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A Laboratory Test Method for Measuring Realistic Trackbed Pressures at the Tie/Ballast Interface

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TECHNICAL SUMMARY

Title

A Laboratory Test Method for Measuring Realistic Trackbed Pressures at the Tie/Ballast Interface

Introduction

This report documents the development of a practical and reliable laboratory method for calibrating pressure cells and quantifying typical railway trackbed pressures at the tie/ballast interface under simulated trackbed conditions. Vertical pressures were applied by a hydraulic compression test machine to prototype sections of the trackbed consisting of a section of rail placed on a tie plate and a section of a wood tie, supported by specially designed frames/boxes containing the ballast and subballast.

Approach and Methodology

The granular material pressure cells were recessed within the bottom of the ties, thus suitably positioned for subsequent in-track measurements. Loading magnitudes, applied by the testing machine, and resulting vertical interfacial pressures were similar to those exerted by locomotives and loaded freight cars traveling at typical freight train speeds.

Particular attention was given to evaluating the effects of various procedures for positioning the cells within the interface and attaching the cells to the ties. Additional attention was given to optimizing the design of the ballast and subballast containment frames and testing procedures so that the stress dissipation would simulate in-track loadings typically produced by freight trains.

Findings

A granular material pressure cell, manufactured specifically to measure pressures of large-size graded aggregates, accurately measured vertical pressures under laboratory simulated in-track loading using known and controlled loadings. Near perfect correlation (R^2 of 0.9997) was obtained between repeated machine applied pressures and measured cell pressures.

Test data indicated minimal variations between:

- Measurements using different cells for identical test conditions,

- Measurements for cells positioned below a solid tie (not practical for in-track applications) and cells recessed in the bottom side of the tie, and

- Measurements with cells “floating” loose within the recesses, cells attached with screws or cells attached with corner braces exhibited minimal variations.

Conclusions

The effects of various alternate procedures were evaluated. The selected procedure provides excellent correlation between the controlled applied machine pressures and the simultaneously measured cell pressures. The selected granular material pressure cell is considered applicable for in-track tie/ballast pressure measurements using the techniques developed in this study. However, the specific procedures utilized to install and position the cells in the trackbed can adversely affect the associated pressure measurements. Following proper techniques for installing and positioning the cells are critical for obtaining realistic pressure values.

Recommendations

For future in-track tie/ballast interface pressure measurements, the instrumented ties should be recessed by routing to provide space to embed and protect the active cell, transducer housing, and instrument cable.

The cells should be attached to the ties with either screws or corner braces and protected from damage.

Publications

Rose, J.G. Clarke, D.B. Liu, L. and T.J. Watts. “Development of a Laboratory Test Method for Measuring Trackbed Pressure at the Tie/Ballast Interface”. Paper 18-00592 TRB 97th Annual Meeting Online. Transportation Research Board, January, 2018, 12 pages.

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SECTION 1 INTRODUCTION

This report documents the development of a practical and reliable laboratory method for calibrating pressure cells and quantifying typical railway trackbed pressures at the tie/ballast interface under simulated trackbed conditions. Vertical pressures were applied by a hydraulic compression test machine to prototype sections of the trackbed consisting of a section of rail placed on a tie plate and a section of a wood tie, supported by specially designed frames/boxes containing the ballast and subballast.

The granular material pressure cells were recessed within the bottom of the ties, thus suitably positioned for subsequent in-track measurements. Loading magnitudes, applied by the testing machine, and resulting vertical interfacial pressures were similar to those exerted by locomotives and loaded freight cars traveling at typical freight train speeds.

Particular attention was given to evaluating the effects of various procedures for positioning the cells within the interface and attaching the cells to the ties. Additional attention was given to optimizing the design of the ballast and subballast containment frames and testing procedures so that the stress dissipation would simulate in-track loadings typically produced by freight trains.

The effects of various alternate procedures were evaluated. The selected procedure provides excellent correlation between the controlled applied machine pressures and the simultaneously measured cell pressures. The selected granular material pressure cell is considered applicable for in-track tie/ballast pressure measurements using the techniques developed in this study. However, the specific procedures utilized to install and position the cells in the trackbed can adversely affect the associated pressure measurements. Following proper techniques for installing and positioning the cells, as described herein, are critical for obtaining realistic pressure values.

SECTION 2 PREVIOUS STUDIES

It has been desirable for years to develop a reasonably simple, accurate, and reliable method to directly measure pressure magnitudes and distributions at the tie/ballast interface in railroad trackbeds. Quantifying the magnitudes and relative distributions of pressures at the tie/ballast interface are important inputs for trackbed engineering design and analysis aspects. The pressures produced by millions of load applications ultimately affect the long-term performance of the track and the service lives of the component materials and layers. Ideally the interstitial pressure intensities at the tie/ballast interface can be reduced by distributing pressures uniformly over large contact areas thereby reducing abrasion, wear, and crushing of the bottom of the tie and the surface layer of the ballast. This also reduces the proportion of the loadings having to be supported by the ties and rail, lengthening the service life of the track.

Recent studies (1) indicated that a specially designed granular materials hydraulic pressure cell manufactured by Geokon was applicable in the laboratory for measuring trackbed pressures at the tie/ballast interface. This cell was developed for measuring pressures in materials containing large, sharp particles -- such as railroad ballast. Prior to the development of this thicker cell for ballast pressure measurements, thinner earth pressure cells, primarily designed for soil applications, but requiring cushioning layers for measuring ballast pressures, were used to satisfactorily measure pressures at the ballast/subballast/subgrade interfaces (2, 3, 4, 5).

The latter study (1) indicated that not only was the thicker cell applicable to reliably and consistently measure pressures, but varying the composition of the supporting ballast did not have significant effects on the accurate transmission of the pressure distribution. Test results using new ballast size material, worn ballast size material, and smaller top-size ballast material (more suitable for laboratory tests) were similar. However, the study assumed the cells would be placed below a solid tie, as had been the situation for the laboratory studies, when used for in-track applications.

This actually proved unsatisfactory (6) since it was impossible to consistently maintain firm contact between the bottom of the tie and cells embedded in the trackbed. On installation, cells were wedged tightly between the crosstie bottom and the open-graded ballast. During the passage of trains, however, impact loadings caused the cells to gradually migrate downward into the ballast. Therefore, the pressure readings decreased with time as a function of train traffic. In effect, the tie “bridged over” the cell.

Figure 2 shows two trackbed installations. The first, a modernly fouled wood tie track, was on the yard lead at TTI Railroad in Paris, KY. The other, near Flat Rock, KY, was on a Class 4 Norfolk Southern (NS) mainline having concrete ties and a thick ballast section with essentially negligible fouling.

Efforts to tighten the cells by inserting thin metal shims to fill the voids between the tie and ballast were only partially successful. The passage of trains still caused the cells to migrate downward, reducing measured pressure values. If the cells were over shimmed, the pressures for the initial several trains would be very high, though decreasing as train traffic accumulated.

Furthermore, the transducer housing containing the strain gages and the instrument cable had to be positioned within the crib area of the track. This negated the possibility of subsequently tamping and surfacing the track to consolidate ballast disturbed and loosened during cell installation.

SECTION 3 CURRENT STUDIES

The primary purpose of this laboratory study was to determine the applicability and repeatability of using recessed hydraulic granular materials pressure cells to accurately determine vertical

Figure 2. Two track sites used for initial attempts to accurately measure tie/ballast interfacial pressures, TTI Railroad yard lead (left) and NS mainline (right).

pressures at the tie/ballast interface in railroad track. The research simulated in-track conditions using a laboratory testing machine to load a section of rail and tie supported by specially designed ballast and subballast containment frames.

One research objective was to explore practices for positioning the cells without adversely affecting typical in-track pressure distributions. Specific focus areas included techniques for attaching the cells to the ties and the influence of cell location within the bottoms of the ties. These findings could ultimately be employed when inserting the cells into in-service track.

The researchers elected to recess the active portion of the cells, the housing containing the strain gages, and the instrument cable into the tie. This placed the active pressure cell face flush with the bottom of the tie, permitting direct contact with the ballast. Routing established the needed spaces in the tie for the pressure cell assemblies. Figure 3 shows views of a routed test tie and pressure cell. The experiment subsequently evaluated the effect of recessing the cells in the tie bottoms.

Figure 3. Routed tie section (left) and pressure cell (right).

SECTION 4 TEST TRACKBED

The prototype laboratory track and support simulated an in-service trackbed. This test section incorporated vertical resiliency so that a typical track deflection of 1/4 to 3/8 in. (6 to 9 mm) would be achieved during loading. The ballast containment box/frame provided lateral ballast confinement in a manner similar to an in-service trackbe. A special resilient, expandable containment frame contained the ballast, while providing minimal lateral support to unduly restrain the ballast from movement.

The subballast, ballast, wood tie, tie plate and rail were typical of materials used in revenue track. Figure 4 provides a typical view of the track and support during a test.

Figure 4. Track section and support used for laboratory tests.

4,1 <u>Ballast and Subballast</u>

Layers of granite ballast and limestone subballast provided support for the pressure cells. The ballast was a mixture of new and worn ballast. The worn condition was achieved by initially subjecting the ballast to the LA Abrasion test to partially round the aggregate particles and provide a larger percentage of fine-sized particles. The larger size particles (plus 1-1/2 in. (38 mm)) were removed to provide more uniform support. Care was taken to insure that the ballast and subballast layers in the prototype track section were adequately and uniformly compacted, with the top surfaces level.

The bottom compression platen of the testing machine was lengthened to 72 in. (1.83 m) using three aluminum beams. The 61 in. (1.55 m) long by 25 in. (0.64 m) wide subballast box frame was positioned on the beams. Nominal 2 in. by 4 in. (50 mm by 100 mm) wood framing studs were used for the subballast frame. The bottom of the frame was composed of 5/8 in. (16 mm) thick layer of plywood with a 3/16 in. (5 mm) thick rubber mat on the underside to simulate a typical resilient roadbed.

A slightly smaller size ballast frame was sized to rest upon the subballast and fit inside the subballast frame. The 2 by 4 wood frame was heightened using a resilient composite lawn edging material. This increased the ballast thickness under the tie, while providing minimal lateral support. The bottom was composed of 3/16 in. (5 mm) thick polyester fiber/rubber-backed floor carpet.

The ballast depth was increased an additional 5 in. (125 mm) using an inner rectangular frame composed entirely of edging material placed directly on the ballast layer. This provided minimal lateral support/resistance to the tie.

The total support for the tie thus consisted of 10 in. (250 mm) of granite ballast (modified #4A grade) and 4 in. (100 mm) of limestone subballast (locally known as dense graded aggregate and typically used for railroad subballast and highway pavement base material.)

4.2 Wood Tie Sections, Tie Plate, and Rail

The test employed short sections of a standard size 9 in. (225 mm) wide by 7 in. (175 mm) thick copper naphthenate treated wood tie. The tie section for single cell testing directly under the rail was 11 in. (275 mm) long.

A standard 8 in. (200 mm) wide by 14 in. (350 mm) long steel tie plate was positioned between the wood tie and rail. A 1/8 in. (3 mm) thick narrow spacer placed within rail seat negated the cant to ensure that vertical loads would be applied through the track and support.

The rail was a 10 in. (250 mm) long section of 136-lb rail conforming to AREMA specifications. This rail spanned the width of the tie plate.

SECTION 5 LABORATORY TEST EQUIPMENT AND DATA ACQUISITION

A typical construction materials Baldwin/Satec hydraulic universal testing machine, having a test range of 300,000 lbf (1,335 kN), applied static compression loads in 1,500 lbf (6.7 kN) increments to a maximum load of 6,000 lbf (26.9 kN). The range of loading on the pressure cells provided pressures exceeding 100 psi (690 kPa), exceeding typical loading magnitudes and pressures exerted on ballast by locomotives and loaded freight cars.

The Geokon Model 3515 granular materials pressure cells, are designed to measure dynamic pressure changes in granular materials like railroad ballast. The cell consists of two circular 8 in. (200 mm) diameter stainless steel plates welded together around the periphery, separated by a small gap (void) filled with hydraulic fluid.

The applied pressure squeezes the two plates together, thus creating fluid pressure between the plates. A pressure transducer in the cell's steel housing transforms the fluid pressure to a current signal. The transducer pressure range is 0 to 360 psi (0 to 2.5 MPa).

The recorded pressure is the average pressure on the active cell area of 50.3 in^2 (324 cm^2). The cell plates are sufficiently thick that they do not deflect locally under normal particle point loads.

Thus, the contact forces from all aggregate particles bearing on the active area influence the pressure reading.

The test used National Instruments Model NI 9203 C Series Current Input Module data logger attached to a laptop computer. The 12Vdc module has eight analog -20 mA to 20 mA current input channels with a maximum 200 kHz sample rate. The tests employed a sampling rate of 2000 samples/s. Figure 5a shows a pressure cell and the data logging system.

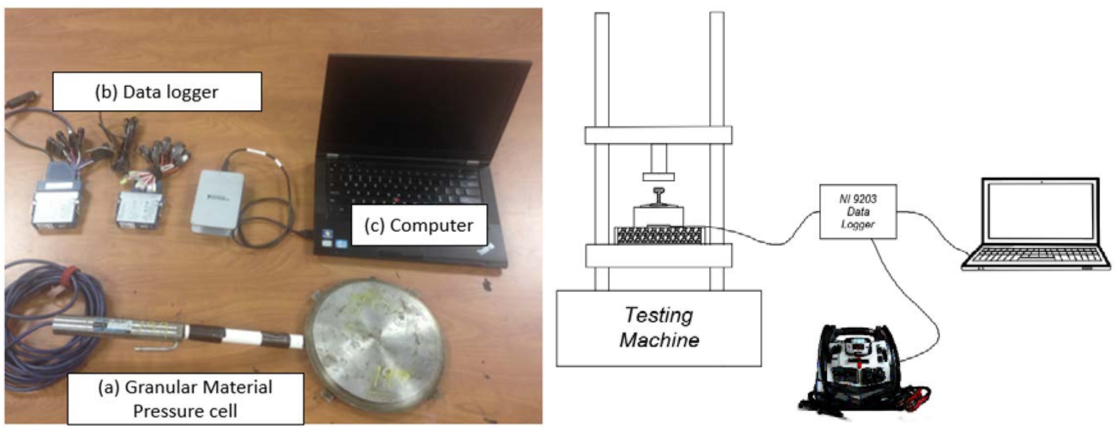


Figure 5a. Pressure cell and data logger module.

The team used LabVIEW to develop a user-friendly program to collect data. Figure 5b shows the main interface. The program can change units from mA to MPa and psi synchronously and show the pressure magnitude trace during the testing procedure. It also induces an automatic zero setting.

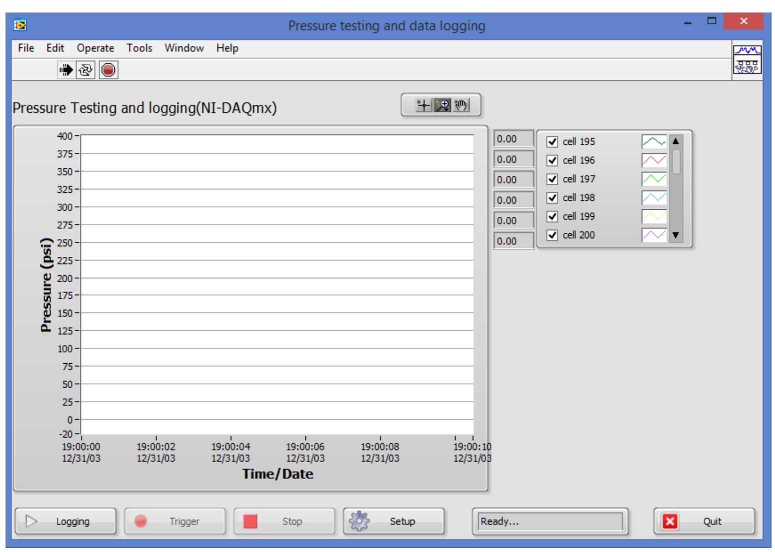


Figure 5b. Interface for LabVIEW program.

SECTION 6 SERIES OF LABORATORY TESTS

The team conducted several series of laboratory tests using conditions simulating in-track loading. A portion of these represented calibration-type validations given the known/controlled magnitude of the machine loading The area of load application from the tie to the ballast was the known active area of the pressure cell. By comparing the calculated machine pressure to the cell pressure indication it was possible to determine the cell accuracy. The validation tests confirmed that the cells did accurately measure the induced pressures.

Next, the effects of several variables were examined to help optimize installation practices used for placement of the cells within the trackbed.

The test sequence involved the following evaluations:

- Measurement Repeatability Within and Between Cells,
- Effect of Cell Location and Position, and
- Effect of Cell Attachment Procedures.

6.1 Measurement Repeatability Within and Between Individual Cells

Repeatability measurements employed four different cells. The only variable was the cell; loading magnitudes and test configurations remained the same. The loading from the tie to the ballast transferred through the complete area of the cell. The overhanging portion of the tie was not permitted to contact the ballast. The ballast was uniformly consolidated to minimize any variation during the test.

Six tests, involving cell pressure readings at four different loading magnitudes, were repeated for each of the four cells. The loading encompassed typical maximum magnitudes directly under a wheel load. The tie section was 11 in. (280 mm) long. A machine load of 6,000 lbf (26.9 kN) induced a pressure of 119 psi (822 kPa) through the cell on the ballast. This is about three times what is considered typical of pressures (neglecting impact) in a typical in-service trackbed.

Figure 6.1a illustrates the relationships of average machine induced stresses and the corresponding average cell measured stresses for the four cells. The results demonstrate near perfect correlation with the deterministic model line (R^2 of 0.9994).

Figure 6.1b shows the relationship for six repeated tests for individual cell # 88. The variations in cell reading are normally less than ± 2 psi (14 kPa) from the average for the repeat tests. The R^2 was 0.9997. The low variations between different cells were expected since each cell is individually calibrated. The low variations in repeat tests indicate that the laboratory test conditions are consistent and the cells are capable of accurately and consistently measuring tie/ballast interface pressures.

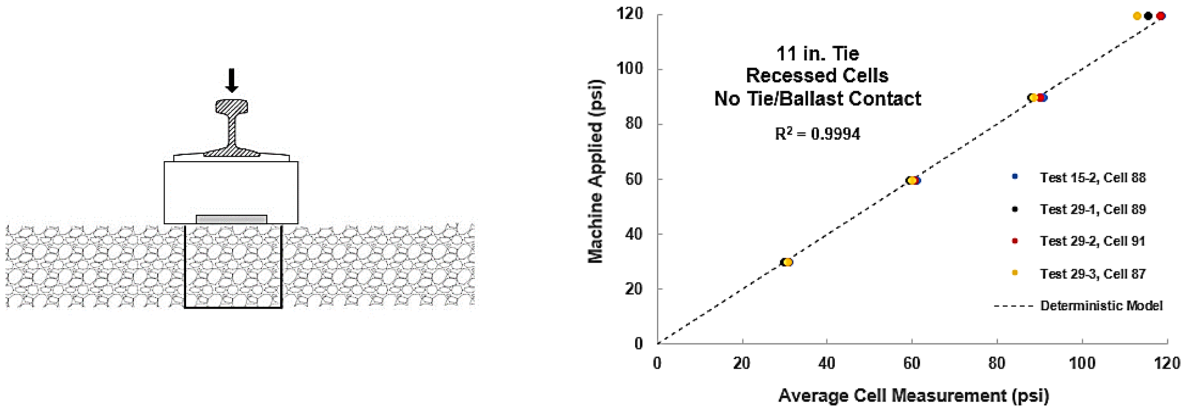
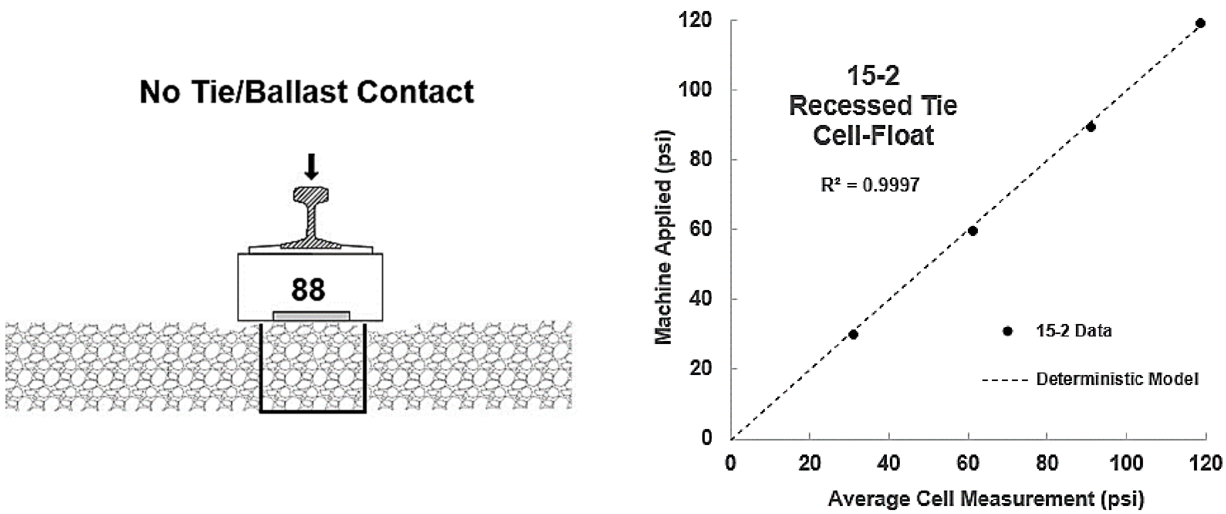


Figure 6.1a. Relationship between machine applied stresses and average cell measured stresses for four cells.



Machine		Test							
		(a)	*(b)*	*(c)*	*(d)*	*(e)*	*(f)*		
Applied (lbf)	**Applied (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Range (psi)**	**AVG (psi)**
1500	29.8	32.8	31.5	31.1	30.8	30.7	30.8	30.7 – 32.8	31.1
3000	59.7	61.7	62.3	61.5	60.7	61.1	60.9	60.7 – 62.3	61.1
4500	89.5	92.6	92.2	91.8	89.9	90.2	90.1	89.9 – 92.6	90.0
6000	119.4	120.1	118.8	118.1	118.2	118.3	118.1	118.1 – 120.1	118.7

Figure 6.1b. Relationship between machine applied stresses and repeated cell measurement stresses for cell # 88; cell data similar for the other three cells.

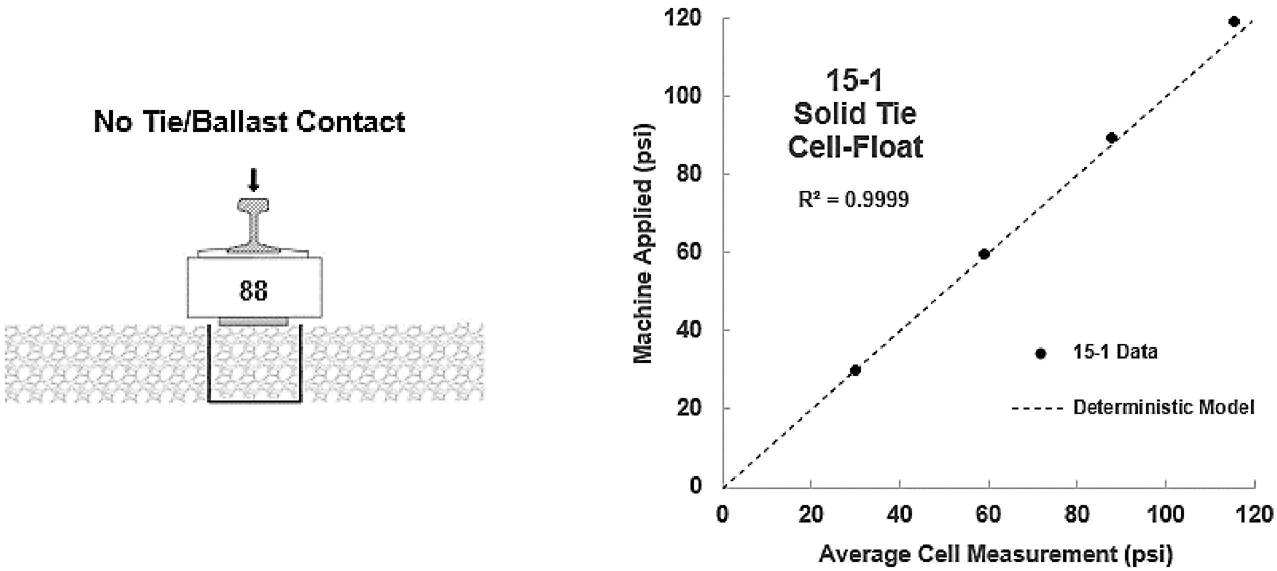
6.2 Effect of Cell Location and Position

Previous in-track tests using pressure cells placed below the tie at the tie/ballast interface have not yielded repeatable and consistent results. This research evaluated the effects of inserting the cells within a recessed cavity at the bottom surface of the tie. One-seventh of the thickness of the tie was removed (routed) to position the 1 in. (25 mm) thick cell and associated housing and cable. Figure 6.2a shows the routed tie and pressure cell.

Figure 6.2a. A typical routed tie with a recess and a pressure cell.

Repeated tests were conducted to assess the effects of recessing the cell within the tie. One setup employed a cell positioned directly below a solid tie; another recessed the cell within the bottom of the tie. Each setup underwent Six repeated tests at four different pressure levels. Only the cell surface contacted the ballast. Ballast was removed below the small area of the tie extruding beyond the cell surface to prevent a portion of the load from being carried by the tie. Figures 6.2b and 6.2c show the machine induced pressure and the cell pressure measurements.

The test data indicates very good correlation between the transmitted test machine pressure and the measured cell pressures. R^2s of 0.9999 and 0.9997 were achieved. The cell positioned below the solid tie recorded about 3 percent lower pressures for the two higher loadings. Test data variations between repeated tests were less than 1 psi (7 kPa). Therefore, recessing the cell within the underside of the tie, as compared to positioning the cell below the tie, has essentially no effect on transmitted pressures.

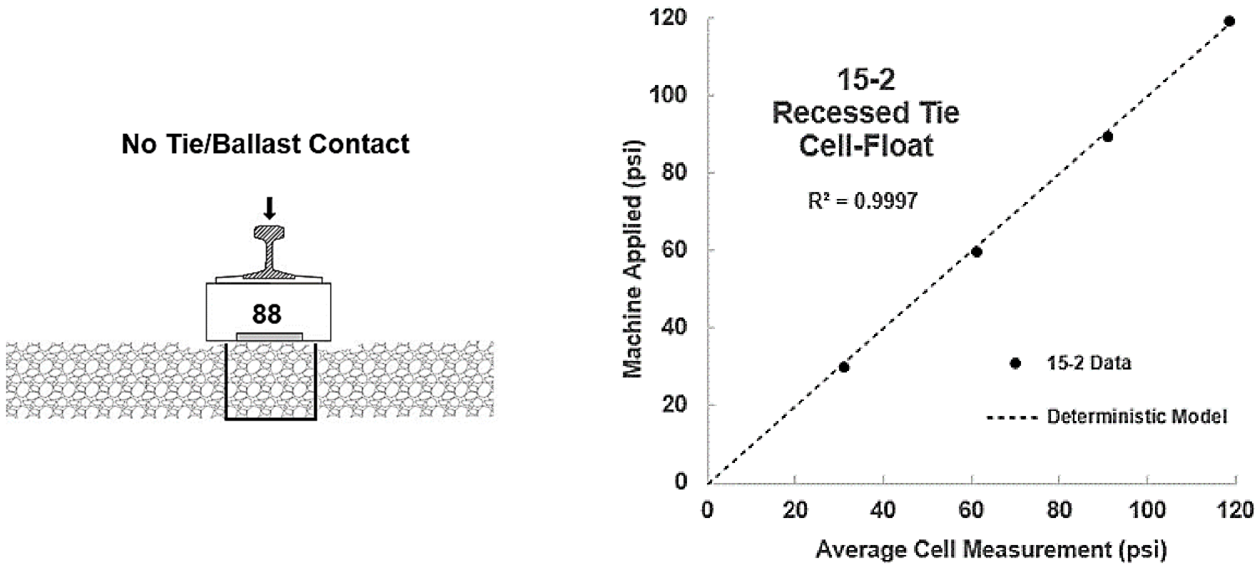


Machine		Test							
		(a)	*(b)*	*(c)*	*(d)*	*(e)*	*(f)*		
Applied (lbf)	**Applied (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Range (psi)**	**AVG (psi)**
1500	29.8	30.1	29.5	30.2	30.5	29.8	30.2	29.5 – 30.5	30.0
3000	59.7	59.2	58.8	58.7	58.8	58.5	59.8	58.5 – 59.8	59.1
4500	89.5	86.8	87.1	87.6	87.5	87.1	87.8	86.8 – 87.8	87.6
6000	119.4	115.4	114.3	114.7	114.6	114.1	114.8	114.1 – 115.4	115.3

Figure 6.2b. Relationship between applied stresses and repeated cell measurement stresses for a solid tie with the cell positioned below the tie.

6.3 <u>Effect of Cell Attachment Procedures</u>

For the preceding laboratory test sequence, the cells below and within the tie were positioned and held secure by the test machine pressure pushing the ballast against the bottom of the cell. The cells were not secured directly to the ties, and could slightly adjust position. However, for in-track application it is desirable to fasten the cell to the tie This prevents the cell and tie from separating during installation. An attached cell cannot subsequently settle in the ballast so that the tie loading "bridges" across the cell, providing lower pressure readings than would be typical for non-instrumented ties.



Machine		Test							
		(a)	*(b)*	*(c)*	*(d)*	*(e)*	*(f)*		
Applied (lbf)	**Applied (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Measured (psi)**	**Range (psi)**	**AVG (psi)**
1500	29.8	32.8	31.5	31.1	30.8	30.7	30.8	30.7 – 32.8	31.1
3000	59.7	61.7	62.3	61.5	60.7	61.1	60.9	60.7 – 62.3	61.1
4500	89.5	92.6	92.2	91.8	89.9	90.2	90.1	89.9 – 92.6	90.0
6000	119.4	120.1	118.8	118.1	118.2	118.3	118.1	118.1 – 120.1	118.7

Figure 6.2c. Relationship between applied stresses and repeated cell measurement stresses for a recessed tie and the cell positioned within the recess in the tie.

The researchers evaluated two methods for affixing the cells to the tie. One method employed screws though integral brackets on the cell body. A second involved retaining the cells using small flat metal corner braces screwed to the tie. The latter method partially demobilized the cells relying on the ballast to hold the cells within the recesses. Test results were compared to control tests without positive attachment (floating). Figure 6.3a shows the floating procedure and the two types of attachment procedures.

Figure 6.3b shows machine induced pressure versus measured cell pressure for the test. The test data indicates very good correlation between the transmitted test machine pressure and the measured cell pressures. All three procedures achieved R^2 values in excess of 0.999.

Figure 6.3a. The floating procedure and two types of attachment procedures.

Test data variations between the floating cell, screw, and corner brace attachments were less than 1 psi (7 kPa). Therefore, varying the cell attachment procedure has essentially no effect on altering transmitted pressures.

SECTION 7 CONCLUDING REMARKS

The research demonstrated a method for realistically calibrating and accurately measuring vertical applied pressures at the tie/ballast interface in the laboratory. It employed a simulated track section consisting of rail, tie plate, wood tie, ballast and subballast to measure pressures at the tie/ballast interface and to calibrate the cells.

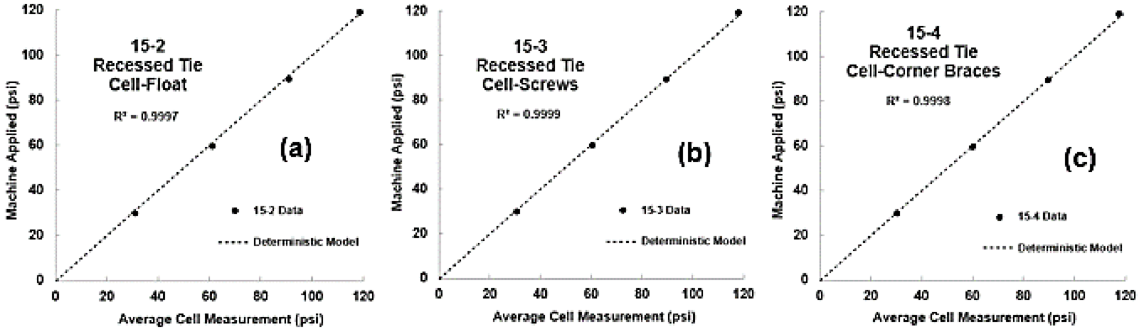
The trackbed support was designed to deflect, under typically in-track applied loading magnitudes, about 1/3 in. (8 mm); typical of in-track deflection for typical 36,000 lbf (161 kN) on-track wheel loadings.

The ballast containment frame was designed to minimally resist lateral movement of the ballast during load application, typical of an in-track trackbed. Particular attention was given to pre-compacting the subballast and ballast layers to simulate a seasoned track support system.

A granular material pressure cell, manufactured specifically to measure pressures of large-size graded aggregates, accurately measured vertical pressures under laboratory simulated in-track loading using known and controlled loadings. Near perfect correlation (R^2 of 0.9997) was obtained between repeated machine applied pressures and measured cell pressures.

The cells were recessed within the bottoms of the ties and protected from damage by the ballast, except for the active surfaces of the circular cells which were flush with the bottoms of the ties.

Test data indicated minimal variations between:



(a) Float

Machine		Test							
		(a)	*(b)*	*(c)*	*(d)*	*(e)*	*(f)*		
Applied (lbf)	Applied (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Range (psi)	AVG (psi)
1500	29.8	32.8	31.5	31.1	30.8	30.7	30.8	30.7 – 32.8	31.1
3000	59.7	61.7	62.3	61.5	60.7	61.1	60.9	60.7 – 62.3	61.1
4500	89.5	92.6	92.2	91.8	89.9	90.2	90.1	89.9 – 92.6	90.0
6000	119.4	120.1	118.8	118.1	118.2	118.3	118.1	118.1 – 120.1	118.7

(b) Screws

Machine		Test							
		(a)	*(b)*	*(c)*	*(d)*	*(e)*	*(f)*		
Applied (lbf)	Applied (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Range (psi)	AVG (psi)
1500	29.8	30.5	30.3	31.2	30.8	30.7	31.5	30.3 – 31.5	30.7
3000	59.7	59.8	60.1	61.3	60.9	60.5	60.8	59.8 – 61.3	60.4
4500	89.5	89.1	89.4	89.7	89.8	89.4	89.6	89.4 – 89.8	89.5
6000	119.4	117.2	117.8	118.1	118.2	117.8	117.7	117.2 – 118.2	118.0

(c) Corner Braces

Machine		Test							
		(a)	*(b)*	*(c)*	*(d)*	*(e)*	*(f)*		
Applied (lbf)	Applied (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Measured (psi)	Range (psi)	AVG (psi)
1500	29.8	29.8	30.4	30.6	30.3	30.8	29.6	29.6 – 30.8	30.2
3000	59.7	59.5	60.1	60.7	59.8	60.3	60.1	59.5 – 60.7	60.0
4500	89.5	88.7	89.5	89.1	90.3	89.7	89.1	88.7 – 90.3	89.4
6000	119.4	116.8	117.3	117.2	117.6	117.1	117.4	116.8 – 117.6	117.5

Figure 6.3b. Relationship between applied stresses and repeated cell measurement stresses for recessed cells having different attachment procedures.

- Measurements using different cells for identical test conditions,
- Measurements for cells positioned below a solid tie (not practical for in-track applications) and cells recessed in the bottom side of the tie, and
- Measurements with cells “floating” loose within the recesses, cells attached with screws or cells attached with corner braces exhibited minimal variations.

For future in-track tie/ballast interface pressure measurements, the instrumented ties should be recessed by routing to provide space to embed and protect the active cell, transducer housing, and instrument cable.

The cells should be attached to the ties with either screws or corner braces arranged as depicted herein.

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