STP 1605, 2018 / available online at www.astm.org / doi: 10.1520/STP160520170025

Timothy D. Stark[1] and Stephen T. Wilk[1]

Review of Size and Loading Conditions for Large-Scale Triaxial Testing

Citation

Stark, T. D. and Wilk, S. T., "Review of Size and Loading Conditions for Large-Scale Triaxial Testing," *Railroad Ballast Testing and Properties, ASTM STP1605*, T. D. Stark, R. Szecsy, and R. H. Swan, Jr., Eds., ASTM International, West Conshohocken, PA, 2018, pp. 152–162, http://dx.doi.org/10.1520/STP160520170025[2]

ABSTRACT

The large particle size of railroad ballast and the wide range of loading conditions make it difficult to appropriately represent ballast behavior in laboratory shear testing. This paper presents an overview of the advantages and disadvantages of large-scale triaxial compression testing of ballast, how it can be used to represent field ballast conditions, and typical results. Minimum size restrictions and diameter along with appropriate confining stress, loading frequencies, and deviator stresses are discussed with examples of the range of loading conditions experienced in the field from field monitoring and numerical modeling. In triaxial compression testing, a specimen diameter of six times the maximum particle size is required. In addition, standard confining stresses can range from 0 kPa to 72 kPa, and the deviator stresses can range from 50 kPa to 360 kPa.

Keywords

ballast, triaxial tests, confining stress, normal stress

Introduction

Railroad ballast is a uniformly graded aggregate that provides support to track superstructure (i.e., crossties and rails). As a result, it is the uppermost support and

Manuscript received March 13, 2017; accepted for publication March 13, 2017.
[1]University of Illinois at Urbana-Champaign, Dept. of Civil and Environmental Engineering, Urbana, IL 61801
T. S. http://orcid.org/XXXX-XXXX-XXXX-XXXX S. W. http://orcid.org/XXXX-XXXX-XXXX-XXXX
[2]ASTM Symposium on *Railroad Ballast Testing and Properties* on May 9, 2017 in Toronto, ON, Canada

damping system for the static and dynamic loads applied to the track by passing traffic. Understanding the gradation, compressibility, shear strength, and stiffness of ballast is important for assessing track support and load distribution among adjacent ties during train loading because the ballast layer undergoes the greatest transient and permanent vertical displacements in the subsurface profile [1].

The stiffness, or modulus, of ballast is a difficult parameter to measure with laboratory testing because of a number of issues including: (1) ballast shear behavior is stress dependent, so field stress conditions must be replicated; (2) ballast gradation varies locally (e.g., crib versus under tie); and (3) ballast is sheared in a state of rotating and varying principal stresses during train passage [2]. The first issue involves determining and applying a representative stress state (e.g., field normal, confining, and deviator stresses) in shear testing. The second issue is representing field ballast gradation in the laboratory because gradation varies with location and time due to ballast fouling and breakdown from repeated applied loads [3]. This results in significant local variations of ballast gradation (e.g., under and alongside ties). The last difficult issue in laboratory ballast testing is accounting for the rotation and variation in principal stresses applied during train passage. Because of the dynamic and nonuniform application of stress applied by the tie to the ballast and the variable ballast confinement conditions, the loading conditions in laboratory shear tests usually do not simulate field loading conditions, which can affect measured shear strength, compressibility, and modulus parameters [2,4].

To address these issues, the main objective of this study is to provide recommendations for representative stress conditions for shear testing and testing device sizes that should be used to obtain meaningful results and minimize boundary testing conditions on measured ballast properties. This paper covers the following main topics: representative stress conditions (i.e., normal, confining, and deviator stresses), moisture conditions for shear testing, and appropriate triaxial compression specimen size.

Simulating Field Conditions

Two important field conditions that should be simulated in laboratory ballast shear testing are (1) in situ normal or confining stress present prior to deviator stress application (i.e., train loading) and (2) specimen moisture condition or wetting prior to shearing. Both of these conditions will impact the measured shear strength, compressibility, and modulus of ballast but especially moisture content for fouled ballast, as shown by Stark et al. [5].

FIELD STRESS CONDITIONS

The three typical stress conditions used for laboratory shear testing are: (1) normal stress for direct shear tests, (2) confining pressure for triaxial compression tests, and (3) applied deviator stress. The normal and confining stresses applied to laboratory specimens should represent the initial stress condition in the ballast prior to train loading while the deviator stress (e.g., horizontal shear load in the direct shear test or axial load in a triaxial compression test) should be representative of train passage. It is important to represent the physical stress conditions of the ballast because the strength envelope for coarse aggregates is stress dependent and can exhibit a cohesion intercept when testing at unrealistically high normal and confining stresses or when boundary conditions impact the test result. The range of normal, confining, and deviator stresses estimated and calculated using a dynamic finite element stress analysis are summarized in **Table 1** and are discussed below.

The normal stress used in laboratory testing should represent the in situ vertical stress of the ballast underneath the tie prior to train loading. This means the normal stress represents the weight of the rail, tie, and ballast acting on the tie-ballast interface. This can be estimated using the weight of these materials or using numerical modeling techniques (or by both). The weight of these materials can be estimated using a 0.2 m by 0.2 m by 2.6 m (0.75 ft by 0.75 ft by 8.5 ft) concrete tie with a density/unit weight of 2400 kg/m^3 (150 lb/ft^3), which provides a tie weight of 325 kg (720 lb). The assumed 136-RE rail has a weight per length of 67.5 kg/m (136 lb/yd) with a distributed length (i.e., tie spacing) of 0.6 m (0.67 yds), which gives a rail weight of 41 kg (90 lb) and a total weight of 365 kg (805 lb) for a tie. It is typically assumed by the American Railway Engineering and Maintenance-of-Way Association [6] that the tie load is distributed to the ballast through only two-thirds of the bottom tie cross section (e.g., 2/3 times 0.2 m times 2.6 m equals 0.35 m^2) producing a normal stress of 10.3 kPa (215 psf) by 365 kg times 9.81 m/s^2 times 0.35 m^2. Due to uneven load distribution and varying tie support [7,8], a normal stress range of 0 kPa to 12 kPa (0–250 psf) at the tie-ballast interface is recommended for direct shear testing.

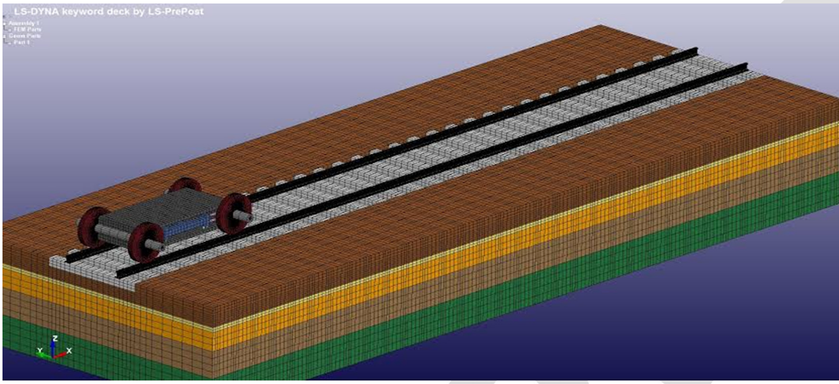
To verify this range of normal stress, a three-dimensional (3D) dynamic finite element stress analysis was conducted to estimate the normal and confining stresses that should be used in laboratory shear strength tests to represent field conditions. The software package LS-DYNA was used and is a 3D finite element method program distributed by Livermore Software Technology Corporation (LSTC) that specializes in nonlinear transient dynamic finite element analyses. As a result, LS-DYNA is capable of modeling the entire track behavior along with the inclusion of train cars and wheel systems.

TABLE 1 Recommended range of normal, confining, and deviator stresses for ballast shear strength testing based on dynamic finite element stress analysis for high-speed passenger and freight.

Stress Condition	SI (kPa)	Imperial (psf)
Normal stress	0 to 24	0 to 500
Confining stress	0 to 72	0 to 1,500
Freight deviator stress	50 to 360	1,000 to 7,500

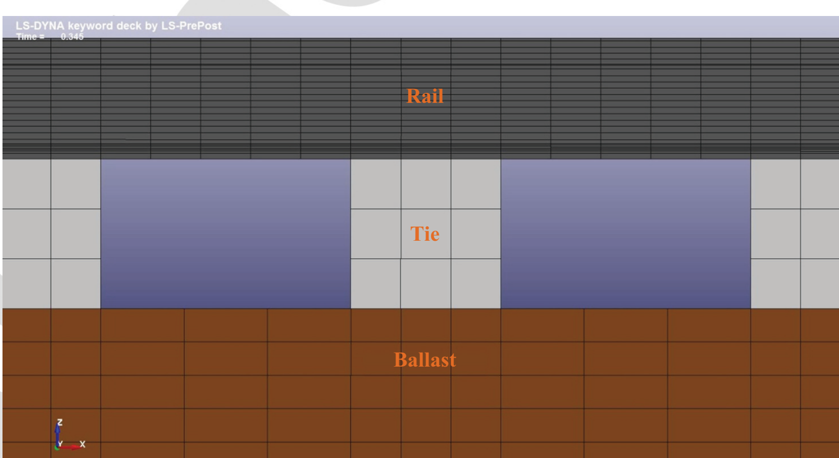
J_ID: STP DOI: 10.1520/STP160520170025 Date: 8-December-17 Stage: Page: 155 Total Pages: 12

FIG. 1 Three-dimensional finite element mesh of track system and wheel set used in LS-DYNA model.



Using LS-DYNA, a 3D track model consisting of the rail, concrete ties, ballast, and subgrade was developed (see Fig. 1) to analyze load and stress distributions throughout the track during train passage; it can also be used to estimate reasonable values of in situ ballast stresses (e.g., normal stresses below the tie prior to train loading). A close-up of a single cross-tie and underlying ballast in the LS-DYNA model is shown in Fig. 2. Building up the track system in the LS-DYNA model from the subgrade to the track system allows the in situ stress state to be estimated prior

FIG. 2 Close-up of finite element mesh showing concrete tie in intimate contact with underlying ballast.



to train passage. The range of normal or vertical stress acting upon the ballast by the tie prior to train loading varies from 6 kPa to 12 kPa (125 psf to 250 psf) depending on the location under the tie in the finite element method model. This range of normal stress for direct shear testing is in agreement with the estimated range of 0 kPa to 12 kPa (0 psf to 250 psf) in **Table 1** for the overlying rail and tie acting on the ballast. If a tie-ballast gap is present, as suggested by Stark and Wilk [1,7] and Wilk, Stark, and Sussmann [8], the normal stress at the tie/ballast interface is at or near zero.

The confining stress used in laboratory triaxial compression testing should represent the in situ confining or lateral stress acting on the ballast underneath the tie prior to train passage. This value is difficult to obtain and field verify, but Selig [9] suggests that large locked-in lateral ballast stresses exist and an earth pressure coefficient (K) as high as the Rankine passive earth pressure coefficient (Kp) is possible. The earth pressure coefficient (K) relates vertical and lateral stresses, and the Rankine passive earth pressure coefficient (Kp) represents the upper limit for lateral stresses before shear failure occurs. Assuming a K-value equal to six for an effective stress friction angle of ballast of 45°, this provides an upper bound of 144 kPa (3,000 psf) for the ballast confining pressure at the tie-ballast interface. Based on the 3D LS-DYNA model, a reasonable range of confining stress for typical track is 0 kPa to 72 kPa (0 psf to 1,500 psf). This range is in agreement with Indraratna et al. [10] who suggest using confining pressures between 10 kPa and 70 kPa (210 psf and 1,460 psf) during triaxial compression testing based on internal confining pressure measurements of Australian tracks ranging from 15 kPa to 60 kPa (315 psf to 1,250 psf).

The deviator stress used in laboratory triaxial compression testing should represent the loading acting on the ballast underneath the tie during train passage. In the United States, wheel loads vary from 22 kN to 180 kN (5 kips to 40 kips) [11], and assuming 40 % of the wheel load is transferred to the tie [6], a reasonable range of deviator stress due to train passage is 50 kPa to 360 kPa (1,000 psf to 7,500 psf).

FIELD MOISTURE CONDITIONS

This section reviews the importance of fouling moisture content on measured ballast strength and stiffness. The fouling of ballast is a track performance issue for railroads because wetting of the fouling material from precipitation and snow melt can result in significant changes in ballast engineering properties. This includes an increase in transient and permanent ballast deformation under train loading [12,13] and decreases in shear strength and modulus [14]. The decrease in modulus for fouled ballast during wetting is especially important because increased track displacement during train passage can lead to the development of track structure problems (e.g., increased tie-ballast gap and elevated pore-water pressures in fouled ballast and subgrade materials), which can decrease bearing capacity and accelerate track degradation.

FIG. 3 Highly fouled ballast at High Tonnage Loop in Pueblo, CO, (a) before and (b) during wetting.

(a) (b)

The results of three different measurement techniques show the addition of water decreases the modulus of fouled ballast by 40 % to 60 %. For example, Light, Ho, and Lambert [14] use laboratory triaxial compression tests to show wet fouled modulus values are 40 % to 60 % lower than dry ballast specimens. Seismic surface wave testing of fouled track sections at the High Tonnage Loop in Pueblo, CO, showed a 55 % decrease in ballast modulus [5] after the track section was soaked by the local fire department (see Fig. 3). A soaking time of only about 10 min did not result in saturated conditions in the fouling material, and the modulus still decreased by 55 % [5]. Field-measured wheel loads, ballast vertical displacements along Amtrak's Northeast Corridor, and FLAC3D software were used to perform an inverse numerical analysis of ballast modulus by Stark and Wilk [7]. This field data and analysis also show a decrease in modulus of about 45 % from measurements obtained in dry conditions during June 2013 to measurements obtained in wet conditions in January 2013.

In particular, Table 2 shows dry fouled ballast exhibits a higher modulus or stiffness than clean ballast because the fouling material fills the voids of the ballast and makes the ballast more like a well-graded material instead of a poorly graded

TABLE 2 Young's modulus for clean and fouled ballast under different moisture conditions.

Ballast Fouling and Moisture Condition	Seismic Surface Wave Testing Modulus [5] MPa (ksi)	Inverse Analysis Modulus [7] MPa (ksi)
Dry clean ballast	205–275 (30–40)	~ 205 (~ 30)
Dry fouled ballast	345–380 (50–55)	~ 380 (~ 55)
Wet fouled ballast (brief wetting)	140–170 (20–25)	~ 70 (~ 10)

J_ID: STP DOI: 10.1520/STP160520170025 Date: 8-December-17 Stage: Page: 158 Total Pages: 12
PROOF COPY [STP20170025]

material. This trend is expected to eventually reverse once enough fouling material is present to cause the ballast particles to lose some particle contact. However, if the fouling material is even briefly soaked, as shown in Fig. 3, the modulus decreases by about 55 %. The inverse analysis of field-measured wheel loads and vertical displacements along the Northeast Corridor shows an even greater reduction to about 70 MPa (10 ksi) in Table 2 that is probably due to the more sustained and thorough wetting experienced at the elevated Upland Street Bridge near Chester, PA, in January 2013. A similar reduction in modulus is reported by Light, Ho, and Lambert [14] in triaxial compression tests discussed in the next section.

Triaxial Compression Tests

This section reviews various ASTM test methods for triaxial compression testing of railroad ballast to estimate the specimen size that should be used to minimize boundary effects on the measured shear strength and modulus and the importance of incorporating principal stress rotation in triaxial compression testing. This is intended to facilitate comparison of triaxial compression test results and minimize confusion for numerical modeling of railroad track structure. Triaxial compression tests can apply repeated loads and yield a stress-strain relationship, which can be used to estimate ballast unload and reload moduli for use in numerical analyses. These are advantages over direct shear tests, which yield only a shear stress-displacement relationship, so Young's modulus cannot be determined directly from the results of direct shear tests. As a result, there is interest in performing triaxial compression tests on ballast [14–17], so using the appropriate specimen size, stress conditions, and moisture content is important in obtaining field representative results for numerical modeling and for comparing results among laboratories.

ASTM D2166/D2166M, *STANDARD TEST METHOD FOR UNCONFINED COMPRESSION TESTING OF COHESIVE SOILS*, AND ASTM D2850, *STANDARD TEST METHOD FOR UNCONSOLIDATED-UNDRAINED TRIAXIAL COMPRESSION TEST ON COHESIVE SOILS*

ASTM D2166/D2166M [18] and ASTM D2850 [19] are the long-standing test methods for measuring the unconsolidated-undrained shear strength of soils. ASTM D2166/D2166M pertains to measuring the unconfined compressive strength of soils, which is a special case of the unconsolidated-undrained triaxial compression test (ASTM D2850) because no confining stress is applied. ASTM D2166/D2166M and ASTM D2850 have the same specimen size requirements, so only the requirements of ASTM 2166/D2166M are presented here.

Section 3.1 of ASTM D2166/D2166M requires a minimum cylindrical specimen diameter (D) of 33 mm (1.3 in.), and the largest particle contained within the test specimen shall be smaller than one-tenth of the specimen diameter. For specimens having a diameter of 72 mm (2.8 in.) or larger, the largest particle size shall be smaller than one-sixth of the specimen diameter. Because ballast particles are large enough to require a specimen diameter greater than 72 mm (2.8 in.), the

ID: myilvaganans Time: 13:22 I Path: //chenas03.cadmus.com/Home$/myilvaganans$/BK-AST-STP1605-170410-stp-2017-0025

TABLE 3 ASTM D2166/D2166M, ASTM D2850, ASTM D4767, and ASTM D7181 required triaxial compression specimen sizes.

ASTM Test Method	Specimen Diameter (D)	Specimen Height to Diameter Ratio (H/D)
ASTM D2166/D2166M and ASTM D2850	$> 6*D_{max}$	2 to 2.5
ASTM D4767 and ASTM D7181	$> 6*D_{max}$	2 to 2.5

triaxial specimen diameter for testing ballast must be greater than or equal to six times the maximum particle size (Dmax) as shown in Table 3.

ASTM D4767, *STANDARD TEST METHOD FOR CONSOLIDATED-UNDRAINED TRIAXIAL COMPRESSION TEST FOR COHESIVE SOILS*, AND ASTM D7181, *STANDARD TEST METHOD FOR CONSOLIDATED DRAINED TRIAXIAL COMPRESSION TEST FOR SOILS*

ASTM D4767 [20] and ASTM D7181 [21] are the test methods for consolidated-undrained and consolidated-drained triaxial compression tests on soils, respectively. The main difference between these two triaxial tests (ASTM D4767 and ASTM D7181) and ASTM D2166/D2166M and ASTM D2850 triaxial tests described earlier is that the specimen is consolidated prior to application of the deviator stress. Consolidating the ballast specimen prior to shearing is appropriate for clean and dry fouled ballast to simulate field conditions. For wet fouled ballast, consolidating the fouling material may not simulate field conditions because the fouling material may not have sufficient time to consolidate in the field prior to deviator stress application, so these materials should be tested under unconsolidated conditions using ASTM D2166/D2166M and ASTM D2850. There is some connection between the amount and type of fouling material and the degree of consolidation prior to deviator stress application, but that is not well understood at this time. As a result, a conservative approach is to assume the fouled ballast will be wetted in the field and unconsolidated prior to deviator stress application.

Section 6.1 of ASTM D4767 and ASTM D7181 also require a minimum cylindrical specimen diameter (D) of 33 mm (1.3 in.) and a specimen diameter at least one-sixth of the diameter of the largest particle within the test specimen. This is the same requirement as ASTM D2166/D2166M and ASTM D2850, as shown in Table 3. Based on the grain size distributions presented in Anderson and Fair [15]; Ebrahimi, Tinjum, and Edil [16]; Light, Ho, and Lambert [14]; Mishra et al. [17]; and in Estaire and Santana [22], Table 4 shows the maximum particle size (Dmax) for the ballast material tested and the minimum required triaxial compression specimen diameter under ASTM D4767 and ASTM D7181. Table 4 shows these ballast triaxial testing studies do not follow ASTM test procedures because the specimen diameter does not satisfy ASTM D4767 and ASTM D7181, which makes it difficult to compare the test results.

TABLE 4 Required triaxial compression specimen sizes for ballast.

Published Research	Specification	Minimum Required Triaxial Compression Specimen Diameter and H/D Ratio	Triaxial Compression Specimen Diameter Used
Anderson and Fair [15]	D_{max}	50 mm (2.0 in.)	
	D (Device Diameter)	300 mm (11.8 in.)	236 mm (9.3 in.)
	H (Device Height)	600 to 700 mm (23.6 to 27.6 in.)	455 mm (17.9 in.)
	H/D Ratio	2 to 2.5	1.9
	D/D_{max} Ratio	6	4.7
Ebrahimi, Tinjum, and Edil [16]	D_{max}	63 mm (2.5 in.)	
	D (Device Diameter)	378 mm (14.9 in.)	305 mm (12.0 in.)
	H (Device Height)	756 to 945 mm (29.7 to 37.2 in.)	610 mm (24.0 in.)
	H/D Ratio	2 to 2.5	2
	D/D_{max} Ratio	6	4.8
Mishra et al. [17]	D_{max}	75 mm (3.0 in.)	
	D (Device Diameter)	450 mm (17.7 in.)	305 mm (12.0 in.)
	H (Device Height)	900 to 1,125 mm (35.4 to 44.3 in.)	610 mm (24.0 in.)
	H/D Ratio	2 to 2.5	2
	D/D_{max} Ratio	6	4.1
Light, Ho, and Lambert [14]	D_{max}	36 mm (1.4 in.)	
	D (Device Diameter)	216 mm (8.5 in.)	250 mm (9.8 in.)
	H (Device Height)	432 to 540 mm (17 to 21.3 in.)	510 mm (20.0 in.)
	H/D Ratio	2 to 2.5	2.0
	D/D_{max} Ratio	6	6.9
Estaire and Santana [22]	D_{max}	70 mm (2.75 in.)	
	D (Device Diameter)	420 mm (16.5 in.)	230 mm (9 in.)
	H (Device Height)	840 to 1,050 mm (33 to 41.3 in.)	460 mm (18 in.)
	H/D Ratio	2 to 2.5	2.0
	D/D_{max} Ratio	6	3.28

Summary and Recommendations

In an effort to standardize railroad ballast testing, this paper summarizes the appropriate stress conditions, test equipment, and field moisture conditions that should be used for laboratory shear strength testing using various ASTM test methods, which are summarized in Table 3 and Table 4. The following summarize the main recommendations for ballast sampling and testing presented herein:

- It is important to apply representative normal, confining, and deviator stresses when performing laboratory shear tests because ballast modulus and shear strength are stress dependent. For ballast shear testing, normal stresses of

0 kPa to 24 kPa (0 psf to 500 psf), confining stresses of 0 kPa to 72 kPa (0 psf to 1,500 psf), and deviator stresses of 50 kPa to 360 kPa (1,000 psf to 7,500 psf) appear representative of field loading conditions for freight traffic. In direct shear tests, the specimen should be sheared to at least 25 mm (1 in.) of horizontal displacement after normal stress application to ensure mobilization of the peak strength. To limit the influence of boundary conditions in these shear tests, Table 3 presents the appropriate specimen sizes for triaxial compression testing devices.

- If fouled ballast is to be shear tested, the fouling material should be soaked or hydrated to simulate field conditions and engineering properties. Table 2 shows the modulus of fouled ballast can decrease by 50 % to 60 % upon wetting.
- To best represent ballast behavior in laboratory settings, appropriate triaxial testing devices are required. This means a device diameter of six times the maximum ballast particle size and a height to diameter ratio of 2 to 2.5.

References

[1] Stark, T. D. and Wilk, S. T., "Root Cause of Differential Movement at Bridge Transitions," *Proc. Inst. Mech. Eng. F J. Rail Rapid Transit,* Vol. 230, No. 4, 2016, pp. 1257–1269.

[2] Powrie, W., Yang, L. A., and Clayton, C. R. I., 2007, "Stress Changes in the Ground Below Ballasted Railway Track during Train Passage," *Proc. Inst. Mech. Eng. F J. Rail Rapid Transit*, Vol. 221, No. 2, pp. 247 – 262.

[3] Selig, E. T. and Waters J. M., *Track Geotechnology and Substructure Management*, Thomas Telford, London, 1994.

[4] Gräbe, P. J. and Clayton C. R. I., "Effects of Principal Stress Rotation on Permanent Deformation in Rail Track Foundations," *J. Geotech. Geoenviorn. Eng.*, Vol. 135, No. 4, 2009, pp. 555–565.

AQ1 [5] Stark, T. D., Wilk, S. T., Dehlin, T. J., Sussmann, T. R., Nazarian, S., and Ho, C. L., "Seismic Testing for Tie-Ballast Interface," *Proceedings of the ASME 2014 Joint Rail Conference*
AQ2 *(JRC2014),* Colorado Springs, CO, April 2–4, 2014.

[6] American Railway Engineering and Maintenance-of-Way Association, *Manual for Railway Engineering*, AREMA, Landover, MD, 2012.

[7] Stark, T. D. and Wilk, S. T., "Factors Causing Differential Movement at Railway Transitions Based on Field Monitoring, Field Inspections, and Numerical Modeling," Federal Railroad Administration, Washington, DC, 2014.

[8] Wilk, S. T., Stark, T. D., and Sussmann, Jr., T. R., "Tie-Ballast Interaction at Railroad Transitions," *Proceedings of Transportation Research Board 94th Annual Conference*, Wash-
AQ3 ington DC, January 11–15, 2015.

[9] Selig, E. T., "Tensile Zone Effects on Performance of Layered Systems," *Geotechnique,* Vol. 37, No. 3, 1987, pp. 247–254.

[10] Indraratna, B., Tennakoon, N. C., Nimbalkar, S. S., and Rujikiatkamjorn, C., "Behavior of Clay-Fouled Ballast under Drained Triaxial Testing," *Geotechnique,* Vol. 63, No. 5, 2013, pp. 410–419.

[11] Van Dyk, B. J., Dersch, M. S., Edwards, J. R., Ruppert, C. J., Jr., and Barkan, C. P. L., "Load Characterization Techniques and Overview of Loading Environment in North America," *Transp. Res. Record*, Vol. 2448, 2014, pp. 80–86.

[12] Han X. and Selig E. T., "Effects of Fouling on Ballast Settlement," *Proceedings of the Sixth International Heavy Haul Railway Conference*, Cape Town, South Africa, April 6–10,
AQ4 1997.

[13] Ebrahimi, A., Tinjum, J. M., and Edil, T. B., "Large-Scale, Cyclic Triaxial Testing of Railway Ballast," presented at the *American Railway Engineering and Maintenance-of-Way Asso-*
AQ5 *ciation Annual Conference,* Orlando, FL, August 29–September 1, 2010.

[14] Light, T. J., Ho, C. L., and Lambert, R. S., "Effect of Moisture on the Engineering Characteristics of Fouled Ballast," *Proceedings of the Transportation Research Board, 93th Annual Meeting,* Washington DC, January 12–16, 2014.

[15] Anderson, W. F. and Fair, P., "Behavior of Railroad Ballast under Monotonic and Cyclic Loading," *J. Geotech. Geoenviron. Eng*., Vol. 134, No. 3, 2008, pp. 316–328.

[16] Ebrahimi, A., Tinjum, J. M., and Edil, T. B., "Protocol for Testing Fouled Railway Ballast in Large-Scale Cyclic Triaxial Equipment," *Geotech. Test. J.*, Vol. 35, No. 5, 2012, pp. 1–9.

[17] Mishra, D., Kazmee, H., Tutumluer, E., Pforr, J., Read, D., and Gehringer, E., "Characterization of Railroad Ballast Behavior under Repeated Loading: Results from New Large Triaxial Test Setup," *Transp. Res. Record*, Vol. 2374, 2013, pp. 169–179.

[18] ASTM D2166/D2166M, *Standard Test Method for Unconfined Compression Testing of Cohesive Soils*, ASTM International, West Conshohocken, Pa, 2013, www.astm.org

[19] ASTM D2850, *Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils,* ASTM International, West Conshohocken, Pa, 2007, www.astm.org

[20] ASTM D4767, *Standard Test Method for Consolidated-Undrained Triaxial Compression Test for Cohesive Soils*, ASTM International, West Conshohocken, Pa, 2011, www.astm.org

[21] ASTM D7181, *Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils*, ASTM International, West Conshohocken, Pa, 2011, www.astm.org

[22] Estaire, J. and Santana, M., "Comportamiento del Balasto Contaminado con Arena Mediante Ensayos Triaxiales de Gran Tamano [Analysis of the Strength of Rockfill is Based on Direct Shear Tests Made in 1 m^3 Box]," *Proceedings of International Commis-*
AQ6 *sion of Large Dams (ICOLD)*, Madrid, Spain, TK, 2006, pp. 1–8.