified through the extensive test program to characterize the track lateral resistance. Also presented in this report is a study dealing with the minimum number of single tie push tests required to characterize a given length of CWR track (for lateral strength).

A total of nine longitudinal resistance panel tests were conducted at TTC. This report presents the results of those tests and provides an evaluation of the influences of tie anchoring and ballast level and consolidation.

The lightweight, portable STPT system was successfully demonstrated as a convenient method for measuring lateral resistance. Test results demonstrated that the equivalent TLPT response can be directly determined from the STPT measurement; thus, the need for any empirically derived correction factor is eliminated.

The large number of tests permitted full characterization of the lateral resistance to support analysis of different track conditions. The contributions from crib, shoulder, and tie bottom were isolated, with the crib being identified as the most important factor. This test database was also used to determine that a test sample size of three ties within a 50 ft cell was sufficient to characterize the track lateral resistance in that cell. As was expected, lateral resistance was found to increase with traffic (MGT); however, a definitive relationship is not apparent, especially in light of the variations in the resistance of recently tamped track.

Track longitudinal resistance was found to depend on crib ballast level, anchoring pattern, and ballast consolidation. Reductions in resistance due to reduced crib ballast, tamping, and reduced rail anchoring were quantified.

1. INTRODUCTION

The track lateral and longitudinal resistances are two of the fundamental parameters controlling track lateral buckling and track shift under thermal and vehicle loads. Thus, the characterization of these parameters is essential in support of the development of track buckling analyses and applicable safety criteria.

Track lateral resistance is primarily the resistance offered by the ballast to oppose lateral movement of the ties. The stiffness of the rail itself also contributes to the track lateral resistance. Track lateral resistance is commonly quantified in either pounds per tie or pounds per inch, which is simply pounds per tie divided by tie spacing. Buckling forces are reacted by this resistance, which, consequently, defines the maximum allowable rail force. While entire track panels have been mobilized to determine resistance, a simpler, less destructive measurement technique was required.

The track lateral resistance generally increases primarily as a function of ballast consolidation due to traffic tonnage (MGT) and decreases primarily as a function of track maintenance work, such as tamping. Proper characterization of the lateral resistance must account for the site conditions of ballast material and ballast shoulder and crib, as well as for the transient conditions of consolidation. A large number of lateral resistance tests have been completed to develop a database in support of a comprehensive characterization study of the track lateral resistance.

The objectives of the program discussed in this report are as follows:

1. Evaluate and compare the track lateral resistance test results from the single tie push tests (STPT) and the track lateral pull tests (TLPT) for the purpose of validating the accuracy and the capabilities of the portable STPT device.
2. Develop a relationship between peak and limiting lateral resistance in order to reduce the required displacement of test ties and thereby limit the track disturbance due to testing.
3. Study the relationship between track consolidation and track lateral resistance.
4. Isolate the tie lateral resistance component influences, which include the ballast shoulder, crib, and tie bottom surface.
5. Determine the test sample size requirements for measurement of the lateral resistance.

The track longitudinal resistance is primarily a function of rail anchoring and ballast longitudinal strength. A program of track longitudinal resistance tests has been completed to develop a database in support of the characterization of this parameter. The objectives of this part of the program discussed in this report are as follows:

6. Evaluate and compare the longitudinal resistance under three conditions, namely, every tie anchored (ETA), every other tie anchored (EOTA), and every third tie anchored (E3TA).

7. Evaluate and compare the longitudinal resistance under tamped and consolidated ballast and full and half crib conditions.

Previous Investigations

It must be stated that the track lateral and longitudinal resistances were evaluated by several previous investigators in the U.S. and abroad. For example, Selig and coworkers (8) used a single tie test method to establish the relationship between ballast consolidation level and MGT. The tie displacements involved in these tests were very small and did not represent the full nonlinear range required for the buckling analysis. A similar condition exists in the field data generated by Goldberg-Ziono and Associates (10). The resistance data generated by Choros et al. is restricted to the laboratory conditions (9). Panel test data was collected by Reiner (11), but it did not include single tie resistance measurements.

A large body of European data (4) was also typically generated over a small deflection range. Furthermore, the European data may not be applicable for the U.S. track conditions.

In general, the primary focus of the available previous studies has been to quantify ballast consolidation and relate it to traffic (MGT). Thus, the large tie deflection studies of the U.S. track presented here were required to develop the relationships necessary for proper buckling analysis.

2. TECHNICAL DISCUSSION

Methods to measure track lateral resistance in the field have been devised in the United States and abroad. The two types of measurement methods investigated here were the Single Tie Push Test (STPT), which mobilizes a single tie laterally, and the Track Lateral Pull Test (TLPT), which mobilizes a track section laterally. In the first method, the resistance is determined by the load-displacement response of the tie, whereas in the second method, resistance is determined by the load-deflection response of the track structure involving the combined effects of rail flexural rigidity, rail longitudinal force, and nonuniform lateral resistance of the ties over the test panel section.

In past studies STPTs were not considered an appropriate means of measuring track lateral resistance because of the scatter in tie resistance values, whereas the TLPT provided a direct measurement of track lateral resistance over a long length. Also, the STPT produced average track lateral resistance values higher than the TLPT, which were then divided by an empirical factor in the range of 1.3 to 1.5 to arrive at equivalent TLPT values (1). From the data collected it will be shown that STPT results are representative of actual nonlinear track lateral resistance and do not require an empirical factor. The TLPT response for STPT data, under applied lateral loads, can be predicted with reasonable accuracy by treating the rails as a beam on nonlinear elastic foundation and the nonlinear spring stiffness by the single tie push test (1).

The advantages of the STPT over the TLPT are:

- The test yields a more fundamental characteristic of ballast resistance since the STPT is not affected by rail rigidity and rail longitudinal force.
- The test equipment is portable and easy to use.
- The test is minimally destructive to track, whereas the TLPT is cumbersome to perform and very destructive.

The primary disadvantage of the STPT, as mentioned before, is the variation of results due to local resistance offered by each tie. However, using a sample mean or average (shown later in Tables 3-1 and 3-2) of individual test results it is possible to determine the buckling and safe allowable temperatures from the safety limit charts currently under preparation at VNTSC. It will be shown in this report that for a 50 ft section of CWR, three randomly selected ties would generally be adequate to yield an average lateral resistance value. Using this average value, the track model can generally predict buckling temperatures to sufficient accuracy.

A significant result of the STPT study is that track lateral resistance can exhibit a "softening" behavior after attaining a peak value at small displacements (between 0.25 to 0.50 in.). The "softening" behavior continues for about 3 to 6 in. after peak resistance, beyond which the resistance remains essentially constant. The peak and limit values will be designated as F_P and F_L and the corresponding displacements as W_P and W_L (Figure 2-1).

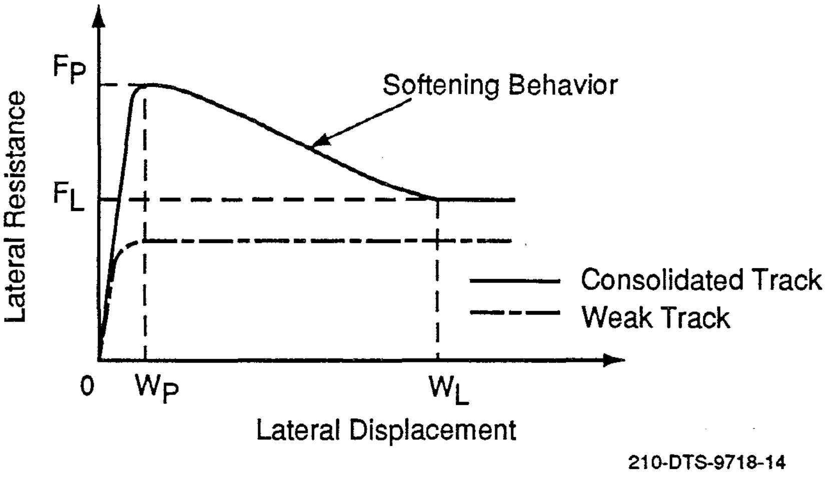

Figure 2-1. Typical STPT Characteristics

The "softening" behavior is prominent in consolidated tracks and is due to the breakdown of the bond between the ballast-tie interface as the tie moves laterally. In addition, as the tie moves laterally it will tend to lift up out of the ballast due to larger voids created between ballast particles as they displace each other. Essentially the lateral movement of the ties in the ballast produces some loss of consolidation. As the strain energy stored in the consolidated ballast is released the ties are pushed up from the ballast. Even in TLPTs, the entire panel tends to lift up. This behavior has also been observed in track buckling field tests carried out in the United Kingdom and the United States. Based on the test data and the foregoing discussion, it can be stated that the softening or "drooping behavior" of the STPT characteristic is inherent in the lateral ballast kinematics, and not a manifestation of the STPT design, hardware, or test methodology.

It has been theoretically shown that the peak resistance (F_P) has significant influence on the upper buckling temperature and that the limit resistance (F_L) controls the lower buckling temperature (2). Therefore, both peak and limit resistance values are necessary for track buckling predictions. Since it is undesirable to displace ties laterally more than 1 in. on revenue service track, a method of determining the limit resistance was required. A solution is to establish a correlation between peak and limit resistance that would allow the limit resistance (3 to 6 in. displacement required) to be derived from peak resistance (~0.25 in. displacement required), thereby subjecting the ballast to minimal disturbance. This has been demonstrated in the present study.

The complete characterization of the track lateral resistance requires a large number of tests under various conditions. Tests were performed under numerous states of ballast consolidation, including fine (0.1 MGT) increments of tonnage up to 2 MGT, to develop a relationship between ballast consolidation and track lateral resistance. Tests were performed with full crib and shoulder ballast, shoulder ballast removed, and crib and shoulder ballast removed in order to isolate the components of lateral resistance. This large database was further utilized to statistically determine the required test sample size for future work.

CWR track tends to move laterally (breathe) to relieve a uniform rail force and longitudinally to balance a non-uniform force throughout a section. The longitudinal resistance of the track consists of the resistance offered by the rail fasteners (spikes, anchors, spring clips, etc.) to oppose rail movement and the resistance from the ballast to oppose longitudinal tie movement. If the track is not properly restrained longitudinally, a non-uniform condition, which can lead to buckling, is more likely to occur due to the forces of train action. The longitudinal resistance of the track is also significant in the analysis of track buckling potential in that during buckling, rail is drawn in from the adjoining track zone. This action is opposed by the longitudinal resistance. In order to characterize the influence of the key parameters that determine longitudinal resistance, tests were performed under three different rail anchoring configurations, under tamped and consolidated conditions, and with full and half full ballast cribs.

3. LATERAL RESISTANCE CHARACTERIZATION

A significant number of individual ties were tested using the STPT and the data reduced by statistical analyses on a "zone" and "cell" basis to facilitate correlations. The zone results are presented in Tables 3-1 and 3-2 which show the sample average, standard deviation, range (maximum /minimum), and sample size. Each of the 12 test zones were divided into several types of cells and defined as follows:

- In zones 1 through 6 a cell is defined as a 50 ft length of track. Each cell had either 15 STPTs, or 1 TLPT performed within it.
- In zones 7 and 8 a cell is also defined as a 50 ft length of track. Each cell had 13 STPTs performed within it.
- In zones 9, 10 and 11 a cell is defined by a specific level of consolidation (for example 0 MGT, 1 MGT, etc.). Each cell had 10 STPTs performed within it at 10 tie intervals (except for cell 1 where the STPTs were performed on every other tie).
- In zone 12 a cell is also defined by a specific level of consolidation. Each cell had 30 STPTs, spaced randomly, performed within it.

A typical test configuration for the first six zones is shown in Figure 3-1, where cells for these test zones had STPTs or TLPTs performed within them, for full crib and shoulder ballast, shoulder ballast removed, and crib and shoulder ballast removed.

Figures 3-2 through 3-7 show the STPT characteristic curves generated from average cell resistance values (15 ties per 50 ft cell, every other tie) in the first six zones. These plots were generated by calculating the average force measured over all tested ties at displacement increments of 0.1 in. up to a total tie displacement of 6 in. Immediately noticeable is the significant reduction in lateral resistance when crib and shoulder ballast are removed. This was consistent throughout all six zones regardless of ballast type (slag/granite), track curvature (tangent/5 deg curve), and consolidation level (0.1 MGT/25.0 MGT). The significance of this result will be discussed in subsection 3.1, where the correlation between TLPT and STPT is determined. The other track condition investigated was the case of shoulder ballast removed, which produced varied reductions in lateral resistance for each test zone.

It was also observed that for low consolidation levels the characteristic early peak resistance at small displacements does not occur (see Figure 3-5), resulting in a dome-shaped curve showing almost constant lateral resistance. However, as the consolidation level increases, the difference between the peak resistance and limit resistance increases, producing the STPT characteristic curve (see Figures 3-2, 3-3, 3-4, 3-6, and 3-7).

Zonal averages were also produced from the cell average data, in the same manner as the cell averages were calculated, for the case of full crib and shoulder ballast as shown in Figure 3-8. This data will be utilized to correlate with the TLPT data in subsection 3.1.

Table 3-1. Summary of Peak Resistance and Corresponding Displacement

Zone	Test Parameters	MGT	Peak Force (lb)				Peak Displacement (in.)				No. of Points
			Avg	S.D.	Max	Min	Avg	S.D.	Max	Min	
1	PR	0	1469	258	2300	940	0.27	0.12	0.85	0.08	89
1	BCC1	0	1129	172	1500	850	0.40	0.25	1.15	0.10	29
1	BCC2	0	227	50	325	150	0.13	0.08	0.33	0.05	15
2	PR	25	1993	397	3030	1175	0.19	0.10	0.50	0.08	91
2	BCC1	25	1078	177	1500	800	0.21	0.12	0.55	0.10	30
2	BCC2	25	209	44	285	125	0.25	0.20	0.75	0.05	13
3	PR	25	2374	351	3320	1550	0.29	0.12	1.05	0.13	88
3	BCC!	25	1504	245	2200	1075	0.23	0.11	0.65	0.10	29
3	BCC2	25	202	64	300	100	0.28	0.28	0.85	0.05	15
4	PR	0	1038	148	1500	700	0.70	0.30	1.55	0.15	71
4	BCC1	0	849	128	1200	650	0.55	0.31	1.25	0.10	30
4	BCC2	0	167	36	250	100	0.28	0.24	0.88	0.08	15
5	PR	100	3176	560	4300	1900	0.31	0.10	0.60	0.13	85
5	BCC1	100	2666	466	4225	1875	0.37	0.17	0.95	0.18	31
5	BCC2	100	468	62	575	350	0.08	0.04	0.18	0.05	14
6	PR	25	2206	411	3390	1250	0.26	0.14	0.85	0.08	78
6	BCC1	25	1790	226	2265	1520	0.18	0.06	0.35	0.10	14
6	BCC2	25	324	126	575	155	0.10	0.07	0.25	0.05	14
7	PR	0	1469	277	1890	840	0.37	0.25	0.90	0.10	24
7	PR	1.2	1551	128	1750	1330	0.34	0.16	0.66	0.10	20
7	PR	5.0	1721	205	2000	1400	0.38	0.24	1.08	0.10	24
7	PR	15.2	1851	289	2450	1295	0.54	0.43	2.02	0.15	24
7	BCC2	0	418	72	510	300	0.53	0.36	1.30	0.05	13
7	BCC2	1.2	418	111	610	280	0.27	0.21	0.60	0.05	8
7	BCC2	15.2	434	64	530	305	0.23	0.10	0.50	0.08	16
8	PR	0	1050	192	1510	700	0.76	0.34	1.40	0.23	24
8	PR	15.2	1771	279	2390	1390	0.31	0.08	0.52	0.13	24
8	BCC2	0	261	64	390	170	0.54	0.34	1.10	0.10	16
8	BCC2	15.2	447	89	630	310	0.18	0.15	0.60	0.02	16
9	PR	0	1532	118	1790	1350	0.57	0.24	0.90	0.15	10
9	PR	1.2	2154	264	2760	1800	0.67	0.25	1.10	0.30	9
9	PR	4.0	2204	350	2700	1740	0.29	0.11	0.45	0.15	10
9	PR	8.4	2658	417	3400	2050	0.49	0.29	0.95	0.20	10
9	PR	15.2	2722	266	3130	2400	0.44	0.19	0.82	0.12	10
10	PR	0	1229	163	1600	1030	0.92	0.53	1.80	0.40	10
10	PR	1.2	1657	291	2050	1200	0.71	0.41	1.50	0.26	10
10	PR	4.0	2170	530	2970	1530	0.70	0.32	1.10	0.25	10
10	PR	8.4	2317	410	2850	1660	0.93	0.19	1.22	0.71	10
10	PR	15.2	1910	250	2380	1660	0.52	0.28	1.00	0.10	10
10	PR	15.2*	2338	656	3460	1300	0.90	0.65	2.10	0.18	10

Table 3-1. Summary of Peak Resistance and Corresponding Displacement (Continued)

Zone	Test Para-meters	MGT	Peak Force (lb)				Peak Displacement (in.)				No. of Points
			Avg	S.D.	Max	Min	Avg	S.D.	Max	Min	
11	PR	0	1830	346	2290	1220	0.35	0.13	0.60	0.20	10
11	PR	2.8	2569	446	3380	1730	0.27	0.12	0.50	0.15	10
11	PR	7.2	3019	488	3500	2190	0.43	0.11	0.60	0.28	10
11	PR	14.0	2394	385	2950	1600	0.27	0.15	0.65	0.18	10
11	PR	14.0*	4028	793	4790	2360	0.42	0.20	0.90	0.23	10
11	PR	14.0*	2860	267	3270	2530	0.39	0.03	0.42	0.35	5
11	PR	N/A	2216	375	2920	1700	0.18	0.04	0.25	0.13	9
12	PR	0.4	1264	222	1720	910	0.31	0.26	0.93	0.08	26
12	PR	5.4	1969	435	3100	1400	0.23	0.16	0.75	0.05	18
12	PR	11.8	1634	352	2325	1000	0.29	0.27	0.90	0.05	29
12	PR	16.3	2006	297	2550	1425	0.19	0.14	0.75	0.05	28
12	PR	24.3	2017	302	2600	1475	0.24	0.15	0.75	0.10	27

Legend:
PR - Peak resistance
BCC1 - Ballast component contribution (no shoulder)
BCC2 - Ballast component contribution (no crib; no shoulder)
SD - Standard deviation
*-Retest (1 month later)

Table 3-2. Summary of Limit Resistance and Corresponding Displacement

Zone	Test Para-meters	MGT	Limit Force (lb)				Limit Displacement (in.)				No. of Points
			Avg	S.D.	Max	Min	Avg	S.D.	Max	Min	
7	LR	0	926	198	1280	500	4.62	0.89	5.90	2.35	24
7	LR	1.2	985	118	1200	700	3.77	1.10	6.15	1.95	20
7	LR	4.0	1025	200	1600	700	4.40	0.96	5.72	2.62	22
7	LR	15.2	1065	291	1920	720	5.67	0.67	7.00	4.50	24
8	LR	0	693	101	870	500	4.08	1.19	6.28	2.49	24
8	LR	15.2	672	101	870	520	4.15	1.05	5.65	1.95	24

Legend: SD - Standard deviation

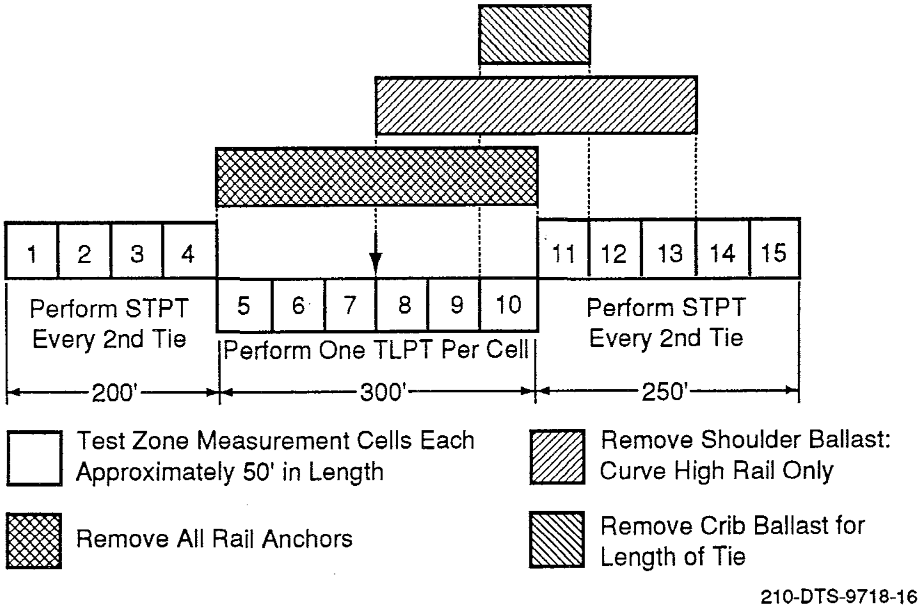

Figure 3-1. Typical Test Configuration - Zones 1 through 6

The other test zones (7 through 12) simulated variations in ballast materials, consolidation, and track curvature that will be discussed later in this report. Overall, the various test conditions facilitated the identification of parameters controlling track lateral resistance and related quantitative correlations.

As stated earlier, there are two salient points in the STPT characteristic curve; namely, the peak and limit resistance values. Tables 3-1 and 3-2 give a summary of results for each. In general, the standard deviation for peak resistance increases with the consolidation level. In percentage, the standard deviation varies in the range of 15 to 20 of the mean, F_{avg}. It should be stressed that some of the cells in each test zone (1 through 6) were spread quite a distance apart and the standard deviation seen for these is high. Within individual cells the standard deviation is much smaller.

The peak resistance distribution plots, for zones 1 through 6, are shown in Figure 3-9. From these plots it can be seen that the standard deviation increases with consolidation level. For tamped and weak tracks, which are generally buckling prone, the "spread" of peaks in the distribution is small, which implies fewer ties would be required to characterize the lateral resistance. Also, for consolidated track, fewer test ties would be required since a greater percentage of error is tolerable in view of the reduced risk in buckling.

3.1 TLPT versus STPT

The purpose of this subsection is to show that the track response under the track lateral pull test (TLPT), in which the entire track structure is mobilized laterally, can be predicted using the averaged single tie push test (STPT) data and treating the rails as a single infinitely long beam

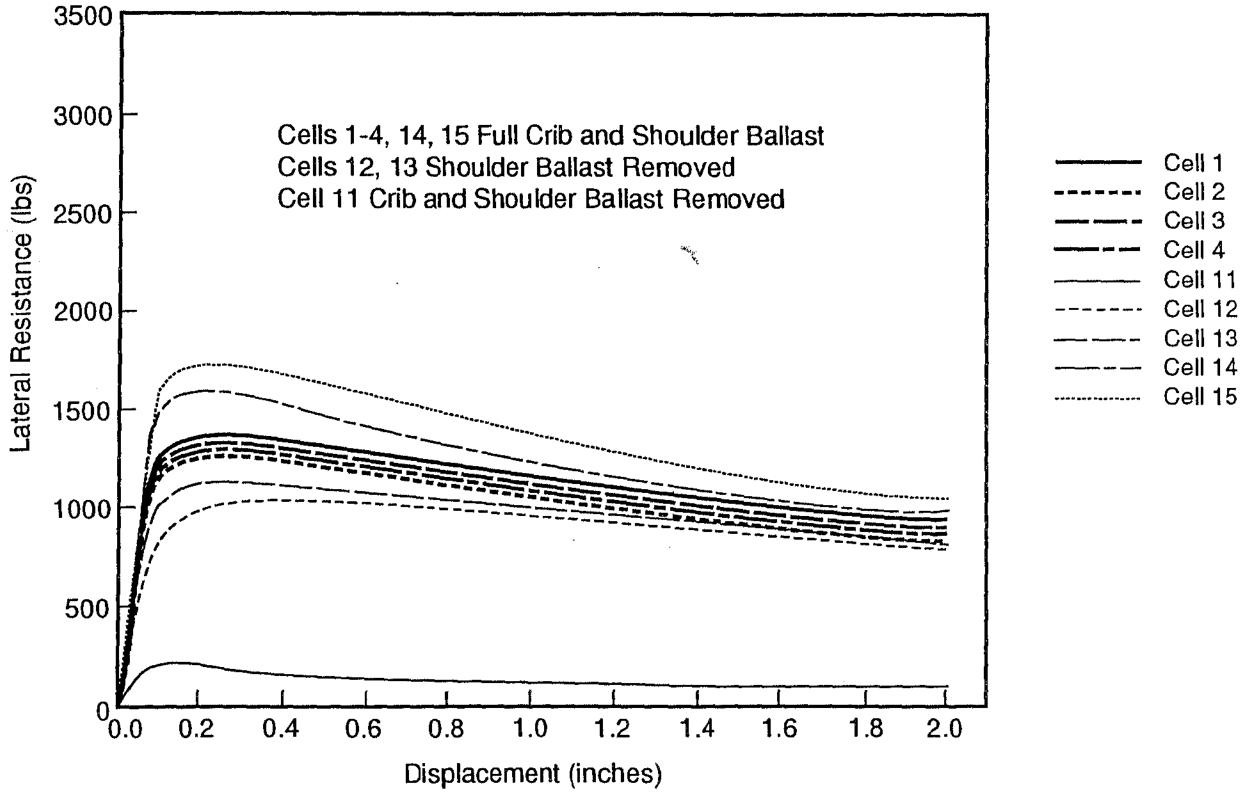

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Figure 3-2. Cell Averages for Zone 1 - 5 deg Curve, Slag, 0.1 MGT

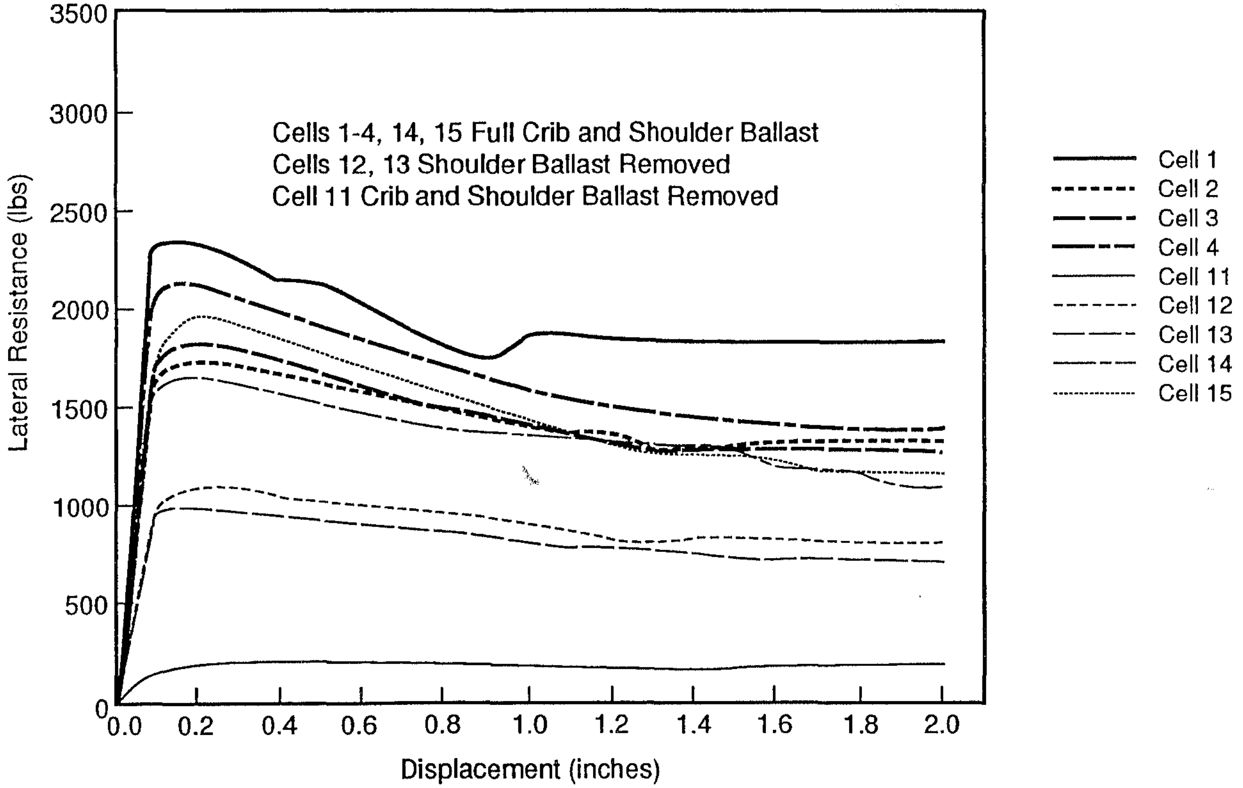

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Figure 3-3. Cell Averages for Zone 2 - 5 deg Curve, Granite, 25.0 MGT

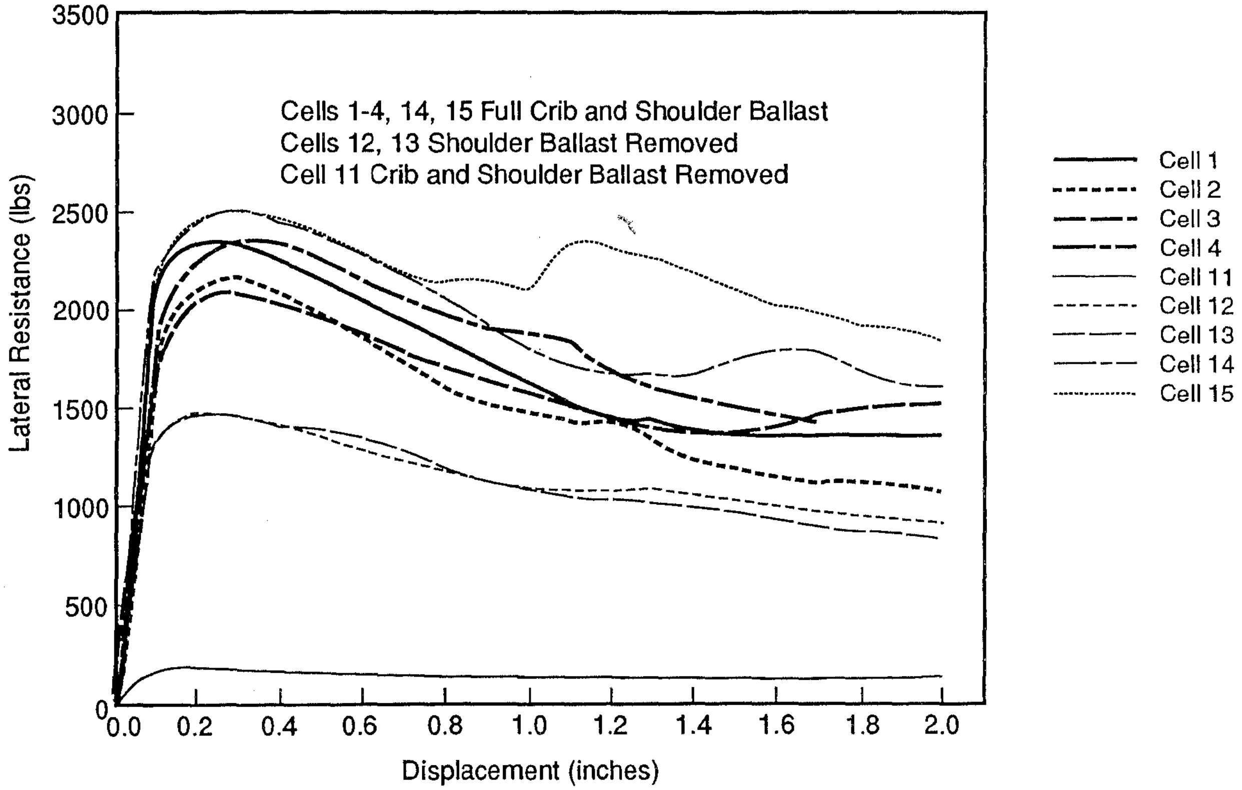

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Figure 3-4. Cell Averages for Zone 3 - 5 deg Curve, Slag, 25.0 MGT

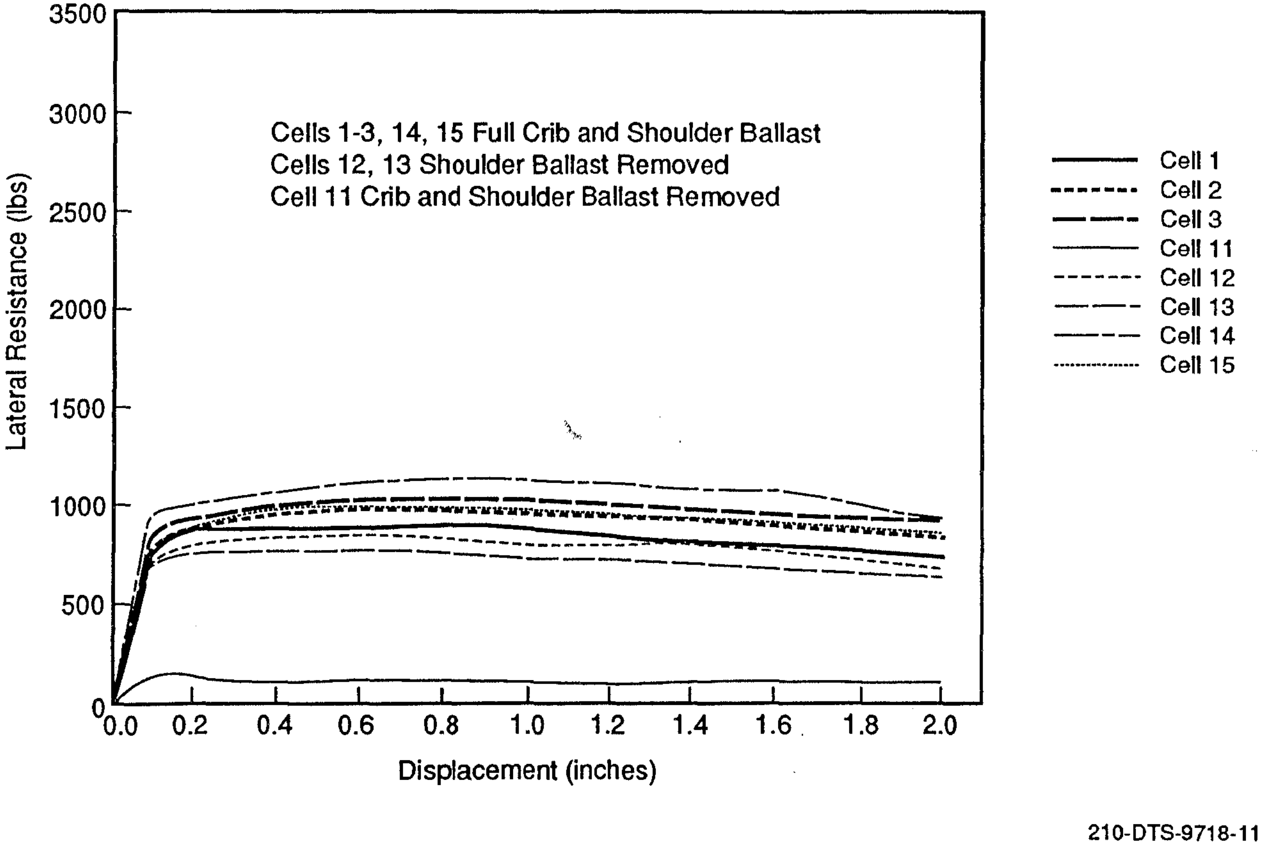

Figure 3-5. Cell Averages for Zone 4 - Tangent, Slag, 0.1 MGT

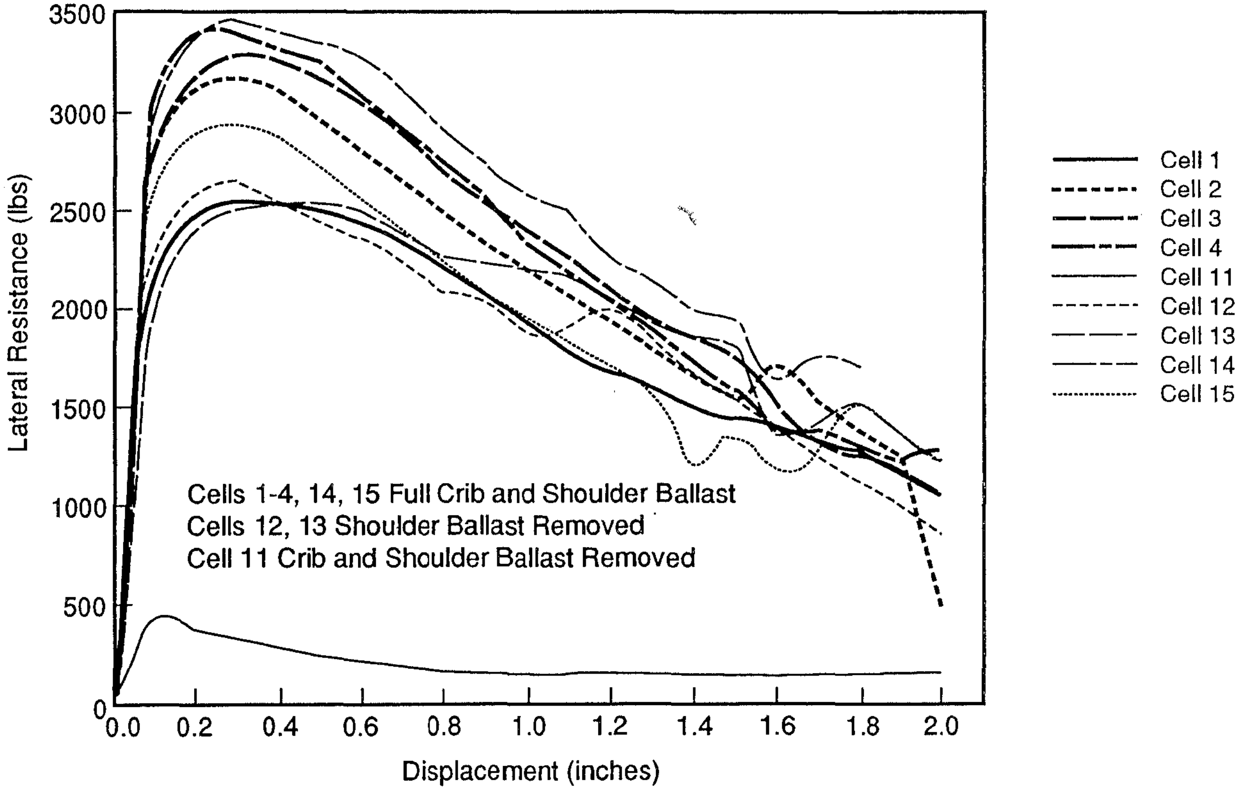

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Figure 3-6. Cell Averages for Zone 5 - Tangent, Slag, 100.0 MGT

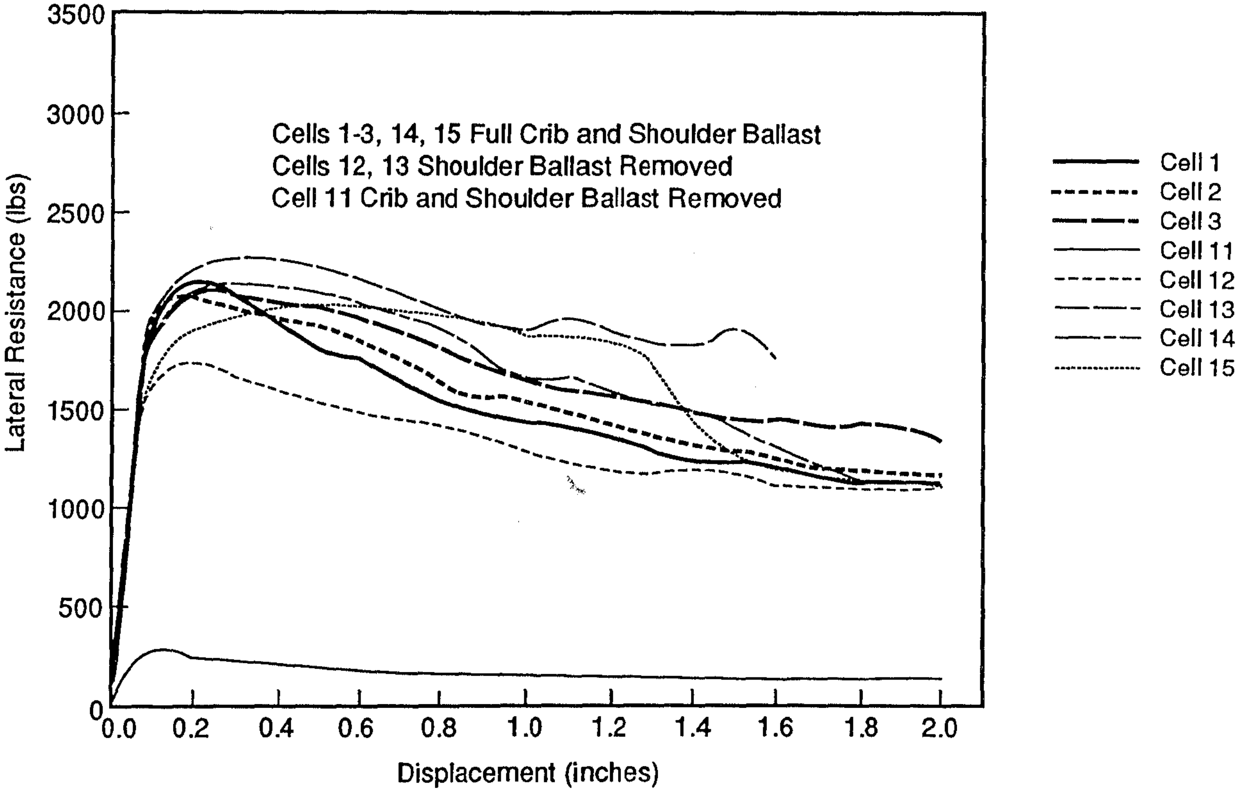

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Figure 3-7. Cell Averages for Zone 6 - Tangent, Granite, 25.0 MGT

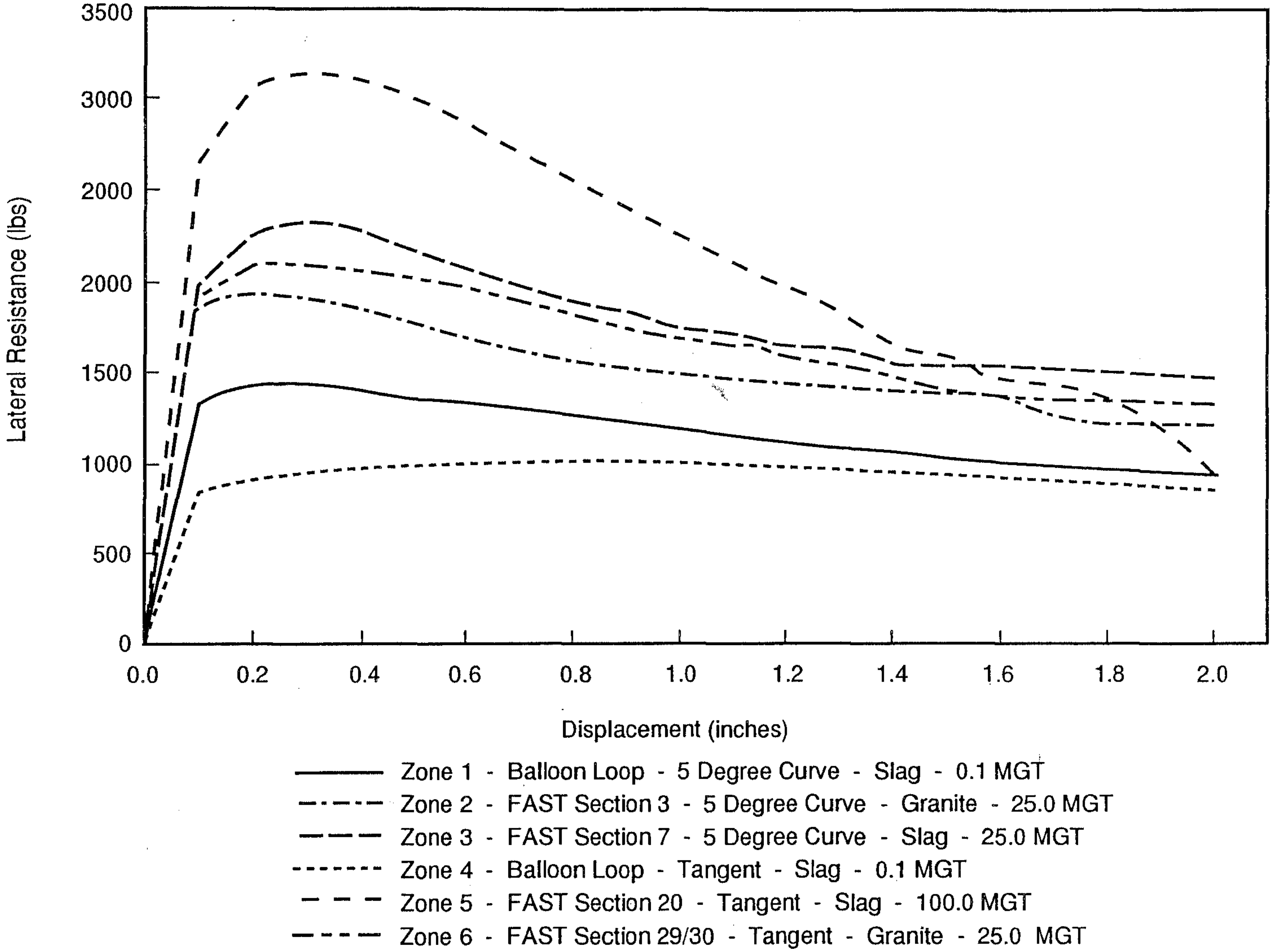

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Figure 3-8. Zonal Averages for Zones 1 through 6 - Full Crib and Shoulder Ballast

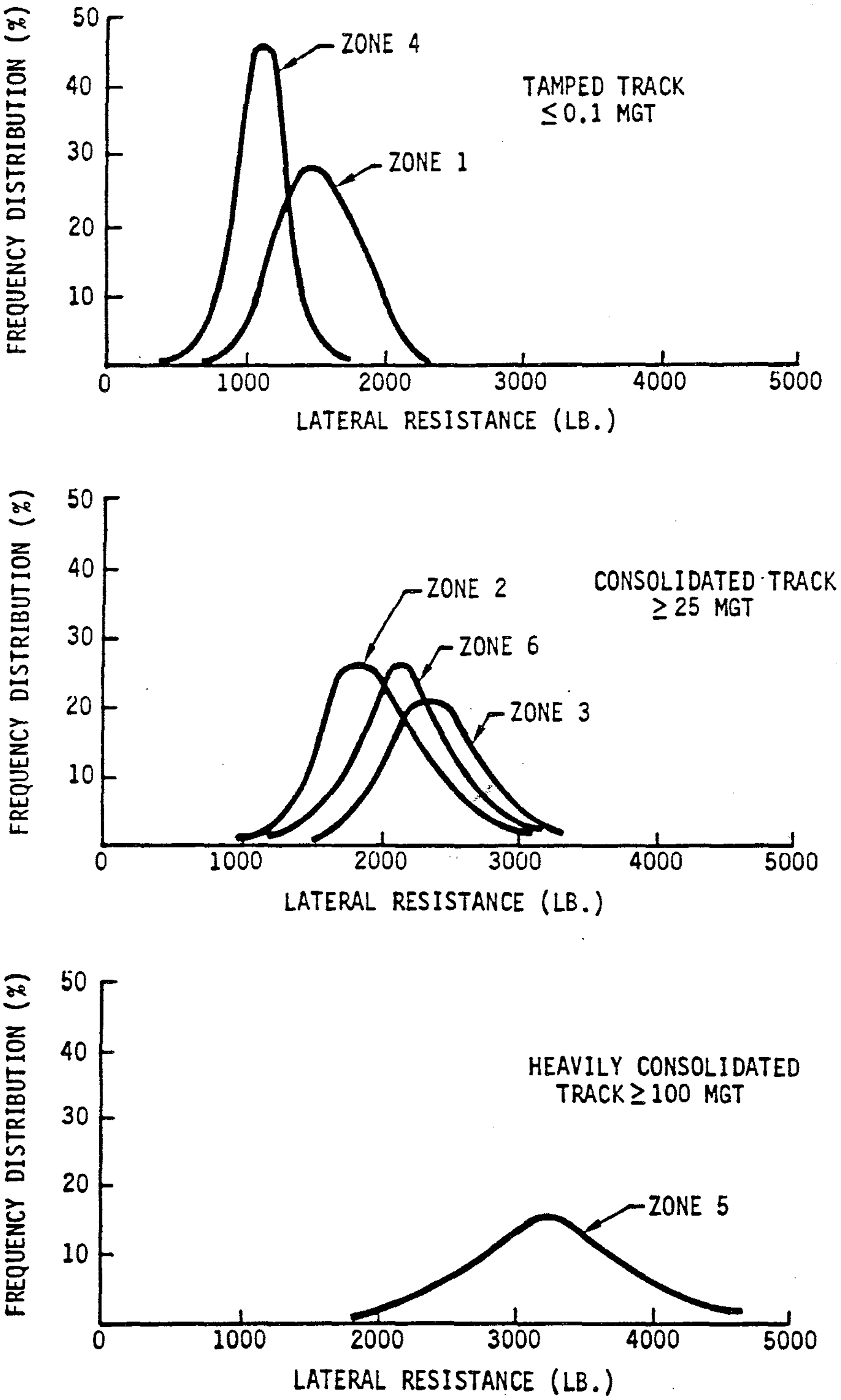


Figure 3-9. Distribution of Peaks in Test Zones 1 through 6

under nonlinear elastic foundation. The general theory for the TLPT response is presented in (1). This theory is utilized in arriving at the correlations presented here. In the analysis, the linear part of each of these curves is neglected and the characteristic curves are idealized as straight lines starting from the peak resistance value to the limit resistance value, after which there is only constant resistance. Using this idealization, the theoretical response of TLPT is predicted for each of the zones and compared with the experimental results as schematically illustrated in Figure 3-10. It should be noted that the STPT characteristic cannot be determined from the TLPT response.

The approach then was to establish a correlation between the STPT and TLPT by analytically converting the STPT data, from zones 1 through 6 (see Figure 3-1), into their respective TLPT responses, after which a qualitative comparison could be made between the two test methods. The results are shown in Figures 3-11 through 3-16. The STPT data typically had six cells per zone for full crib and shoulder ballast, two cells per zone for shoulder ballast removed, and one cell per zone for crib and shoulder ballast removed.

The zone average STPT results for full crib and shoulder ballast were shown in Figure 3-8. In Figures 3-11 through 3-16 the analytically predicted TLPT response using STPT nonlinear characteristics is shown as the "Theory" and the TLPT as the "Experiment". The analysis used to convert the STPT data to TLPT form requires three important parameters: the average peak resistance (F_P), average limit resistance (F_L), and the interval of displacement between which the peak and limit resistance occur. These parameters are essential in determining the appropriate TLPT response with respect to the STPT "softening" behavior. The TLPT data was based on three cells per zone for full crib and shoulder ballast, one cell per zone for shoulder ballast removed, and one cell per zone for crib and shoulder ballast removed. All data is averaged on a zone basis.

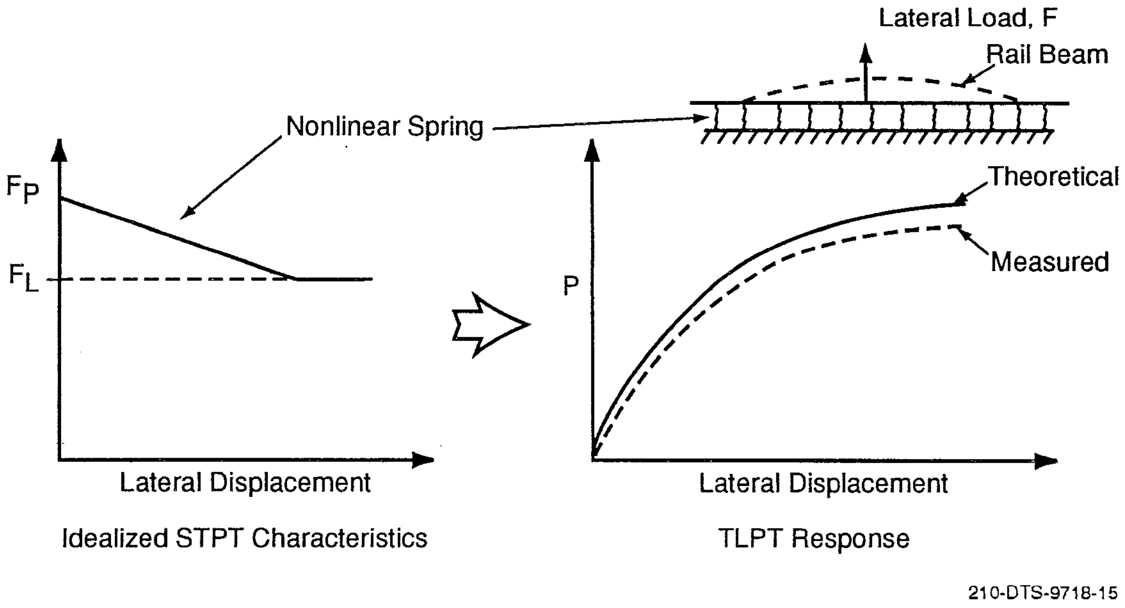


Figure 3-10. STPT-TLPT Correlation Procedure

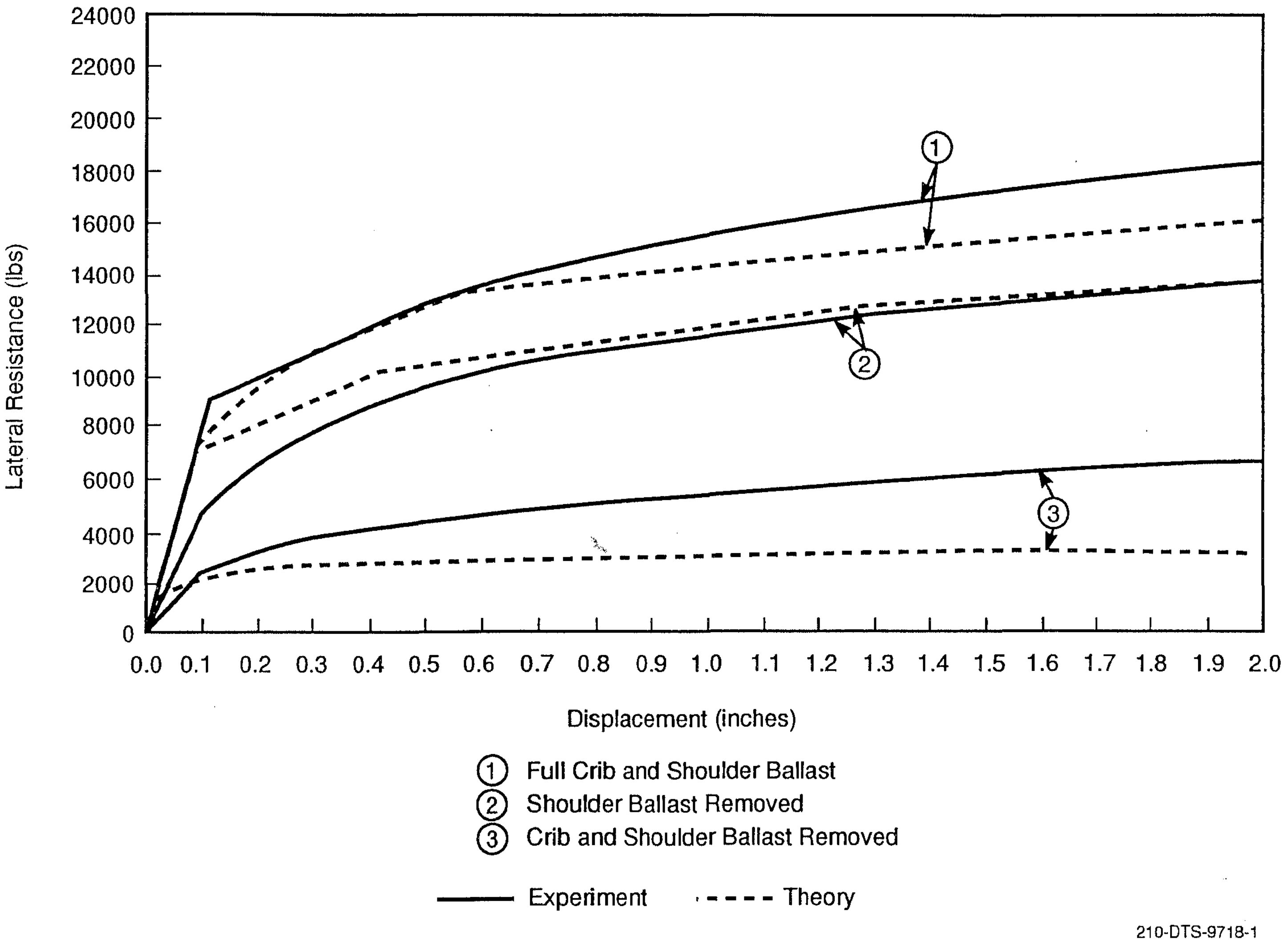


Figure 3-11. Comparison of TLPT versus STPT for Zone 1

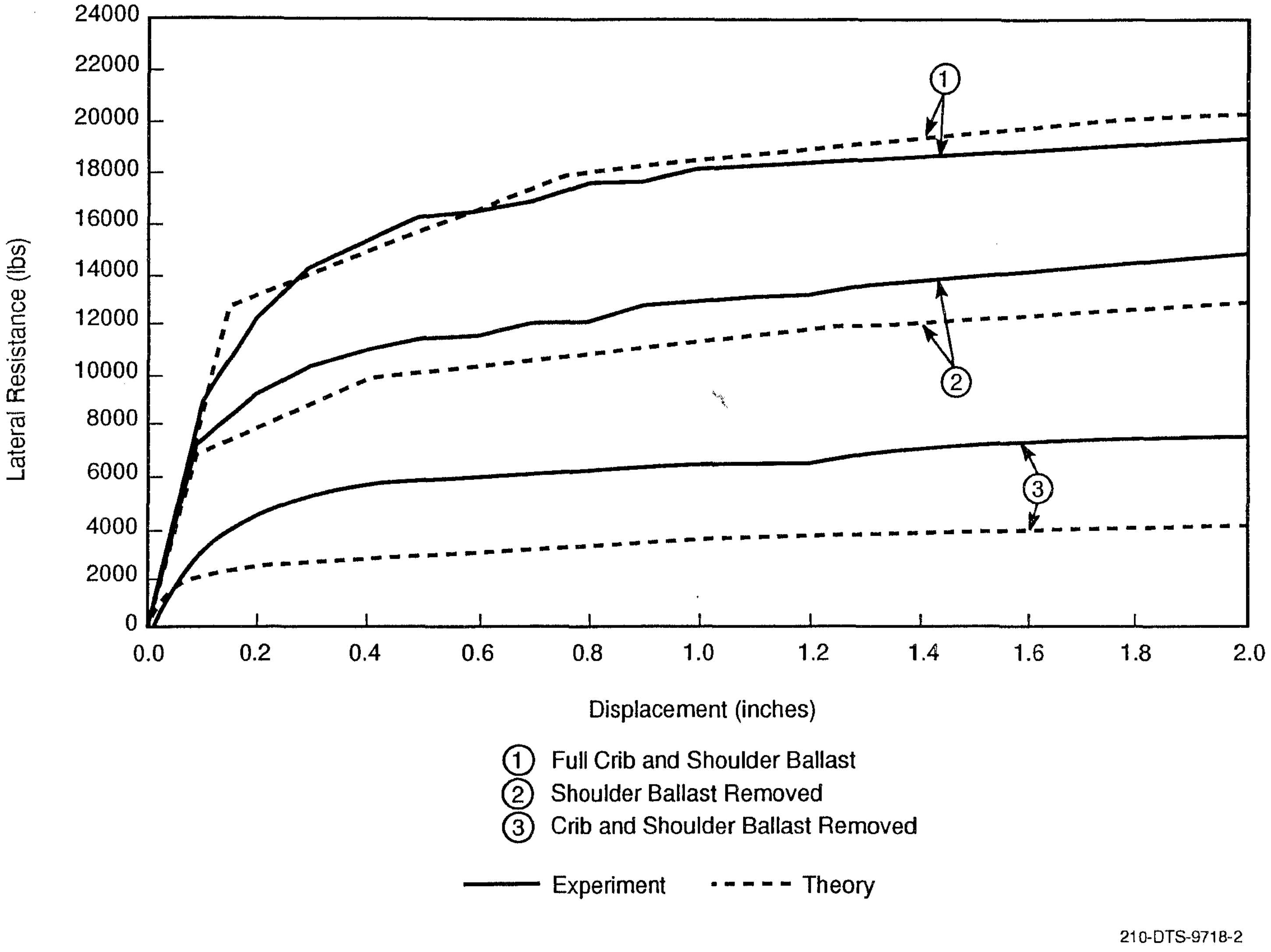


Figure 3-12. Comparison of TLPT versus STPT for Zone 2

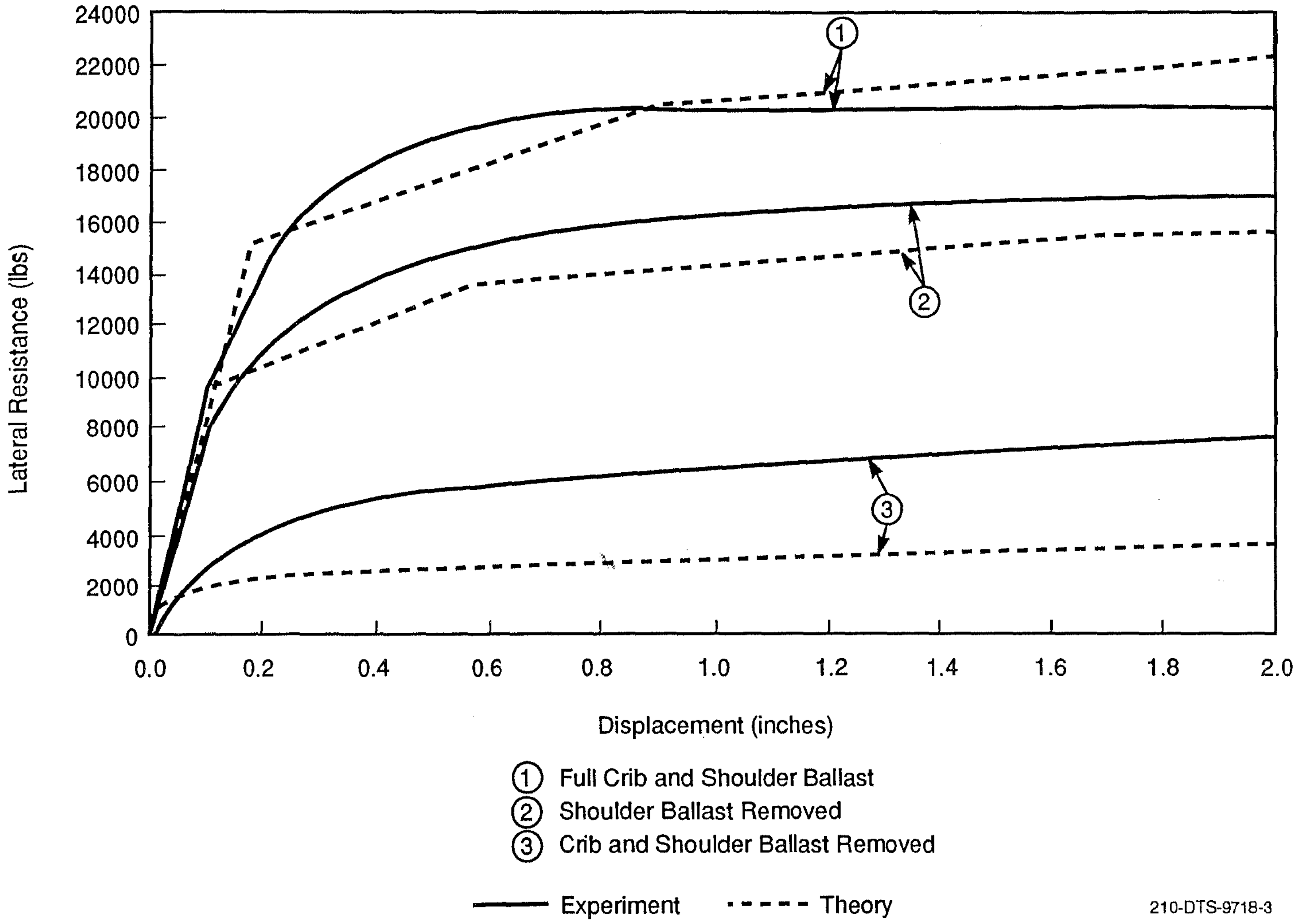


Figure 3-13. Comparison of TLPT versus STPT for Zone 3

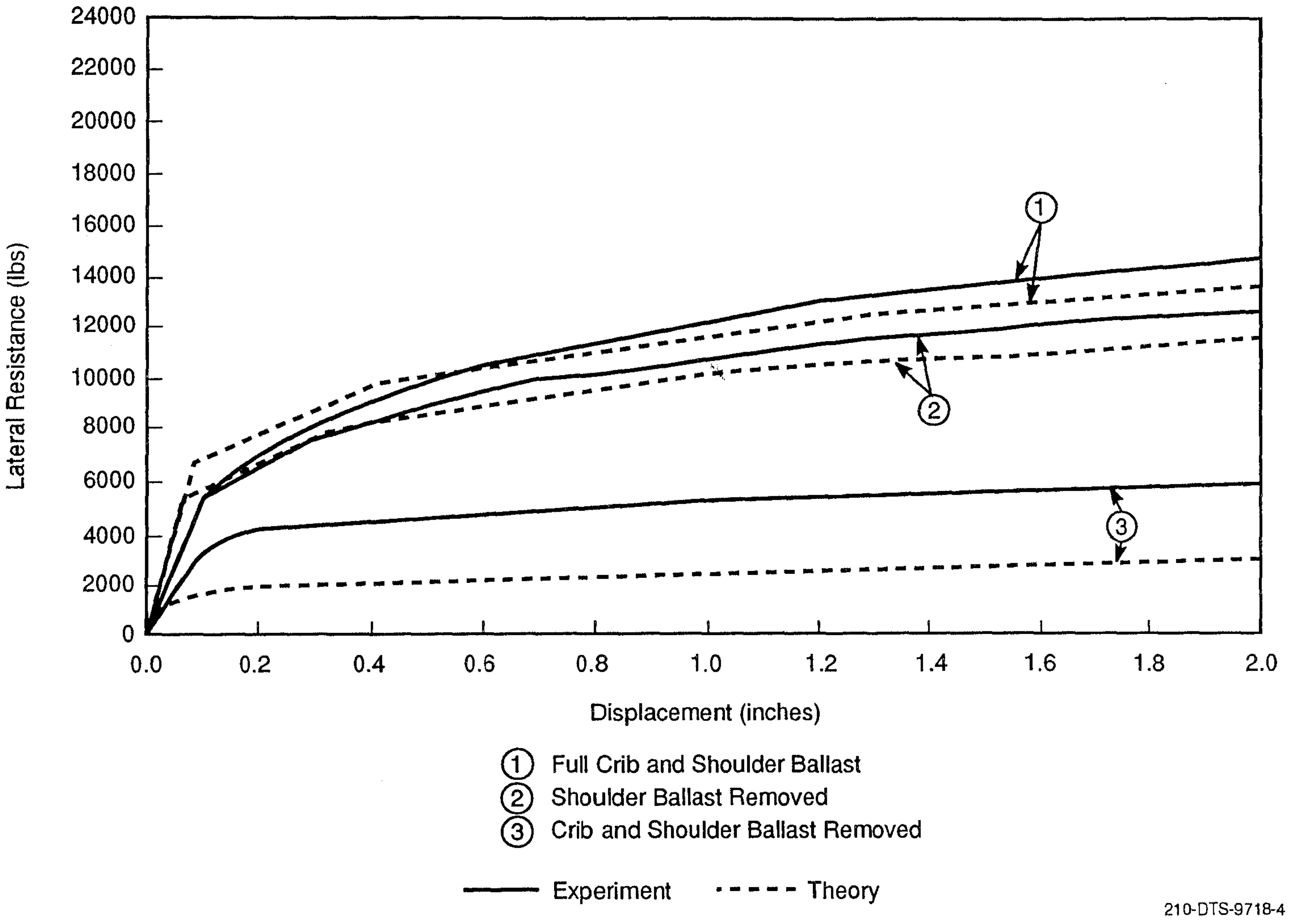


Figure 3-14. Comparison of TLPT versus STPT for Zone 4

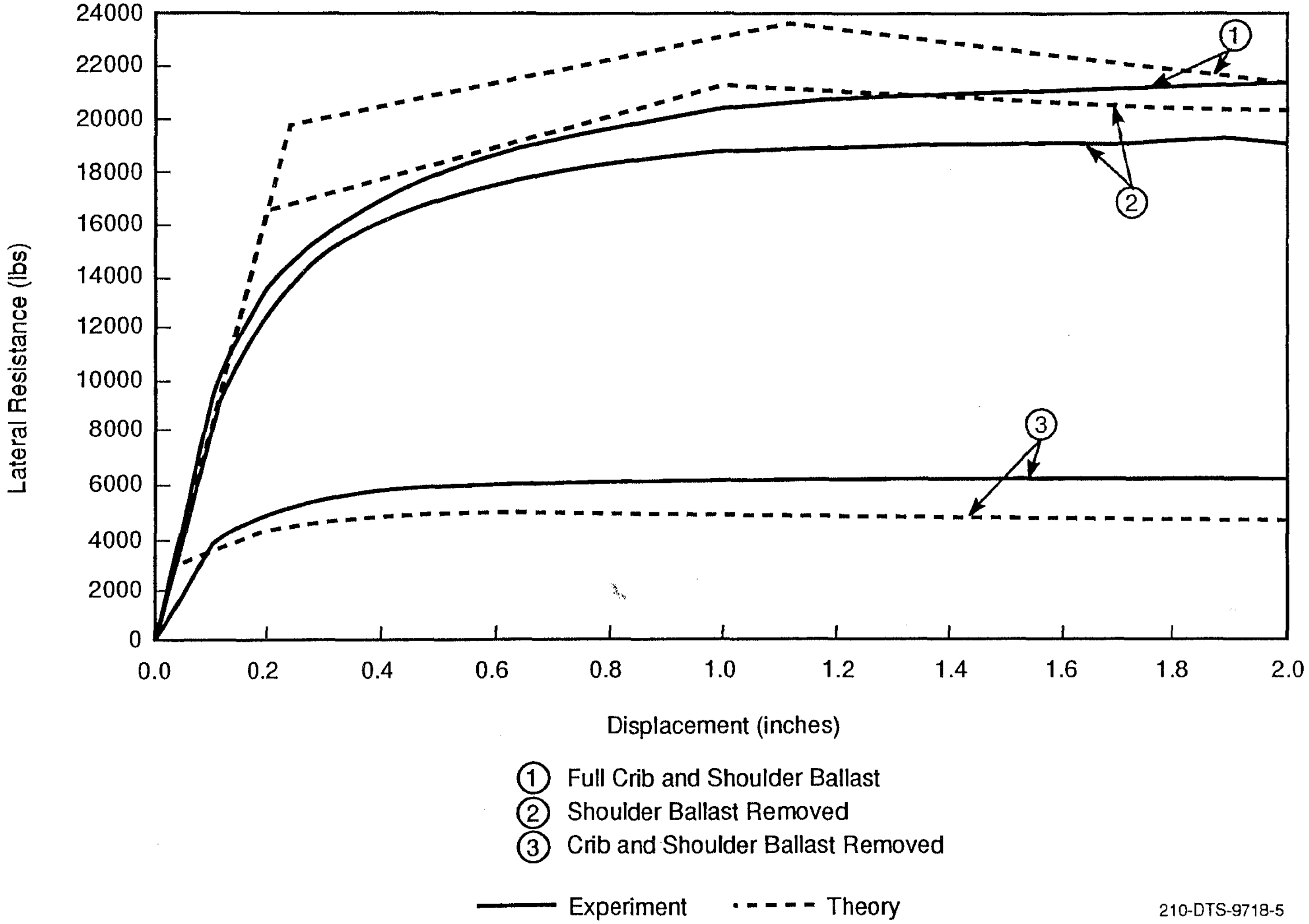


Figure 3-15. Comparison of TLPT versus STPT for Zone 5

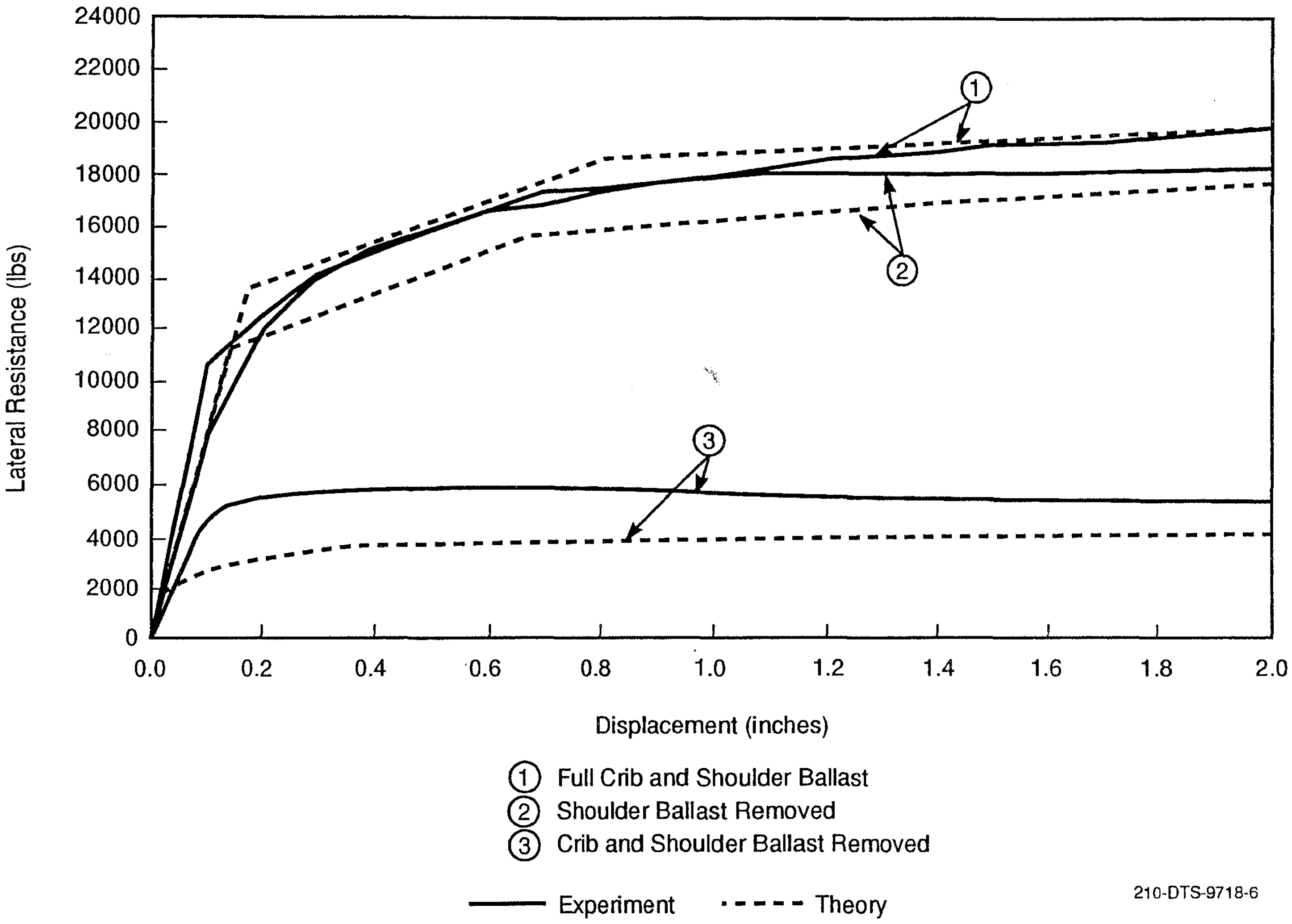


Figure 3-16. Comparison of TLPT versus STPT for Zone 6

Correlations were also made for 1 and 2 in. displacements (see Table 3-3), which show that a nearly 1:1 relationship exists between TLPT and STPT respectively, for the track conditions of "full crib and shoulder ballast" (FCS) and "shoulder ballast removed" (SR). However, for the track condition of "crib and shoulder ballast removed" (CSR) the relationship is not equivalent, but ~1:1.8 based on an average of the six test zones. This inconsistency is attributed to the poor track preparation for the single tie tests, in which both crib and shoulder ballast were removed without proper precautions to minimize the tie lift. Therefore the STPT data for the condition is not considered in further analysis. It is also apparent from Table 3-3 that for the track conditions of FCS and SR there is a direct correlation between STPT and TLPT regardless of track curvature, ballast, and tonnage.

Table 3-3. Predicted versus Measured Loads for TLPT

			F at 1 in. (kips)			F at 2 in. (kips)		
Test Zone	MGT	Track Condition	Theory	Exper.	Corr.	Theory	Exper.	Corr.
1	0.1	FCS	14.2	15.4	1.09	16.0	18.2	1.14
5 deg Curve		SR	11.9	11.5	0.97	13.5	13.8	1.02
Slag		CSR	3.0	5.4	1.81	3.2	6.8	2.14
2	0.1	FCS	18.4	18.0	0.98	20.3	19.2	0.95
5 deg Curve		SR	11.3	12.9	1.13	12.8	14.7	1.15
Slag		CSR	3.5	6.5	1.87	4.0	7.5	1.86
3	25	FCS	20.6	20.3	0.98	22.2	20.2	0.91
5 deg Curve		SR	14.2	16.1	1.13	15.4	16.8	1.09
Granite		CSR	3.0	6.5	2.18	3.3	7.5	2.26
4	0.1	FCS	11.7	12.2	1.04	13.6	14.7	1.08
Tangent		SR	10.1	10.8	1.06	11.5	12.6	1.10
Slag		CSR	2.5	5.2	2.12	2.9	5.8	1.98
5	100	FCS	22.9	20.1	0.88	21.1	21.0	0.99
Tangent		SR	21.0	18.6	0.88	19.9	18.8	0.94
Slag		CSR	4.6	6.0	1.29	4.4	5.9	1.35
6	25	FCS	18.7	17.9	0.95	19.7	19.7	1.00
Tangent		SR	16.2	14.9	0.92	17.5	16.2	0.92
Granite		CSR	3.8	5.7	1.49	4.0	5.2	1.31

$$\text{Correlation (Corr.)} = \frac{\text{Exper. (TLPT)}}{\text{Theory (STPT)}}$$

In general, from the overall response shown in Figures 3-11 through 3-16 it can be concluded that the agreement between theory and experiment is reasonable. *Hence, it can also be concluded that the TLPT response can be directly determined from the averaged STPT characteristic. This is accomplished when the nonlinear resistance characteristics are taken into account as was done in the above analysis. Therefore, it is not necessary to rely on empirical factors to obtain equivalent panel (TLPT) resistance from the measured, individual tie (STPT) resistance.*

3.2 F_P versus F_L

As previously stated in this report, the STPT load-displacement curve shows that after peak resistance (F_P) has been attained there is a noticeable decrease in lateral resistance. This decrease in resistance tended to continue until a limit resistance (F_L) was reached, after which it remained constant. The peak and limit resistances were found to significantly influence the upper and lower buckling temperatures respectively (2).

The purpose of the STPT is to measure lateral resistance with as little disturbance to the ballast-tie interface as is necessary. In order to perform this task, the limit resistance must also be known, which requires large tie displacements of 3 to 6 in. Therefore, a correlation study was performed to establish a relationship between F_P and F_L, which would require only the peak resistance to be measured and permit the limit resistance to be analytically determined. The beneficial consequence of the correlation is minimal disturbance of the ballast-tie interface. Also, with only the peak resistance being measured this would facilitate any field testing, allowing for larger sampling through a track section.

The results of the study are shown in Figures 3-17a and 3-17b for granite (6 deg curve) and slag (tangent) ballast respectively. These tests were performed on the High Tonnage Loop (HTL) at TTC. Linear regression lines have been fitted to the granite and slag data and the following equations were the results:

TTC: Granite, $F_L=(0.3F_P+500)\text{lb}$ $F_P>726$ (3-1)

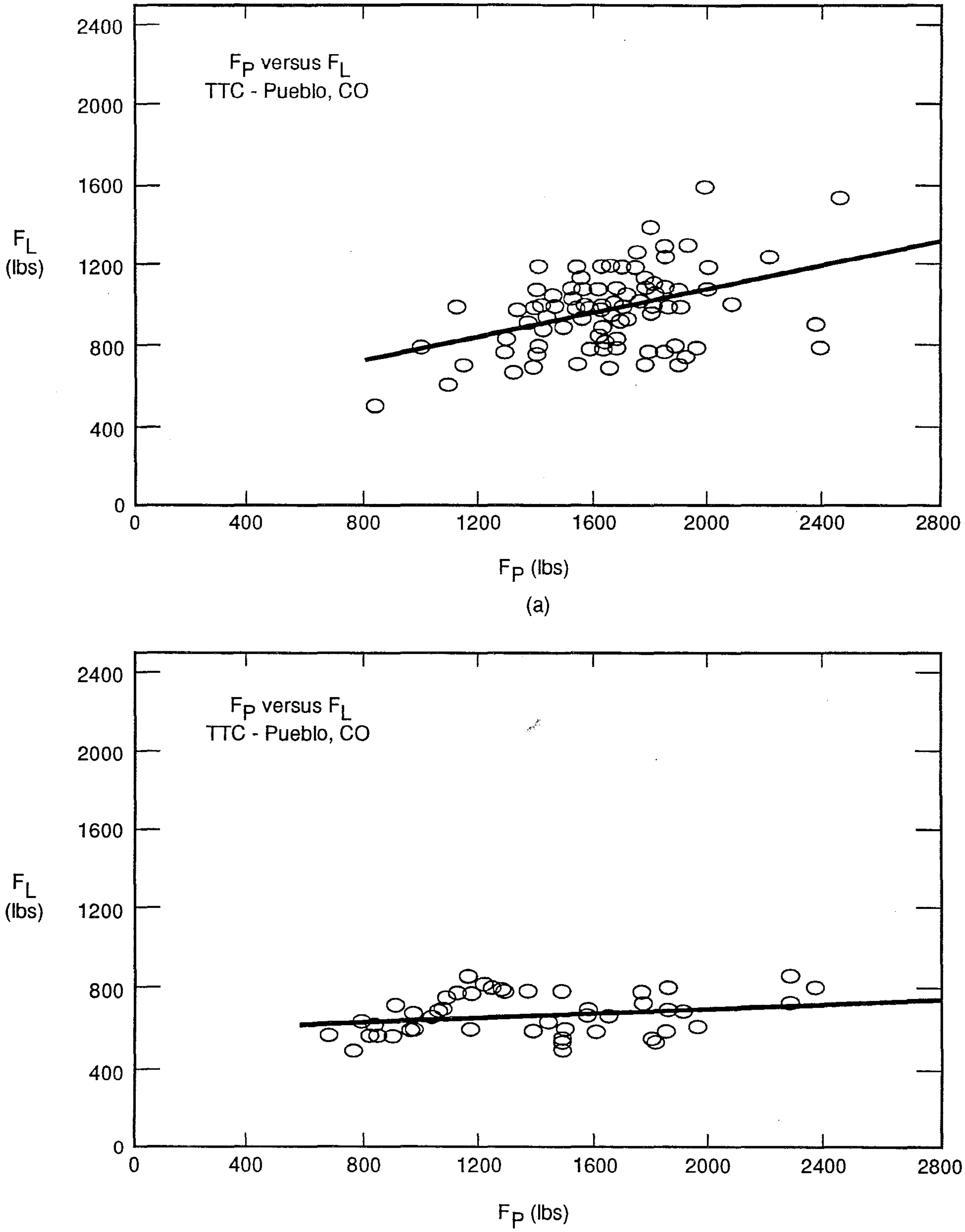
For $F_P<726$, it is assumed $F_L=F_P$

TTC: Slag, $F_L=(0.06F_P+600)\text{lb}$ $F_P>638$ (3-2)

For $F_P<638$, it is assumed $F_L=F_P$

The granite ballast has a noticeably steeper slope than the slag ballast, indicating a higher limit resistance and, hence, a higher buckling strength than the slag ballast. The foregoing equations are being utilized in the current development of buckling safety guidelines for CWR track.

Additional tests (6) were performed on revenue service track with a high degree of curvature. The test sites were located near Sante Fe, NM, on the ATSF Railroad, and Bluefield, WV, on the Norfolk Southern Railroad with track curvatures of 10 and 12 deg respectively. Similar large



(a)

(b)

Figure 3-17. Peak versus Limit Resistance for (a) Granite and (b) Slag - TTC displacement STPT tests were performed to establish the F_P versus F_L relationship for high degree curved track. The results are shown in Figures 3-18a and 3-18b, respectively, for slag and granite ballast.

ASTF (Slag): $F_L=(0.38F_P+508)\text{lb}$ $F_P>1100$ (3-3)

For $F_P<1100$, it is assumed $F_L=F_P$

NS (Granite): $F_L=(0.16F_P+1000)\text{lb}$ $F_P>1200$ (3-4)

For $F_P<1200$, it is assumed $F_L=F_P$

An overall relationship between F_P and F_L for all the data above is presented in Figure 3-19. The result is encouraging, and with further testing and analyses it may be possible to use a single relationship between F_P and F_L that will be independent of track curvature and ballast type.

$$F_L=(0.36F_P+388)\text{lb} \qquad F_P>600 \qquad (3\text{-}5)$$

For $F_P<600$, it is assumed $F_L=F_P$

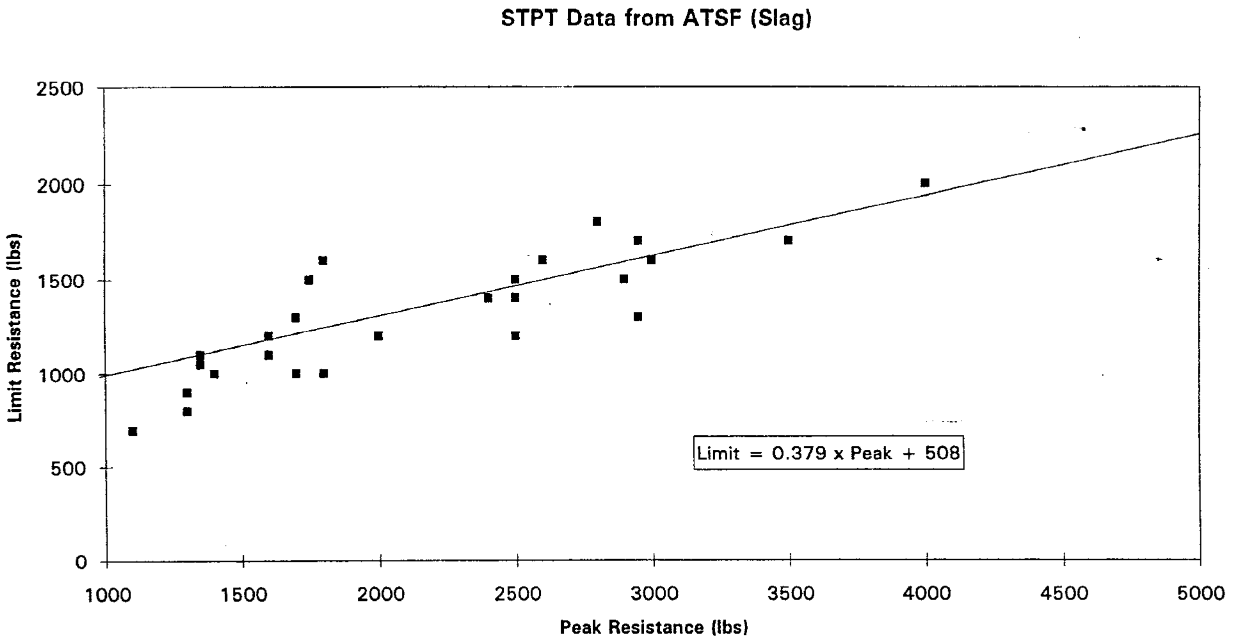
Hence, based on all the track resistance characteristic data to date, the above equation (3-5) may be used for F_P versus F_L determination, and for buckling and track lateral shift analysis. However, given the limited revenue service data, which may therefore be site specific, equations 3-1 and 3-2 are recommended for use in the computer model (7).

3.3 Effect of Track Consolidation

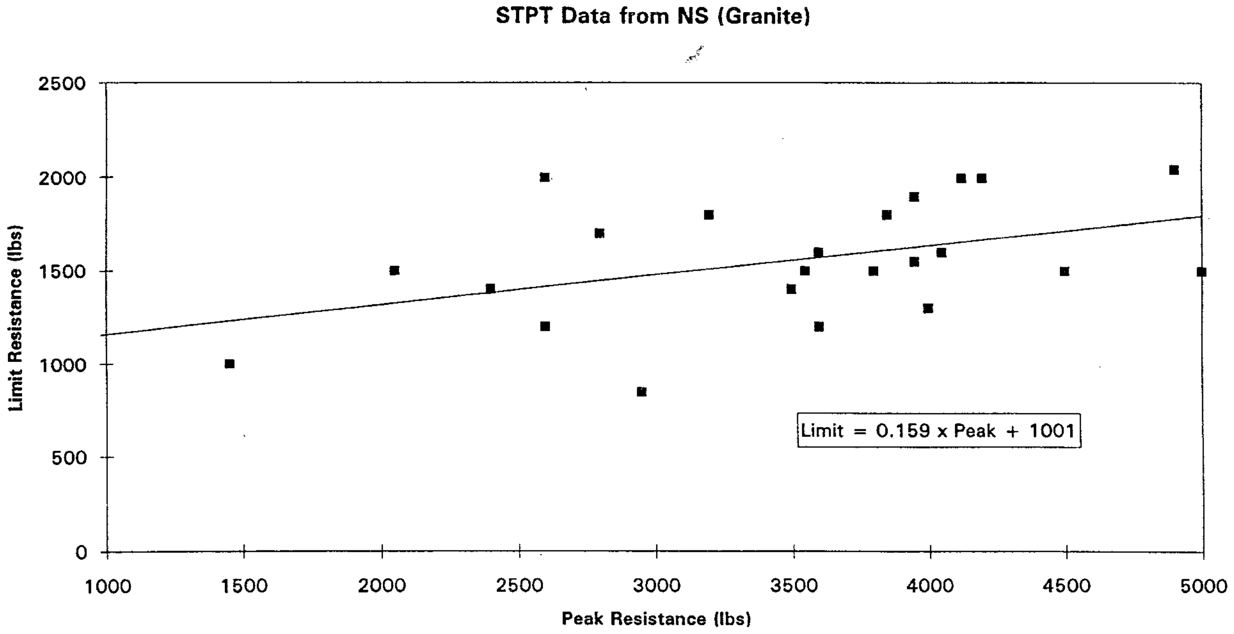
It is well known in the literature that track consolidation by traffic, measured in million gross tons (MGT), increases the track lateral resistance up to some limit, beyond which consolidation will have negligible influence. What is commonly assumed in the literature is that there is a unique relationship between MGT and the absolute value of track lateral resistance. The problem is that immediately after tamping or other maintenance operations, the track lateral resistance drops to a low and unpredictable value. The gain in track lateral resistance from this condition would depend on the level of consolidation. Without the knowledge of the initial value of track lateral resistance, it is not possible to predict the absolute track lateral resistance at a given MGT.

Tests to understand the influence of consolidation, using the STPT, were performed at TTC (Pueblo, CO) and on the CSX (Barboursville, WV). The results are presented in Figures 3-20 through 3-22.

Results from TTC for granite, traprock, and slag ballast (zones 9, 10, and 11, respectively, in Table 3-1), which were subjected to the same traffic levels, are shown in Figure 3-20a. It should be noted that the starting resistances, at the 0.1 MGT tamped track condition, were not equal for



(a)



(b)

Figure 3-18. Peak versus Limit Resistance for (a) ATSF (Slag) and (b) NS (Granite)

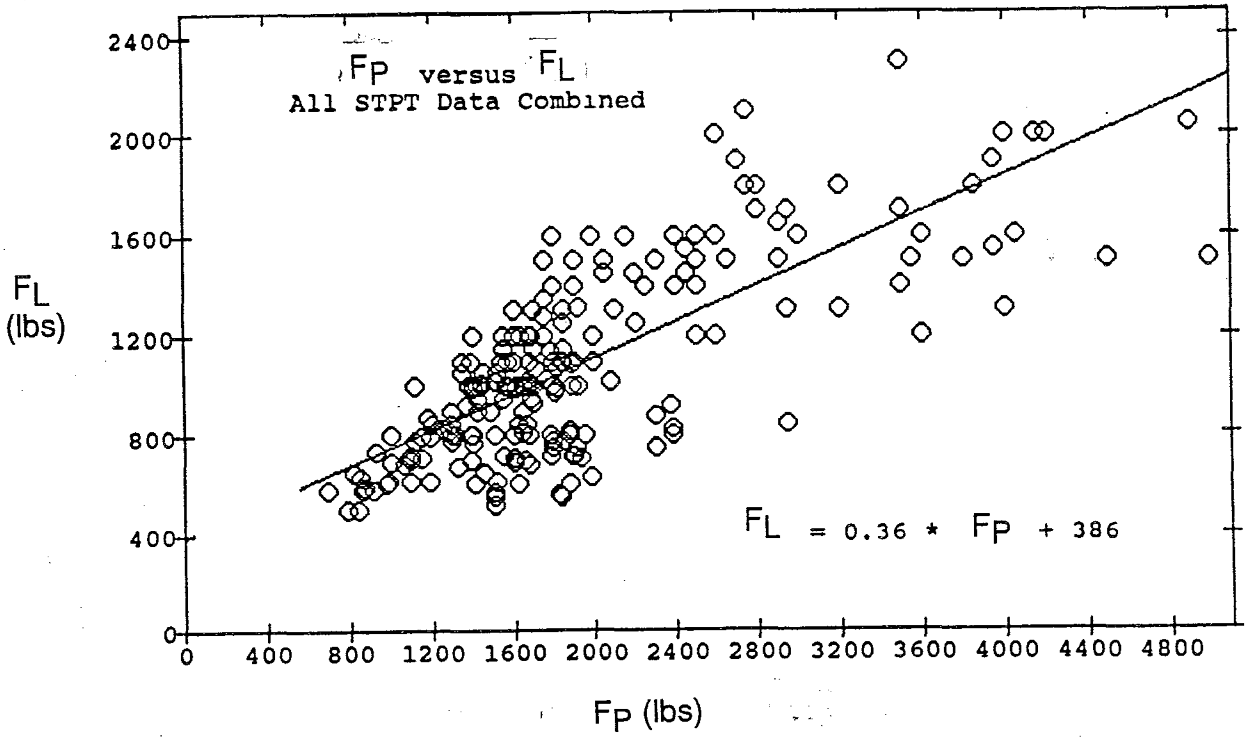


Figure 3-19. Peak versus Limit Resistance for All Data

each test location even though the same tamping procedure was employed. The starting values (1,800 lb for slag 1,520 lb for granite, 1,220 lb for traprock) should be considered site specific and would also be influenced by the type of tamping operations. Previous track operations at these locations, tie conditions, age, and track lateral resistance levels prior to track maintenance can play an important role on the reduced track lateral resistance levels such as after tamping. In view of the variability of the track resistance at the tamped condition, the data from all sources (Figures 3-20a, 3-21, and 3-22) are normalized and presented in an incremental form in Figure 3-20b.

Additional tests (zones 11 and 10 in Table 3-1) were performed on the slag and traprock at the 14.0 and 15.2 MGT levels, respectively, to corroborate the initial set of results. The second set of results showed the slag to have lower lateral resistance indicating possible ballast disturbance due to some environmental/mechanical activity. An increase in consolidation was measured in the traprock.

A finer interval of consolidation was also investigated where data was collected from 0 to 1 MGT at 0.1 MGT increments. The results of this investigation, shown completely in Figure 3-21, are shown in detail in Figure 3-23. A significantly greater lateral resistance was recorded after 0.1 MGT had been applied, as compared to the recently tamped condition. The data recorded from tests conducted at 0.1 MGT intervals to 1.0 MGT, and at 1.2, 1.4, and 2.0 MGT, indicated that the lateral resistance remained fairly constant or increased only slightly with MGT within the data scatter recorded. Based on an average tamped resistance, this data will be useful

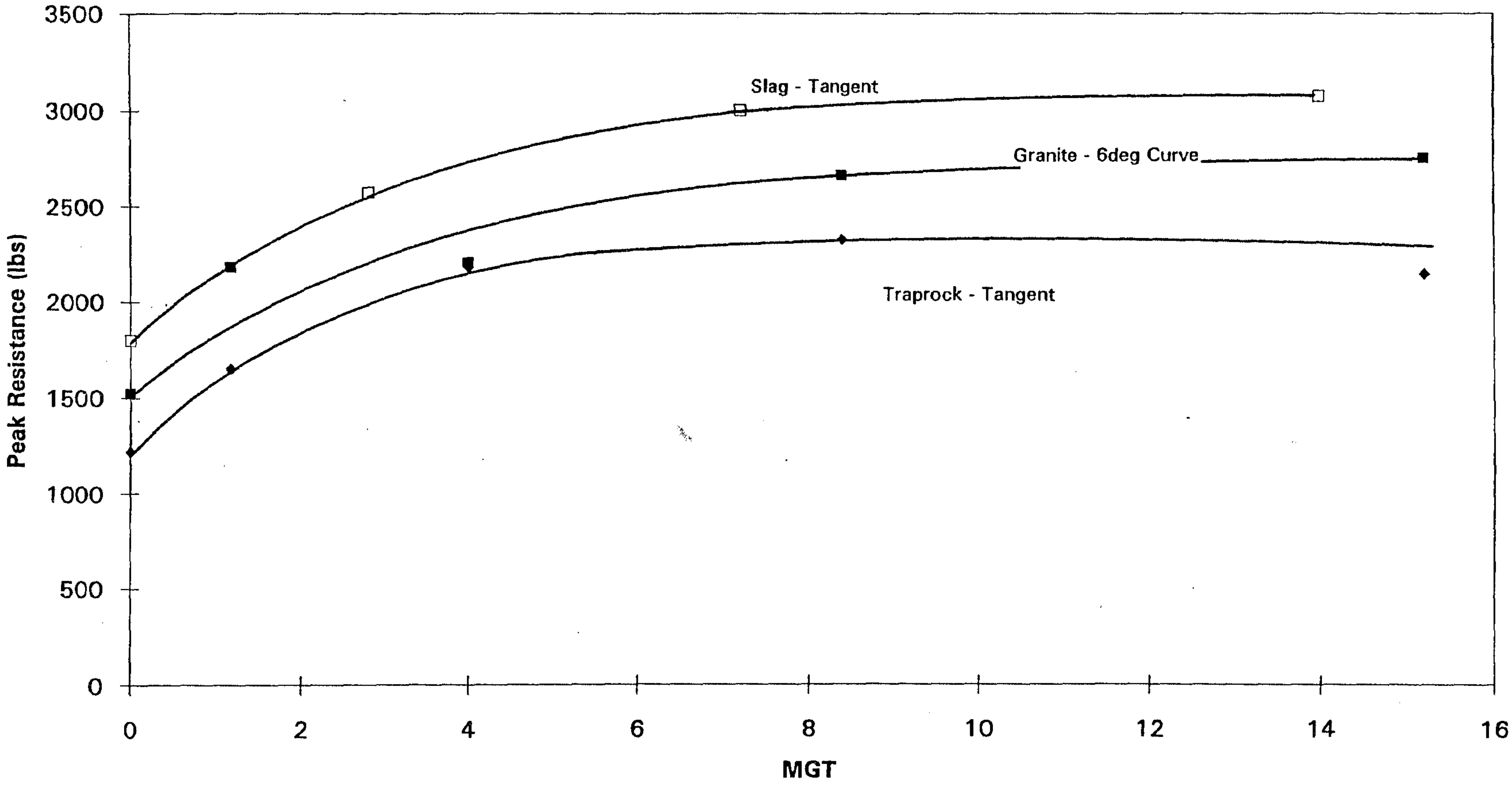


Figure 3-20a. Consolidation Influence - TTC

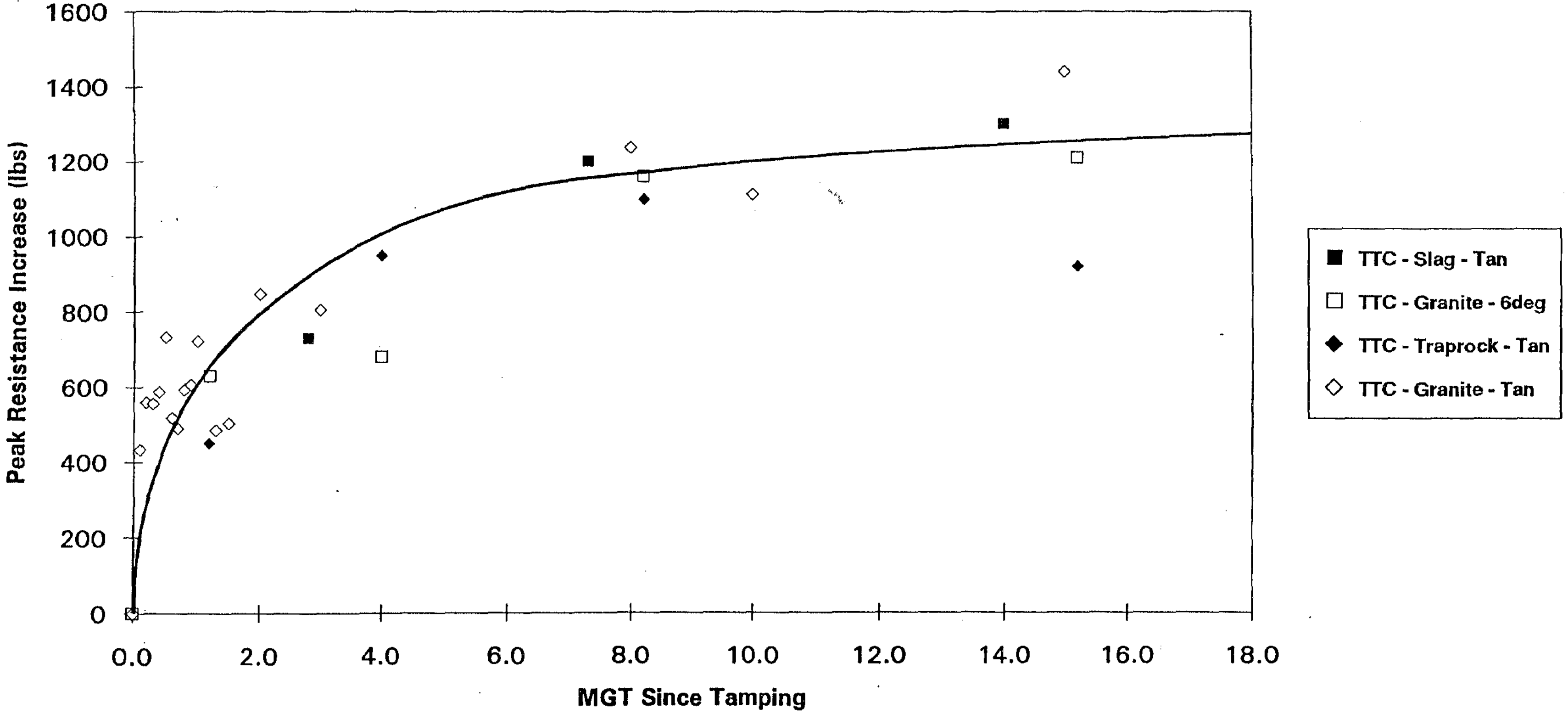


Figure 3-20b. Track Lateral Resistance Increase

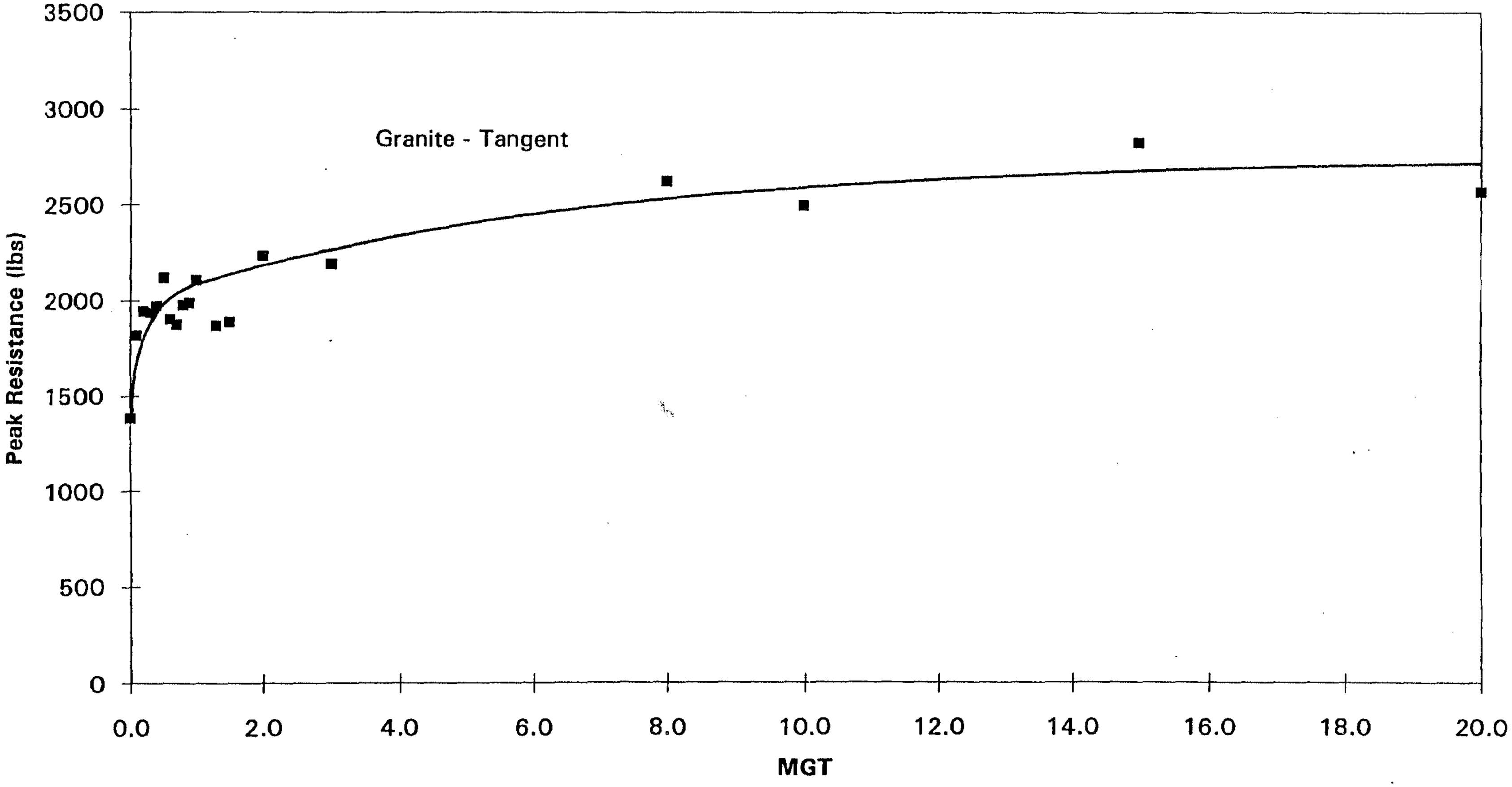


Figure 3-21. Consolidation Influence - TTC

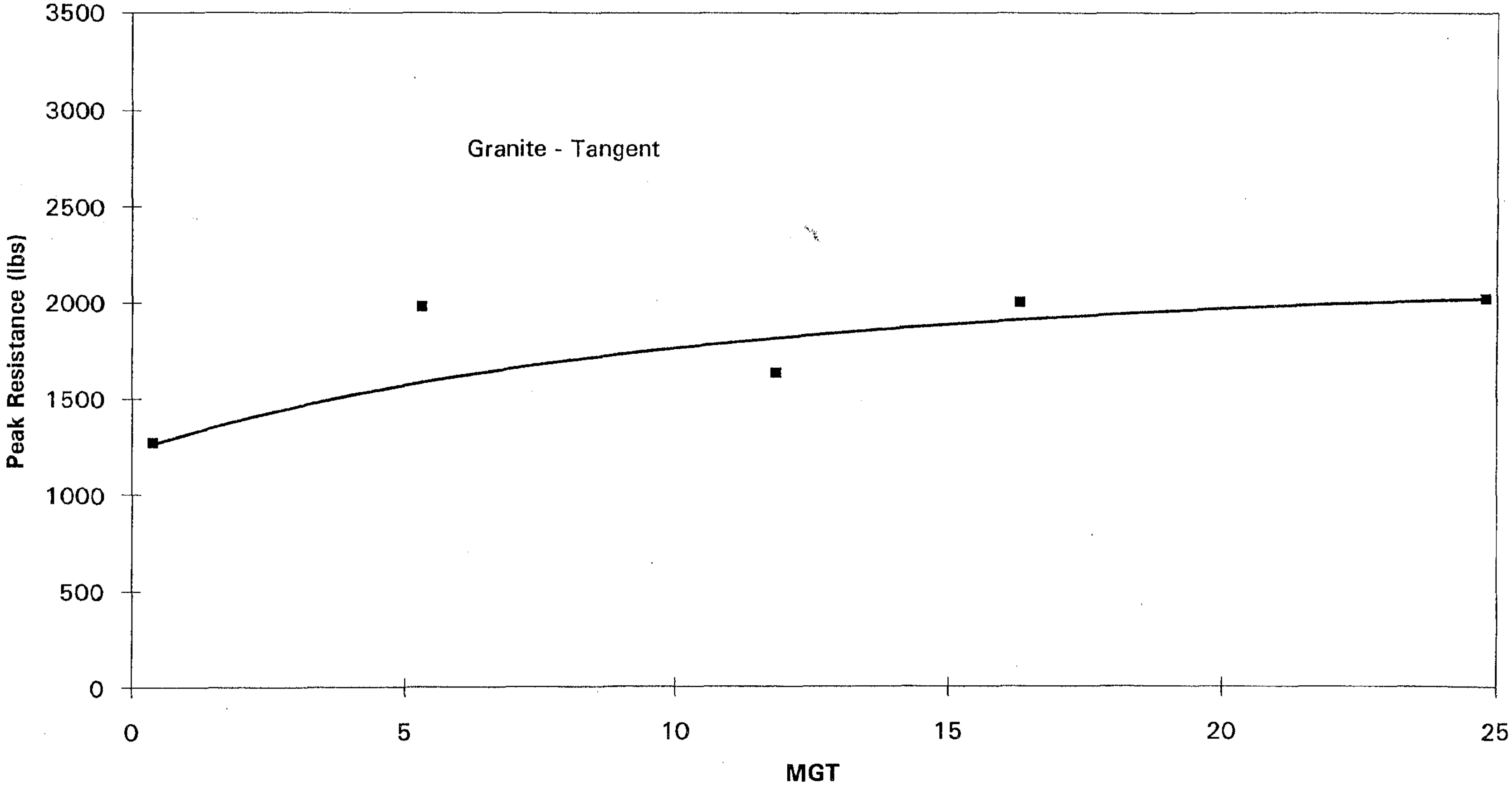


Figure 3-22. Consolidation Influence - CSXT

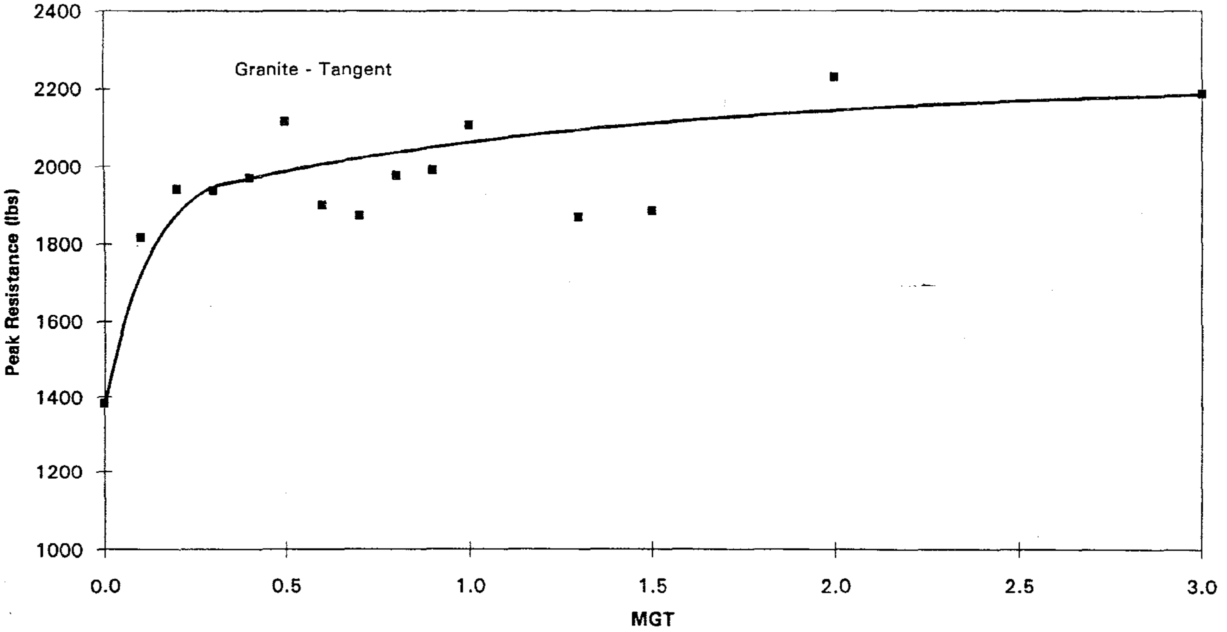


Figure 3-23. FAST Ballast Resistance Characterization (BRC V) Tests Consolidation Influence

in estimating the required consolidation levels for a tamped track to attain the desired strength and for determining the slow order period for CWR tracks.

The CSX results (zone 12 in Table 3-1), shown in Figure 3-22, for granite ballast showed a steady and uniform increase in consolidation. The data collected for the 11.8 MGT level was subjected to freeze-thaw conditions, which might explain the decrease in consolidation. There is no apparent correlation between the TTC and CSX granite ballast.

In all the consolidation studies the track lateral resistance, although increasing, did fluctuate as MGT increased, as seen in Figures 3-20 to 3-23. Track ballast in revenue service is subjected to the cyclic train passage loads of compaction and uplift and the environmental conditions such as freeze-thaw, erosion, and solid subsidence, all of which may affect track lateral resistance. The effect of environment may be the cause of the decrease in track lateral resistance at the test site on the CSX railroad (see Figure 3-22) during winter and early spring. Before the 11.8 MGT measurements the test site experienced freeze-thaw conditions, with freezing temperatures and snow during the night, while the following day was sunny and warm (well above freezing).

3.4 Effect of Track Curvature

Attempts have been made to separate the influence of track curvature on track lateral resistance characteristics. No significant results were obtained. There is no apparent difference in the effect of consolidation on tangent and curved tracks based on the obtained data.

3.5 Crib, Shoulder, and Bottom Ballast Contributions

Contributions to the overall ballast resistance come from crib, shoulder, and bottom ballast. The relative proportions of these contributions are important in the dynamic buckling predictions since they determine the net track lateral resistance of ties under track uplift. They are also of interest to the industry in relation to track maintenance.

As stated in subsection 3.1, test zones 1 through 6 were tested, with both the STPT and TLPT, for varying track conditions: full crib and shoulder ballast, shoulder ballast removed, and crib and shoulder ballast removed. The results of these tests provided the necessary information to determine the track lateral resistance contributions from crib, shoulder and bottom ballast for each test zone. Recall from subsection 3.1 that the correlation between STPT and TLPT, for crib and shoulder ballast removed, was not 1:1, but ~1:1.8. Therefore, the TLPT results were used to calculate the percent ballast component contributions that are shown in Figure 3-24 for 1 in. and 2 in. deflections. The results indicate no significant difference between 1 in. and 2 in. deflections. However, there are zonal differences due primarily to varying consolidation levels. The differences are reasonable and do not preclude taking an overall average for the six zones as shown in Figure 3-25 for 2 in. deflection. The resulting proportions for crib, shoulder, and bottom are 48 percent, 18 percent, and 34 percent, respectively.

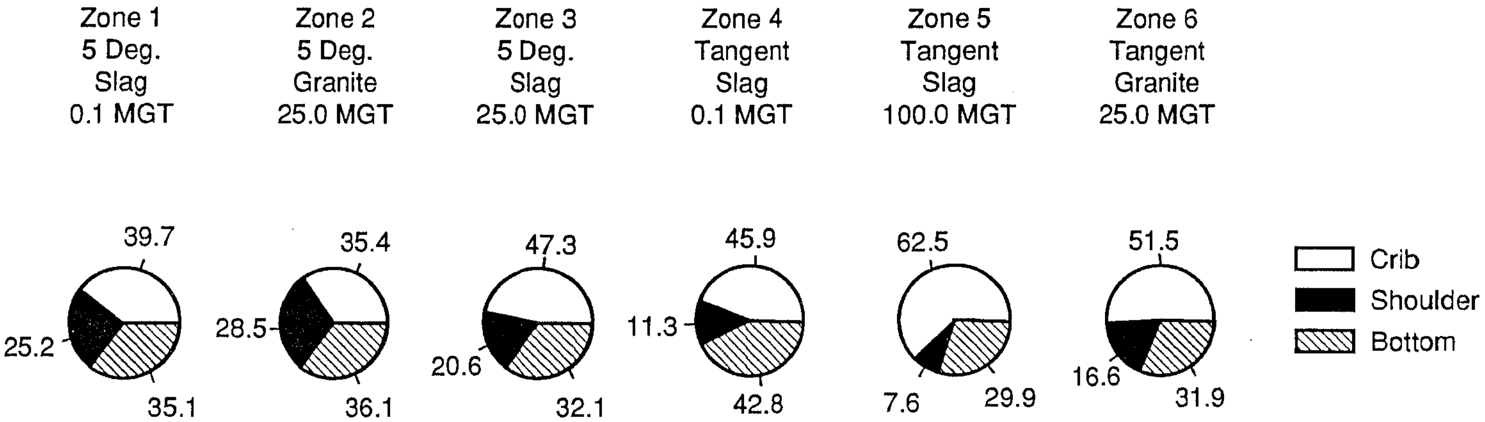
The direct test evaluations of track resistance contributions from the crib and the bottom (under tie) ballast are difficult because the tie bottom ballast by itself is not as effective as it will be in the presence of the crib ballast, which adds to the vertical stiffness of the track structure. As the tie tends to float with lateral movement, the bottom ballast friction drops substantially in the absence of the crib ballast. Therefore, the contributions from the crib and bottom ballast, although separated here for facilitating inputs to the track buckling computer model, should not be considered as two separate physical entities.

3.6 Influence of Loading Rate

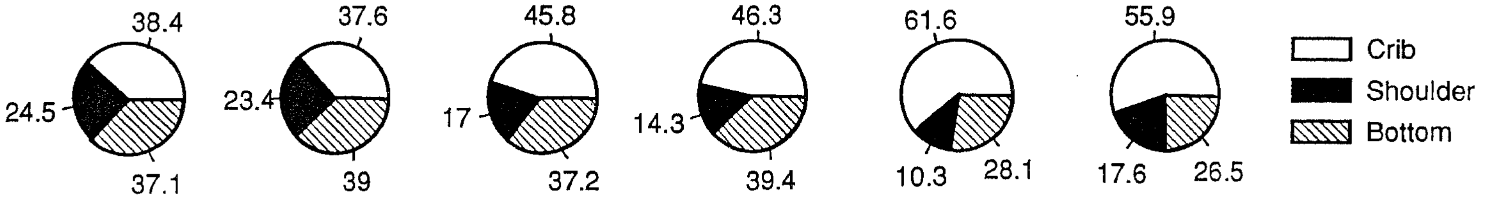
A study was performed to detect any differences in the STPT characteristic curve by varying the rate at which the STPT applied its steady-state load, via electric hydraulic pump, over a 2 in. tie displacement. The loading rates utilized in the tests included: 1) slow, metered flow loading in which test times were 10 to 30 minutes; 2) normal, metered flow loading in which test times were approximately 30 seconds; and 3) fast, unmetered flow loading in which test times were 2 to 3 seconds. The results indicate that varying the loading rate does not influence the STPT characteristic curve.

3.7 STPT Sampling Size

As stated earlier, the track lateral resistance for a given cell, for zones 1 through 6, is defined as the average of all the individual test ties within the cell (i.e., every other tie). The cell length is typically 50 ft and the maximum number of ties that can be tested is about 15 (20 in. tie spacing). This is because the ties adjacent to the test tie share the same crib ballast and therefore



Note: Percentages Based on 1" Displacement



Note: Percentages Based on 2" Displacement

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Figure 3-24. Percent Ballast Component Contribution - TLPT - TTC

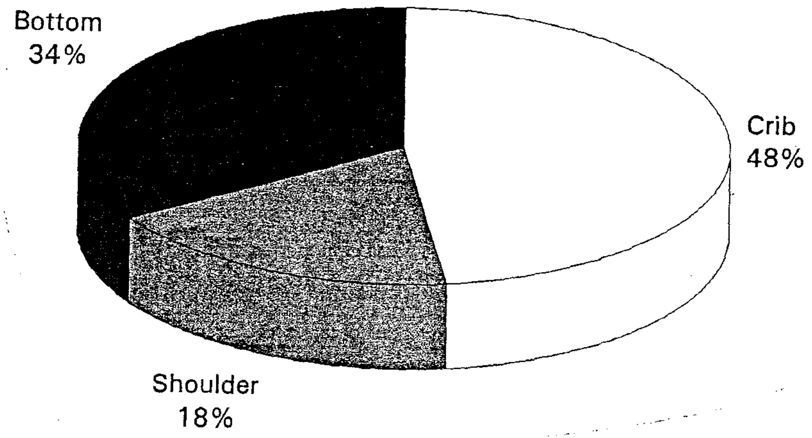


Figure 3-25. Percent Ballast Component Contribution Summary - TTC

cannot be tested, since the ballast has been previously disturbed. Since it may be time-consuming and undesirable to test all 15 ties in a given cell, the question arises whether statistically meaningful results can be obtained by testing a fewer number of ties. To answer this question, which has a bearing on STPT as a practical measurement tool, a sample study is presented here.

The discussion will be restricted to the peak values of the resistance for ties in cells with full crib and shoulder ballast in zones 1 through 6. In each cell there are 15 peak values, F_i (i=1,...15). The average of these (F_m) is the cell average value for the peaks. Suppose three randomly selected ties in the cell have F_a, F_b, F_c values for the peaks. The average, F_o, of these three values differs in general from the cell average, F_m, and the percent error can be computed using the following equation:

Percent Error = $(F_m - F_o)/F_m$

Using a random number generator, in each trial the numbers F_a, F_b, and F_c have been selected and the percent error calculated. Five trials were made, each producing different tie combinations. The maximum error obtained in these trials is recorded in Figure 3-26 for all cells with full crib and shoulder ballast in all six zones. As seen from Figure 3-26, the worst maximum error is about 20 percent. This error may be tolerable in buckling calculations.

For a sample size of five ties, the results are shown in Figure 3-27. In the majority of situations, the error is under 10 percent for this sampling size.

If the data for all cells in all the zones (1 through 6) are averaged, the distribution, with respect to sample size, is typically as shown in Figure 3-28. The sample size of three seems to perform much better than previously discussed. However, the length of a buckled section of track is typically on the order of 30 ft and thus comparable to the 50 ft test cell size. Therefore, in order to ensure adequate safety, a sample of three ties is needed from each cell. For example, it would not be sufficient to randomly select 18 ties within a 300 ft zone as each 50 ft cell may not be evaluated and a potential buckling zone may go undetected.

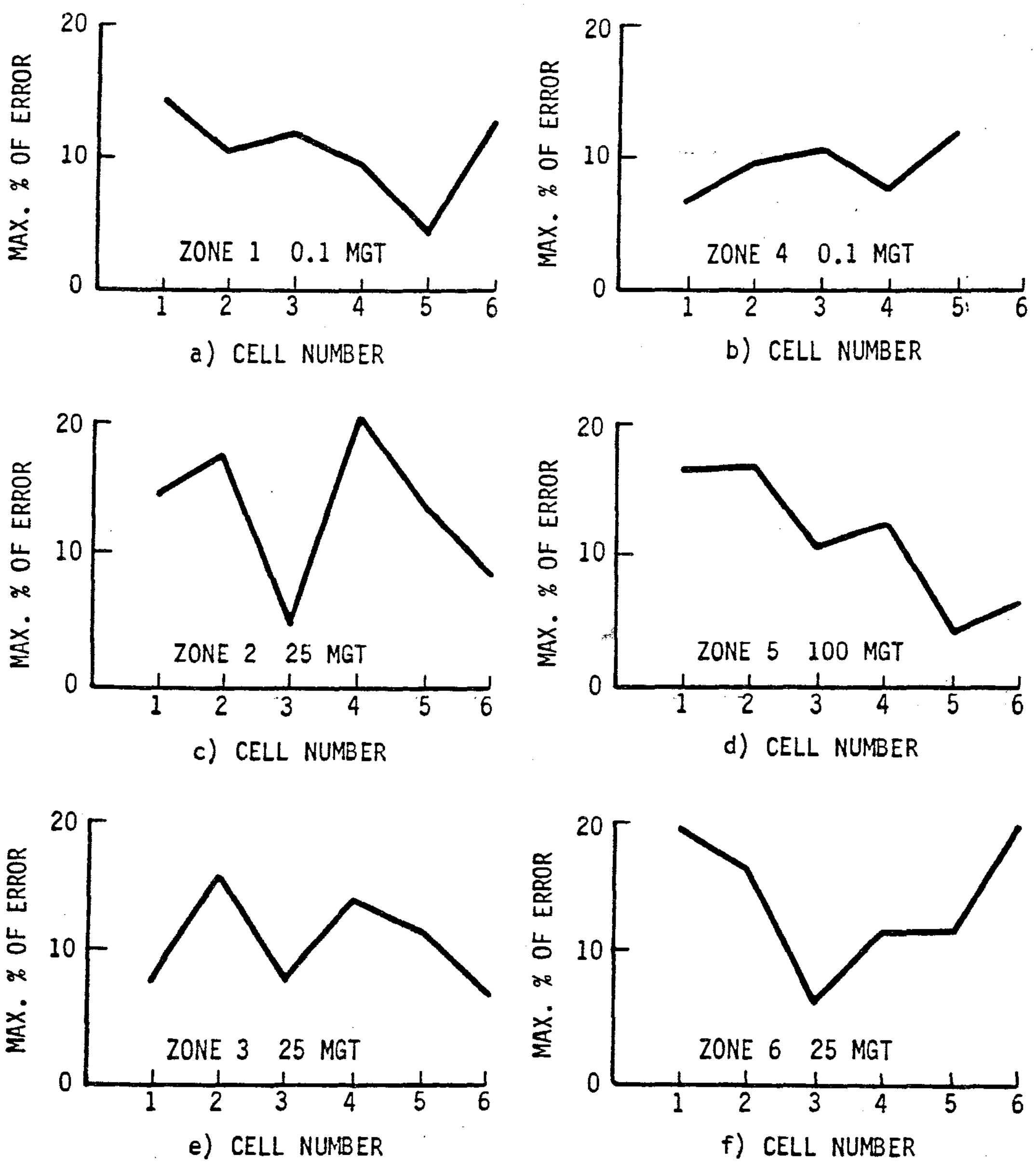


Figure 3-26. Maximum Percent Error in Peak Resistance for Sample = 3

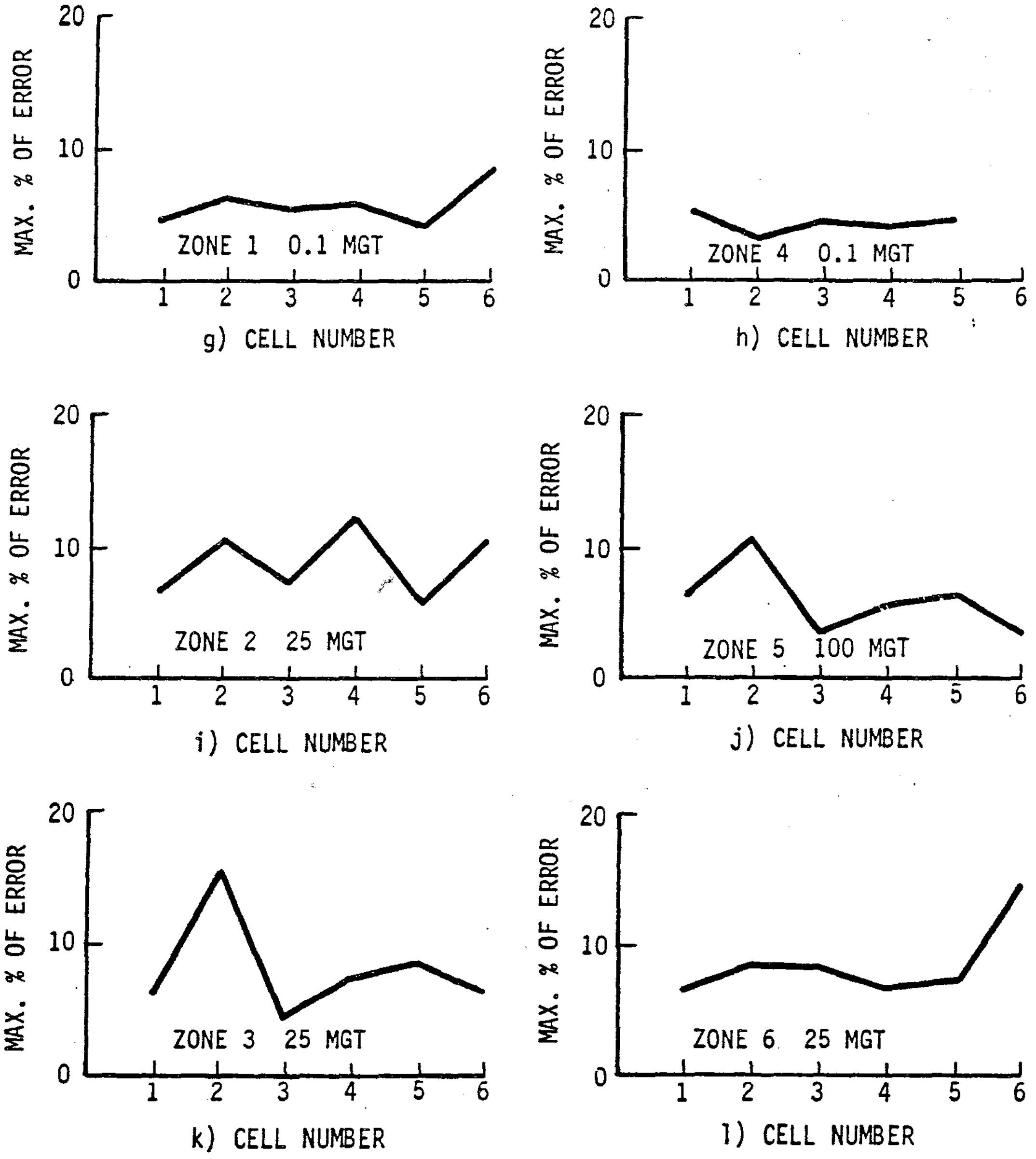


Figure 3-27. Maximum Percent Error in Peak Resistance for Sample = 5

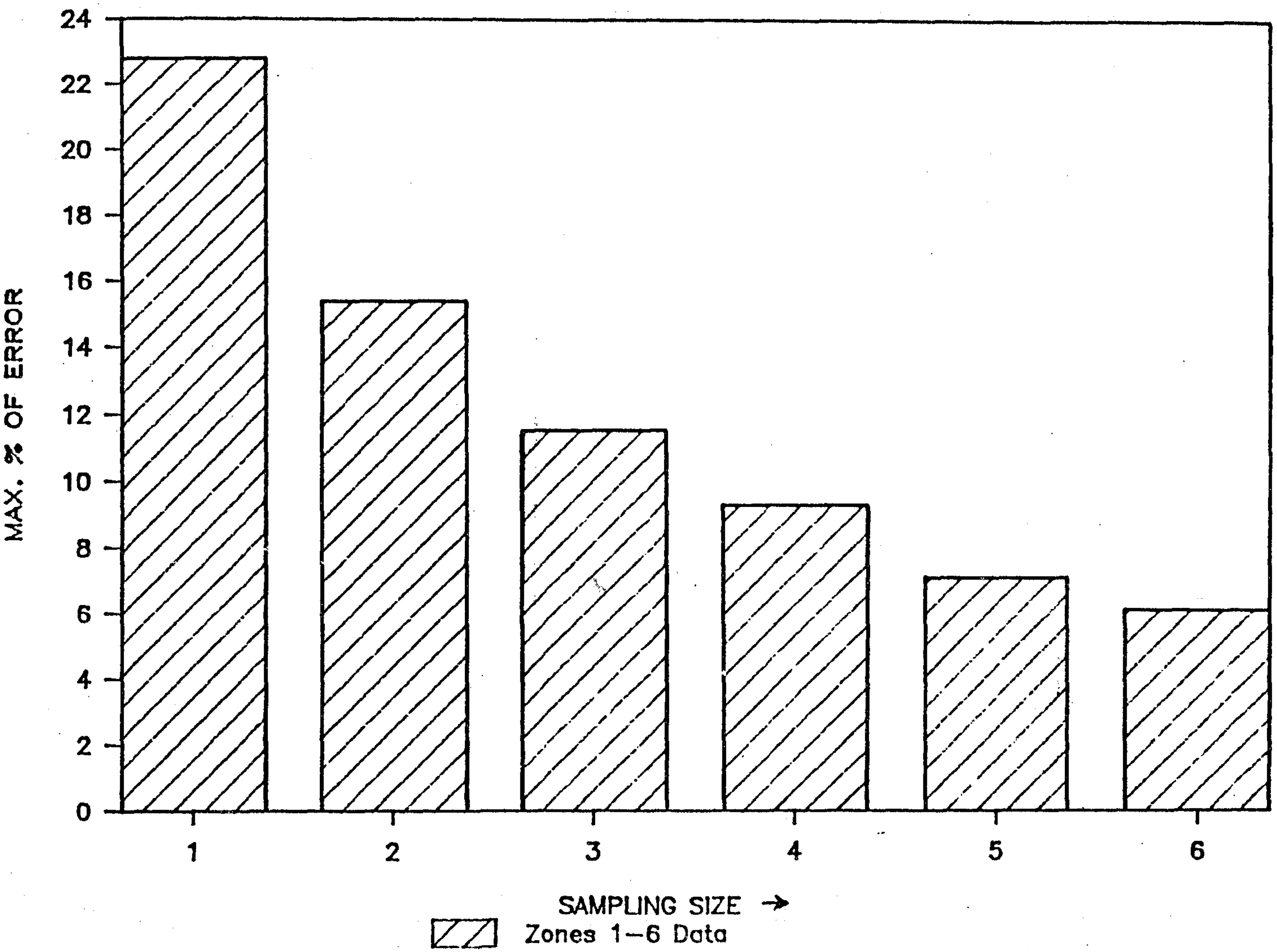


Figure 3-28. Maximum Error in Resistance Based on Sample Size

From the result in Figure 3-26, it is also seen that for tamped and low consolidation level tracks, the percent error becomes small compared to that of highly consolidated tracks. Although the error in highly consolidated tracks appears to be large, the overall buckling risk is small, in view of the high track lateral resistance. *Hence, in all cases, a sampling size of three per every 50 ft section appears to be adequate in practice.*

4. LONGITUDINAL RESISTANCE CHARACTERIZATION

Track longitudinal resistance is defined as the resistance offered by ties and/or ballast to movement of the rails in the longitudinal direction. The longitudinal resistance for unanchored or loosely anchored ties is very low, while higher for properly anchored ties.

Track longitudinal resistance is an important parameter in buckling prevention since it directly relates to the control of rail neutral temperature of CWR (7).

It has been found that track longitudinal resistance varies with rail displacement, as shown in Figure 4-1a. Because of small longitudinal displacements that occur during track buckling, the initial stiffness of k_f is adequate for track buckling analyses.

4.1 Test Hardware

The track longitudinal resistance was determined by isolating a four-tie or eight-tie panel from the rest of the track, and applying a longitudinal load to both rails by means of a hydraulic cylinder (Figure 4-1b). The longitudinal load was applied to the test panel until the panel displacement reached a maximum of 2 in. A total of nine tests were performed on panels in Section 18 of the FAST outer loop at TTC, Pueblo, CO. The variables tested were: rail anchoring method (every-tie anchored [ETA], every-other-tie anchored [EOTA], and every-third-tie anchored [E3TA]) and ballast condition (consolidated, tamped, and half-crib), as indicated in Table 4-1.

4.2 Test Results and Discussion

Data recorded were applied longitudinal load, longitudinal displacement, and rail/tie displacement. The load and displacement data were recorded directly onto an x-y plotter. A summary of the test results is presented in Table 4-2.

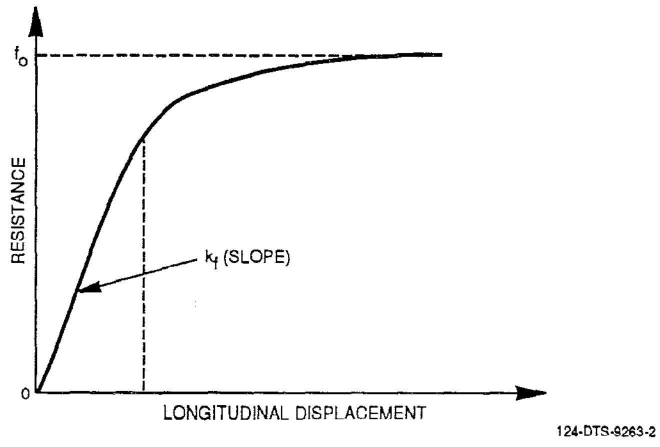


Figure 4-1a. Typical Longitudinal Resistance Characteristic

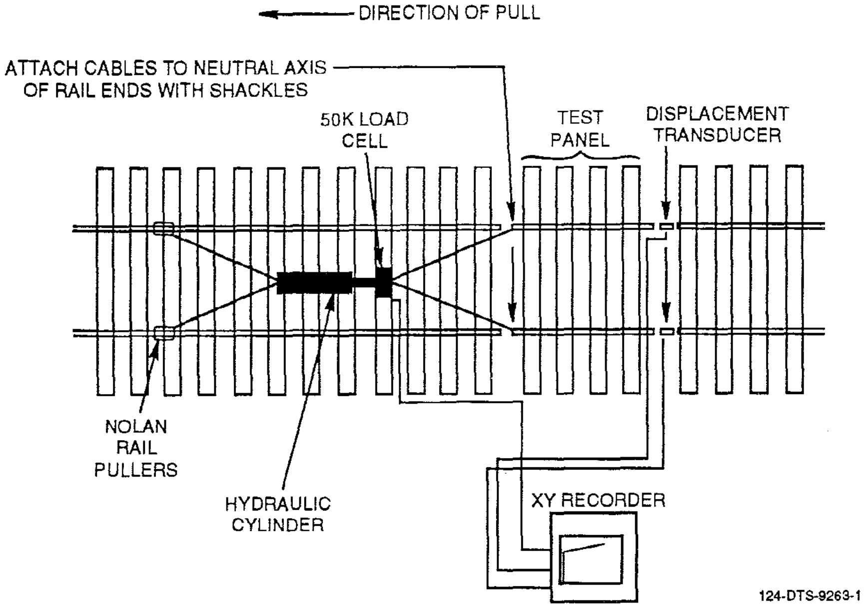


Figure 4-1b. Longitudinal Resistance Test Hardware

Table 4-1. Test Matrix

Test No.	Anchoring	Crib Level	Ballast Condition	No. of Ties in Test Panel
1	ETA	Full	Consolidated	4
2	EOTA	Full	Consolidated	4
3	ETA	Half	Consolidated	4
4	EOTA	Half	Consolidated	4
5(a)	ETA	Full	Tamped	4
5(b)	ETA	Full	Tamped	8
6	E3TA	Full	Tamped	8
7	ETA	Full	Tamped	8

The test data does show the significant influence of crib ballast and anchoring pattern on the track longitudinal resistance, as well as the influence of track consolidation. The effect of the panel size (four-tie versus eight-tie) indicated a difference greater than 10 percent for displacements less than 0.50 in. and a difference less than 10 percent at displacements greater than 0.75 in.

The full-crib ballast condition increases the track longitudinal resistance over 50 percent compared to that of the half-crib ballast condition. Track consolidation can increase the track

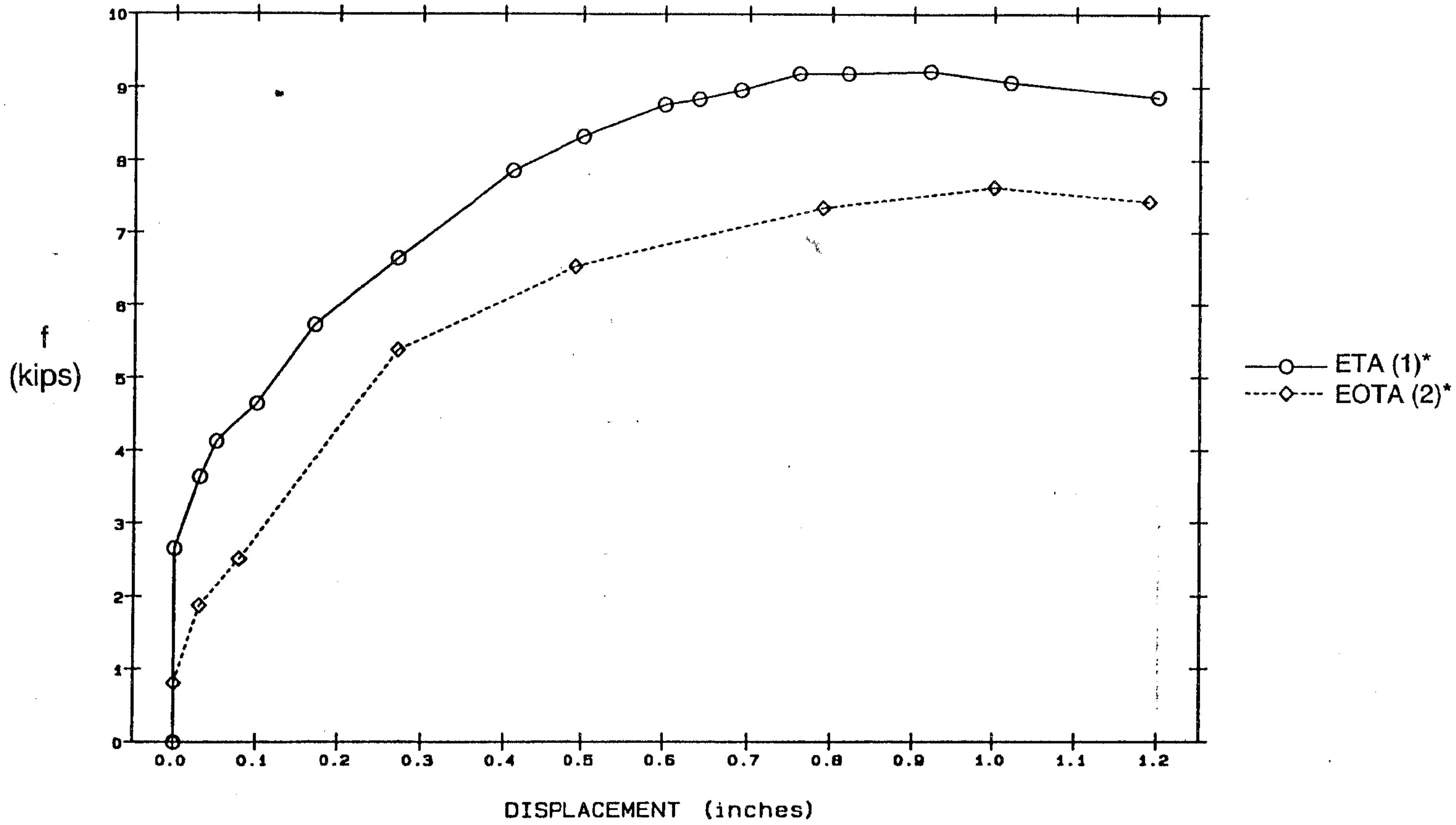
Table 4-2. Track Longitudinal Resistance Summary

	Consolidated (kips/tie)			ETA (kips/tie)			EOTA (kips/tie)			ETA and Tamped (kips/tie)			8-Tie and Tamped (kips/tie)		
Defl. (in.)	ETA (1)	EOTA (2)	% Diff.	C (1)	T (5)	% Diff.	FC (2)	HC (4)	% Diff.	4-Tie (5)a	8-Tie (5)b	% Diff.	E3TA (6)	ETA (7)	% Diff.
0.25	1.62	1.27	21.6	1.62	0.85	47.5	1.27	0.63	50.0	0.85	1.28	33.6	0.89	1.28	30.5
0.50	2.08	1.64	21.2	2.08	1.33	36.1	1.64	0.71	56.7	1.33	1.51	11.9	1.17	1.51	22.5
0.75	2.29	1.81	21.0	2.29	1.52	33.6	1.81	0.74	59.1	1.52	1.67	9.0	1.31	1.67	21.6
1.00	2.28	1.91	16.2	2.28	1.56	31.6	1.91	0.74	61.3	1.56	1.72	9.3	1.39	1.72	19.2
Limit	2.31	1.91	17.3	2.31	1.61	30.3	1.91	0.74	61.3	1.61	1.77	9.0	1.48	1.77	16.4

Condition	Linear Stiffness, k_f (kips/in./in.)		Constant Resistance, f_0 (kips/in.)
	at 0.25 in.	at 0.50 in.	
ETA (consolidated)	0.324	0.208	0.116
EOTA (consolidated)	0.254	0.164	0.096
ETA (tamped)*	0.213	0.142	0.085
EOTA (consolidated 1/2 crib)	0.126	0.071	0.037
E3TA (tamped)	0.178	0.117	0.074

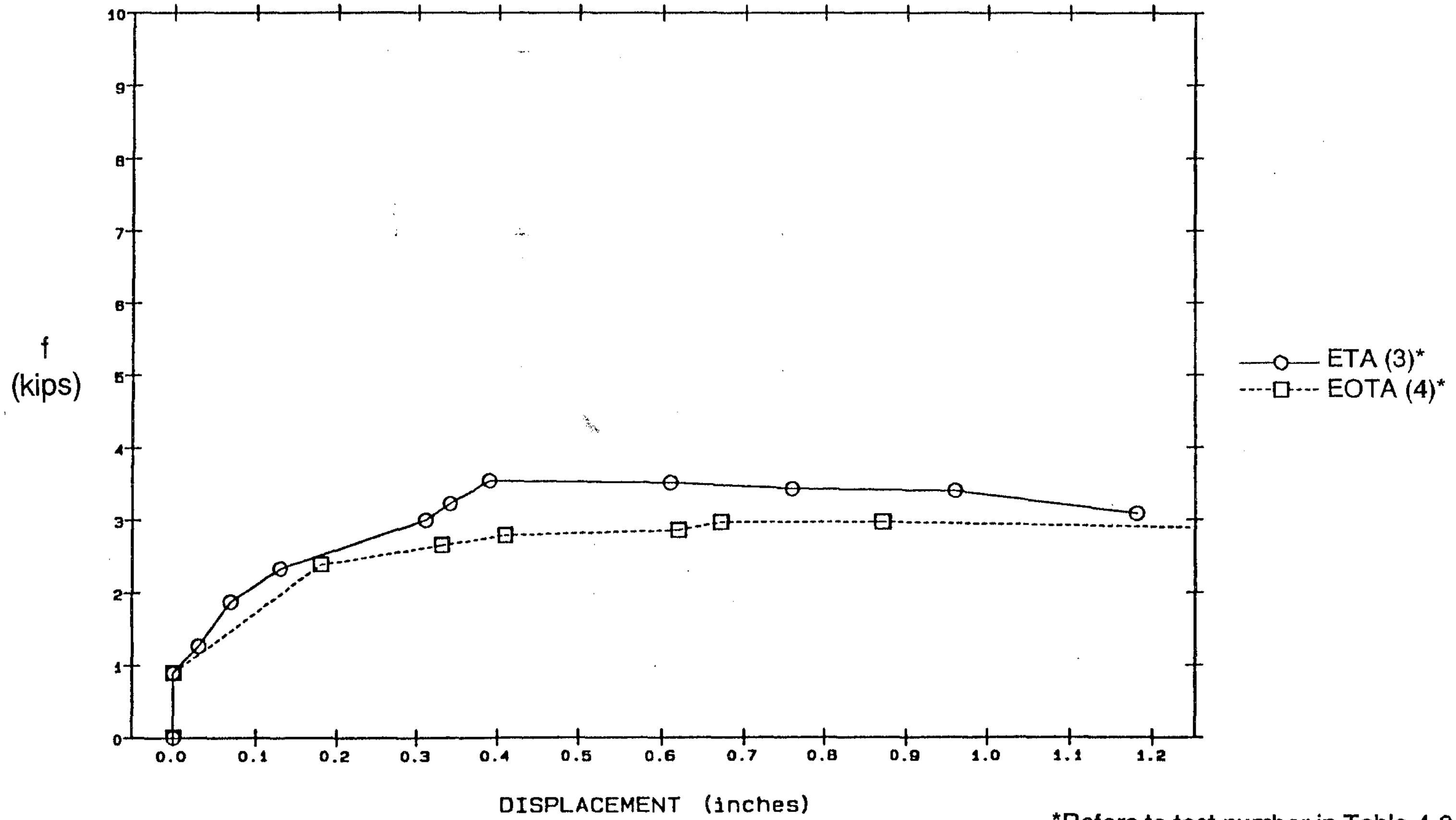
ETA: Every tie anchored	T: Tamped	FC: Full crib	*Average of 4-tie and 8-tie panel
EOTA: Every other tie anchored	C: Consolidated	HC: Half crib	( ) Test No.

longitudinal resistance by about 30 percent. Anchoring every tie increases track longitudinal resistance by about 20 percent in consolidated tracks when compared to the resistance given by every-other-tie anchoring. For tamped tracks, anchoring every third tie reduces track longitudinal resistance by about 30 percent at small displacements (0.25 in.) compared to the every-other-tie anchored condition (see Figures 4-2 through 4-5).



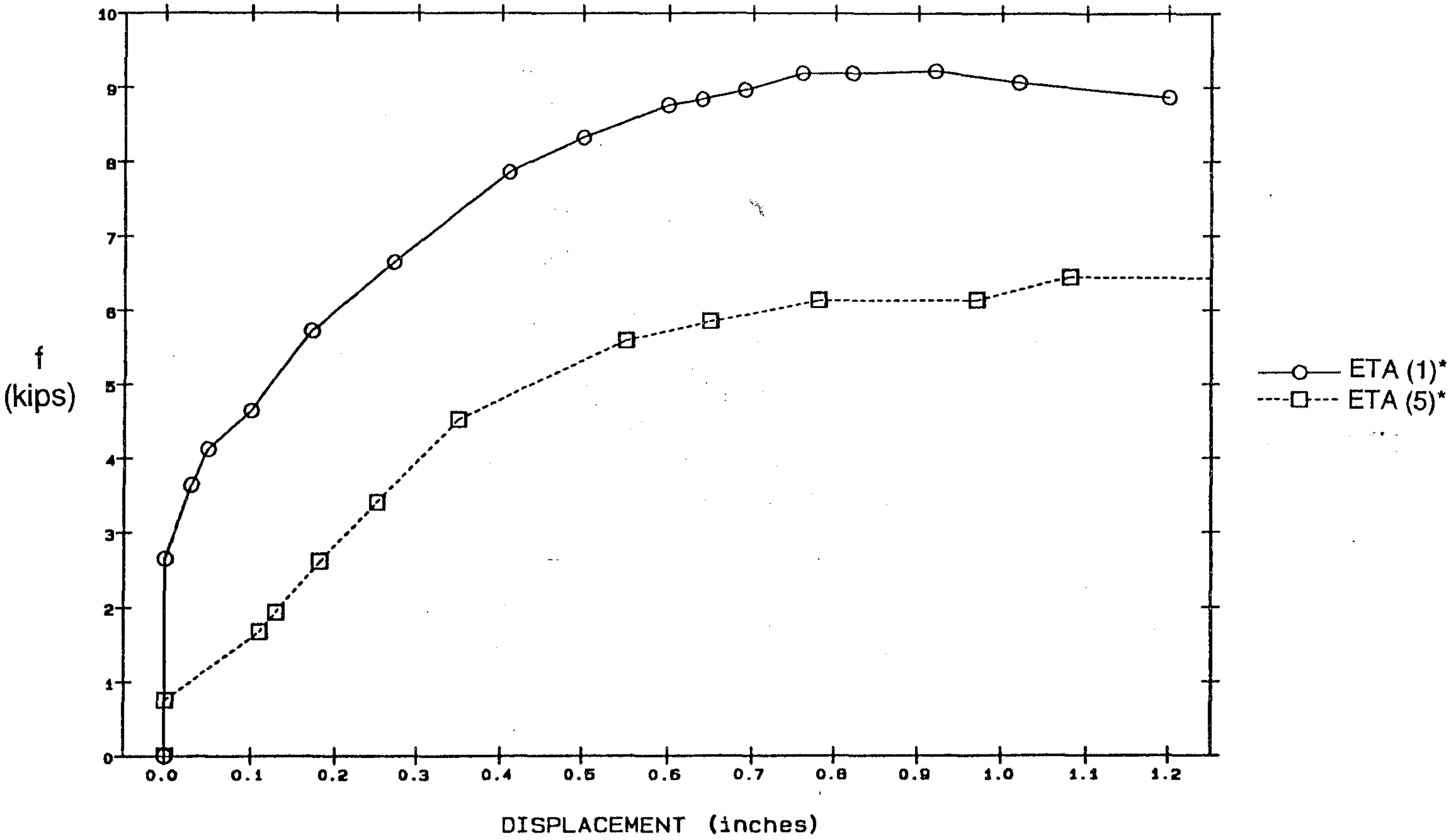
*Refers to test number in Table 4-2.

Figure 4-2. Longitudinal Resistance Comparisons - ETA versus EOTA (Full Crib)



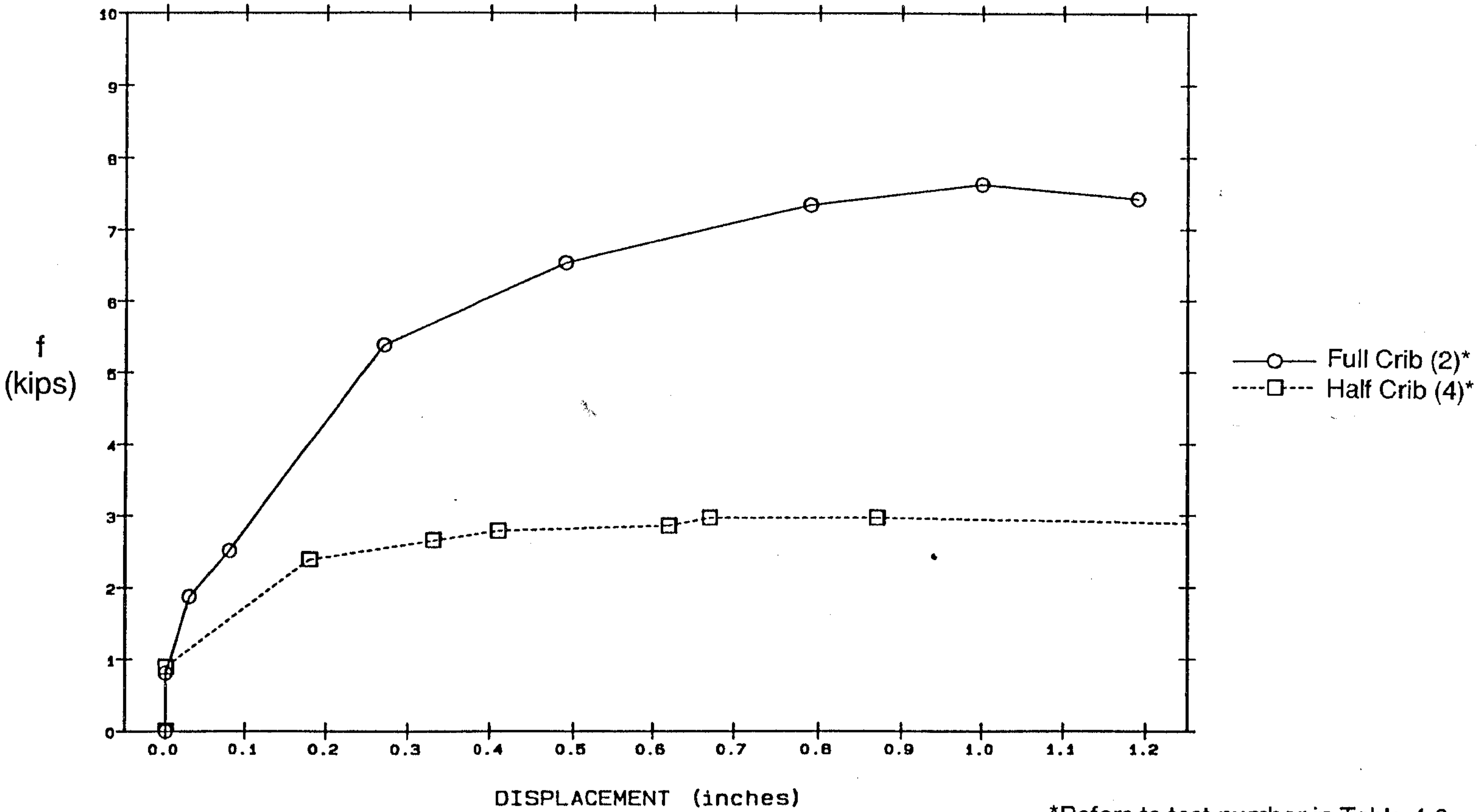
*Refers to test number in Table 4-2.

Figure 4-3. Longitudinal Resistance Comparisons - ETA versus EOTA (1/2 Crib Ballast)



*Refers to test number in Table 4-2.

Figure 4-4. Longitudinal Resistance Comparisons - Consolidated versus Tamped



*Refers to test number in Table 4-2.

Figure 4-5. Effect of Crib Ballast Level on Longitudinal Resistance

5. CONCLUSIONS

1. A technique has been developed for the measurement of track lateral resistance that can provide guidance to maintenance activities for improved CWR safety. The technique is based on the single tie push test (STPT) concept with the associated prototype fixture.

2. The STPT fixture is man-portable and far less cumbersome for field application than the track lateral pull test (TLPT) method. The STPT device can determine the peak value of track lateral resistance by mobilizing the tie laterally for small displacements averaging 0.25 in. It is inexpensive and convenient for quick evaluations of track lateral resistance in the field. From the STPT values, the panel (TLPT) response can be determined theoretically, thus eliminating the need for panel testing.

3. The track lateral resistance has a nonlinear softening characteristic. In general, there are two salient points of the characteristic: a peak value occurring at a fractional lateral displacement, and a limit value at displacements of a few inches. The peak value is sensitive to the consolidation level. For tamped and weak tracks, the peak and limit values are very close. The limit value does not increase at the same rate as the peak value with increasing consolidation. Among many factors, ballast type and shoulder width seem to influence the limit resistance value.

4. An empirical correlation has been developed between the peak and limit track lateral resistance values, enabling the estimation of the complete nonlinear characteristic by mobilizing the tie a fraction of an inch. Primarily, the correlation depends on the ballast material, but there are other influencing factors, such as tie condition and ballast shoulder width, which affect the correlation by giving an individual signature to a track section.

5. Granite ballast has a higher limit track lateral resistance compared to that of slag ballast, given that all other conditions such as the peak track lateral resistance, tie condition, ballast shoulder width, and crib level are consistent.

6. Track consolidation by traffic (measured in MGT) does increase the peak track lateral resistance up to some plateau, as is well-known in the literature. The lateral resistance is recovered to about 90 percent of its fully consolidated value by about 5 MGT and after 20 MGT, the incremental increase in resistance is negligible. However, there is no simple one-to-one relationship, between MGT and track lateral resistance, which is valid under all track conditions. Likewise, there are variations in the tamped track lateral resistance due to varying railroad tamping procedures. Starting with measured track lateral resistance for tamped track, it is possible to estimate the track lateral resistance increase with MGT for given ballast type and tie construction.

7. Environmental factors, such as freeze-thaw and erosion due to rain, can significantly affect track lateral resistance. Hence, if it is to be assumed that ballast consolidation has taken place through train operation, environmental degradation of track lateral resistance should also be evaluated.

8. The contributions of the crib, shoulder, and bottom ballast, with respect to the track lateral resistance, vary with field conditions. It has been estimated that, for wood tie track, the proportions are 10 to 20 percent for shoulder, 25 to 35 percent for bottom, and the remaining from the crib. The crib is the most important as it enables the tie bottom to function in an effective manner while also contributing a significant proportion of the track lateral resistance in the form of side friction. The crib resistance is high, owing to its confined state, and under consolidation there will be a large normal pressure on the vertical side surfaces in contact with the crib ballast. Also, the shoulder contribution depends on consolidation and width, which is not effective beyond a certain limit (<24 in. generally).

9. The test data did not reveal any noticeable influence of varying track curvature on track lateral resistance.

10. The loading rate of the STPT fixture did not show any significant influence on the STPT characteristic curve. It can be concluded that the ballast resistance is not strain rate dependent.

11. There is scatter in the STPT measured values. This is due to the variability of individual tie resistance, which reflects the difficulty in maintaining uniform track lateral resistance in the field through track construction and maintenance. This variability is what needs to be precisely measured for buckling safety, and the STPT is well-suited for this purpose. A random sample of three test ties in a 50 ft long track section yields an average track lateral resistance within 20 percent of the average of all ties measurable within the section. This is considered to be tolerable, as there is an adequate margin of safety in the safety predictions.

    A sample size of five ties within the 50 ft consolidated section, referred to above, gives the track lateral resistance within 10 percent error, which is considered to be more than adequate in field applications.

    In the case of tamped track, there is more uniformity, and the percent error is much less than that quoted earlier. The evaluation of tamped track is more critical and the STPT is well-suited to evaluate its buckling safety.

12. The track longitudinal resistance increases quickly for displacements under 0.1 in. and tends to level off at about 1 in. The track longitudinal resistance depends on crib ballast level, anchoring pattern, and consolidation. Full-crib ballast condition can increase the track longitudinal resistance by about 50 percent over the half-crib condition. Consolidation can increase the track longitudinal resistance by about 30 percent over the tamped condition. Anchoring every third tie reduces the track longitudinal resistance by about 30 percent of the value for every other tie anchored.

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