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TOP-MOUNTED SOCKETS FOR WEAK-POST MGS ON CULVERTS

Submitted by

Scott K. Rosenbaugh M.S.C.E., E.I.T.
Research Engineer

Mojdeh Asadollahi Pajouh, Ph.D., P.E.
Assistant Professor
University of Nevada-Las Vegas

Ronald K. Faller, Ph.D., P.E.
Research Professor & MwRSF Director

MIDWEST ROADSIDE SAFETY FACILITY
Nebraska Transportation Center
University of Nebraska-Lincoln

Main Office
Prem S. Paul Research Center at Whittier School
Room 130, 2200 Vine Street
Lincoln, Nebraska 68583-0853
(402) 472-0965

Outdoor Test Site
4630 N.W. 36th Street
Lincoln, Nebraska 68524

Submitted to

MIDWEST POOLED FUND PROGRAM
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Lincoln, Nebraska 68502

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16. Abstract

Top-mounted sockets for use with the weak-post, Midwest Guardrail System (MGS) on low-fill culverts were developed, tested, and evaluated. The system was adapted from the MGS bridge railing (and its other adaptations) for attachment to the top slab of a concrete box culvert. Three design concepts were developed and evaluated through dynamic component testing. Both lateral and longitudinal impacts were conducted on the design concepts while mounted to simulated concrete culverts. Two concepts, a cylindrical concrete foundation and a steel tube socket assembly, proved strong enough to withstand the impact loads transferred from the posts without sustaining significant damage or displacements. However, the third concept, a concrete slab, fractured and allowed the sockets to rotate back without developing the full bending strength of the posts. Thus, only the cylindrical concrete foundation and the steel tube socket assembly in combination with the weak-post, MGS were determined to be crashworthy according to the *Manual for Assessing Safety Hardware* (MASH) Test Level 3 (TL-3) impact safety criteria.

The new top-mounted, socketed, weak-post, W-beam MGS for low-fill culverts was designed with multiple advantages over other guardrail treatments for culverts. The guardrail system has an unrestricted system length and does not require a transition when attached to standard MGS. The top-mounted system can be placed parallel to the roadway with a constant lateral offset regardless of the position and orientation of the culvert headwall. Additionally, the attachment configurations were designed utilizing epoxy anchors, enabling the system to be installed on new or existing culverts. Finally, the sockets remain undamaged during impact events, which allows for quick guardrail repairs by simply removing damaged posts, placing new replacement posts into the sockets, and replacing any damaged guardrail sections.

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UNCERTAINTY OF MEASUREMENT STATEMENT

The Midwest Roadside Safety Facility (MwRSF) has determined the uncertainty of measurements for several parameters involved in standard full-scale crash testing and non-standard testing of roadside safety features. Information regarding the uncertainty of measurements for critical parameters is available upon request by the sponsor and the Federal Highway Administration.

INDEPENDENT APPROVING AUTHORITY

The Independent Approving Authority (IAA) for the data contained herein was Dr. Joshua Steelman, Assistant Professor.

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Midwest Roadside Safety Facility

J.D. Reid, Ph.D., Professor
J.C. Holloway, M.S.C.E., E.I.T., Research Engineer & Assistant Director –Physical Testing Division
K.A. Lechtenberg, M.S.M.E., E.I.T., Research Engineer
R.W. Bielenberg, M.S.M.E., E.I.T., Research Engineer
J.D. Schmidt, Ph.D., P.E., Research Assistant Professor
C.S. Stolle, Ph.D., Research Assistant Professor
A.T. Russell, B.S.B.A., Testing and Maintenance Technician II
E.W. Krier, B.S., Construction and Testing Technician II
S.M. Tighe, Construction and Testing Technician I
D.S. Charroin, Construction and Testing Technician I
R.M. Novak, Construction and Testing Technician I
T.C. Donahoo, Construction and Testing Technician I
J.T. Jones, Construction and Testing Technician I
C.I. Sims, Construction and Testing Technician I
J.E. Kohtz, B.S.M.E., CAD Technician
E.L. Urbank, B.A., Research Communication Specialist
Z.Z. Jabr, Engineering Technician
Undergraduate and Graduate Research Assistants

California Department of Transportation
Bob Meline, Chief, Roadside Safety Research Branch
David Whitesel, P.E., Transportation Engineer
John Jewell, P.E., Senior Transportation Engineer, Specialist

Florida Department of Transportation
Derwood C. Sheppard, Jr., P.E., Design Standards Publication Manager, Roadway Design Engineer

Georgia Department of Transportation
Brent Story, P.E., State Design Policy Engineer
Frank Flanders IV, P.E., Assistant State Design Policy Engineer

Hawaii Department of Transportation
James Fu, P.E., State Bridge Engineer
Dean Takiguchi, P.E., Engineer, Bridge Design Section
Kimberly Okamura, Engineer, Bridge Design Section

Illinois Department of Transportation
Filiberto Sotelo, Safety Evaluation Engineer
Martha Brown, P.E., Safety Evaluation Unit Chief

Indiana Department of Transportation
Todd Shields, P.E., Maintenance Field Support Manager
Katherine Smutzer, P.E., Standards Engineer
Elizabeth Phillips, P.E., Standards and Policy Manager

Iowa Department of Transportation
Chris Poole, P.E., Roadside Safety Engineer
Brian Smith, P.E., Methods Engineer
Daniel Harness, P.E., Transportation Engineer Specialist
Dean Sayre, P.E., Roadside Safety Engineer
Stuart Nielsen, P.E., Transportation Engineer Administrator, Design
Elijah Gansen, P.E., Geometrics Engineer

Kansas Department of Transportation
Ron Seitz, P.E., Director of Design
Scott King, P.E., Road Design Bureau Chief
Thomas Rhoads, P.E., Road Design Leader, Bureau of Road Design
Brian Kierath Jr., Engineering Associate III, Bureau of Road Design

Kentucky Department of Transportation
Jason J. Siwula, P.E., Assistant State Highway Engineer
Kevin Martin, P.E., Transportation Engineer Specialist
Gary Newton, Engineering Tech III, Design Standards

Minnesota Department of Transportation
Michael Elle, P.E., Design Standards Engineer
Michelle Moser, P.E., Assistant Design Standards Engineer

Missouri Department of Transportation
Sarah Kleinschmidt, P.E., Policy and Innovations Engineer

Nebraska Department of Transportation
Phil TenHulzen, P.E., Design Standards Engineer
Jim Knott, P.E., Construction Engineer
Mike Owen, P.E., State Roadway Design Engineer
Matt Neemann, P.E., Traffic Control Engineer
Jodi Gibson, Research Coordinator

New Jersey Department of Transportation
Hung Tang, Senior Engineer, Transportation
Joseph Warren, Senior Engineer, Transportation

North Carolina Department of Transportation
Neil Mastin, P.E., Manager, Transportation Program Management – Research and Development
D. D. "Bucky" Galloway, P.E., CPM, Field Operations Engineer
Brian Mayhew, P.E., State Traffic Safety Engineer
Joel Howerton, P.E., Plans and Standards Engineer

Ohio Department of Transportation
Don Fisher, P.E., Roadway Standards Engineer

South Carolina Department of Transportation
J. Adam Hixon, P.E., Design Standards Associate
Mark H. Anthony, P.E., Letting Preparation Engineer
Henry Cross, P.E., Design Standards Engineer
Jason Hall, P.E., Engineer

South Dakota Department of Transportation
David Huft, P.E., Research Engineer
Bernie Clocksin, P.E., Standards Engineer

Utah Department of Transportation
Shawn Debenham, Traffic and Safety Specialist
Glenn Blackwelder, Operations Engineer

Virginia Department of Transportation
Charles Patterson, P.E., Standards/Special Design Section Manager
Andrew Zickler, P.E., Complex Bridge Design and ABC Support Program Manager

Wisconsin Department of Transportation
Erik Emerson, P.E., Standards Development Engineer
Rodney Taylor, P.E., Roadway Design Standards Unit Supervisor

Wyoming Department of Transportation
William Wilson, P.E., Architectural and Highway Standards Engineer

Federal Highway Administration
David Mraz, Division Bridge Engineer, Nebraska Division Office

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1 INTRODUCTION

1.1 Background

Concrete box culverts are routinely installed under roadways in order to allow water drainage without affecting the motoring public. Unfortunately, these box culverts can also represent a hazard on the roadside when they do not extend outside of the clear zone and often require safety treatments in the form of roadside barriers. The most common safety barriers utilized to shield these areas are W-beam guardrail systems. However, low-fill culverts with less than 40 in. (1,016 mm) of soil fill prevent the proper installation of standard guardrail posts due to a lack of available embedment depth. Numerous box culverts across the country utilize low-fill soil above the top slab, typically in the range of 1 to 3 ft (0.3 to 0.9 m). Previous crash testing has shown that W-beam installations with shallow post embedment do not perform adequately and are prone to vehicle override [1]. Therefore, low-fill culverts require specialized guardrail systems to safely treat the hazard.

Currently, three different types of guardrail systems are being used to treat cross-drainage box culverts: (1) guardrail systems anchored to the top slab of the culvert; (2) long-span guardrail systems; and (3) guardrail systems mounted to the outer face of the culvert headwall. Top-mounted guardrail systems typically consist of steel posts welded to base plates, which are bolted to the top slab of the culvert. Anchoring the guardrail posts to the culvert's top slab ensures that the post will provide the lateral stiffness necessary for the barrier to contain and safely redirect errant vehicles. One such system developed at the Midwest Roadside Safety Facility (MwRSF) incorporated W6x9 (W152x13.4) steel posts spaced 37½ in. (953 mm) on center, a 27¾-in. (705-mm) top rail height, a deformable ½-in. (13-mm) base plate, and four 1-in. (25-mm) diameter threaded anchors [2-4], as shown in Figure 1. The system was originally designed and successfully tested to the safety performance criteria of National Cooperative Highway Research Program (NCHRP) Report No. 350 [5], but was also successfully tested to American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (MASH) [6] standards with a top rail height of 31 in. (787 mm) and the post offset 12 in. (305 mm) from the headwall [7].

A similar system developed by the Texas Transportation Institute (TTI) was configured to satisfy MASH safety performance criteria. The system utilized W6x9 (W152x13.4) steel posts spaced 75 in. (1,905 mm) on center, a thicker, ⅞-in. (22-mm) base plate, and a 31-in. (787-mm) top rail height [8], as shown in Figure 2. Both top-mounted guardrail systems described herein were designed for use with a minimum fill depth of 9 in. (229 mm) on the culverts. Note, the evaluation criteria did not change for Test Level (TL-3) guardrail systems in the 2016 edition of MASH. Thus, TL-3 guardrail systems developed to satisfy MASH 2009 would be crashworthy according to MASH 2016 [9] as well.

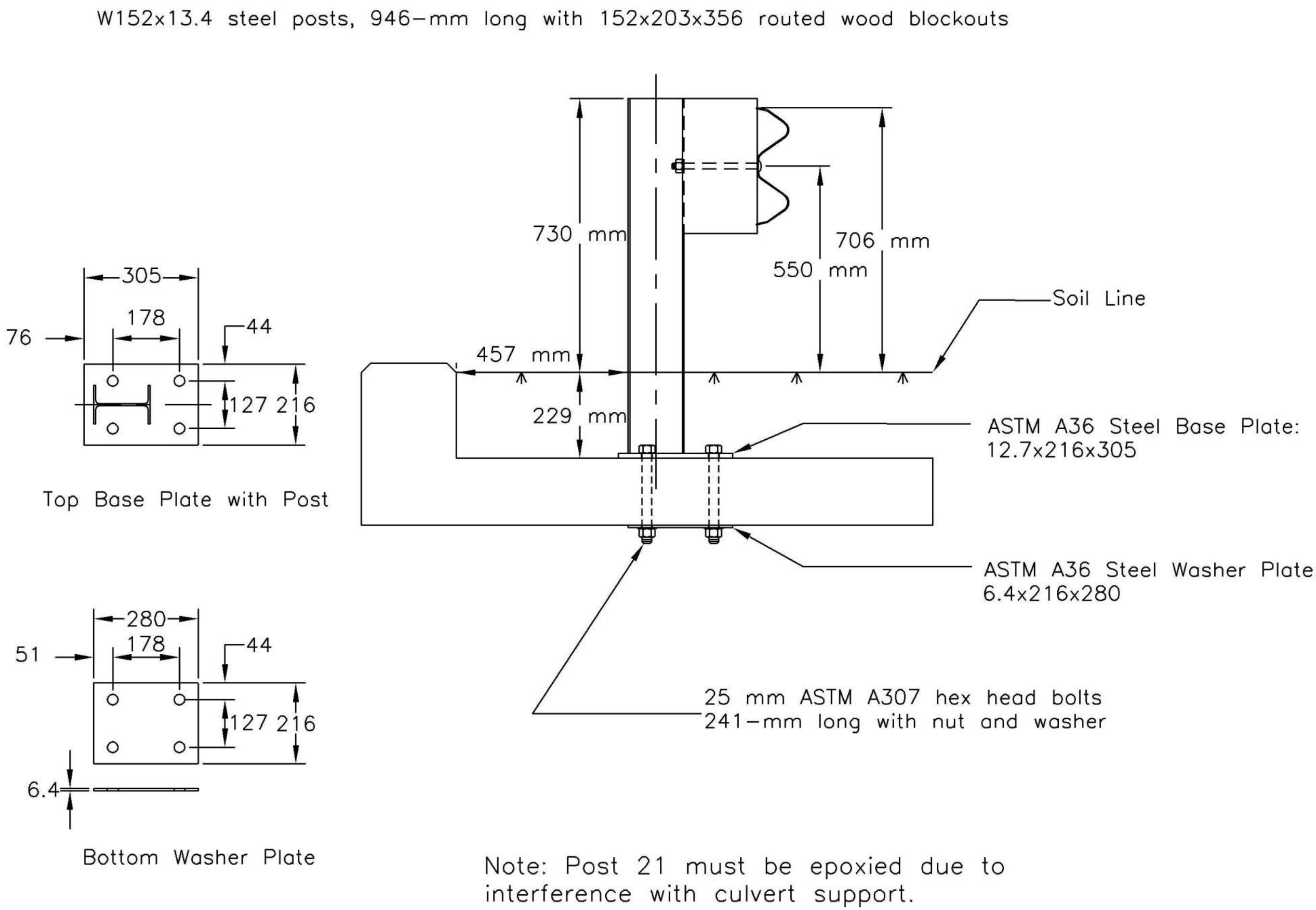
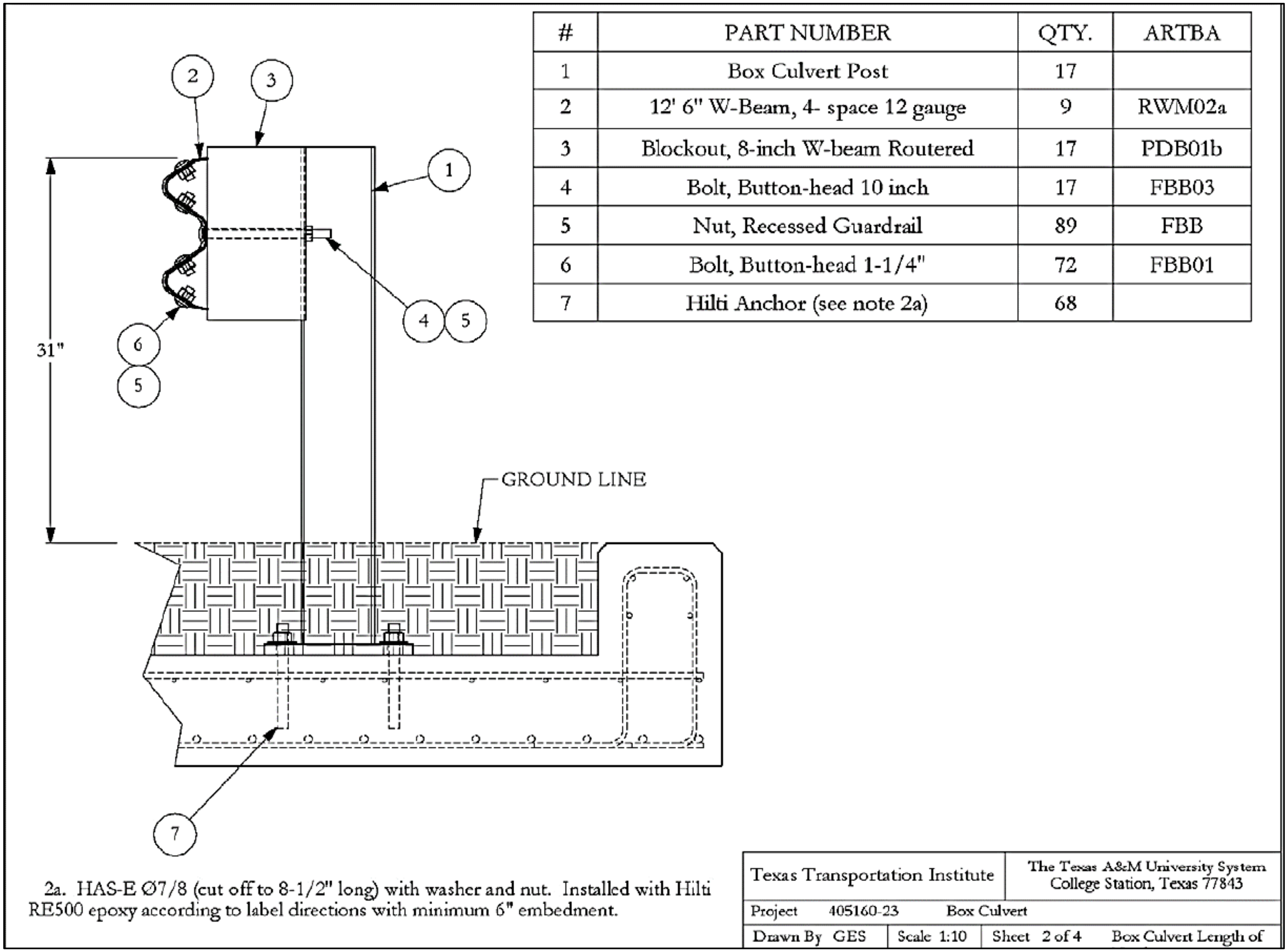


Figure 1. W-beam System Attached to Low-Fill Culverts Developed at MwRSF [2-4]



#	PART NUMBER	QTY.	ARTBA
1	Box Culvert Post	17	
2	12' 6" W-Beam, 4- space 12 gauge	9	RWM02a
3	Blockout, 8-inch W-beam Routered	17	PDB01b
4	Bolt, Button-head 10 inch	17	FBB03
5	Nut, Recessed Guardrail	89	FBB
6	Bolt, Button-head 1-1/4"	72	FBB01
7	Hilti Anchor (see note 2a)	68	

Figure 2. W-beam System Attached to Low-Fill Culverts Developed at TTI [8]

Although top-mounted guardrail designs provide a crashworthy treatment for culvert openings, they have disadvantages. The systems described above were MASH crash-tested with lateral offsets between the back of the post and the inside of the culvert headwall measuring 12-in. (305-mm) and 18-in. (457-mm), respectively. These post offsets are necessary to allow the post to rotate back freely without contacting the headwall. If rotation is restricted by placing the post too close to the headwall, the posts can become snag points or climbing ramps and may result in vehicle instabilities [2]. However, these lateral offsets, coupled with the footprint of the system itself, result in the loss of 5 ft (1.5 m) or more of traversable roadway width. Extending the culvert length another 5 ft (1.5 m) to gain back this loss in roadway width can drastically increase costs. Additionally, when these systems are impacted, the damaged posts must be replaced, similar to standard guardrail installations. However, the fill soil must be removed around damaged top-mounted posts to gain access to the anchor bolts. This soil removal and replacement after the new post is installed adds to repair time and labor costs.

Long-span guardrail systems contain unsupported lengths of W-beam rail that span over the top of culverts. These barrier systems do not require attachment to the culvert, thus allowing the culvert and the barrier system to operate independently. One crashworthy system consists of 100 ft (30.5 m) of nested, 12-gauge (2.66-mm thick) W-beam guardrail centered over a 25-ft (7.6-m) unsupported span length [10-12], as shown in Figure 3. A 27¾-in. (705-mm) top rail height was utilized for the entire system. Three wooden Controlled Releasing Terminal (CRT) posts were placed adjacent to and on both sides of the unsupported span length in order to prevent vehicle pocketing and snagging. This system was designed and successfully crash tested to NCHRP Report No. 350 safety performance criteria.

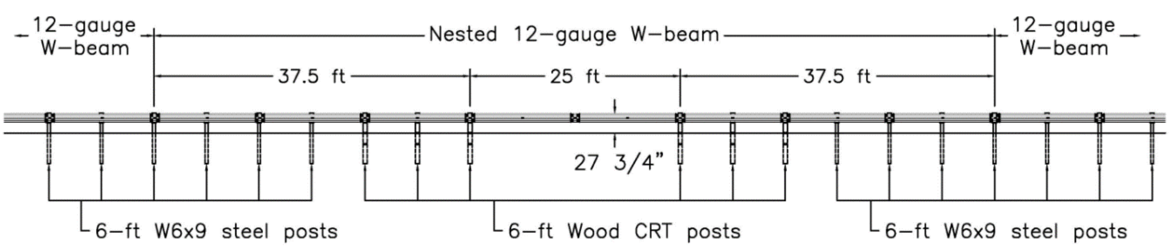


Figure 3. NCHRP Report No. 350-Compliant Long-Span Guardrail System [10-12]

The Midwest Guardrail System (MGS) long-span system is an updated version of the original system and was designed to satisfy MASH safety standards. The MGS long-span system maintained the 25-ft (7.6-m) unsupported span length and the use of six CRT posts, as shown in Figure 4. However, only a single layer of 12-gauge (2.66-mm thick) W-beam was utilized, the rail height was increased to 31 in. (787 mm), and the rail splices were moved to post mid-spans [13-14].

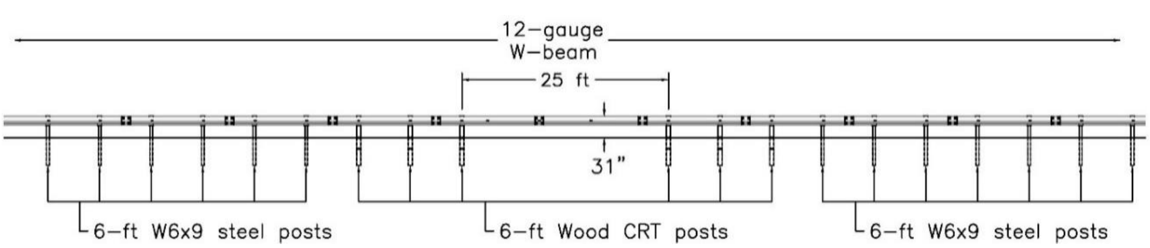


Figure 4. MASH-Compliant, MGS Long-Span Guardrail System [13-14]

Long-span guardrail systems do not require additional components for attachment to the culvert and provide a cost-effective method for shielding culverts. Further, long-span systems can be installed with the back of the post even with the interior face of the culvert headwall. Thus, long-span systems do not intrude into the roadway width as much as top-mounted systems. However, the NCHRP Report No. 350 long-span system utilizes double blockouts for a 16-in. (406-mm) total depth, while the MGS long-span system utilizes 12-in. (305-mm) deep blockouts. These blockout depths, in addition to the 8-in. (203-mm) deep post, still result in a loss of nearly 4 ft (1.2 m) of traversable roadway width. Finally, long-span systems are limited to a maximum unsupported span length of 25 ft (7.6 m), and it is recommended to place the adjacent guardrail posts no closer than 1 ft (0.3 m) from the edge of the culvert. Thus, box culverts with a width, or roadway length, greater than 23 ft (7.0 m) cannot be treated with current long-span W-beam systems.

Although the weak-post, MGS bridge rail was not originally designed for use on culverts, it had some similarities to culvert-mounted barrier systems. The weak-post, MGS bridge rail incorporates 31-in. (787-mm) tall W-beam guardrail and attaches to concrete bridge decks (similar to concrete box culverts). The use of weak, S3x5.7 (S76x8.5) posts and the method of post attachment to the bridge deck make this system unique. The posts are inserted into HSS4x4x⅜ steel sockets placed along the outside edge of the bridge deck. Each socket is attached to the bridge deck with a 1-in. (25-mm) diameter ASTM A307 vertical through-bolt and a bottom steel angle, as shown in Figure 5. The placement of the posts and sockets off the edge of the bridge deck, coupled with the use of W-beam backup plates instead of blockouts, allows for minimal intrusion into the roadway and maximizes the traversable width [15-16].

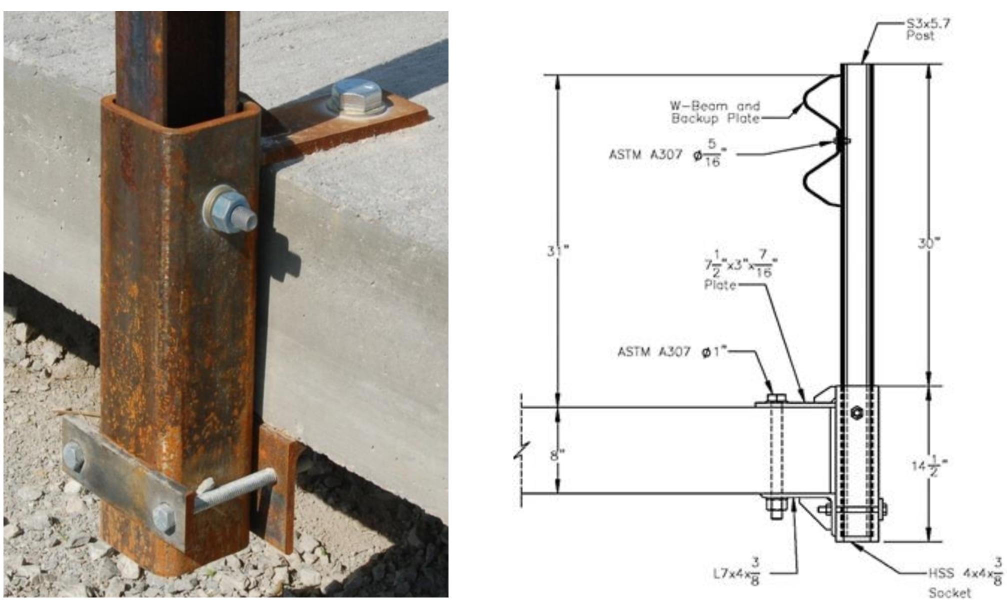


Figure 5. Weak-Post, MGS Bridge Rail Attached to Concrete Deck [15-16]

The use of weak S3x5.7 (S76x8.5) posts limits the load transferred to the bridge deck and prevents deck damage. During the successful MASH (TL-3) crash testing program, the posts were bent over while only minor cracking was observed in the bridge deck. Without significant damage to the deck or attachment sockets, repairs to an impacted system require only the removal of the damaged posts and rail segments, insertion of new posts, and attachment of new W-beam segments. Thus, repair to the system should be relatively quick and easy. Finally, the posts were spaced at half-post spacing, or 37½ in. (953 mm) on center. The combination of a weaker post and reduced post spacing makes the lateral stiffness and dynamic deflection of the weak-post, MGS bridge rail very similar to that observed for the standard MGS. Therefore, a stiffness transition is not required between the bridge rail and the adjacent MGS installations.

Recognizing the potential benefits of adapting the MGS bridge rail for other uses, MwRSF developed a side-mounted socket system for weak-post MGS attached to the outside face of culvert headwalls [17]. The posts were inserted into side-mounted, steel sockets that would remain undamaged during impacts. Thus, damaged posts could be replaced without any soil removal or the need for a post driver. Five attachment concepts, including a top-mounted, single-anchor concept, a top-mounted double-anchor concept, a wrap-around concept, a side-mounted through-bolt concept, and a side-mounted epoxy-anchored concept were developed and evaluated through dynamic component testing. Although all designs prevented damage to the socket assembly and culvert headwall, the top-mounted, single-anchor design and the side-mounted, epoxy-anchored design were recommended for use based on ease of fabrication and installation. Photographs and design details of these systems are shown in Figures 6 and 7, respectively. Similar to the original MGS bridge rail, the system utilized a top rail height of 31 in. (787 mm) supported by S3x5.7 (S76x8.5) posts, spaced 37½ in. (953 mm) on center and positioned within HSS4x4x⅜ steel socket tubes attached to the outside face of the culvert headwall. Although the system was based on the weak-post MGS bridge rail, the socket assembly and attachment hardware had to be modified for the system to be mounted to the outside face of culvert headwalls, as shown in Figure 7.

Top-Mounted Side Mounted

Figure 6. Top- and Side-Mounted Configurations for Guardrail on Culvert Headwalls

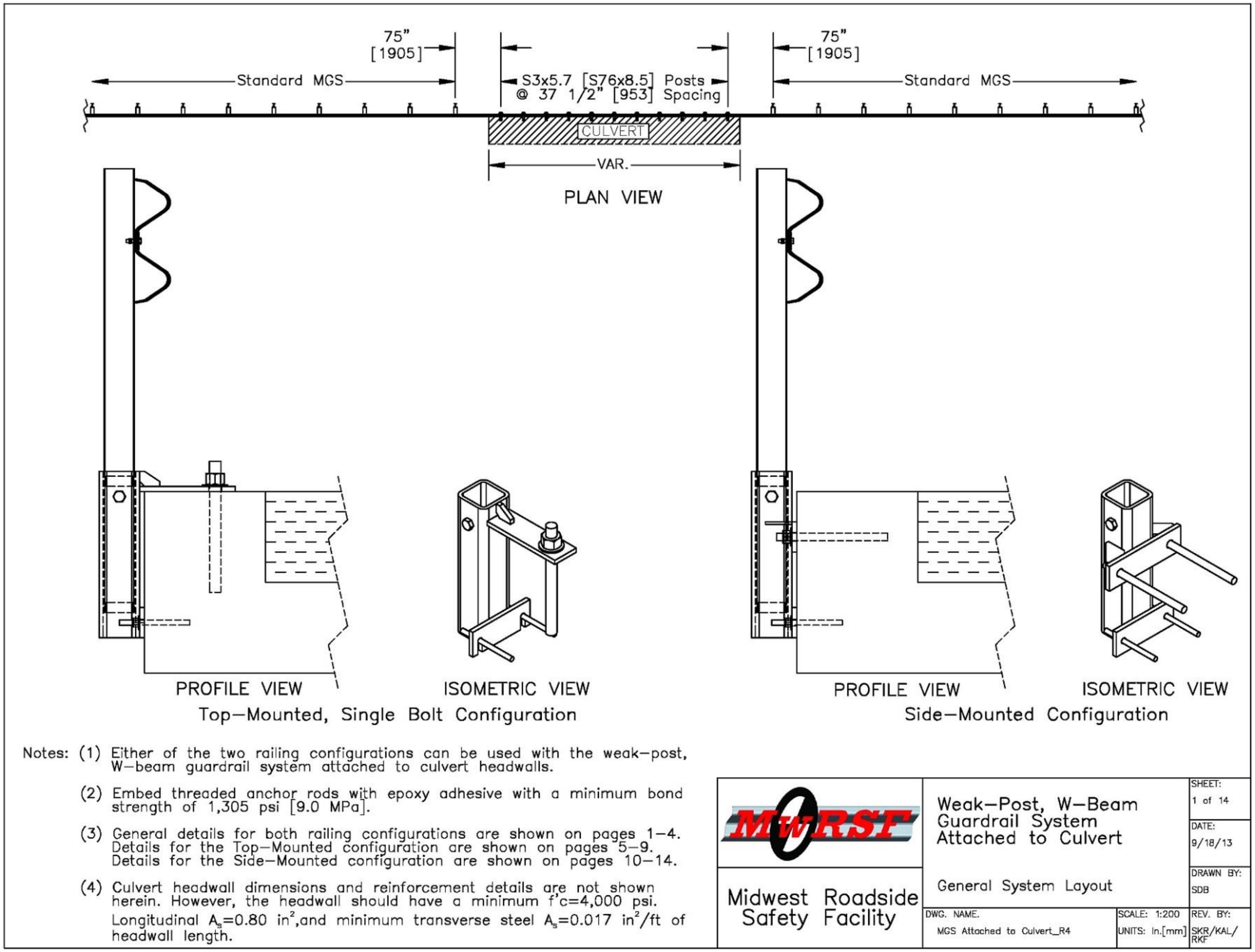


Figure 7. Weak-Post, W-Beam Guardrail System on Culvert Headwalls, System Layout

There are many installations where the culvert or roadway geometry is not compatible with the aforementioned side-mounted system. For example, the culvert headwall may be farther from the roadway than the adjacent guardrail system. Additionally, there may be a fill slope between the edge of the roadway and the culvert headwall, and the side-mounted guardrail system was only designed for level terrain applications. Therefore, a need existed to develop a top-mounted socket to attach the weak-post W-beam guardrail system to the top slab of low-fill box culverts.

1.2 Objective

The objective of this research effort was to develop a top-mounted, socketed guardrail system for use on low-fill culverts that would satisfy the TL-3 safety performance criteria of MASH 2016. The new system needed to accommodate soil fill heights between 1 and 3 ft (0.3 to 0.9 m). It was anticipated that the weak-post, socketed, guardrail system (i.e., the MGS bridge rail and the weak-post guardrail system mounted to culvert headwalls) would be modified to attach the steel support sockets to the top slab of culverts. The steel sockets should remain undamaged during impact events. The new guardrail system would address the disadvantages of current culvert treatments by providing an unrestricted system length, minimizing repair time and effort, avoiding fill slopes adjacent to culvert headwalls, and maintaining the ability to be utilized without a stiffness transition between upstream and downstream guardrails.

1.3 Scope

The research began with a literature review of previous guardrail systems designed for use on low-fill culverts as well as the weak-post MGS bridge rail. A number of top-mounted socket systems were investigated through brainstorming and concept development. A simulated critical culvert was then constructed at the MwRSF testing grounds. Next, three design options were fabricated, installed on the simulated culvert, and subjected to dynamic component testing. Testing was conducted in both the lateral and longitudinal directions to evaluate the performance of each design option under both critical loading scenarios. Finally, the results from the component tests were utilized to guide the selection of the final designs and make appropriate recommendations for future use.

2 BARRIER ATTACHMENT DESIGNS

2.1 Design Criteria

The objective of this project was to develop a top-mounted, socketed, guardrail system for low-fill culverts that satisfied the safety performance criteria of MASH 2016 TL-3. More specifically, it was desired to modify the previously developed weak-post, side-mounted, socketed, guardrail systems (i.e., the MGS bridge rail and the weak-post guardrail system mounted to culvert headwalls) for use as a top-mounted system. Thus, the new barrier was to be a 31-in. (787-mm) tall W-beam system that incorporated many of the barrier components from these two existing systems.

For consistency among these barrier systems, it was desired to utilize the same post assembly as the previous weak-post, socketed, guardrail systems. Thus, 44-in. (1,118-mm) long S3x5.7 (S76x8.5) posts which had ¼-in. (6-mm) thick standoff plates at the base of the post, as shown in Figure 8, were incorporated into the design. The posts were spaced at 37.5 in. (953 mm), similar to the existing weak-post, TL-3 systems. It was also desired to utilize the same HSS 4x4x⅜ steel tube sockets to maintain installation tolerances and limit the motion of the post within the socket. Similar to previous systems, the socket was required to extend 2 in. (51 mm) above the ground line to encompass the upper standoff plates on the post and to ensure the posts would bend at the same location during impacts. Thus, the new top-mounted guardrail system would provide the same stiffness and performance as the previously developed systems.

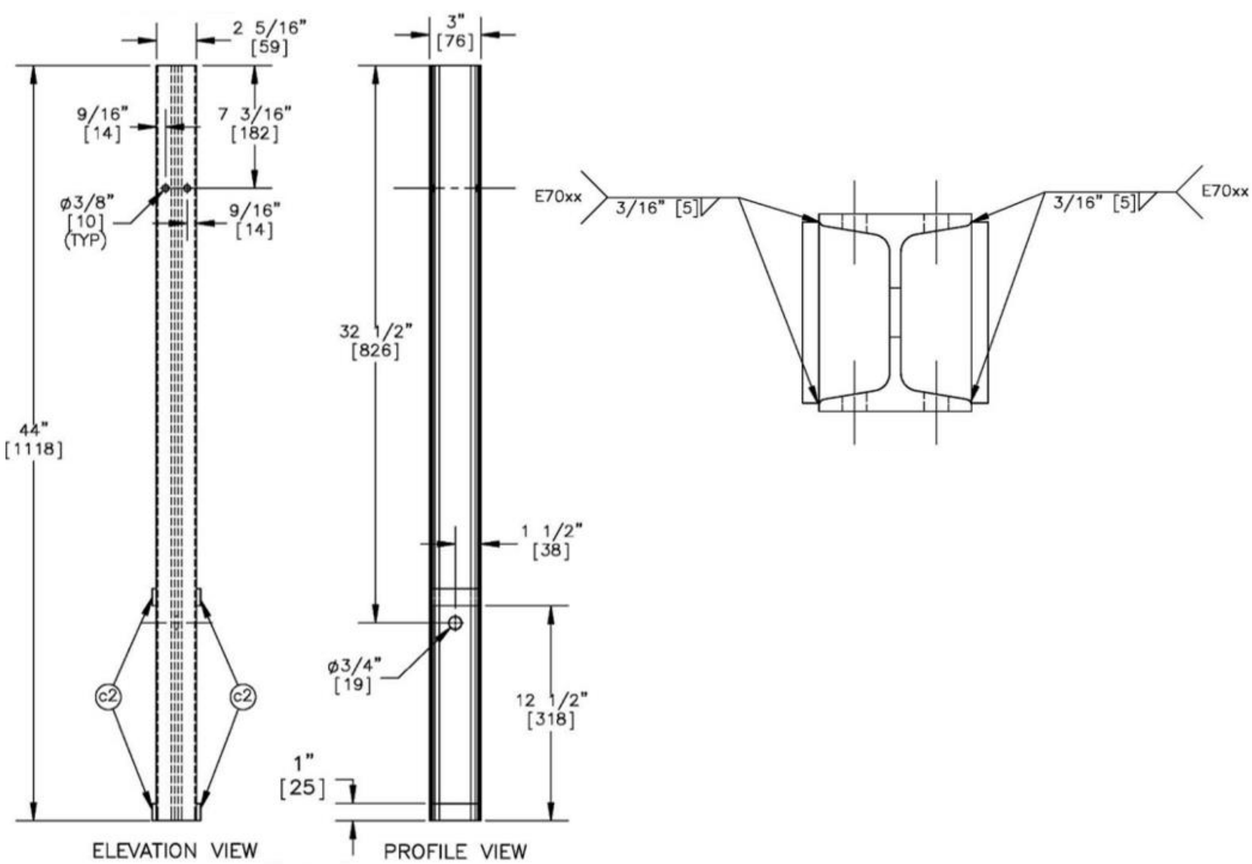


Figure 8. Post Assembly for Socketed, Weak-Post Guardrail Systems

Recognizing that the barrier (i.e., the post) resistance forces would be identical to the previously developed systems, the performance criteria for the top-mounted sockets was simply to transfer the impact loads, which were limited to the plastic bending forces of the posts, to the top slab of the culvert without sustaining significant damage. Minor damage to the socket in the form of steel deformations or concrete cracking would be allowed as long as the socket assembly could be reused without requiring repairs. Additionally, socket displacements during impacts had to be limited to ensure damaged posts could be replaced without resetting of the socket. Previous studies on socketed foundations for cable barrier posts have specified a 1-in. (25-mm) maximum displacement of sockets at the ground line to ensure reusability [18-19]. The same restriction was adopted for the top-mounted sockets on culverts developed herein. The culvert and all attachment hardware were to remain undamaged.

The top-mounted sockets were desired for use on both new and existing culvert structures. Thus, neither the sockets nor any attachment hardware could be cast into the culvert slab. Subsequently, the sockets had to be attached to the culvert utilizing either epoxy anchors or through bolts.

Since culvert depths vary by site location, the top-mounted sockets needed to be compatible for a variety of soil fill depths. Preliminary discussions with the project sponsors established a desire for the top-mounted socketed design to accommodate soil fill between 1 ft (0.3 m) and 3 ft (0.9 m). However, the post assembly (i.e., the location of the standoff plates near the bottom of the post) required the post to extend 12 in. (305 mm) below the ground line. It was assumed that any socket design would require some kind of base plate, which would require the socket assembly to extend beyond 12 in. (305 mm). Thus, the minimum soil fill height was increased slightly to 12.5 in. (318 mm). Note, MGS posts utilize a 40-in. (1,016-mm) embedment depth, so a socketed guardrail installation would not be necessary for culverts with soil fill depths equal to or greater than 40 in. (1,016 mm) as standard MGS may be installed at these locations.

2.2 Design Concepts

Three separate design concepts to support the top-mounted, steel sockets were evaluated as part of this study: (1) a cylindrical concrete foundation, (2) an all-steel socket assembly, and (3) a concrete slab. These design concepts are discussed in the following sections.

2.2.1 Cylindrical Concrete Foundations

Socketed foundations had previously been developed to anchor and support the posts of cable median barriers. In fact, MwRSF had previously developed a series of socketed foundations to support S3x5.7 (S76x8.5) posts as part of the development of a new non-proprietary cable barrier system [18]. These reinforced concrete foundations were cylindrical in shape and incorporated a 4-in. x 4-in. (102-mm x 102-mm) steel tube socket, which was embedded down the center of the foundation, as shown in Figure 9. Each foundation was reinforced with both vertical rebar and transverse hoops.

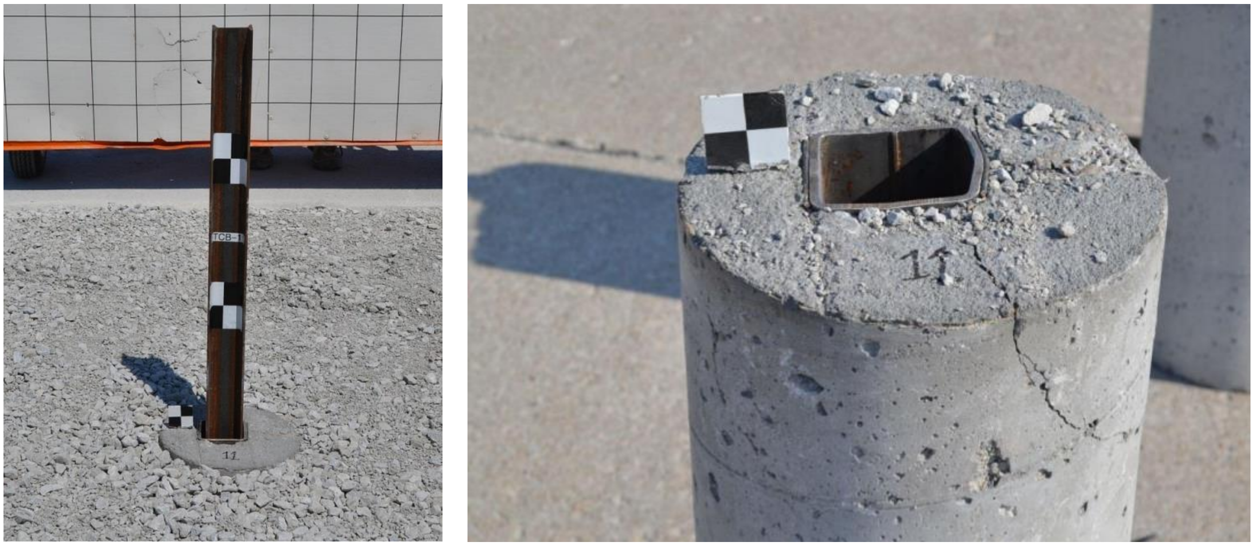


Figure 9. Cylindrical Concrete Foundations for S3x5.7 (S76x8.5) Cable Barrier Posts [18]

These socketed foundations were designed for, and evaluated with, S3x5.7 (S76x8.5) posts and showed only minor damage and/or movement when subjected to impact loading. Thus, adapting these concrete foundations for attachment to the top of culvert slabs was selected as a potential design for the top-mounted, socketed guardrail system for culverts designed herein. However, a few design changes were necessary. First, the steel socket had to be extended 2 in. (51 mm) above the top of the concrete foundation in order to accommodate the post assembly and maintain strength, as described previously in Section 2.1. Second, the vertical rebar was extended out of the bottom of the foundation so that it could be anchored to the top slab of a culvert utilizing drilled holes and epoxy. Although the socket depth and cylinder diameter would remain constant, the height of the cylindrical foundation would vary to match the soil fill depth of the culvert. Sketches of the cylindrical concrete foundation mounted to the top slab of a culvert are shown in Figure 10. Further details on the cylindrical concrete foundation design are shown in Chapter 4.

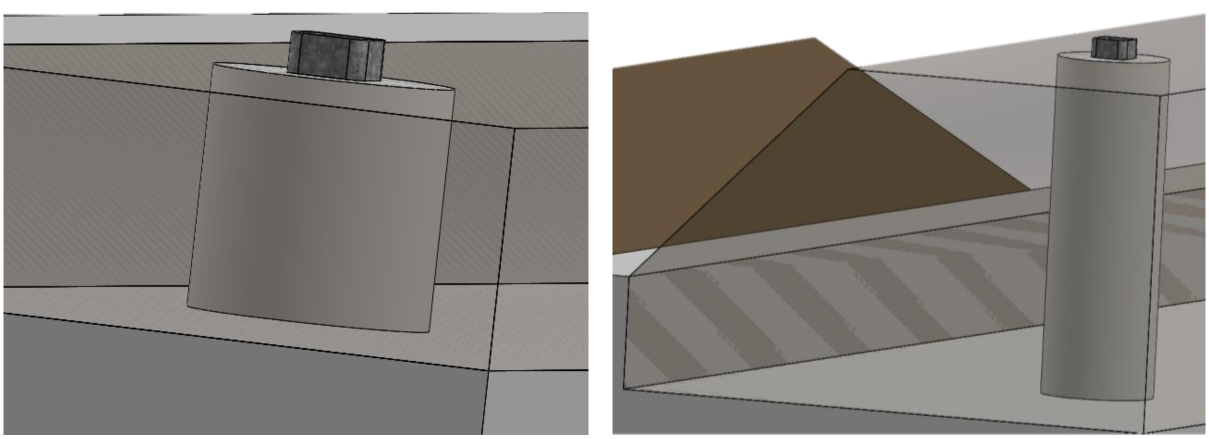


Figure 10. Concrete Foundation Design Concept for 1-ft (0.3-m) and 3-ft (0.9-m) Soil Fill Depths

2.2.2 Steel Tube Socket Assembly

The second design concept selected for evaluation was a steel socket assembly consisting of the HSS 4x4x⅜ steel tube sockets, a base plate, and any additional reinforcements necessary to prevent deformations during loading. The steel tube was placed in the center of a ½-in. (13-mm) thick base plate, which would be anchored to the top slab of the culvert utilizing either epoxy or through bolting. Gusset plates would be used to strengthen the attachment of the tube to the base plate and prevent rotation during impacts. The height of the steel tube would vary based on the soil fill depth to ensure that the top of the socket extended 2 in. (51 mm) above the ground line, as shown in Figure 11. A bolt was to be placed through the tube preventing a post from being inserted more than 12 in. (305 mm) below the ground line.

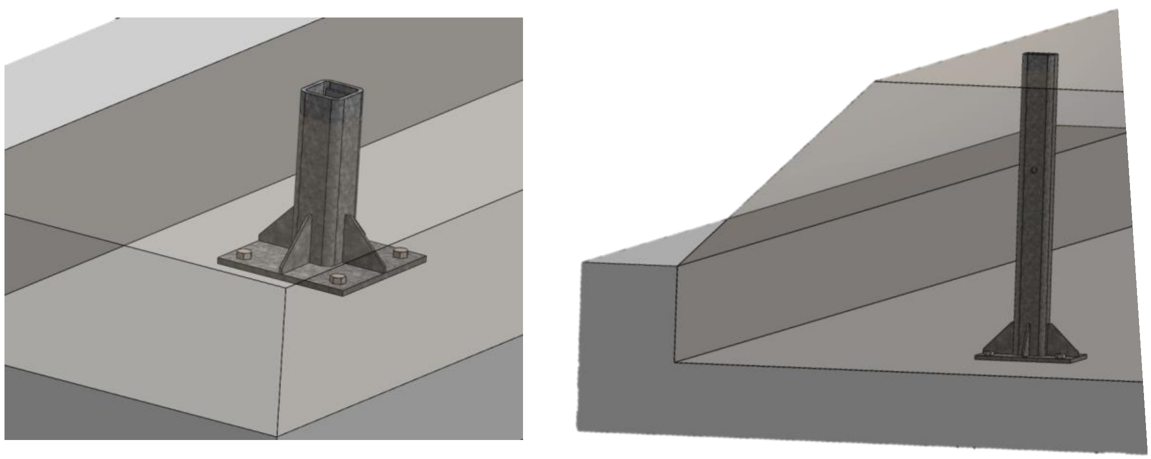


Figure 11. Steel Socket Assembly Design Concept for 1-ft (0.3-m) and 3-ft (0.9-m) Soil Fill Depths

After this concept was selected for further design and evaluation, it was discovered that the HSS 4x4x⅜ steel tube sockets were not strong enough to support the impact loads transferred from the guardrail posts, especially for large soil fill depths. As such, the tubes were strengthened with 6-in. (152-mm) wide by ¼-in. (6-mm) thick plates on the front and back sides of the tube. These plates not only doubled the bending strength of the socket assembly, but also increased the soil resistance to displacement by increasing the width of the socket assembly by 50 percent. Further details on the steel socket design are shown in Chapter 4.

2.2.3 Concrete Slab

The final design concept selected for evaluation was a steel socket embedded within a concrete slab. MwRSF had previously developed weak-post MGS systems for use in either asphalt or concrete mow strips [20]. For a 4-ft (1.2 m) wide by 4-in. (102-mm) thick concrete mow strip, the S3x5.7 (S76x8.5) posts were inserted into 4-in. (102-mm) square leave outs located down the middle of the mow strip and driven 36 in. (914 mm) into the soil underneath the mow strip. When subjected to impact loading, this configuration proved strong enough to prevent damage to the concrete mow strip and forced the post to bend over above the ground line. Thus, it was thought that placing steel sockets within a 4-in. (102-mm) thick concrete slab, as shown in Figure 12, would result in a similar performance. The advantage of this design is that neither the slab nor the steel sockets need to be anchored to the culvert. Thus, the culvert and the barrier system act independently of each other. Additionally, the same slab and socket geometry could be utilized for all culvert installations regardless of the soil fill depth. Further details on the concrete slab design are shown in Chapter 4.

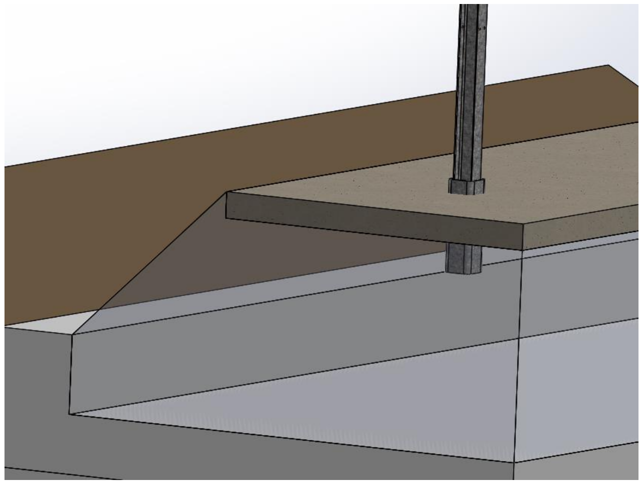


Figure 12. Concrete Slab Design Concept

3 EVALUATION CRITERIA AND TEST CONDITIONS

3.1 Testing Criteria

New highway barriers are typically evaluated through full-scale crash testing in accordance with MASH 2016 safety performance criteria in order to be deemed crashworthy. However, the original weak-post, MGS bridge rail [15-16] had already satisfied MASH TL-3 criteria, and this study focused only on adapting the original system for use as a top-mounted barrier on low-fill box culverts. In fact, the W-beam rail, rail-to-post attachment hardware, mounting height, post assembly, and socket tube all remained unchanged from the original bridge rail. The only new components in these concepts were the attachment hardware utilized to mount the socket to the top slab of the culvert. Further, the new socket assemblies and attachment hardware were designed to withstand impact loads and remain undamaged, while the post and rail components deform and absorb energy. If these new components were shown to withstand extreme loading conditions without damage to the socket assembly or the culvert slab, the new weak-post guardrail attached to concrete box culvert systems would perform similarly to the original weak-post bridge rail. Thus, full-scale testing was deemed unnecessary, and the evaluation of the new design concepts was limited to dynamic component testing. A similar design approach was successfully utilized to adapt the weak-post, MGS bridge rail for attachment to the face of culvert headwalls [17].

Each of the design concepts was subjected to dynamic impacts and evaluated based on displacement and damage as the post was bent over during the impact event. The sockets were required to displace less than 1 in. (25 mm), as measured at the ground line. Damage needed to be limited such that repairs to the socket assemblies would not be necessary, and only posts and guardrail segments would need to be replaced after an impact event.

3.2 Critical Testing Conditions

Two critical impact conditions were identified for the evaluation of the design concepts. The first involved a lateral impact (90-degree impact angle) on the post at a height of 24⅞ in. (632 mm). The impact height corresponds to the height to the center of the W-beam rail, while the impact angle results in strong-axis bending of the post, or the maximum lateral loading to a single post and socket location. If a socket can withstand the full lateral capacity of the post without significant deformations or damage, it would be able to provide the anchorage support needed for the guardrail system to perform as intended. Similar impact conditions are routinely used to observe the performance of guardrail posts installed in soil. The second critical test condition involved a longitudinal impact (0-degree impact angle) where a post was subjected to weak-axis bending. The longitudinal impacts were conducted with a load height of 12 in. (305 mm) to simulate a small car bumper impacting posts during a redirection. This second impact was deemed critical because it induces high shear loads into the socket which may result in socket displacements and/or rotations in the longitudinal direction.

The configuration of the culvert and the location of the socket on the culvert were also critical to the performance of the socket design concepts. In general, the maximum soil fill depth would be critical as it would induce the highest bending loads to the socket assembly. Thus, nearly all of the dynamic component tests were conducted on a simulated culvert with a 3-ft (0.9-m) soil fill depth. However, minimizing the soil fill depth would minimize the soil resistance against the socket assembly and may result in higher anchor loads. Since the cylindrical concrete foundations only had one front anchor (in the tension area) as opposed to the two anchors on the front side of the steel socket assembly, the concrete foundation installed on a simulated culvert with a 12.5-in. (318-mm) soil fill depth was selected as the critical configuration to evaluate socket anchorage.

It was also recognized that the soil fill on top of culverts and beyond the roadway shoulder is often sloped. Sloped terrain can significantly affect the performance of a guardrail system by reducing the soil fill behind the post, or in this case, the socket. The original weak-post MGS bridge rail and all of its adaptations have been developed and evaluated solely on level terrain in front of the barrier. However, the terrain behind the barrier may vary from level terrain (mow strips) to a vertical drop off (bridge rail and culvert headwall). Thus, the top-mounted socket design concepts were placed adjacent to the slope break point of a 2H:1V slope during the dynamic component testing and evaluation herein. The 2H:1V slope began at the simulated culvert headwall and extended up to the desired soil fill depth before leveling off.

3.3 Scope

A total of five dynamic component tests were conducted on critical configurations of the various design concepts, as described in Section 3.2. Each design concept was impacted laterally (causing strong-axis bending) with an impact height of 24⅞ in. (632 mm). Pending successful lateral tests, the design concepts were then subjected to a longitudinal impact (weak-axis) with an impact height of 12 in. (305 mm). The target impact velocity was 20 mph (32 km/h) for all five tests. The bogie testing matrix, which describes details for each test, is shown in Table 1. Material specifications for all construction materials used in the culvert and barrier components are contained in Appendix A.

During the evaluation and testing of weak-posts in pavement mow strips, different failure patterns were observed depending on the number of posts impacted. During single post component tests, only localized damage was observed directly behind the post. However, if two posts were impacted simultaneously, the stress distributions from adjacent posts would overlap and cause the mow strip to fail and split down the middle. This behavior was observed in dual post component testing as well as in the full-scale crash test [20]. Therefore, the lateral component test on the concrete slab design concept was conducted as a dual post impact with the posts spaced 37.5 in. (953 mm) on center.

Placement of a fill slope adjacent to the socket assemblies would adversely affect the path and stability of the bogie vehicle during longitudinal impacts. Instead of constructing separate culverts to conduct the longitudinal tests, the test articles installed for longitudinal impacts were rotated 90 degrees. Thus, the bogie tow path, which ran laterally with respect to the culvert, could remain on level terrain prior to impact, but the impact loads would be through the longitudinal, or weak axis, of the post and socket assembly. This resulted in a reduced, and unrealistic, amount of soil fill behind the longitudinally impacted test articles. However, if damage and displacement was limited under these conditions, the socket assembly would certainly also perform acceptably in more favorable and realistic conditions with the additional soil behind the test article.

Table 1. Bogie Testing Matrix

Test No.	Design Concept	Soil Fill Depth	Impact Angle (Relative to Post & Socket)	Impact Height	Target Impact Velocity
TMS-1	Cylindrical Concrete Foundation	12.5 in. (318 mm)	90° (lateral)	24⅞ in. (632 mm)	20 mph (32 km/h)
TMS-2	Steel Tube Socket Assembly	36 in. (914 mm)	90° (lateral)	24⅞ in. (632 mm)	20 mph (32 km/h)
TMS-3	Steel Tube Socket Assembly	36 in. (914 mm)	0° (longitudinal)	12 in. (305 mm)	20 mph (32 km/h)
TMS-4	Cylindrical Concrete Foundation	36 in. (914 mm)	0° (longitudinal)	12 in. (305 mm)	20 mph (32 km/h)
TMS-5	Concrete Slab	36 in. (914 mm)	90° (lateral)	24⅞ in. (632 mm)	20 mph (32 km/h)

3.4 Test Facility

Physical testing of the post and socket assemblies mounted to the top of a simulated culvert was conducted at the MwRSF Outdoor Test Site, which is located at the Lincoln Air Park on the northwest side of the Lincoln Municipal Airport. The facility is approximately 5 miles (8 km) northwest from the University of Nebraska-Lincoln’s city campus.

3.5 Equipment and Instrumentation

Equipment and instrumentation utilized to collect and record data during the dynamic component tests included a bogie vehicle, accelerometers, a retroreflective optical speed trap, high-speed and standard-speed digital video, and still cameras.

3.5.1 Bogie

A rigid-frame bogie vehicle was used to impact the post and socket assemblies. Two different impact heads were used in the testing. For the lateral impacts, the bogie head was constructed of an 8-in. (203-mm) diameter, ½-in. (13-mm) thick steel pipe, with ¾-in. (19-mm) neoprene belting wrapped around the pipe. For the longitudinal impacts, the bogie head consisted of a 2½-in. x 2½-in. x $^{5}/_{16}$-in. (64-mm x 64-mm x 8-mm) square tube mounted on the outside flange of a W6x25 (W152x37.2) steel beam with reinforcing gussets. The impact heads were bolted to the bogie vehicle, creating a rigid frame with impact heights of 24⅞ in. (632 mm) and 12 in. (305 mm), respectively. Photographs of the bogie with both impact heads are shown in Figure 13. The weight of the bogie with the addition of the mountable impact heads varied slightly between tests, but was approximately 2,000 lb (907 kg). The bogie vehicle weight for each test is shown on the individual test summaries provided in Appendix B.

Lateral Impact Head Longitudinal Impact Head

Figure 13. Rigid-Frame Bogie Equipped with Lateral and Longitudinal Impact Heads

The tests were conducted using a steel, corrugated-beam guardrail to guide the tire of the bogie vehicle, as shown in Figure 13. A pickup truck was used to push the bogie vehicle to the targeted impact velocity of 20 mph (32 km/h). After reaching the target velocity, the push vehicle braked, allowing the bogie to be free rolling as it came off the track. A remote braking system was installed on the bogie, allowing it to be brought safely to rest after the test.

3.5.2 Accelerometers

A combination of three different environmental shock and vibration sensor/recorder systems were used to measure the accelerations along the longitudinal axis of the bogie vehicle. The accelerometer systems utilized for each test are shown in Table 2. The accelerometers were mounted near the center of gravity (c.g.) of the bogie vehicle.

Two first two systems, the SLICE-1 and SLICE-2 units, were modular data acquisition systems manufactured by Diversified Technical Systems, Inc. (DTS) of Seal Beach, California. The acceleration sensors were mounted inside the bodies of custom built SLICE 6DX event data recorders and recorded data at 10,000 Hz to the onboard microprocessor. Each SLICE 6DX was configured with 7 GB of non-volatile flash memory, a range of ±500 g's, a sample rate of 10,000 Hz, and a 1,650 Hz (CFC 1000) anti-aliasing filter. The "SLICEWare" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

The third accelerometer system was a two-arm piezoresistive accelerometer system manufactured by Endevco of San Juan Capistrano, California. Three accelerometers were used to measure each of the longitudinal, lateral, and vertical accelerations independently at a sample rate of 10,000 Hz. The accelerometers were configured and controlled using a system developed and manufactured by DTS of Seal Beach, California. More specifically, data was collected using a DTS Sensor Input Module (SIM), Model TDAS3-SIM-16M. The SIM was configured with 16

MB SRAM and 8 sensor input channels with 250 kB SRAM/channel. The SIM was mounted on a TDAS3-R4 module rack. The module rack was configured with isolated power/event/communications, 10BaseT Ethernet and RS232 communication, and an internal backup battery. Both the SIM and module rack were crashworthy. The “DTS TDAS Control” computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

Table 2. Accelerometers Used for Each Component Test

Test No.	Accelerometers		
	SLICE-1	SLICE-2	TDAS
TMS-1	X	X	
TMS-2	X	X	
TMS-3	X	X	
TMS-4		X	X
TMS-5		X	X

3.5.3 Retroreflective Optic Speed Trap

The retroreflective optic speed trap was used to determine the speed of the bogie vehicle before impact. Three retroreflective targets, spaced at approximately 18-in. (457-mm) intervals, were applied to the side of the bogie vehicle, and a light beam Emitter/Receiver was placed perpendicular to the path of bogie vehicle. When the emitted beam of light was reflected by the targets and returned to the Emitter/Receiver, a signal was sent to the Optic Control Box, which in turn sent a signal to the data acquisition computer as well as activated the External LED box. The computer recorded the signals and the time each occurred. The speed was then calculated using the spacing between the retroreflective targets and the time between the signals. LED lights and high-speed digital video analysis are only used as a backup in the event that vehicle speeds cannot be determined from the electronic data.

3.5.4 Digital Photography

One AOS high-speed digital video camera and two GoPro digital video cameras were used to document each test. The AOS high-speed camera had a frame rate of 500 frames per second and the GoPro digital video cameras each had a frame rate of 120 frames per second. The high-speed camera was placed with a view perpendicular to the bogie’s direction of travel, while the placement of the other digital cameras varied by test. A Nikon digital still camera was also used to document pre- and post-test conditions for all tests.

3.6 End of Test Determination

When the impact head initially contacts the test article, the force exerted by the surrogate test vehicle is directly perpendicular. However, as the post rotates, the surrogate test vehicle’s orientation and path moves further from perpendicular. This introduces two sources of error: (1) the contact force between the impact head and the post has a vertical component and (2) the impact head slides upward along the test article. Therefore, only the initial portion of the accelerometer trace may be used since variations in the data become significant as the system rotates and the surrogate test vehicle overrides the system. Additionally, guidelines were established to define the end of test time using the high-speed video of the impact. The first occurrence of either of the following events was used to determine the end of the test: (1) the test article fractures or (2) the surrogate vehicle overrides/loses contact with the test article.

3.7 Data Processing

The electronic accelerometer data obtained in dynamic testing was filtered using the SAE Class 60 Butterworth filter conforming to the SAE J211/1 specifications [21]. The pertinent acceleration signal was extracted from the bulk of the data signals. The processed acceleration data was then multiplied by the mass of the bogie to get the impact force using Newton’s Second Law. Next, the acceleration trace was integrated to find the change in velocity versus time. Initial velocity of the bogie, calculated from the speed trap data, was then used to determine the bogie velocity, and the calculated velocity trace was integrated to find the bogie’s displacement, which is also the displacement of the post. Combining the previous results, a force vs. deflection curve was plotted for each test. Finally, integration of the force vs. deflection curve provided the energy vs. deflection curve for each test.

4 DESIGN DETAILS

4.1 Simulated Culvert Design

As discussed in Section 1.1, a version of this socketed, weak-post MGS system was previously adapted for use on culvert headwalls [17]. That previous study included a review of state DOT culvert standards to identify a critical culvert configuration based on top slab thickness, headwall height, headwall width, and steel reinforcement in both the top slab and the headwall. A simulated culvert incorporating the critical configuration was constructed and utilized during the physical testing and evaluation of the headwall-mounted sockets. The same critical culvert configuration was selected for use in the evaluation of the top-mounted sockets. Since physical testing during the previous project resulted in no damage to the culvert due to flexure or shear loads, only anchor pullout was anticipated as a possible mode of failure for the testing described herein. Thus, the culvert installations utilized to evaluate the top-mounted sockets consisted only of a simulated top slab and headwall that were placed directly on the supporting soil (i.e., vertical support walls were not included in the test article).

Since the top-mounted sockets needed to be evaluated at different soil fill depths, two simulated culverts were constructed at the MwRSF test site. One culvert was constructed with a 12.5-in. (318-mm) soil fill depth, while the second culvert was configured with a 36-in. (914-mm) soil fill depth. A 2H:1V soil grade was utilized adjacent to both culvert headwalls to achieve the necessary soil fill depths. Detailed drawings for the simulated culvert with a 12.5-in. (318-mm) soil fill depth are shown in Figures 14 through 18, while details of the simulated culvert with a 36-in. (914-mm) soil fill depth are shown in Figures 19 through 23. Material specifications for construction materials used in the culvert are contained in Appendix A.

4.2 Top-Mounted Sockets for Weak-Posts

Three different design concepts were evaluated for use as top-mounted sockets for the weak-post MGS: (1) cylindrical concrete foundations, (2) steel tube socket assemblies, and (3) a concrete slab. Design details for each concept are provided in the following sections. Detailed drawings and installation photographs for all five of the dynamic component tests conducted on these design concepts are shown in Figures 24 through 50. Material specifications for all construction materials used in the culvert and barrier components are contained in Appendix A.

All of the test articles were evaluated in combination with the same weak-post assemblies, which consisted of 44-in. (1,118-mm) long S3x5.7 (S76x8.5) posts with four 1-in. (25-mm) tall post standoffs welded between the flanges near the bottom of the post. The posts were ASTM A992 steel, while the post standoffs were fabricated from ASTM A36 steel.

4.2.1 Cylindrical Concrete Foundations

The cylindrical concrete foundations measured 12 in. (305 mm) in diameter and were reinforced by a combination of vertical rebar and transverse hoops, both of which were #4 rebar. The concrete had a minimum compressive strength of 3,500 psi (24 MPa) and all rebar were ASTM A615 grade 60. The vertical rebar extended 7 in. (178 mm) from the bottom of the concrete foundation and were epoxied into the top slab of the simulated culvert. The epoxy anchorage had a bond strength of 1,305 psi (9.0 MPa). A 14-in. (356-mm) long HSS 4x4x⅜ steel tube socket was embedded 12 in. (305 mm) down the center of each foundation and extended 2 in. (51 mm) from the top surface. The sockets were fabricated from ASTM A500 Grade B steel. The concrete foundations were positioned on the culvert such that the back edge of the foundation was adjacent with the slope break point of the soil fill. Additionally, the height of each concrete foundation matched the soil fill depth of the culvert. Thus, the foundation's top surface was flush with the level soil fill, while the top of the socket extended 2 in. (51 mm) above the ground line.

Two different height concrete foundations were fabricated and tested. A 12.5-in. (318-mm) tall foundation was evaluated in test no. TMS-1, and a 36-in. (914-mm) tall foundation was evaluated in test no. TMS-4. Design details and installation photographs for the 12.5-in. (318-mm) tall concrete foundation are shown in Figures 24 through 29 and Figure 30, respectively. Design details and installation photographs for the 36-in. (914-mm) tall concrete foundation are shown in Figures 41 through Figure 48 and Figure 49, respectively. Note, test no. TMS-4 was conducted as a 0-degree impact test (longitudinal impact). Thus, the post assembly was rotated 90 degrees and the bogie impacted through the weak axis of the post. The concrete foundation did not need to be rotated as it was rotationally symmetric.

4.2.2 Steel Tube Socket Assembly

Each steel tube socket assembly was fabricated from an HSS 4x4x⅜ (HSS 102x102x9.5) steel tube, two ¼-in. (6-mm) thick steel plates, and a ½-in. (13-mm) thick base plate. The ASTM A500 Grade B sockets extended from the top-mounted base plate to 2 in. (51 mm) above the ground line for a total length of 37.5 in. (953 mm). The 6-in. wide by 29-in. long by ¼-in. thick (152-mm x 737-mm x 6-mm) plates were welded to the front and back faces of the socket beginning 8 in. (203 mm) from the top of the socket and extending to the base plate. Two gusset plates located on the front and back side of the assembly were utilized to anchor the socket to the base plate. The ½-in. (13-mm) thick base plate was anchored to the top slab of the culvert with four ¾-in. (19-mm) diameter threaded rods. The threaded rods were embedded 7 in. (178 mm) into the slab using an epoxy with a bond strength of 1,305 psi (9.0 MPa). All of the steel plates were fabricated from ASTM A572 Grade 50 steel, while the threaded rods were ASTM A449. A $^{5}/_{8}$-in. (16-mm) dia. bolt was placed through the socket to support the post vertically and prevent it from being inserted all the way into the socket. Design details and installation photographs of the steel tube socket assemblies are shown in Figures 31 through 39 and Figure 40, respectively.

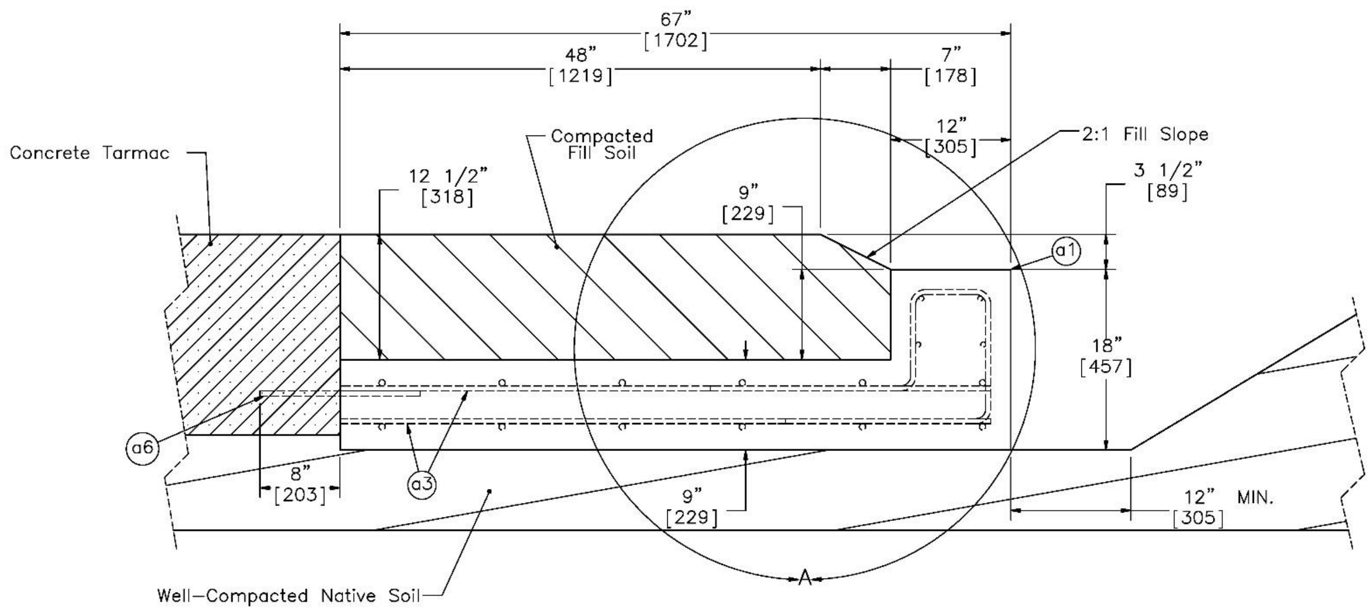
The test installations were installed on the simulated culvert with a 36-in. (914-mm) soil fill depth and positioned such that the back of the socket was adjacent to the 2H:1V slope break point. Note, test no. TMS-3 was conducted as a 0 degree impact test (longitudinal impact). Thus, the steel tube socket assembly and post were rotated 90 degrees on the culvert such that the bogie impacted through the weak axis of the socket and post. This was done only for testing purposes, and the reinforcing plates should always be located on the front and back faces of the socket in actual installations.

4.2.3 Concrete Slab

A 36-in. (914-mm) wide by 4-in. (102-mm) thick unreinforced concrete slab was installed on the simulated culvert with a 36-in. (914-mm) soil fill depth. The slab was placed with its back edge at the slope break point of the 2H:1V soil slope. HSS 4x4x⅜ (HSS 102x102x9.5) steel tubes measuring 14 in. (356 mm) long were placed 24 in. (610 mm) from the back of the slab, or 12 in.

(305 mm) from the front of the slab. The tops of the sockets extended 2 in. (51 mm) above the top of the slab. The concrete had a compressive strength of 4,000 psi (27.6 MPa), and the socket was fabricated from ASTM A500 Grade B steel. Design details for the concrete slab are shown in Figure 41 and Figure 42 and test installation photographs are shown in Figure 50.

As discussed previously, the concrete slab concept was tested in a dual post configuration to evaluate the potential for shear cracks to form in the slab between the posts. Thus, two sockets were placed within the concrete slab spaced 37.5 in. (953 mm) apart, and test no. TMS-5 was conducted with the bogie vehicle impacting both posts simultaneously.



ELEVATION VIEW

Notes: (1) The slope behind the culvert system is not critical (drawn as 2H:1V).

(2) Minimum 28-day concrete compressive strength (f'c) of 4,000 psi [27.6 MPa].

(3) Area below culvert system shall be well-compacted native soil.

(4) 2" [51] minimum clear cover for all steel reinforcement.

(5) Part a6 shall be spaced on 18" [457] centers (adjacent to a3 bars) and epoxied into the tarmac using Powers Fasteners AC100+ Gold epoxy or an equivalent epoxy with a minimum bond strength of 1,305 psi [9.0 MPa].

(6) Compacted fill soil should consist of crushed limestone material that meets AASHTO M147 Grade B soil requirements.

(7) Construction joint may be placed between the deck and headwall.

Midwest Roadside Safety Facility

Culvert with 12-1/2 in. Soil Fill

Elevation View

SHEET: 1 of 5

DATE: 8/9/16

DRAWN BY: DTM

DWG. NAME. 12-5FillCulvert_r9

SCALE: 1:15

UNITS: in.[mm]

REV. BY: SKR/TJD/KAL/RKF/JCH

Figure 14. Simulated Culvert with 12.5-in. (318-mm) Soil Fill

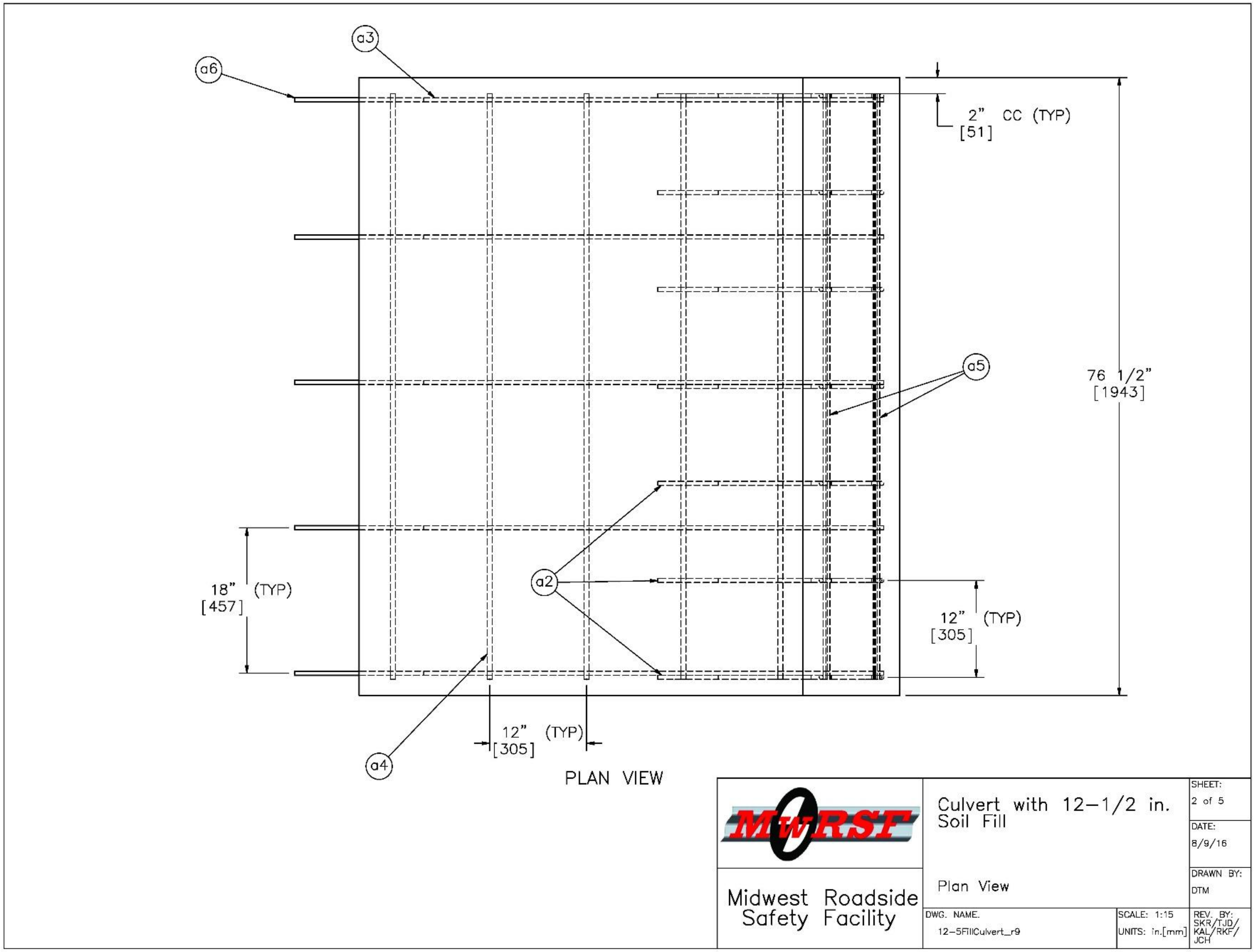


Figure 15. Simulated Culvert with 12.5-in. (318-mm) Soil Fill, Plan View

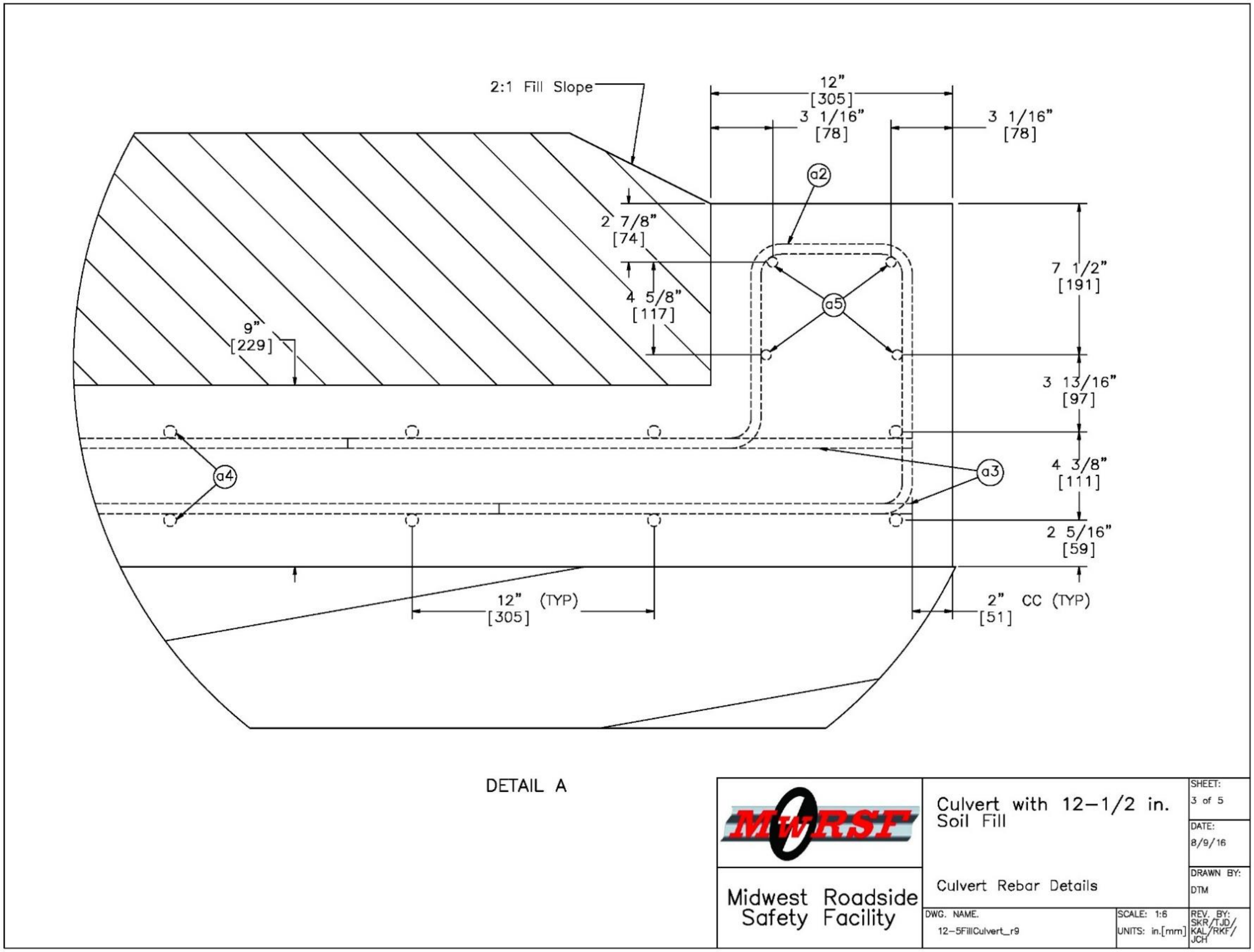
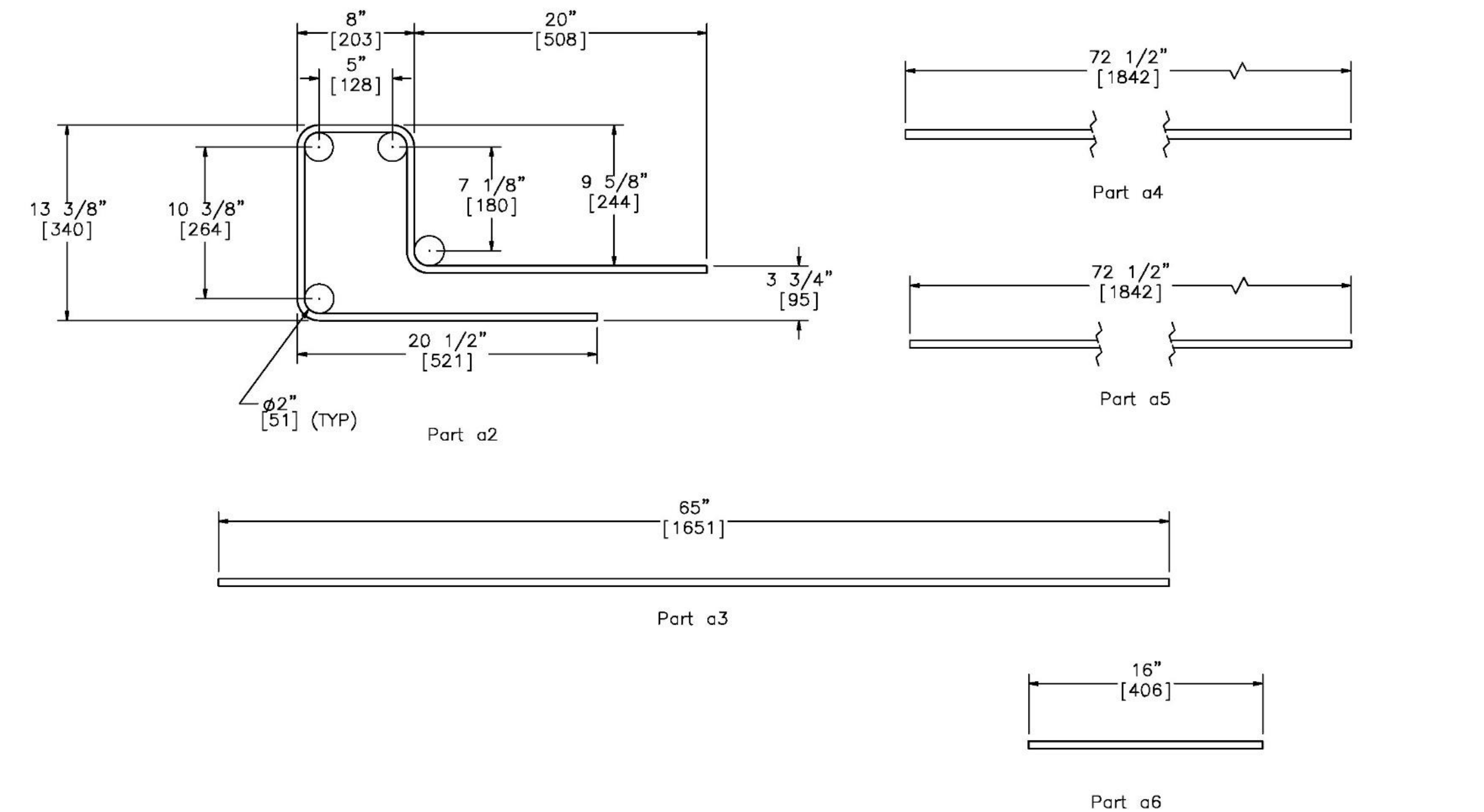


Figure 16. Simulated Culvert with 12.5-in. (318-mm) Soil Fill, Rebar Configuration



BILL OF BARS				
ITEM NO.	QTY.	BAR SIZE	TOTAL UNBENT LENGTH	MATERIAL SPEC
a2	7	#4 [13]	68 1/4" [1,734]	ASTM A615 Grade 60
a3	10	#4 [13]	65" [1,651]	ASTM A615 Grade 60
a4	12	#5 [16]	72 1/2" [1,842]	ASTM A615 Grade 60
a5	4	#4 [13]	72 1/2" [1,842]	ASTM A615 Grade 60
a6	5	#4 [13]	16" [406]	ASTM A615 Grade 60

MwRSF
Midwest Roadside Safety Facility

Culvert with 12-1/2 in. Soil Fill

Rebar Details

SHEET: 4 of 5
DATE: 8/9/16
DRAWN BY: DTM
DWG. NAME. 12-5FillCulvert_r9
SCALE: 1:10
UNITS: in.[mm]
REV. BY: SKR/TJD/KAL/RKF/JCH

Figure 17. Simulated Culvert with 12.5-in. (318-mm) Soil Fill, Reinforcement Details

Item No.	QTY	Description	Material Specifications
a1	–	Reinforced Concrete Culvert Deck and Headwall	Min. f'c = 4,000 psi [27.6 MPa]
a2	7	#4 Bent Rebar, Vertical Hoop, 68 1/4" [1,734] Total Length Unbent	ASTM A615 Grade 60
a3	10	#4 Straight Rebar, 65" [1,651] Long	ASTM A615 Grade 60
a4	12	#5 Straight Rebar, 72 1/2" [1842] Long	ASTM A615 Grade 60
a5	4	#4 Straight Rebar, 72 1/2" [1842] Long	ASTM A615 Grade 60
a6	5	#4 Straight Rebar, 16" [406] Long	ASTM A615 Grade 60
–	–	Epoxy Resin	Min. bond strength of 1,305 psi [9.0 MPa]

Midwest Roadside Safety Facility	Culvert with 12-1/2 in. Soil Fill	SHEET: 5 of 5
		DATE: 8/9/16
	Bill of Materials	DRAWN BY: DTM
	DWG. NAME. 12-5FillCulvert_r9 / SCALE: None / UNITS: in.[mm]	REV. BY: SKR/TJD/KAL/RKF/JCH

Figure 18. Simulated Culvert with 12.5-in. (318-mm) Soil Fill, Bill of Materials

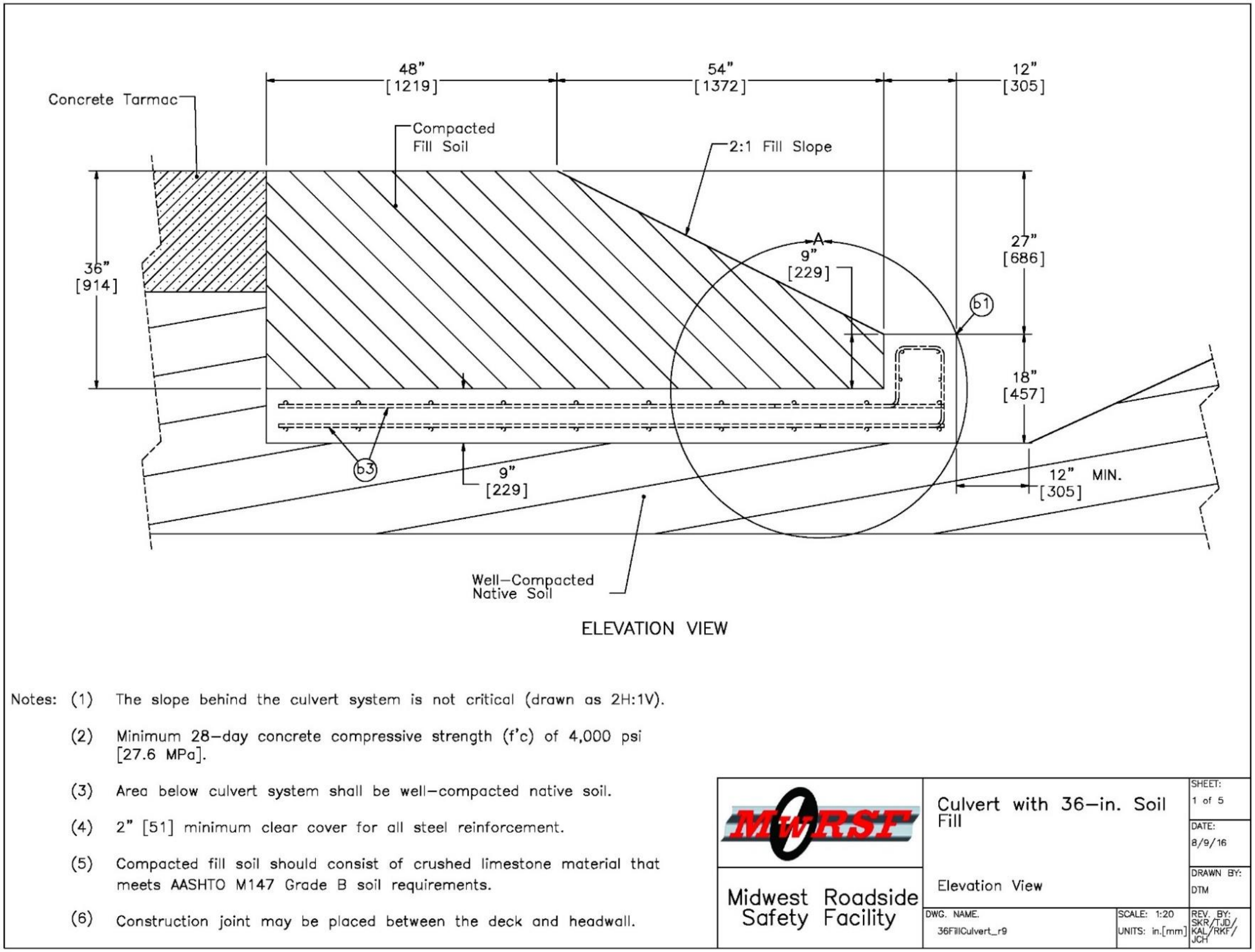


Figure 19. Simulated Culvert with 36-in. (914-mm) Soil Fill

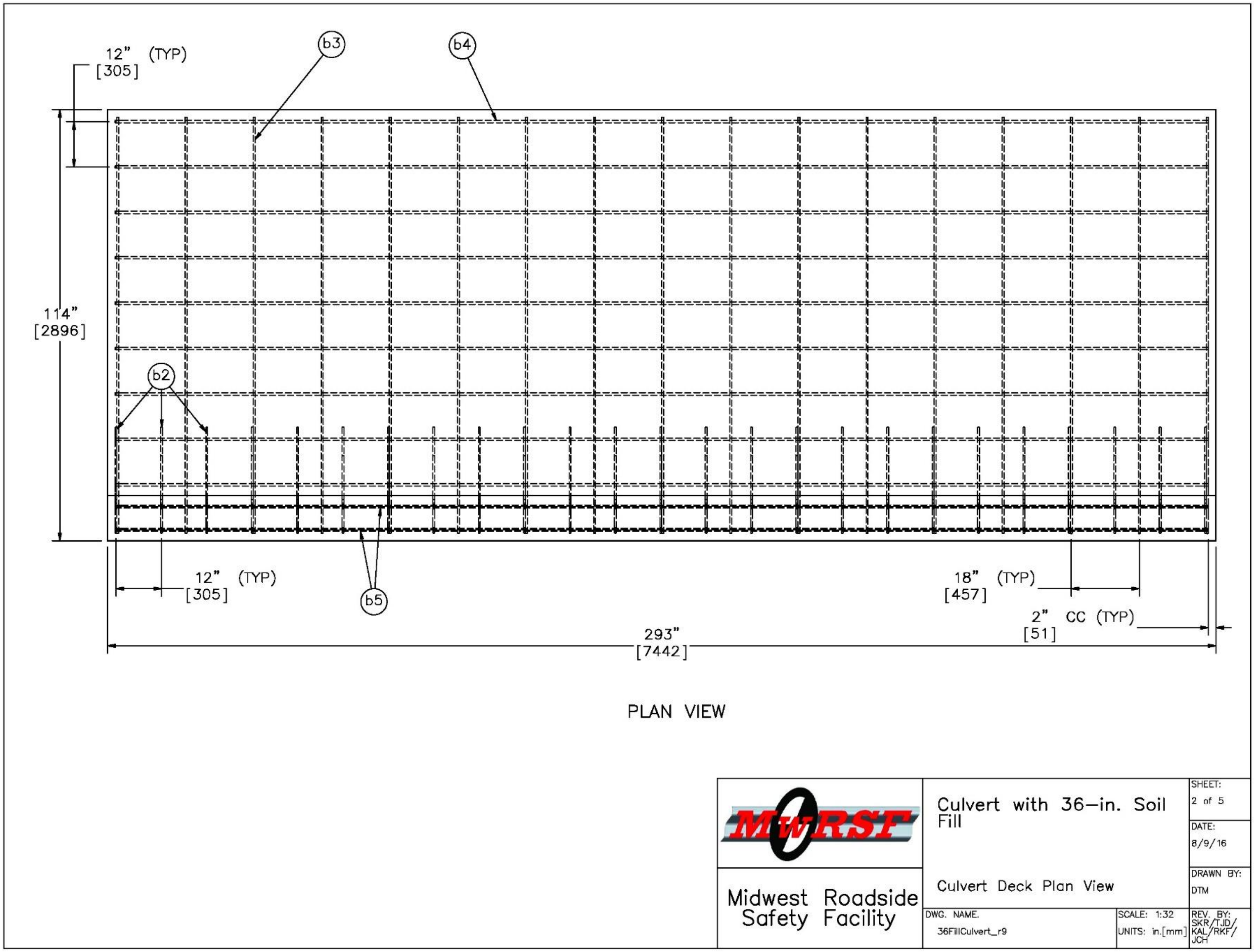


Figure 20. Simulated Culvert with 36-in. (914-mm) Soil Fill, Plan View

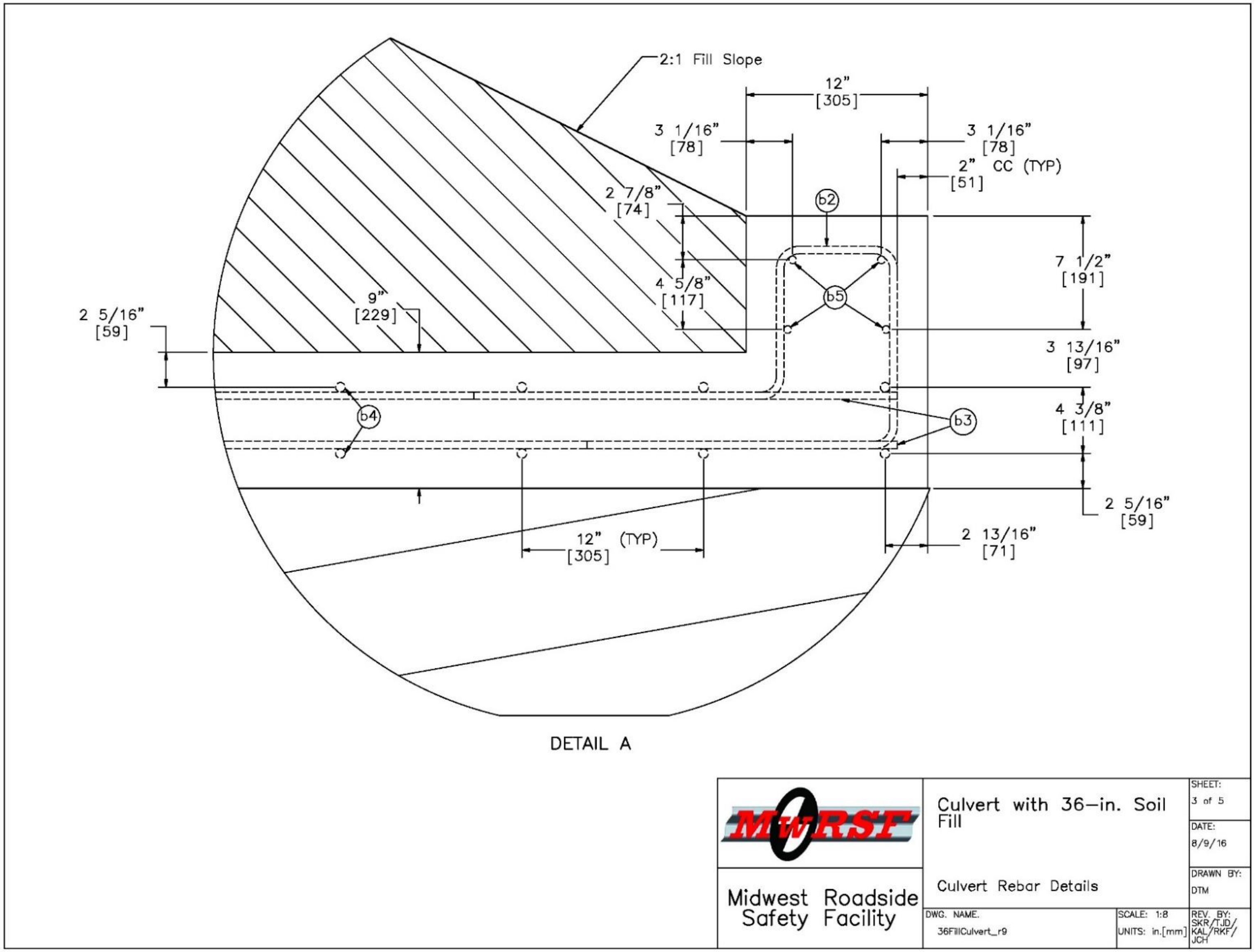
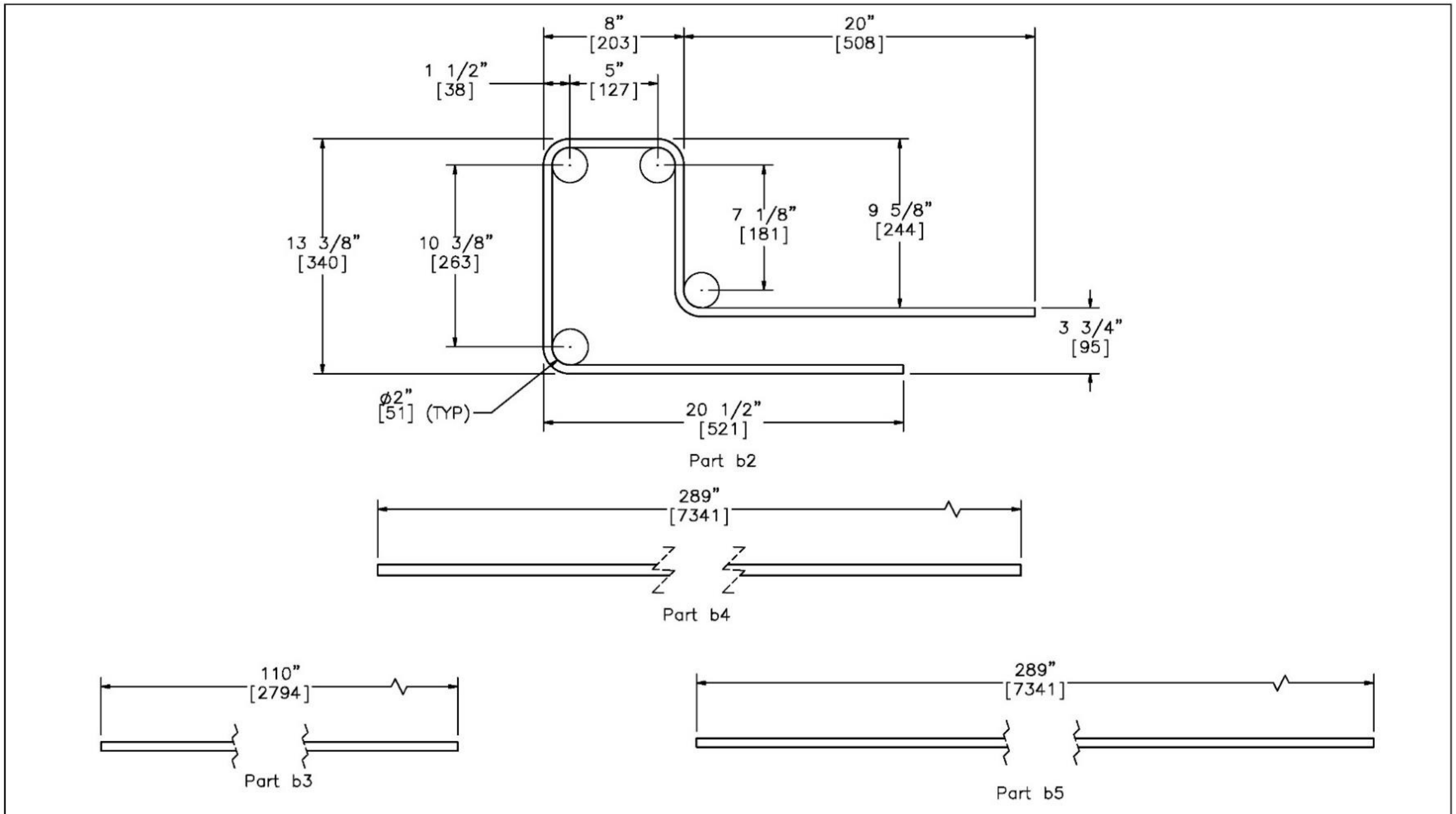


Figure 21. Simulated Culvert with 36-in. (914-mm) Soil Fill, Rebar Configuration



BILL OF BARS				
ITEM NO.	QTY.	BAR SIZE	TOTAL LENGTH	MATERIAL SPEC
b2	25	#4 [13]	68 1/4" [1,734]	ASTM A615 Grade 60
b3	34	#4 [13]	110" [2,794]	ASTM A615 Grade 60
b4	20	#5 [17]	289" [7,341]	ASTM A615 Grade 60
b5	4	#4 [13]	289" [7,341]	ASTM A615 Grade 60

Midwest Roadside Safety Facility

Culvert with 36–in. Soil Fill

Rebar Details

SHEET: 4 of 5

DATE: 8/9/16

DRAWN BY: DTM

DWG. NAME. 36FillCulvert_r9

SCALE: 1:8
UNITS: in.[mm]

REV. BY: SKR/TJD/KAL/RKF/JCH

Figure 22. Simulated Culvert with 36-in. (914-mm) Soil Fill, Reinforcement Details

Item No.	QTY.	Description	Material Specifications
b1	–	Reinforced Concrete Culvert Deck and Headwall	Min. f'c = 4,000 psi [27.6 MPa]
b2	25	#4 Bent Rebar, Vertical Hoop, 68 1/4" [1,734] Total Length Unbent	ASTM A615 Grade 60
b3	34	#4 Straight Rebar, 110" [2,794] Long	ASTM A615 Grade 60
b4	20	#5 Straight Rebar, 289" [7,341] Long	ASTM A615 Grade 60
b5	4	#4 Straight Rebar, 289" [7,341] Long	ASTM A615 Grade 60

Midwest Roadside Safety Facility

Culvert with 36–in. Soil Fill

Bill of Materials

SHEET: 5 of 5

DATE: 8/9/16

DRAWN BY: DTM

DWG. NAME. 36FillCulvert_r9

SCALE: NONE

UNITS: in.[mm]

REV. BY: SKR/TJD/KAL/RKF/JCH

Figure 23. Simulated Culvert with 36-in. (914-mm) Soil Fill, Bill of Materials

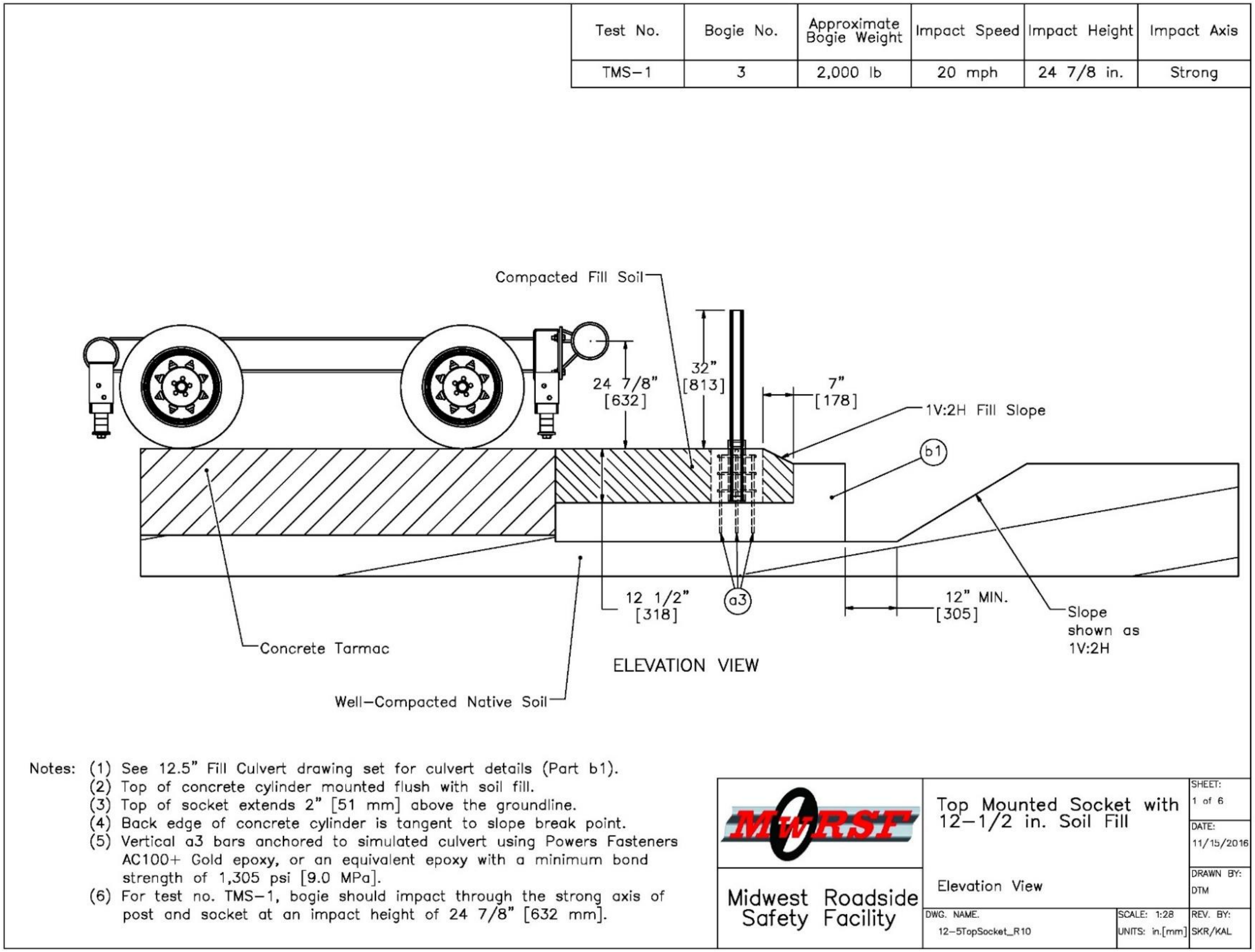


Figure 24. Cylindrical Concrete Foundation for 12.5-in. (318-mm) Soil Fill, Test Layout, Test No. TMS-1

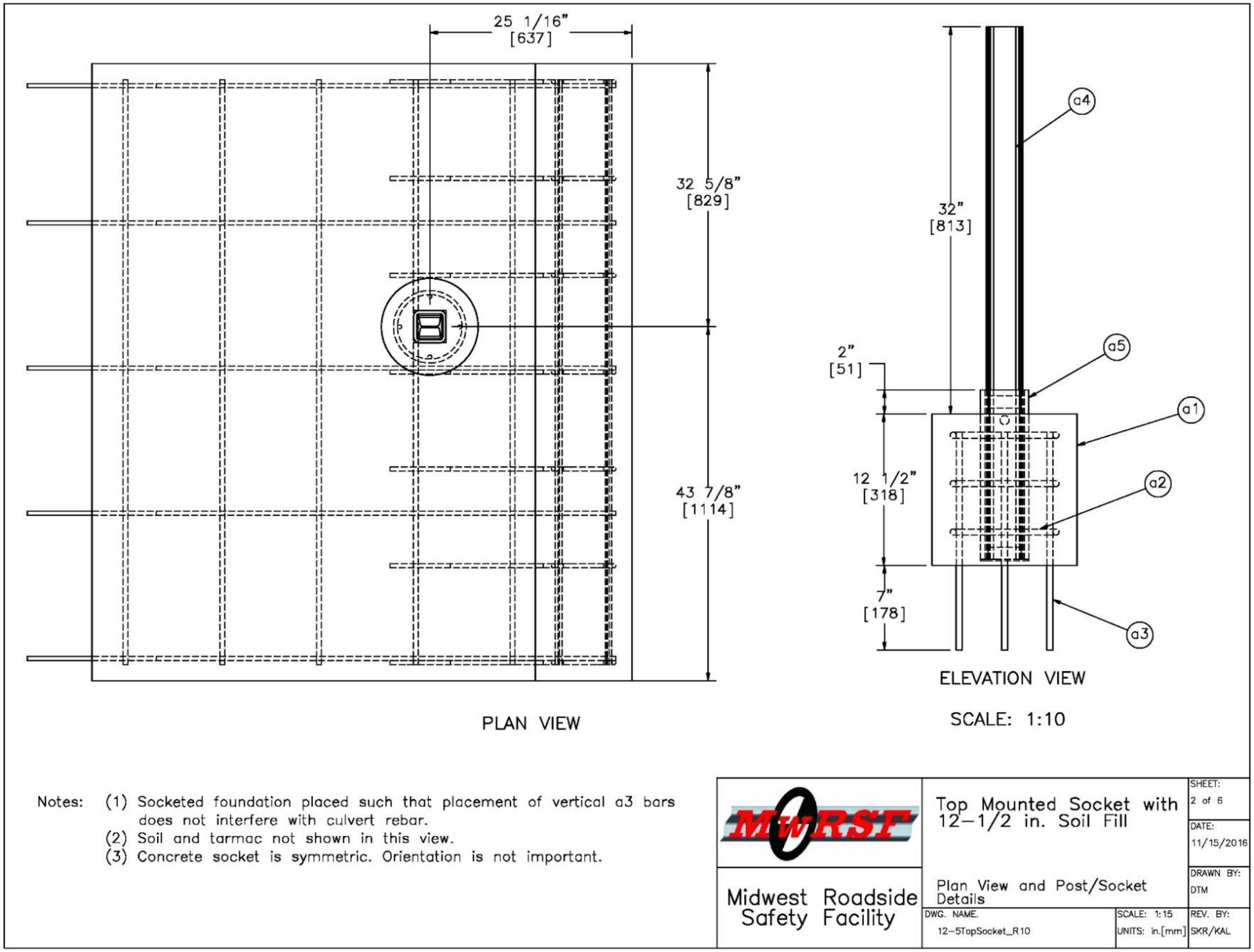


Figure 25. Cylindrical Concrete Foundation for 12.5-in. (318-mm) Soil Fill, Design Layout, Test No. TMS-1

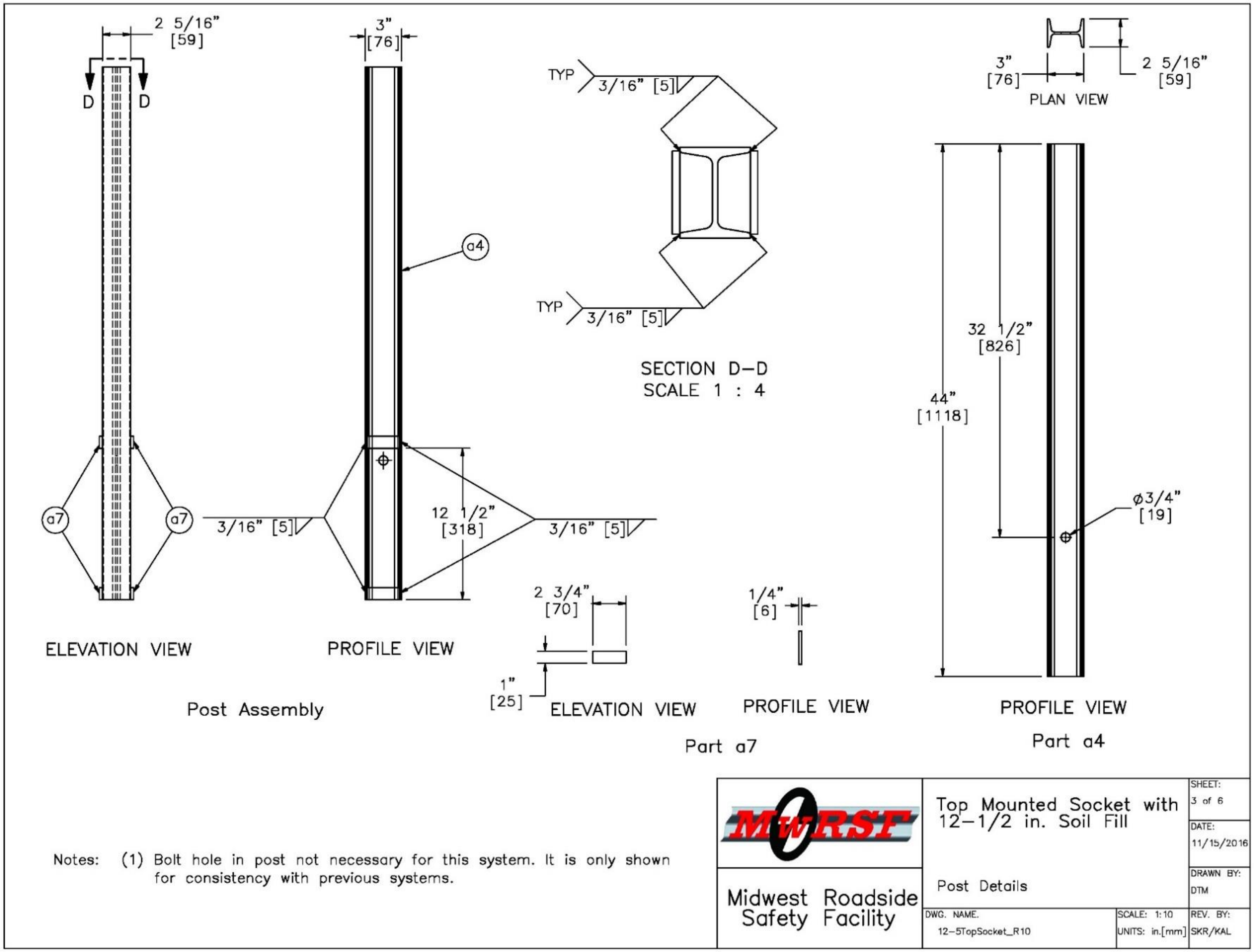


Figure 26. Post Assembly Details, Test No. TMS-1

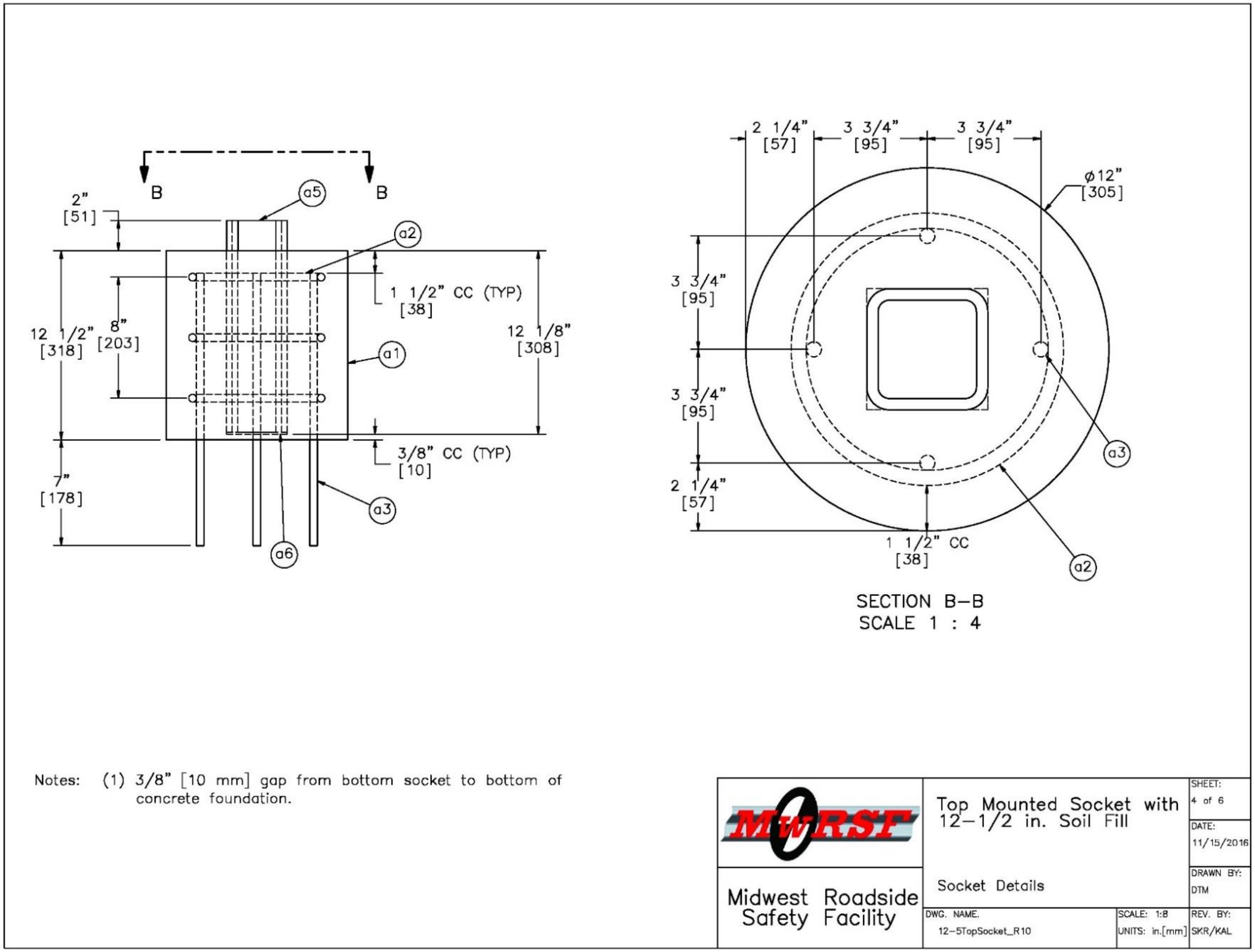
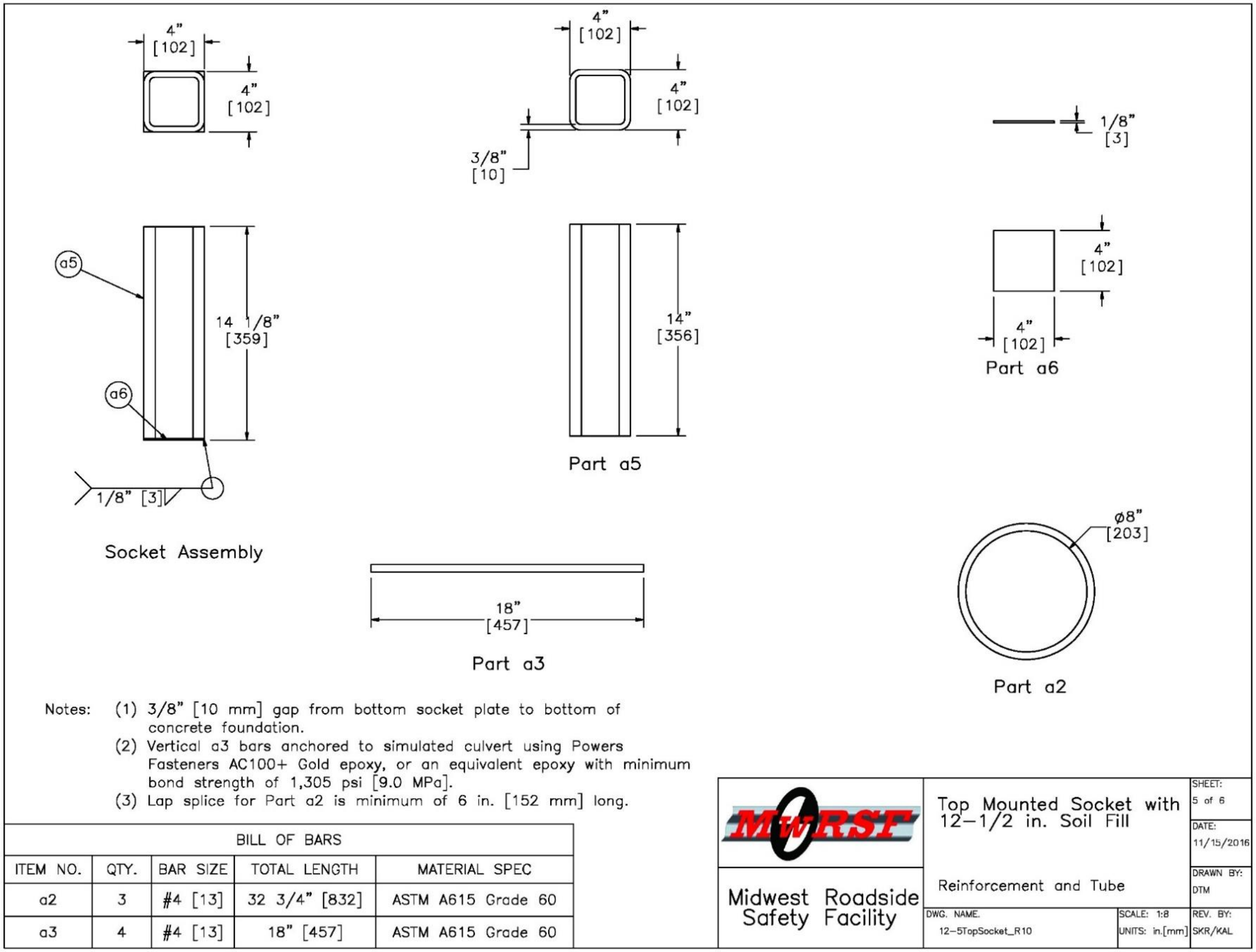


Figure 27. Cylindrical Concrete Foundation for 12.5-in. (318-mm) Soil Fill, Design Details, Test No. TMS-1



BILL OF BARS

ITEM NO.	QTY.	BAR SIZE	TOTAL LENGTH	MATERIAL SPEC
a2	3	#4 [13]	32 3/4" [832]	ASTM A615 Grade 60
a3	4	#4 [13]	18" [457]	ASTM A615 Grade 60

Figure 28. Cylindrical Concrete Foundation for 12.5-in. (318-mm) Soil Fill, Steel Component Details, Test No. TMS-1

Item No.	QTY.	Description	Material Specification	Galvanization Specifications (See Notes)	Hardware Guide
a1	1	Concrete Shaft, 12 1/2" [318] Long	Min 3,500 psi [24 MPa] Compressive Strength	–	–
a2	3	#4 Circular Rebar, 8" [203] ID	ASTM A615 Grade 60	Epoxy–Coated (See Note 2)	–
a3	4	#4 Rebar, 18" [457] Long	ASTM A615 Grade 60	Epoxy–Coated (See Note 2)	–
a4	1	S3x5.7 [S76x8.5] Post, 44" [1245] Long	ASTM A572 Gr. 50, ASTM A992, ASTM A209 Gr. 50	AASHTO M111 (ASTM A123)	PSF01
a5	1	HSS 4"x4"x3/8" [HSS 102x102x9.5], 14" [406] Long	ASTM A500 Grade B	AASHTO M111 (ASTM A123)	–
a7	4	2 3/4"x1"x1/4" [70x25x6] Post Standoff	ASTM A36	AASHTO M111 (ASTM A123)	PSF01
b1	1	Simulated Culvert with 12.5" Soil Fill	–	–	–
–	–	Epoxy Adhesive	Min. bond strength of 1,305 psi [9.0 MPa]	–	–
a6	1	4"x4"x1/4" [102x102x6] Steel Plate	ASTM A36		

Notes: (1) Steel post and socket components do not need to be galvanized for testing purposes.
(2) Rebar must be epoxy coated for testing.

Midwest Roadside Safety Facility

Top Mounted Socket with 12–1/2 in. Soil Fill

Bill of Materials

SHEET: 6 of 6
DATE: 11/15/2016
DRAWN BY: DTM
DWG. NAME. 12–5TopSocket_R10
SCALE: None
UNITS: in.[mm]
REV. BY: SKR/KAL

Figure 29. Cylindrical Concrete Foundation for 12.5-in. (318-mm) Soil Fill, Bill of Materials, Test No. TMS-1

Figure 30. Installation Photographs, 12.5-in. (318-mm) Concrete Foundation, Test No. TMS-1

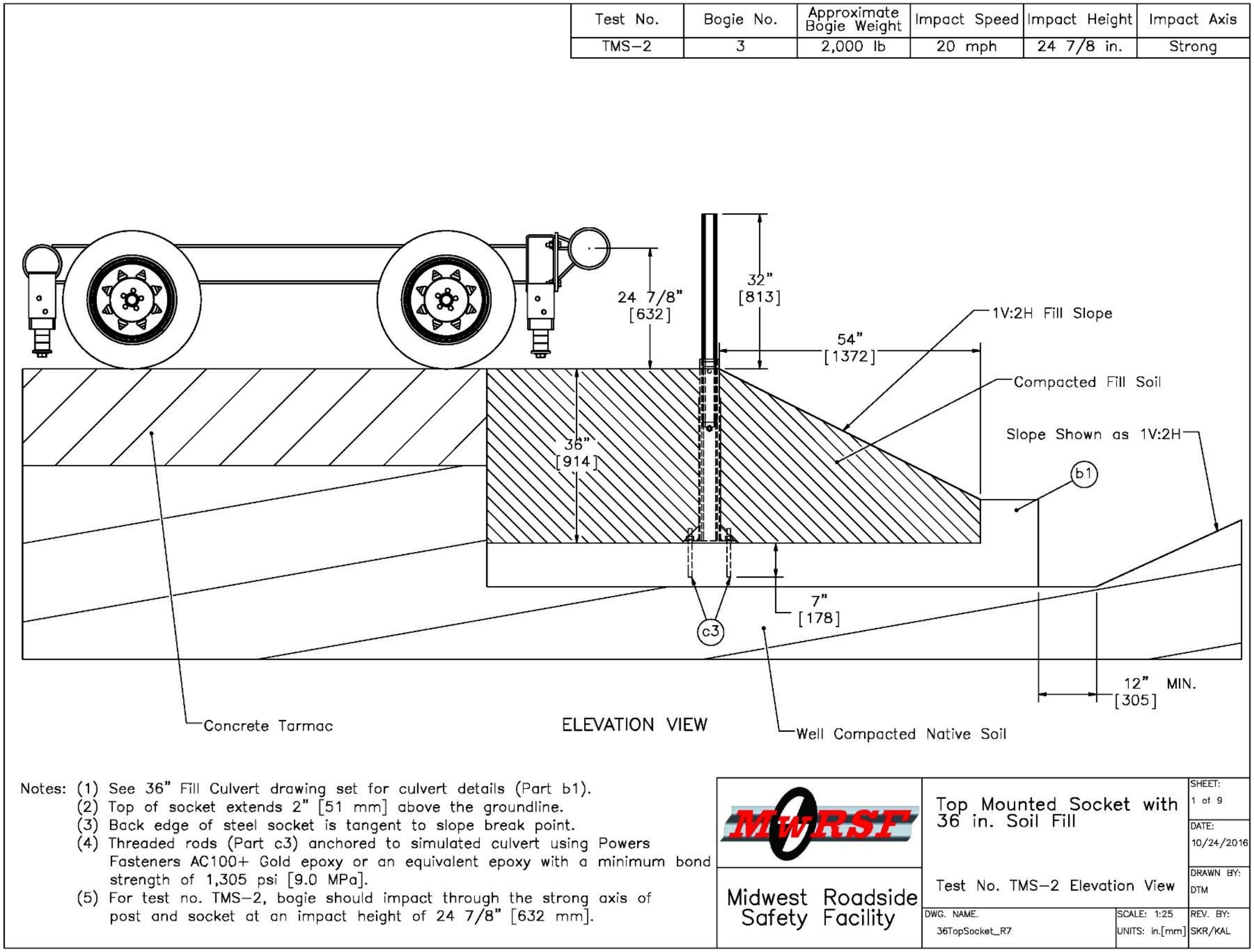
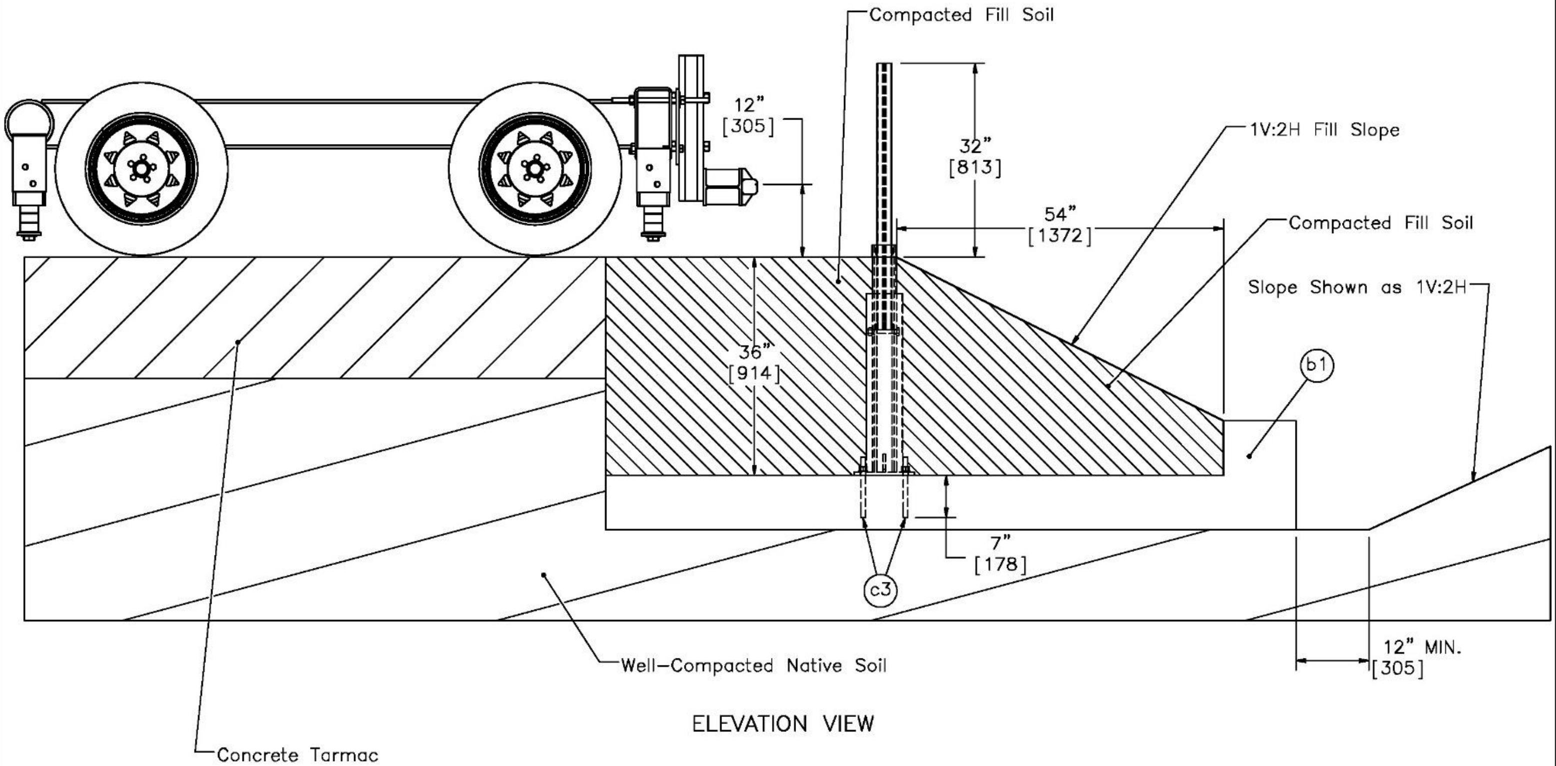


Figure 31. Steel Tube Socket Assembly for 36-in. (914-mm) Soil Fill, Test Layout, Test No. TMS-2

Test No.	Bogie No.	Approximate Bogie Weight	Impact Speed	Impact Height	Impact Axis
TMS-3	3	2,000 lb	20 mph	12 in.	Weak



Notes:
(1) See 36" Fill Culvert drawing set for culvert details.
(2) Top of socket extends 2" [51 mm] above the groundline.
(3) Back edge of steel socket is tangent to slope break point.
(4) Threaded rods (Part c3) anchored to simulated culvert using Powers Fasteners AC100+ Gold epoxy or an equivalent epoxy with a minimum bond strength of 1,305 psi [9.0 MPa].
(5) For test no. TMS-3, bogie should impact through the weak axis of post and socket at an impact height of 12" [305 mm].

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Midwest Roadside Safety Facility

Top Mounted Socket with 36 in. Soil Fill

Test No. TMS-3 Elevation View

SHEET: 2 of 9
DATE: 10/24/2016
DRAWN BY: DTM
DWG. NAME. 36TopSocket_R7
SCALE: 1:25
UNITS: in.[mm]
REV. BY: SKR/KAL

Figure 32. Steel Tube Socket Assembly for 36-in. (914-mm) Soil Fill, Test Layout, Test No. TMS-3

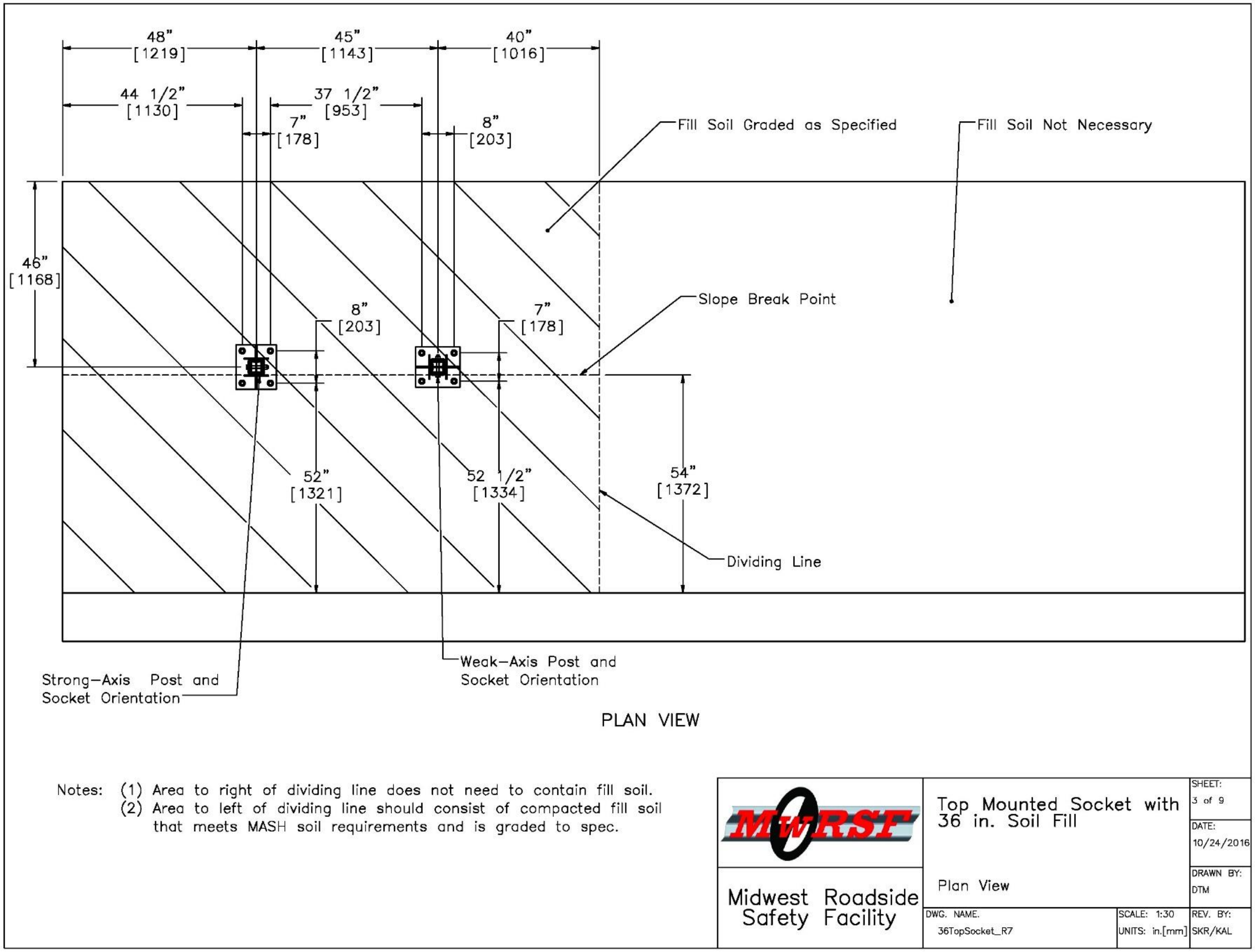


Figure 33. Steel Tube Socket Assembly for 36-in. (914-mm) Soil Fill, Installation Layout, Test Nos. TMS-2 and TMS-3

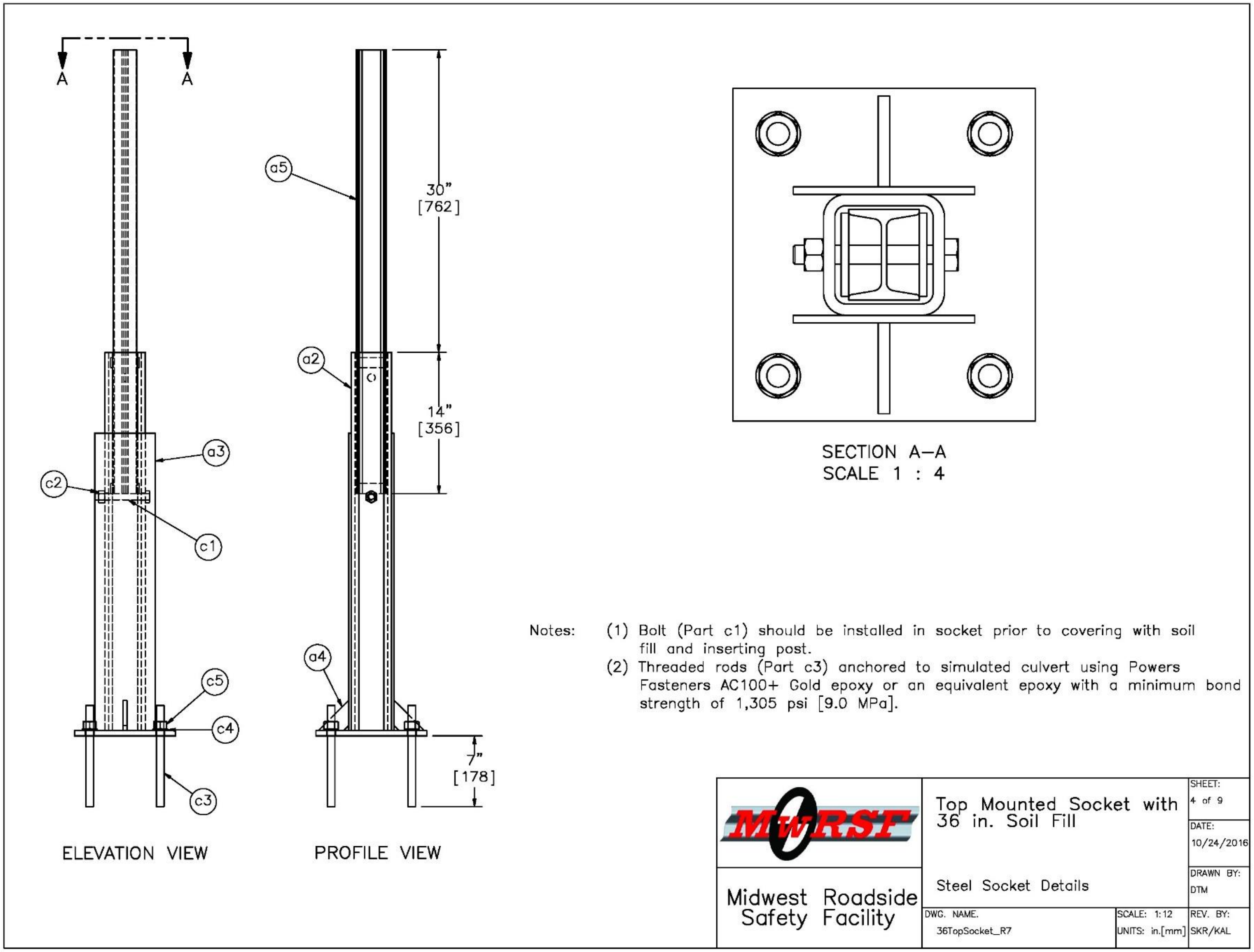


Figure 34. Steel Tube Socket Assembly for 36-in. (914-mm) Soil Fill, Design Details, Test Nos. TMS-2 and TMS-3

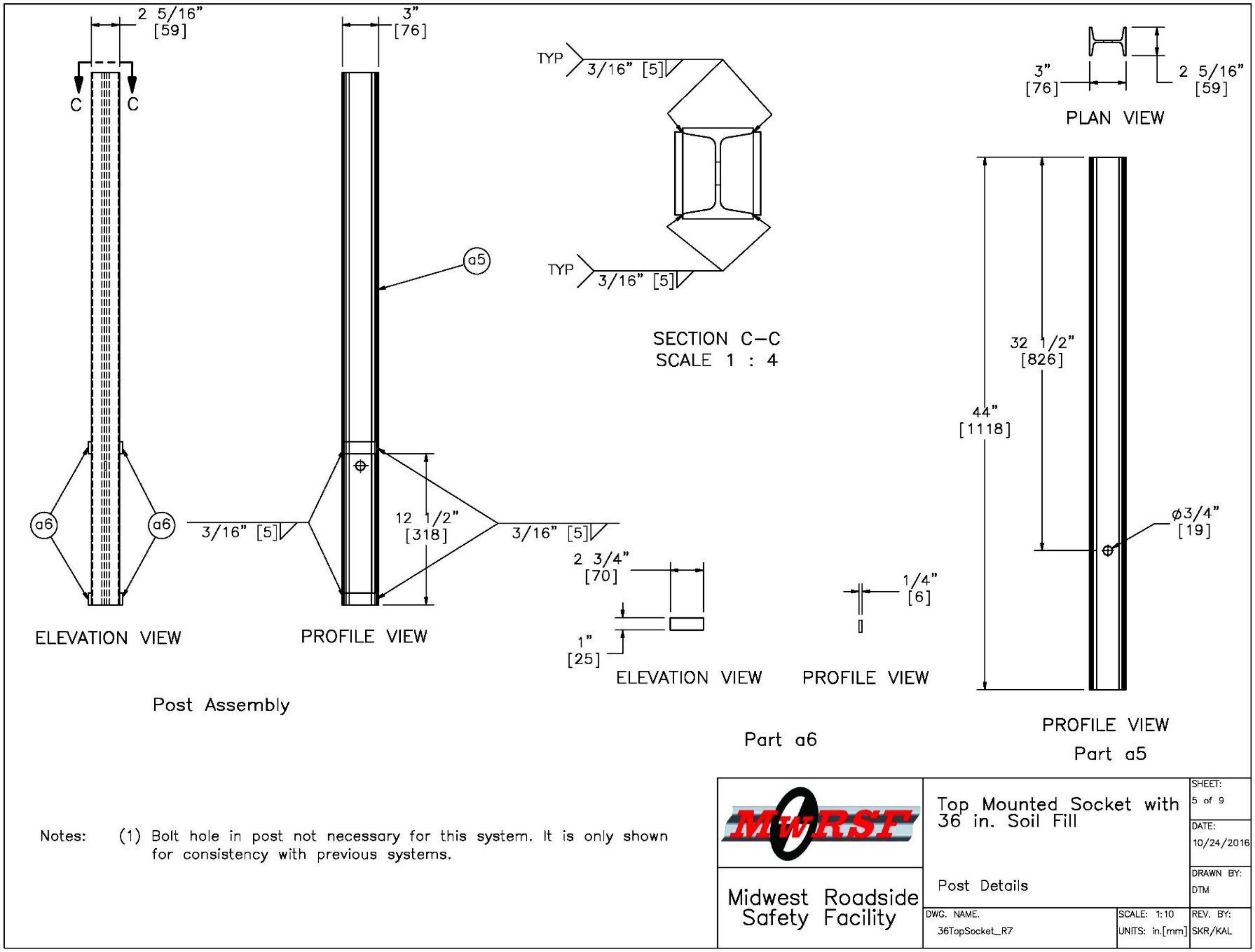


Figure 35. Post Assembly Details, Test Nos. TMS-2 and TMS-3

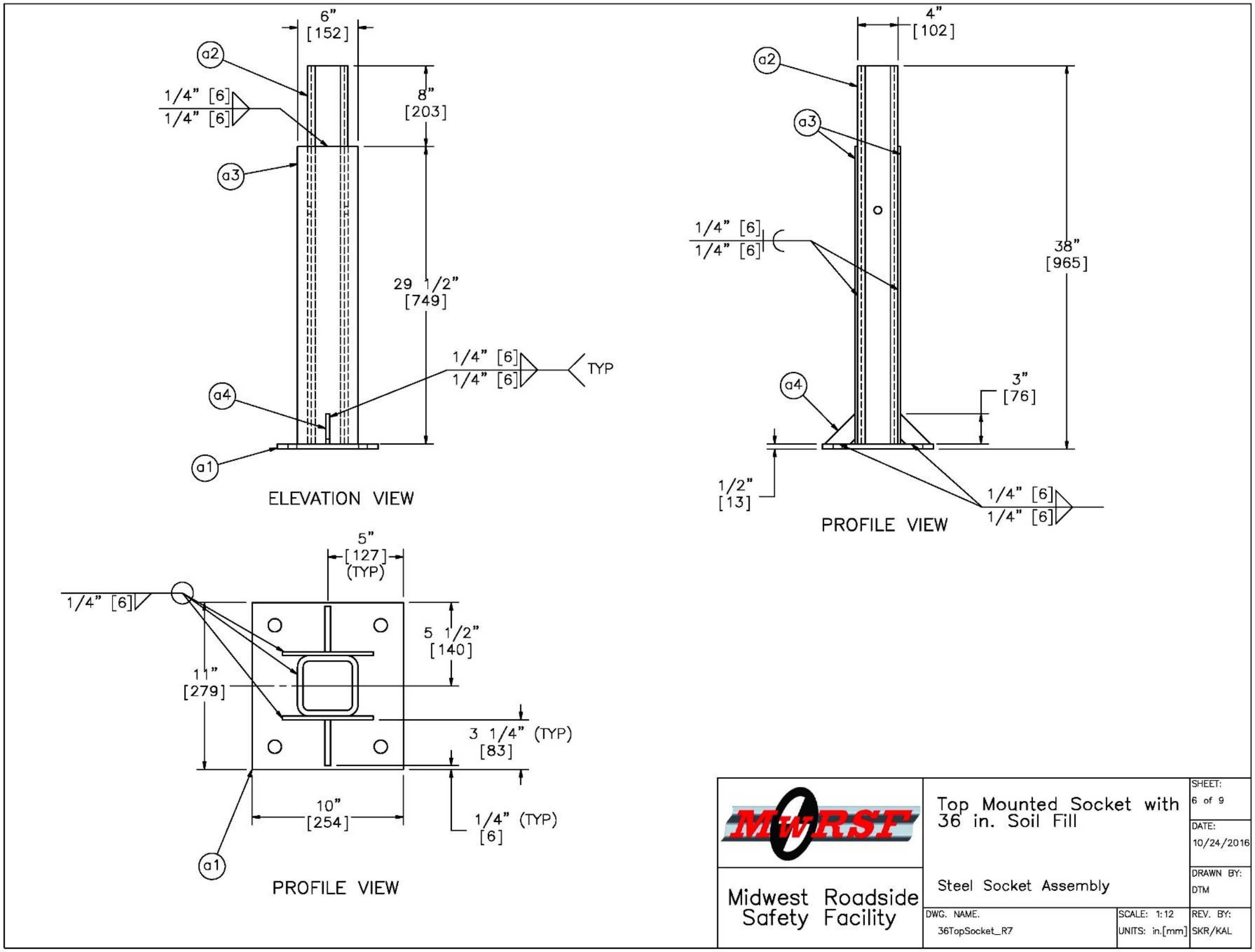


Figure 36. Steel Tube Socket for 36-in. (914-mm) Soil Fill, Socket Assembly Details, Test Nos. TMS-2 and TMS-3

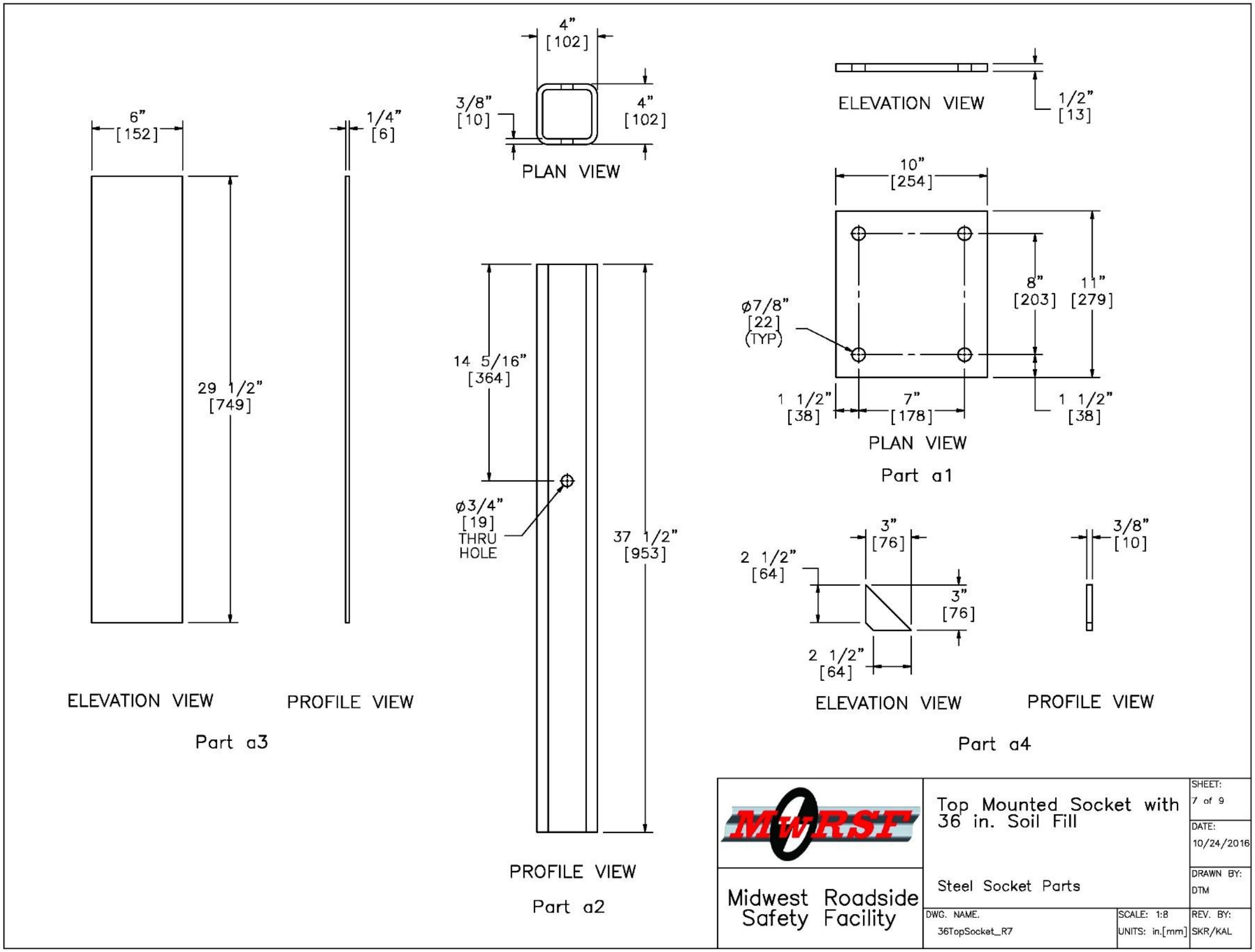


Figure 37. Steel Tube Socket for 36-in. (914-mm) Soil Fill, Component Details, Test Nos. TMS-2 and TMS-3

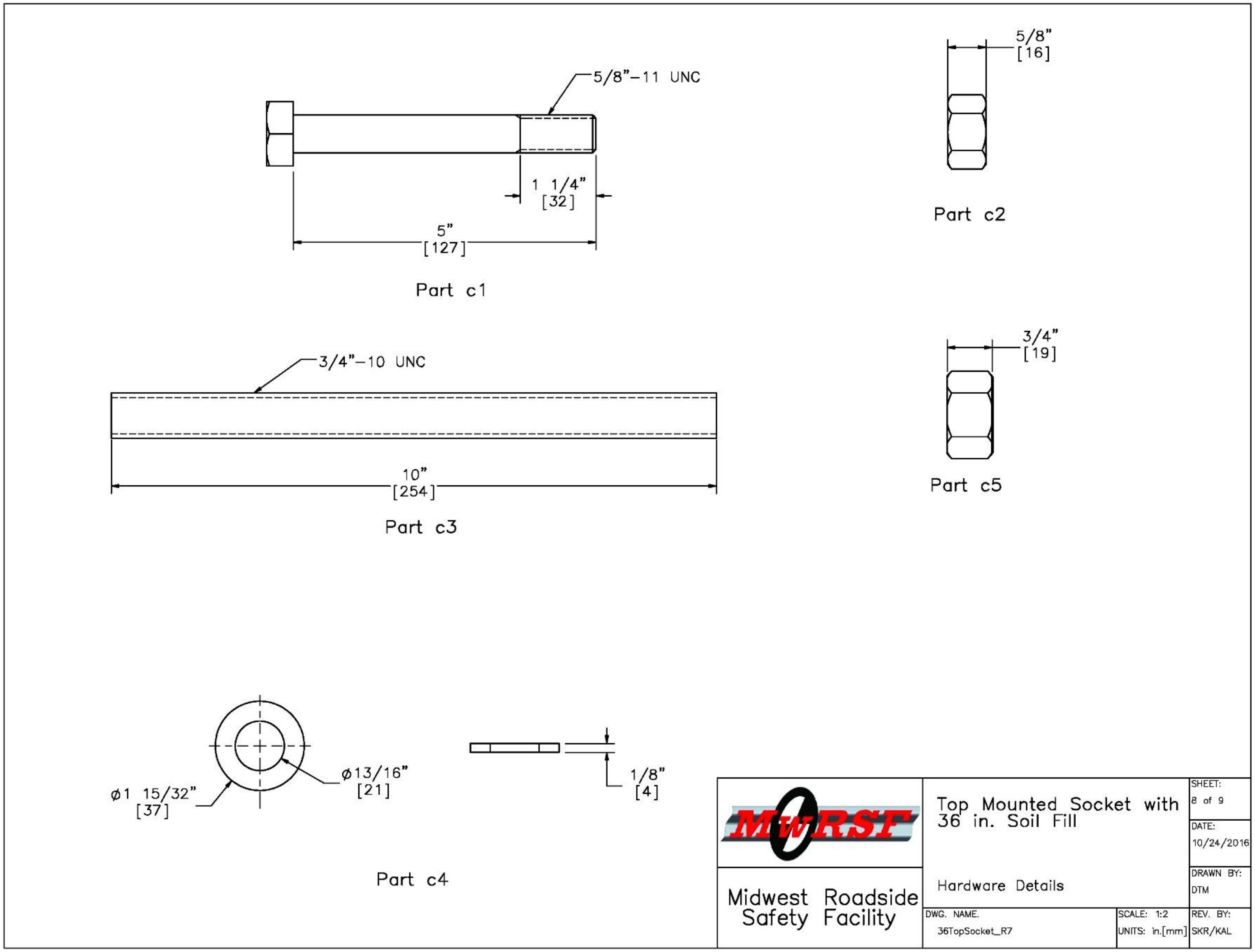


Figure 38. Steel Tube Socket for 36-in. (914-mm) Soil Fill, Connection Hardware, Test Nos. TMS-2 and TMS-3

Item No.	QTY.	Description	Material Specification	Galvanization Specification (See Note 1)	Hardware Guide Designation
a1	2	10"x11"x1/2" [254x279x13] Steel Plate	ASTM A572 Grade 50	AASHTO M111 (ASTM A123)	–
a2	2	HSS 4"x4"x3/8" [102x102x9.5] Tube, 37 1/2" [953] Long	ASTM A500 Grade B	AASHTO M111 (ASTM A123)	–
a3	4	6"x29"x1/4" [152x737x6.4] Steel Plate	ASTM A572 Grade 50	AASHTO M111 (ASTM A123)	–
a4	4	3"x3"x3/8" [76x76x9.5] Steel Gusset	ASTM A572 Grade 50	AASHTO M111 (ASTM A123)	–
a5	2	S3x5.7 [S76x8.5], 44" [1118] Long	ASTM A572 Gr. 50, ASTM A992, ASTM A209 Gr. 50	AASHTO M111 (ASTM A123)	PSF01
a6	8	2 3/4"x1"x1/4" [70x25x6] Post Standoff	ASTM A36	AASHTO M111 (ASTM A123)	PSF01
b1	1	Simulated Culvert with 36" Soil Fill	–	–	–
c1	2	5/8" [16] Dia. UNC, 5" [127] Long Heavy Hex Bolt	ASTM A325 Type 1	AASHTO M232 (ASTM A153)	FBX16b
c2	2	5/8" [16] Dia. UNC Heavy Hex Nut	ASTM A563DH	AASHTO M232 (ASTM A153)	FBX16b
c3	8	3/4" [19] Dia. UNC, 10" [254] Long Threaded Rod	ASTM A449	AASHTO M232 (ASTM A153)	FRR20b
c4	8	3/4" [19] Dia. Hardened Round Washer	ASTM F436 Type 1	AASHTO M232 (ASTM A153)	FWC20b
c5	8	3/4" [19] Dia. UNC Heavy Hex Nut	ASTM A563DH	AASHTO M232 (ASTM A153)	FNX20b
–	–	Epoxy Adhesive	Min. bond strength of 1,305 psi [9.0 MPa]	–	–

Notes: (1) Steel components do not need to be galvanized for testing.

MwRSF

Midwest Roadside Safety Facility

Top Mounted Socket with 36 in. Soil Fill

Bill of Materials

SHEET: 9 of 9

DATE: 10/24/2016

DRAWN BY: DTM

DWG. NAME. 36TopSocket_R7

SCALE: None UNITS: in.[mm]

REV. BY: SKR/KAL

Figure 39. Steel Tube Socket for 36-in. (914-mm) Soil Fill, Bill of Materials, Test Nos. TMS-2 and TMS-3

Figure 40. Installation Photographs, Steel Tube Sockets, Test Nos. TMS-2 and TMS-3

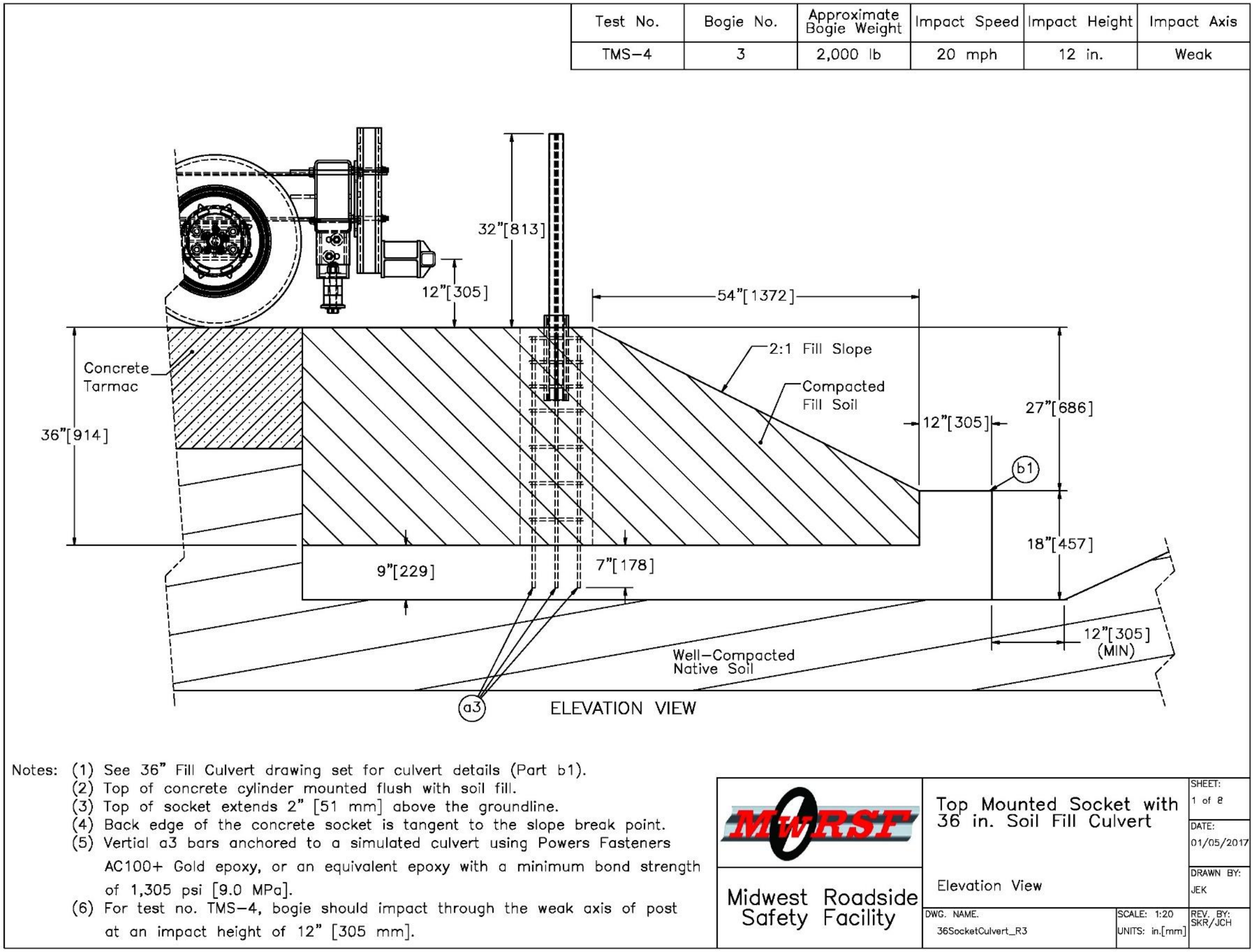
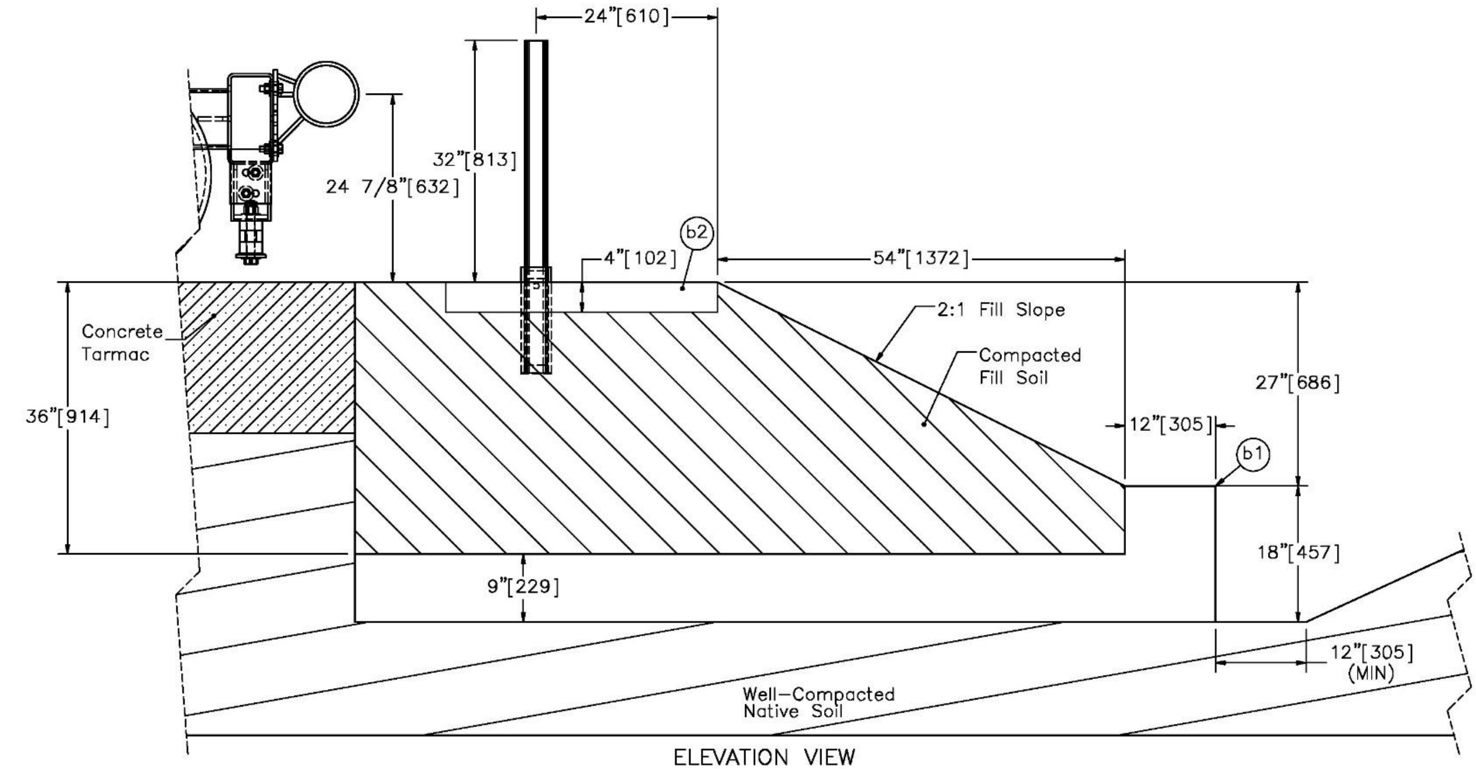


Figure 41. Cylindrical Concrete Foundation for 36-in. (914-mm) Soil Fill, Test Layout, Test No. TMS-4

Test No.	Bogie No.	Approximate Bogie Weight	Impact Speed	Impact Height	Impact Axis
TMS-5	2	5,000 lb	20 mph	24 7/8"	Strong



Notes: (1) See 36" Fill Culvert drawing set for culvert details (Part b1).
(2) Top of socket extends 2" [51 mm] above the groundline.
(3) Back edge of the concrete pad (Part b2) is at the slope break point.
(4) For test no. TMS-5, bogie should impact through the strong axis of two posts spaced 37 1/2" [953 mm] apart at an impact height of 24 7/8" [632 mm].

Midwest Roadside Safety Facility

Top Mounted Socket with 36 in. Soil Fill Culvert

Elevation View

SHEET: 2 of 8

DATE: 01/05/2017

DRAWN BY: JEK

DWG. NAME. 36SocketCulvert_R3

SCALE: 1:20
UNITS: in.[mm]

REV. BY: SKR/JCH

Figure 42. Cylindrical Slab on 36-in. (914-mm) Soil Fill, Test Layout, Test No. TMS-5

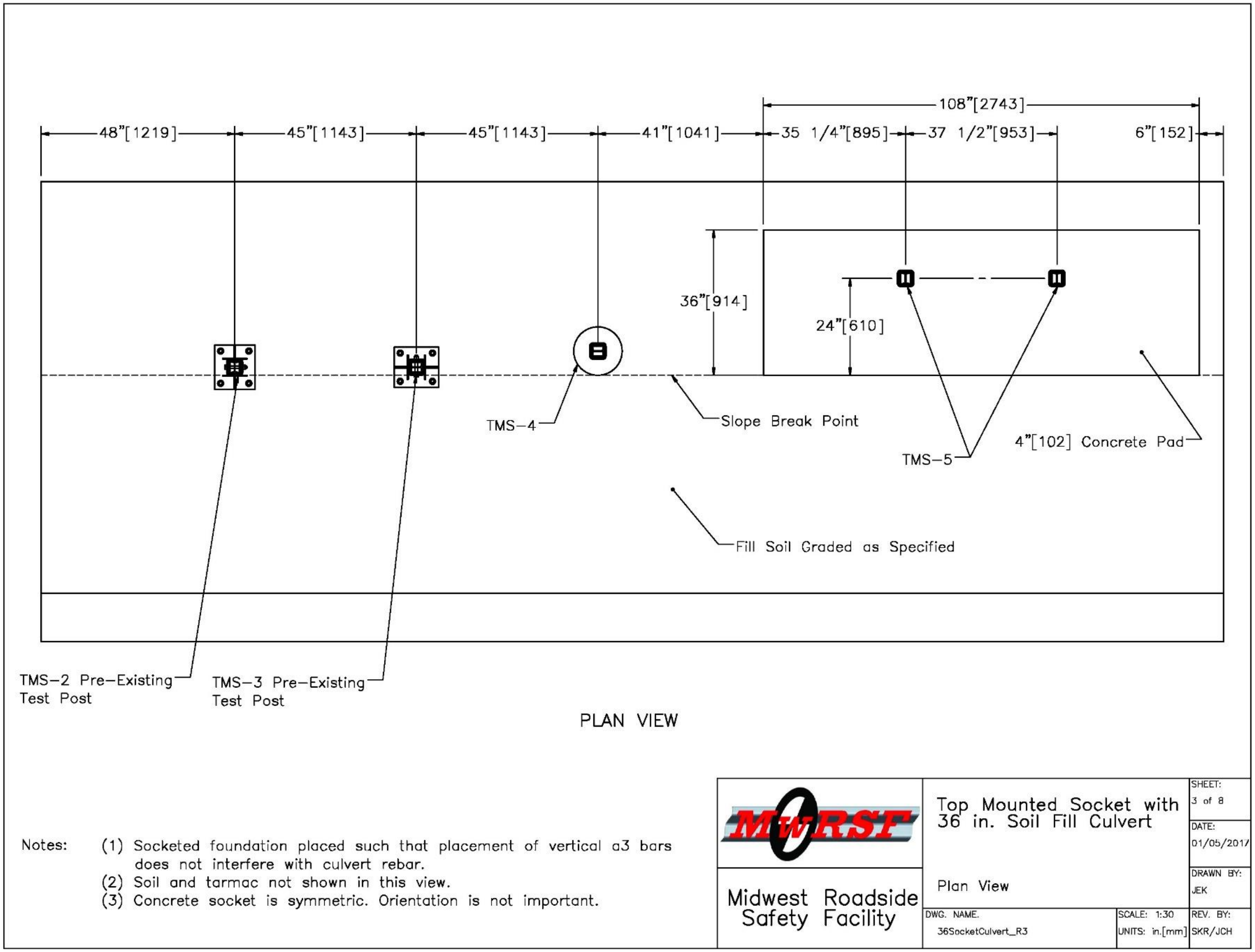


Figure 43. Test Installation Layout on 36-in. (914-mm) Soil Fill Culvert, Test Nos. TMS-2 through TMS-5

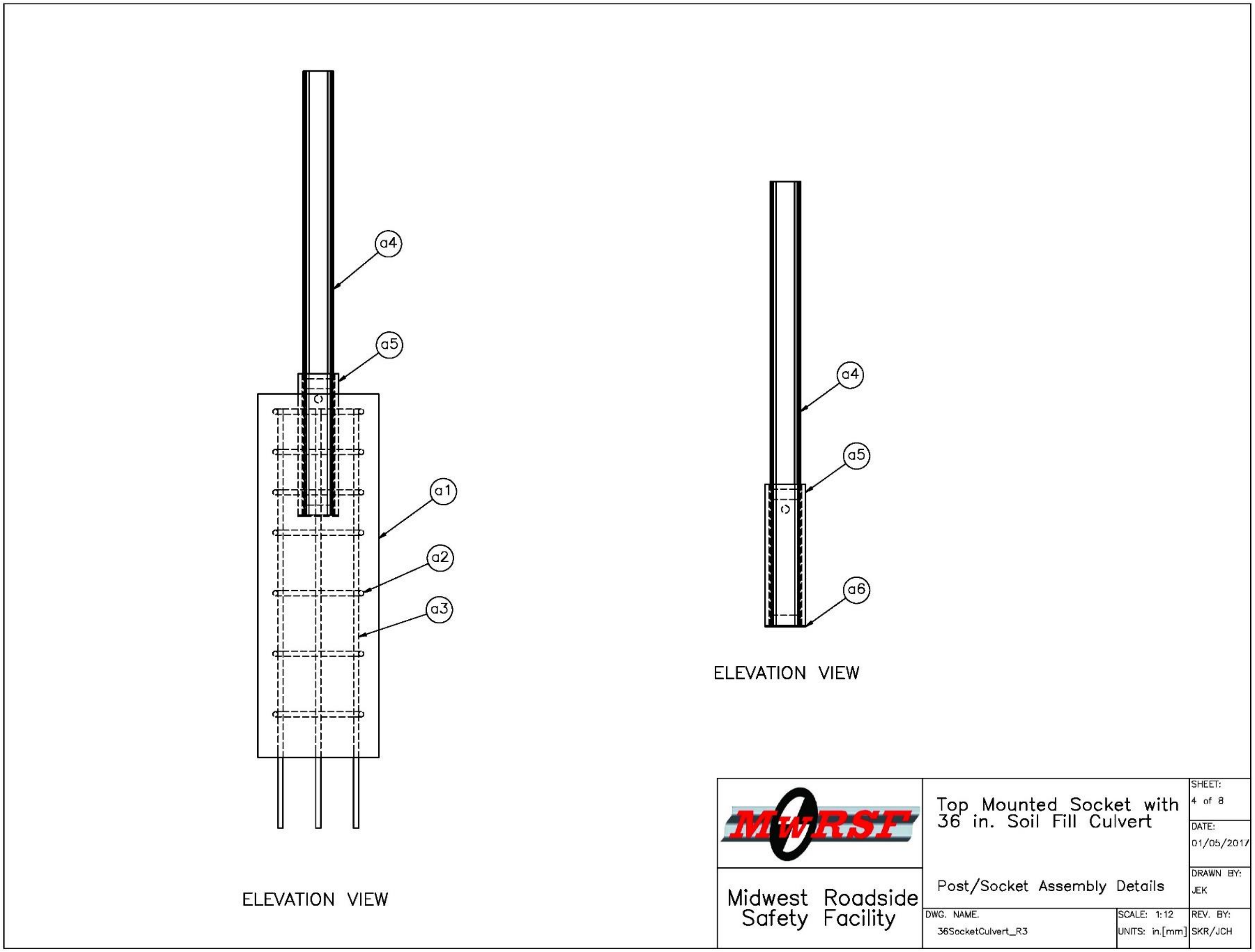


Figure 44. Post and Socket Configuration Details, Test Nos. TMS-4 and TMS-5

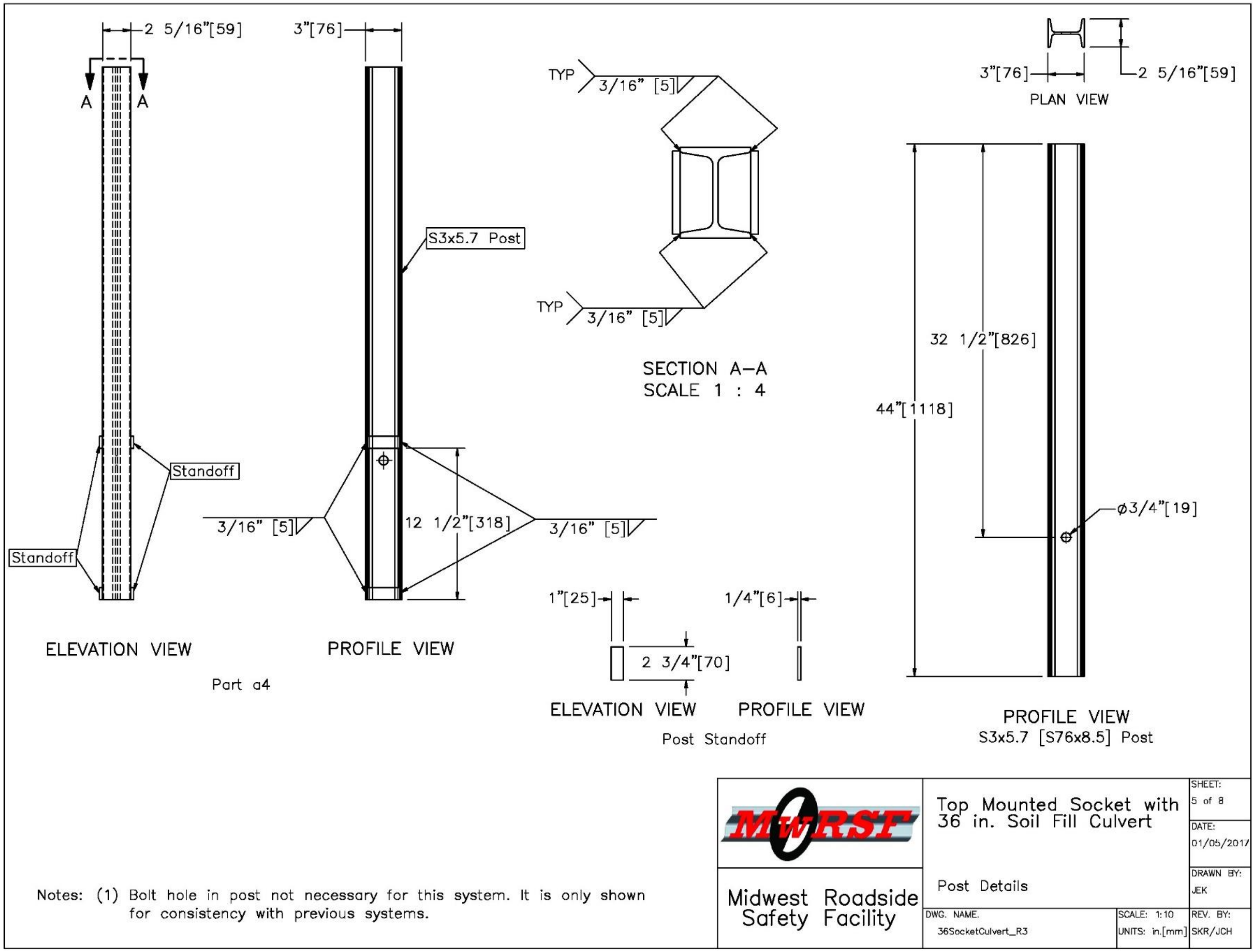


Figure 45. Post Assembly Details, Test Nos. TMS-4 and TMS-5

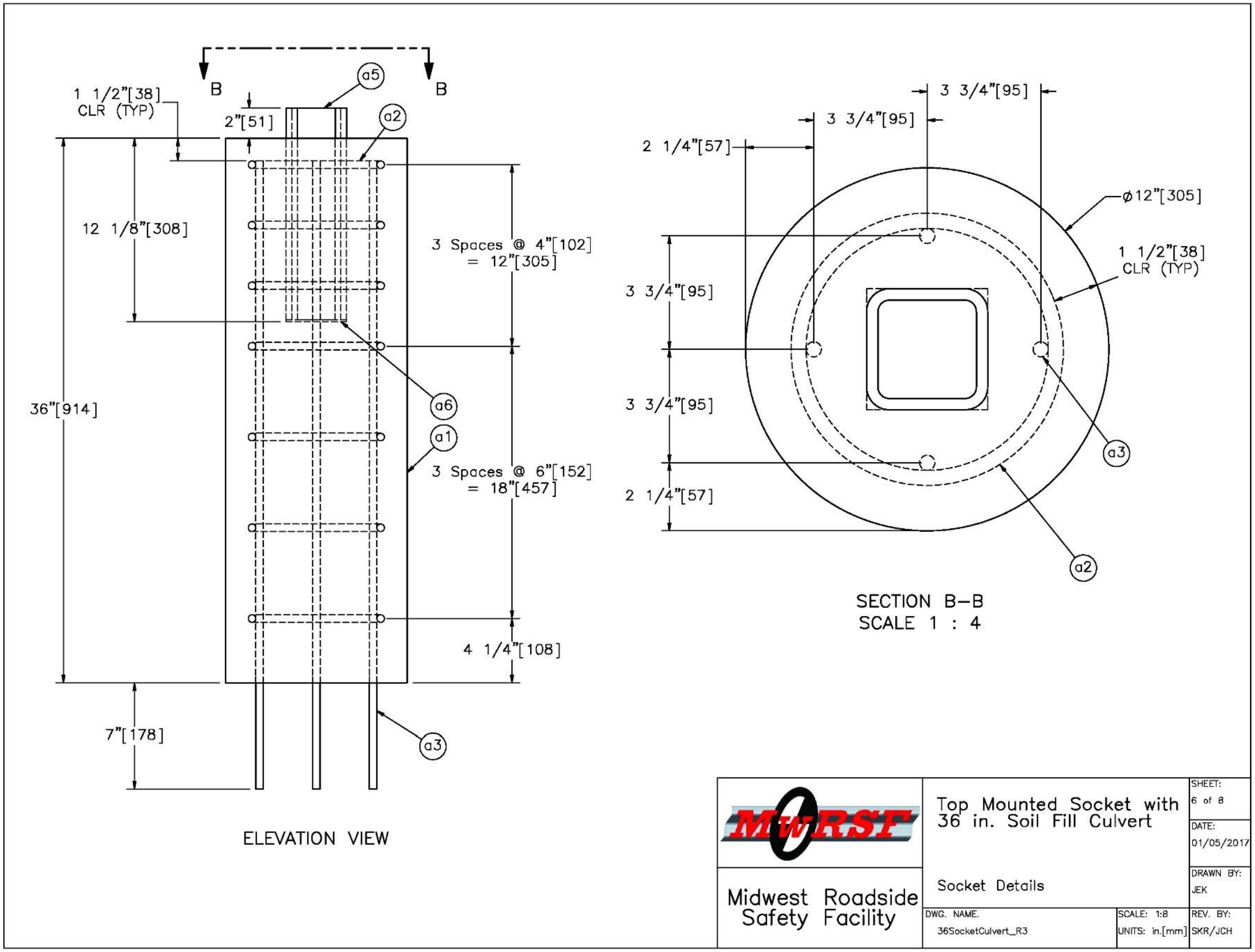
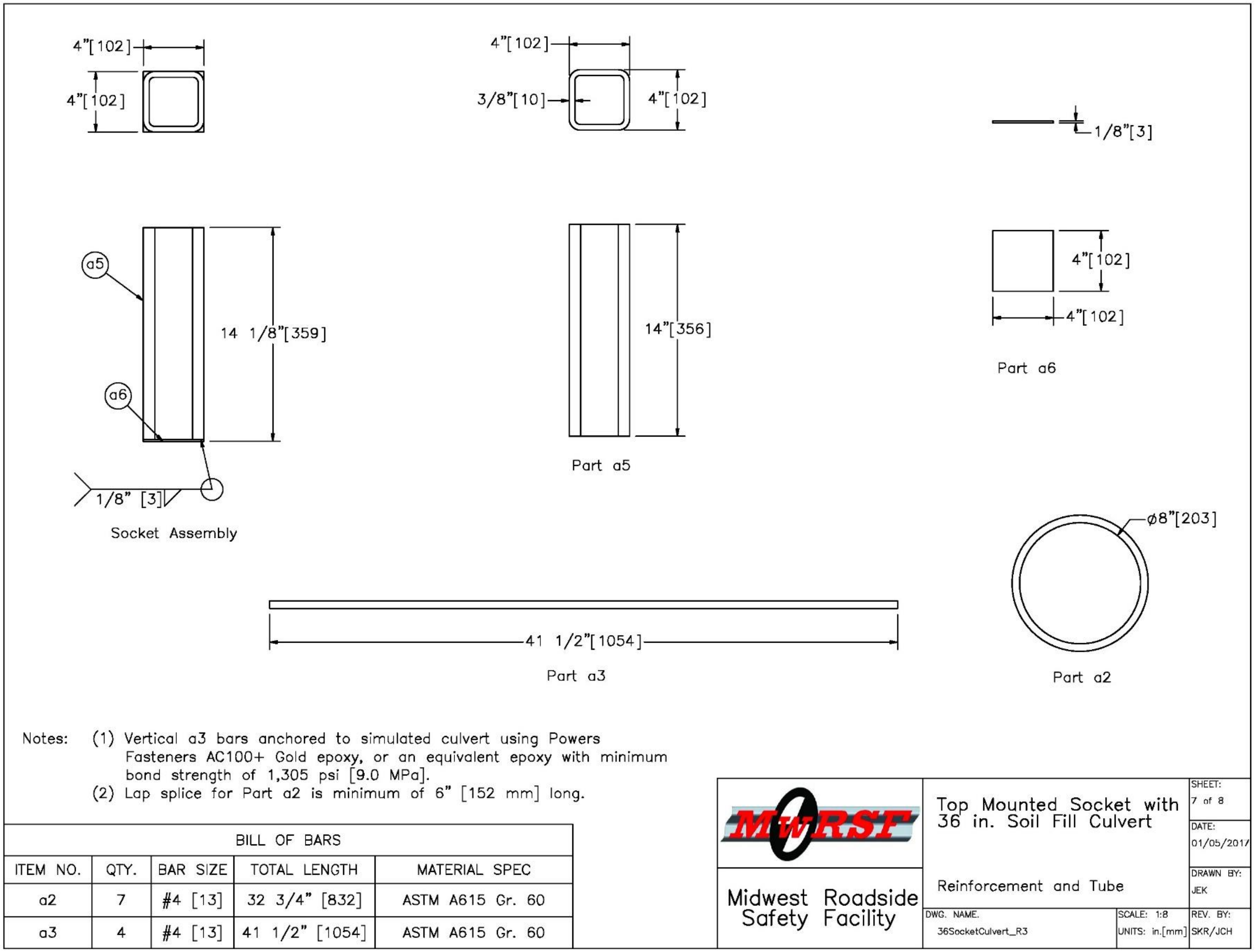


Figure 46. Cylindrical Concrete Foundation for 36-in. (914-mm) Soil Fill, Design Details, Test No. TMS-4



BILL OF BARS

ITEM NO.	QTY.	BAR SIZE	TOTAL LENGTH	MATERIAL SPEC
a2	7	#4 [13]	32 3/4" [832]	ASTM A615 Gr. 60
a3	4	#4 [13]	41 1/2" [1054]	ASTM A615 Gr. 60

Figure 47. Cylindrical Concrete Foundation for 36-in. (914-mm) Soil Fill, Component Details, Test No. TMS-4

Item No.	QTY.	Description	Material Spec	Galvanization Spec	Hardware Guide
a1	1	Concrete Shaft, 36" [914] Long	Min 3,500 psi [24 MPa] Compressive Strength	–	–
a2	7	#4 Circular Rebar, 8" [203] ID	ASTM A615 Gr. 60	Epoxy–Coated	–
a3	4	#4 Rebar, 41 1/2" [1,054] Long	ASTM A615 Gr. 60	Epoxy–Coated	–
a4	3	S3x5.7 [S76x8.5], 44" [1,245] Long Post and Standoffs	Post – ASTM A572 Gr. 50 or ASTM A992 or ASTM A209 Gr. 50 Standoff – ASTM A36	*AASHTO M111 (ASTM A123)	PSF01
a5	3	HSS 4"x4"x3/8" [HSS 102x102x9.5], 14" [406] Long	ASTM A500 Gr. B	*AASHTO M111 (ASTM A123)	–
a6	3	4"x4"x1/4" [102x102x6] Steel Plate	ASTM A36	*AASHTO M111 (ASTM A123)	–
b1	1	Simulated Culvert with 36" [914] Soil Fill	–	–	–
b2	1	108"x36"x4" [2,743x914x102] Concrete Pad	Min. f'c = 4,000 psi [27.6 MPa]	–	–
–	1	Epoxy Adhesive	Min. bond strength of 1,305 psi [9.0 MPa]	–	–

* Steel post and socket components do not need to be galvanized for testing purposes.

Midwest Roadside Safety Facility

Top Mounted Socket with 36 in. Soil Fill Culvert

Bill of Materials

SHEET: 8 of 8

DATE: 01/05/2017

DRAWN BY: JEK

DWG. NAME. 36SocketCulvert_R3

SCALE: None UNITS: in.[mm]

REV. BY: SKR/JCH

Figure 48. 36-in. (914-mm) Concrete Foundation and Concrete Slab, Bill of Materials, Test Nos. TMS-4 and TMS-5

Figure 49. Installation Photographs, 36-in. (914-mm) Concrete Foundation, Test No. TMS-4

Figure 50. Installation Photographs, Concrete Slab, Test No. TMS-5

5 COMPONENT TESTING RESULTS AND DISCUSSION

5.1 Testing Results

Five dynamic component tests were conducted on the various design concepts for top-mounted sockets on concrete box culverts. The accelerometer data for each test was processed in order to obtain force vs. deflection and energy vs. deflection curves. Although both transducers produced similar results, the forces and bogie displacements described herein were calculated from the SLICE-2 accelerometer. Test results from each individual transducer are provided in Appendix B. Socket displacements were in reference to the top of the socket and were measured utilizing the high-speed video. A summary of the testing results is provided in Section 5.2. Weather conditions for each test as recorded by the National Oceanic and Atmospheric Administration (station 14939/LNK) are shown in Table 3.

Table 3. Weather and Atmospheric Conditions, Lateral Impact Testing

Test No.	Test Date	Temp. (˚F)	Hum. (%)	Wind Speed (mph)	Sky Conditions	Pavement Surface	Previous 3-Day Precip. (in.)	Previous 7-Day Precip. (in.)
TMS-1	12/12/2016	38	48	13	Clear	Dry	0	0
TMS-2	12/12/2016	38	48	13	Clear	Dry	0	0
TMS-3	12/13/2016	24	33	0	Clear	Dry	0	0
TMS-4	01/20/2017	45	93	4.7	Clear	Dry	0	0
TMS-5	01/20/2017	45	93	4.7	Clear	Dry	0	0

5.1.1 Test No. TMS-1

Test no. TMS-1 was conducted on a cylindrical concrete foundation with a 12.5-in. (318-mm) soil fill depth. During test no. TMS-1, the bogie impacted the post at a height of 24⅞ in. (632 mm), a speed of 21.7 mph (34.9 km/h), and an angle of 90 degrees, causing strong-axis bending in the post. Upon impact, the post began to deflect backward, while motion to the socket and concrete foundation was minimal. By 0.010 s, a plastic hinge had formed in the post at the top of the socket. The fill at the back side of the socket had minimal lateral displacement. At 0.075 s after impact, the post began to tear adjacent to the upper post standoff welded to the flanges. The post continued to bend backward until the bogie overrode the post at 0.080 s after impact.

Upon post-test examination, the socket and attachment hardware were found to be intact and free from plastic deformations. Concrete shear cracks were observed on the concrete foundation extending from the back corners of the socket, but were not significant enough to affect the structural integrity of the foundation. The socket had negligible dynamic movement and no permanent set displacements. Thus, the socket would not require repairs if a new post were to be installed in the socket. The post was bent over and torn at the top of the socket. The entire front flange and web of the post were torn just above the post standoffs. No damage was observed to the simulated culvert or attachment hardware.

Force vs. deflection and energy vs. deflection curves were created from the accelerometer data, as shown in Figure 51. The post and socket assembly provided a peak resistance of 7.6 kips (33.8 kN) and maintained a relatively constant force of approximately 7 kips (31 kN) over the first 12 in. (305 mm) of deflection. The resistance then steadily decreased through the remainder of the test. The post and socket assembly absorbed 125.0 k-in. (14.1 kJ) of energy before the bogie overrode the post at a deflection of 26.7 in. (678 mm). Time-sequential photographs are shown in Figures 52 and 53, while post-impact photographs are shown in Figure 54.

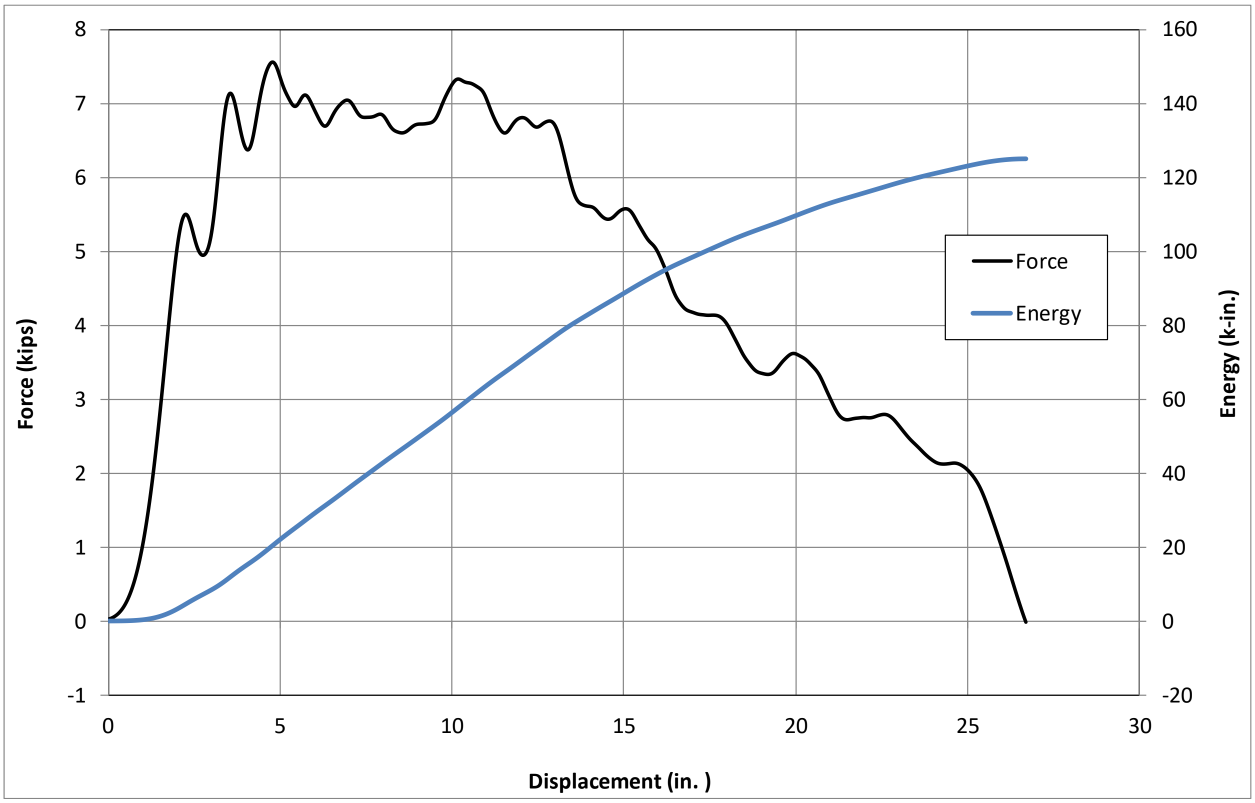
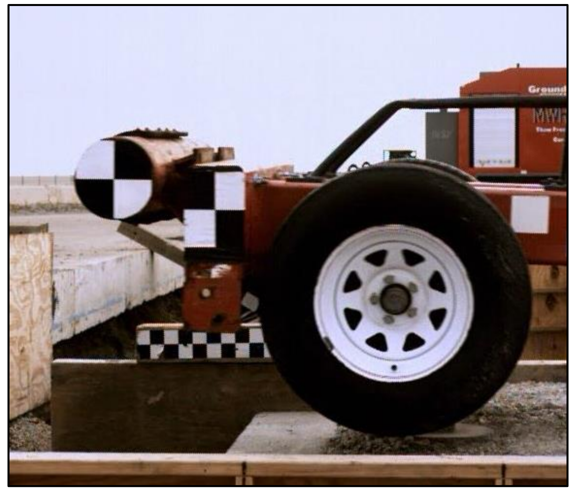


Figure 51. Force vs. Deflection and Energy vs. Deflection, Test No. TMS-1

IMPACT



0.120 sec

0.040 sec

0.160 sec

0.080 sec

0.200 sec

Figure 52. Time-Sequential Photographs, Test No. TMS-1

IMPACT

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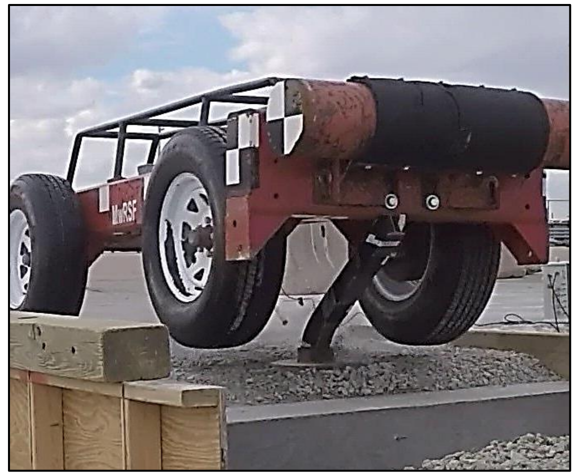

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Figure 53. Additional Time-Sequential Photographs, Test No. TMS-1

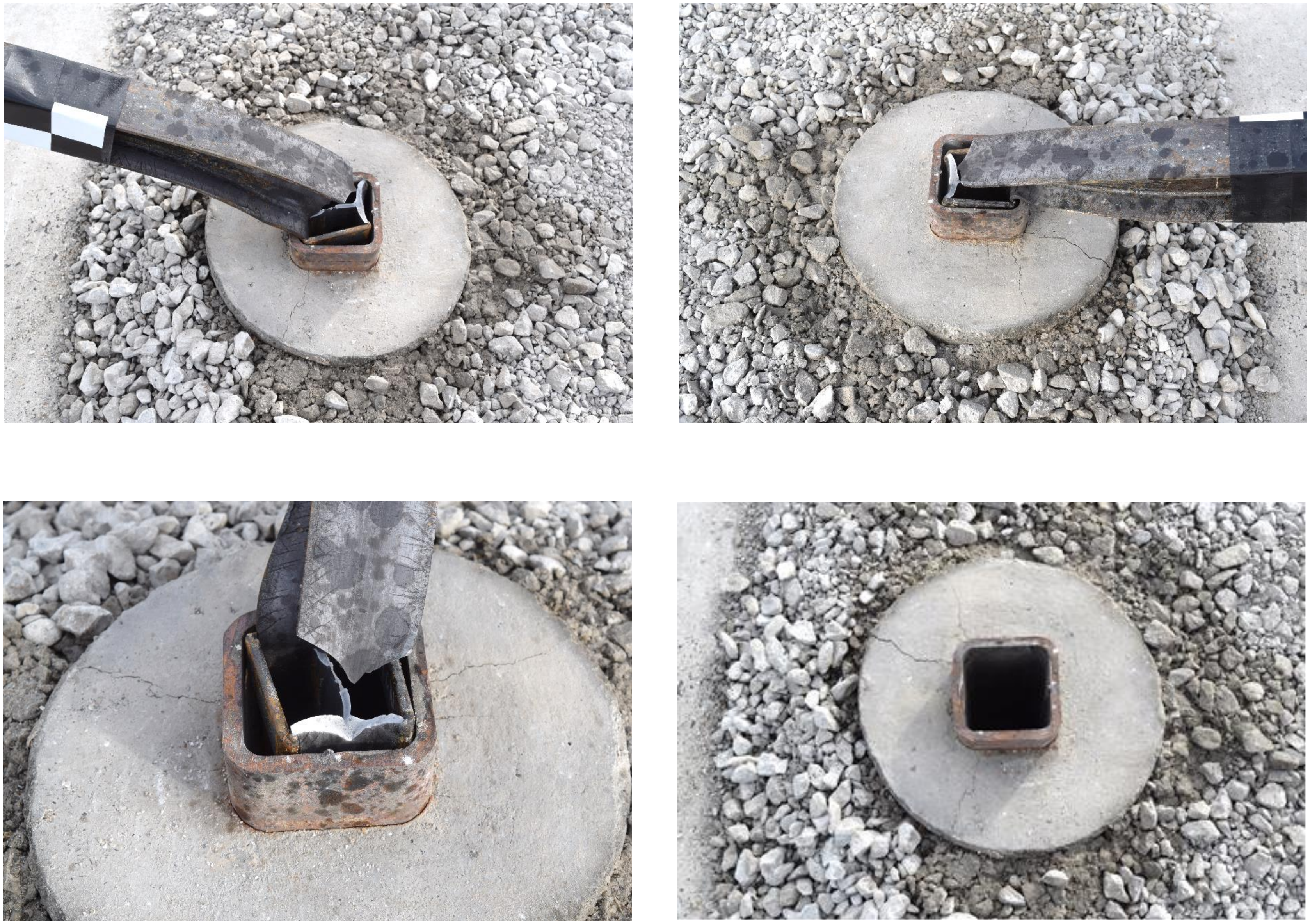

Figure 54. Post-Impact Photographs, Test No. TMS-1

5.1.2 Test No. TMS-2

Test no. TMS-2 was conducted on a steel tube socket assembly with a 36-in. (914-mm) soil fill depth. During test no. TMS-2, the bogie impacted the post at a height of 24⅞ in. (632 mm), a speed of 21.1 mph (33.9 km/h), and an angle of 90 degrees, causing strong-axis bending in the post. At 0.004 s after impact, the top of the socket began to shift backward and displace the soil behind the socket. By 0.010 s, a plastic hinge had formed in the post adjacent to the top of the socket. At 0.028 s after impact, the socket reached its maximum lateral deflection of 1.0 in. (25 mm). The post continued to bend over until the bogie overrode the post at 0.088 s after impact.

Upon post-test examination, the socket and attachment hardware were found to be intact with minimal plastic deformations. The permanent set displacement of the socket was 0.52 in. (13 mm), which was within the 1-in. (25mm) limit and not significant enough to require repairs if a new post were to be installed in the socket. The post was bent backward and slightly twisted. A small tear was observed in the front flange of the post adjacent to the welded post standoff. No damage was observed to the simulated culvert or attachment hardware.

Force vs. deflection and energy vs. deflection curves were created from the accelerometer data, as shown in Figure 55. The post and socket assembly provided a peak resistance of 6.9 kips (30.7 kN) and maintained a relatively constant force of approximately 6 kips (27 kN) over the first 15 in. (381 mm) of deflection. The resistance then steadily decreased through the remainder of the test. The post and socket assembly absorbed 127.9 k-in. (14.5 kJ) of energy before the bogie overrode the post at a deflection of 28.1 in. (714 mm). Time-sequential photographs are shown in Figures 56 and 57, while post-impact photographs are shown in Figure 58.

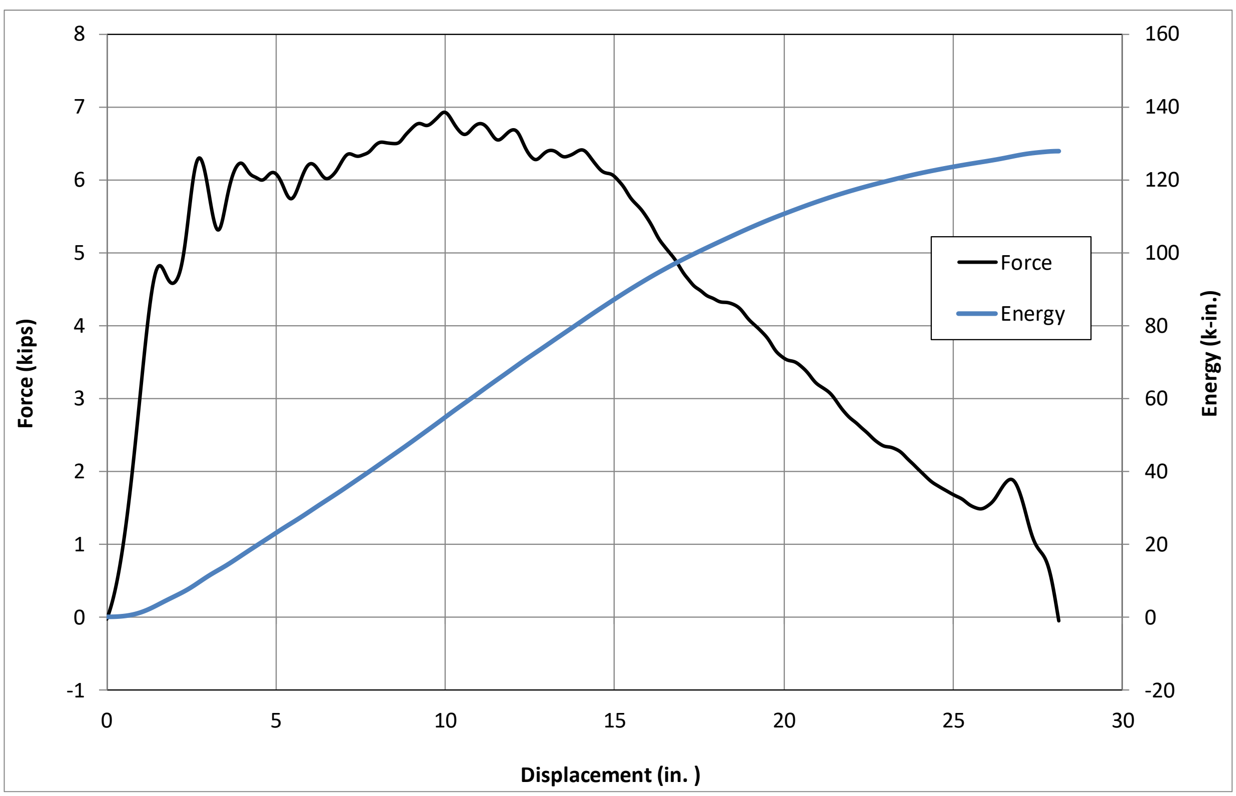

Figure 55. Force vs. Deflection and Energy vs. Deflection, Test No. TMS-2

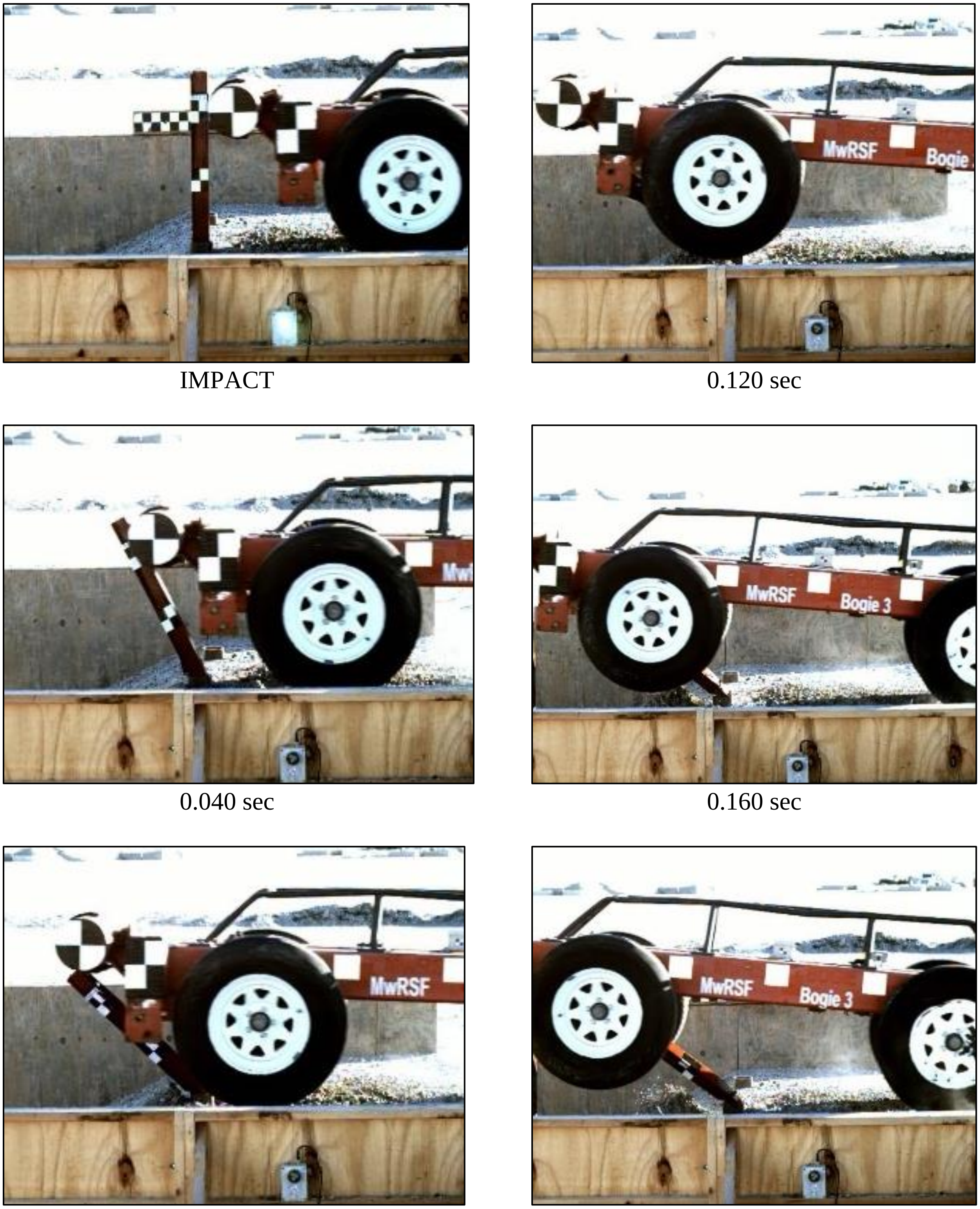

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Figure 56. Time-Sequential Photographs, Test No. TMS-2

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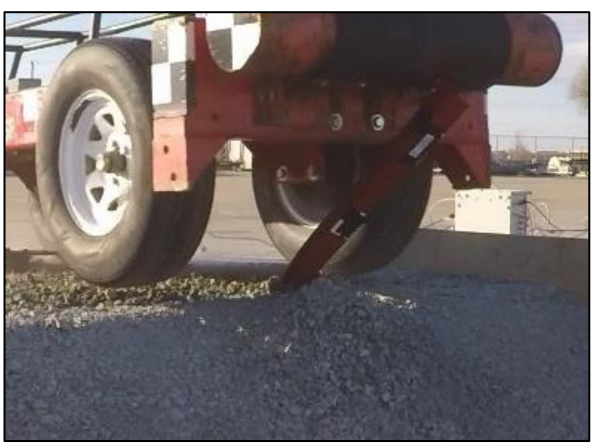

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Figure 57. Additional Time-Sequential Photographs, Test No. TMS-2

Figure 58. Post-Impact Photographs, Test No. TMS-2

5.1.3 Test No. TMS-3

Test no. TMS-3 was conducted on a steel tube socket assembly with a 36-in. (914-mm) soil fill depth. During test no. TMS-3, the bogie impacted the post with an impact height of 12 in. (305 mm), a speed of 21.3 mph (34.3 km/h), and an angle of 0 degrees, causing weak-axis bending in the post. At 0.006 s after impact, the top of the socket began to shift backward and displace the soil behind the socket. By 0.014 s, a plastic hinge had formed in the post adjacent to the top of the socket. At 0.024 s after impact, the socket reached its maximum deflection of 0.85 in. (22 mm). The post continued to bend over until the bogie overrode the post at 0.096 s after impact.

Upon post-test examination, the socket and attachment hardware were found to be intact with only minimal plastic deformations. The socket's permanent set displacement of 0.23 in. (6 mm) was within the 1-in. (25-mm) limit and not significant enough to require repairs if a new post were to be installed in the socket. The post was bent over with a plastic hinge formed at the top of the socket. No damage was observed to the simulated culvert or attachment hardware.

Force vs. deflection and energy vs. deflection curves were created from the accelerometer data, as shown in Figure 59. The post and socket assembly provided a peak resistance of 12.3 kips (54.7 kN) before rapidly dropping below 6 kips (26.7 kN) and steadily declining through the rest of the impact event. The post and socket assembly absorbed 99.4 k-in. (11.2 kJ) of energy before the bogie overrode the post at a deflection of 34.0 in. (864 mm). Time-sequential photographs are shown in Figure 60 and 61, while post-impact photographs are shown in Figure 62.

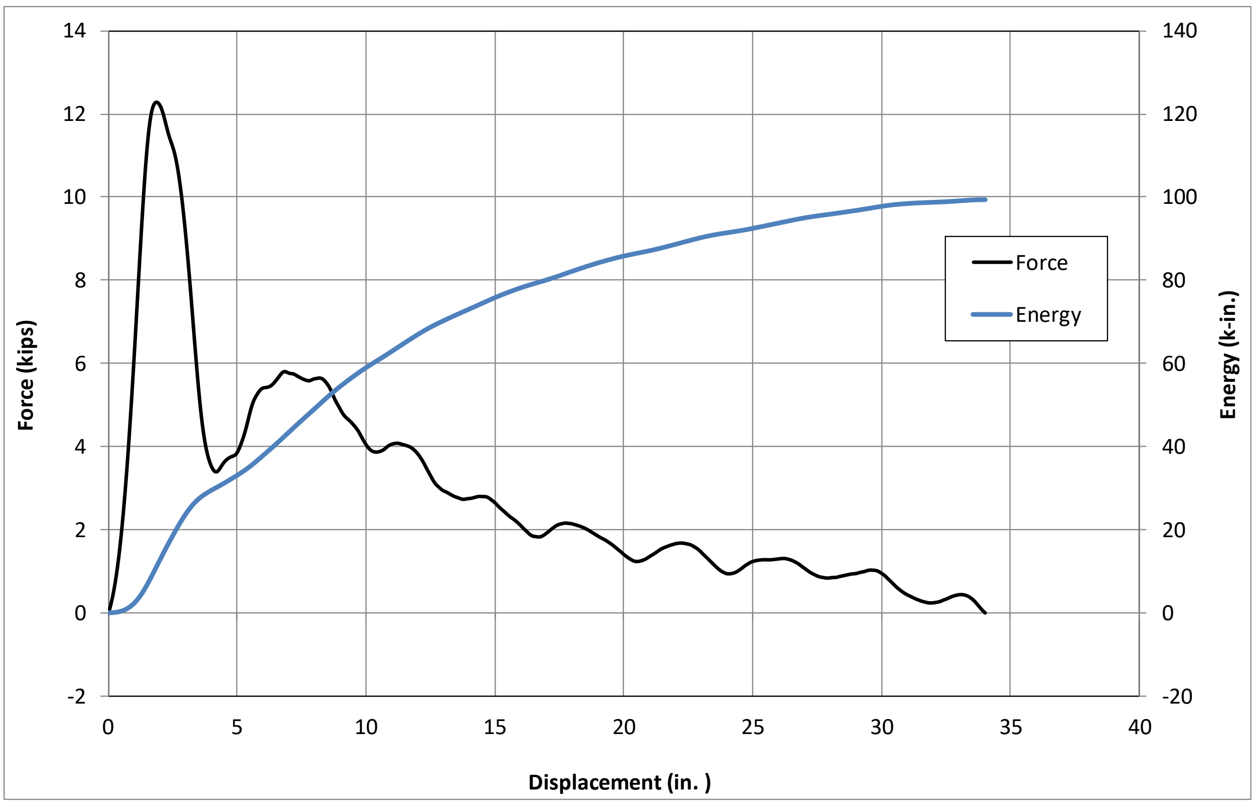

Figure 59. Force vs. Deflection and Energy vs. Deflection, Test No. TMS-3

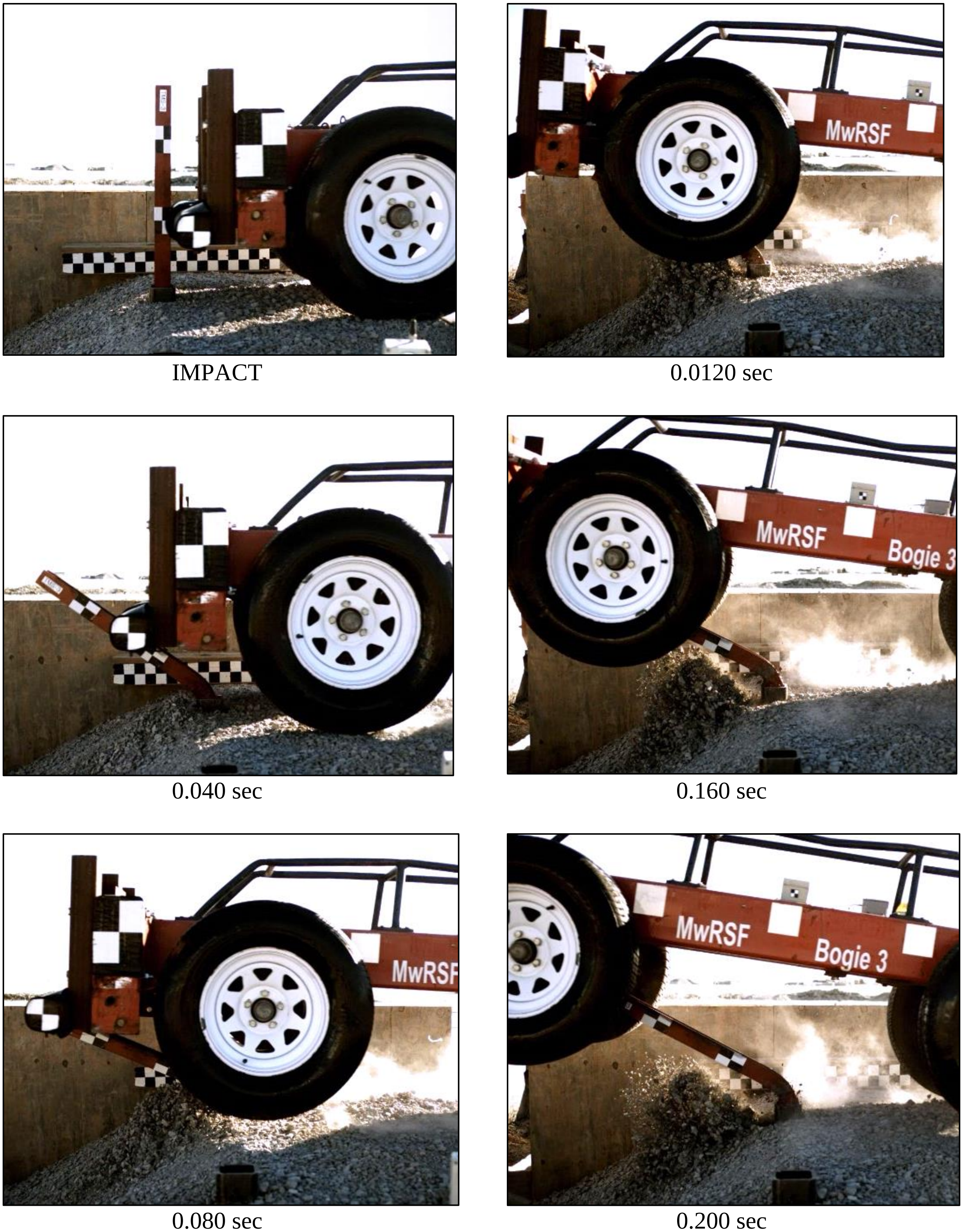

Figure 60. Time-Sequential Photographs, Test No. TMS-3

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Figure 61. Additional Time-Sequential Photographs, Test No. TMS-3

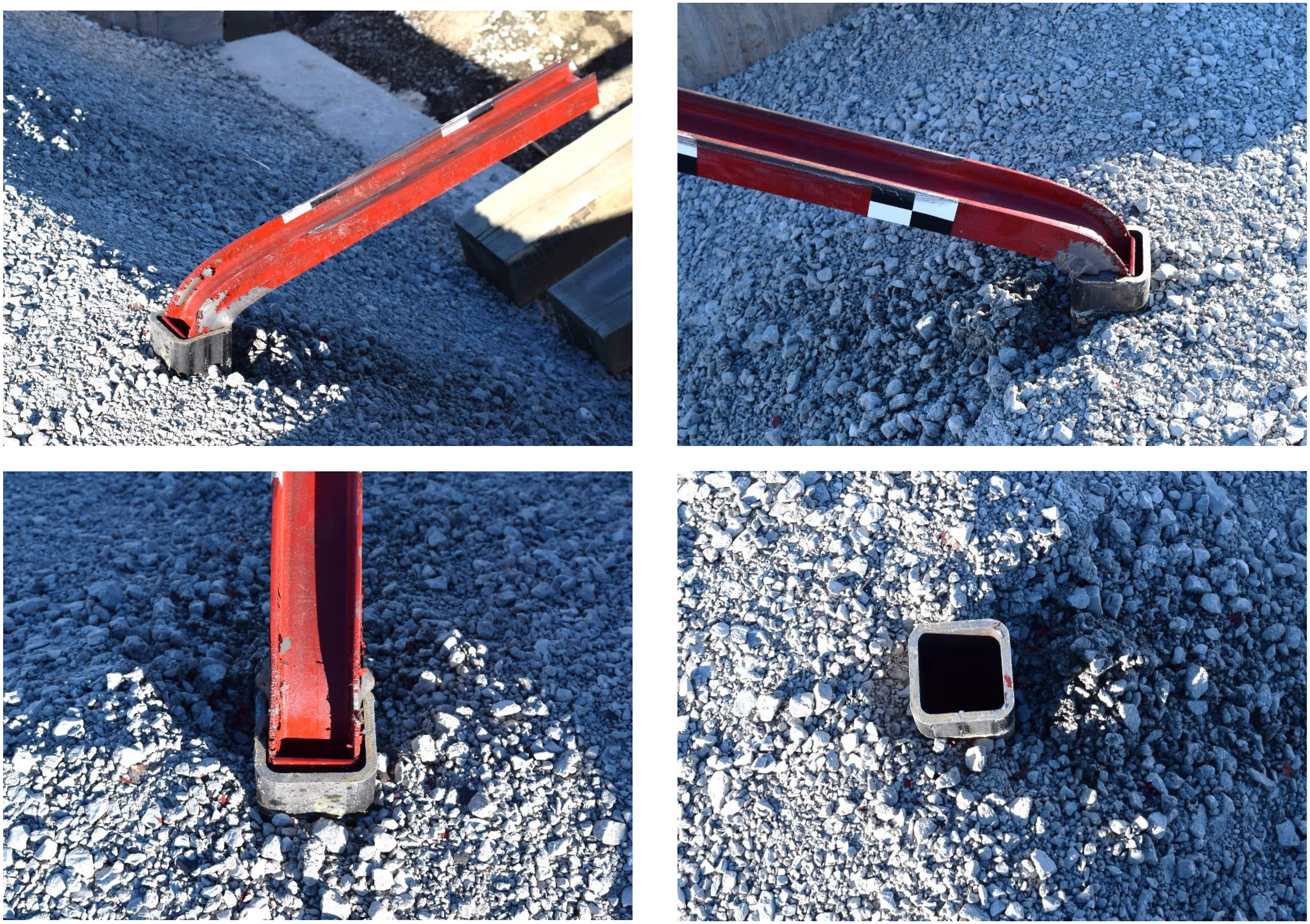

Figure 62. Post-Impact Photographs, Test No. TMS-3

5.1.4 Test No. TMS-4

Test no. TMS-4 was conducted on a cylindrical concrete foundation with a 36-in. (914-mm) soil fill depth. During test no. TMS-4, the bogie impacted the post with an impact height of 12 in. (305 mm), a speed of 25.2 mph (40.7 km/h), and an angle of 0 degrees, causing weak-axis bending in the post. At 0.006 s after impact, the concrete foundation and the socket shifted slightly backward and displaced the soil behind the foundation. By 0.012 s, the socket reached its maximum displacement of 0.25 in. (6 mm), and a plastic hinge had formed in the post adjacent to the top of the socket. The post continued to bend over until the bogie overrode the post at 0.090 s after impact.

Upon post-test examination, the socket and attachment hardware were found to be intact and free from plastic deformations. The concrete foundation and the socket remained undamaged and had a permanent set displacement of 0.06 in. (2 mm), which was not significant enough to require repairs if a new post were to be installed in the socket. The post was bent over adjacent to the top of the socket. No damage was observed to the simulated culvert or attachment hardware.

Force vs. deflection and energy vs. deflection curves were created from the accelerometer data, as shown in Figure 63. The post and socket assembly provided a peak resistance of 13.3 kips (59.2 kN), then dropped quickly to around 6 kips (26.7 kN) and steadily dropped through the remainder of the impact. The post and socket assembly absorbed 116.2 k-in. (13.1 kJ) of energy before the bogie overrode the post at 36.4 in. (925 mm) of deflection. Time-sequential photographs are shown in Figures 64 and 65, while post-impact photographs are shown in Figure 66.

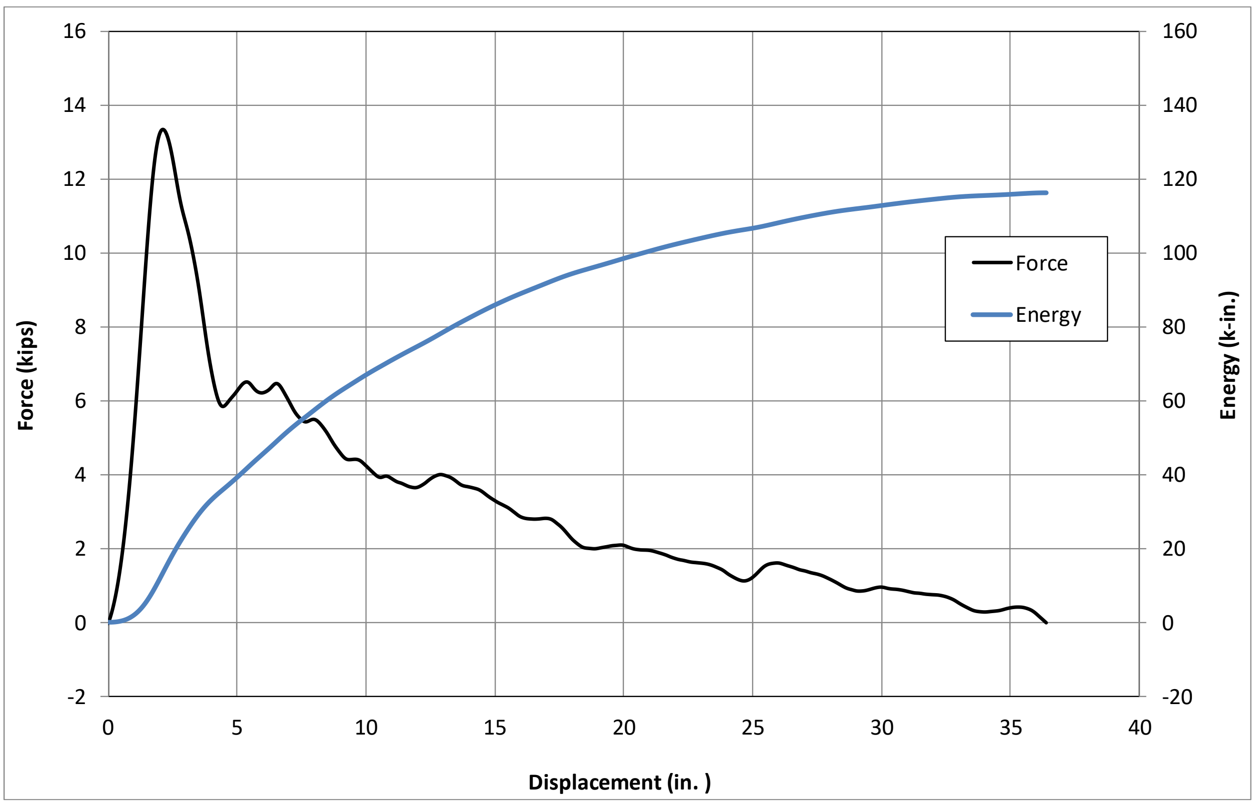

Figure 63. Force vs. Deflection and Energy vs. Deflection, Test No. TMS-4

IMPACT

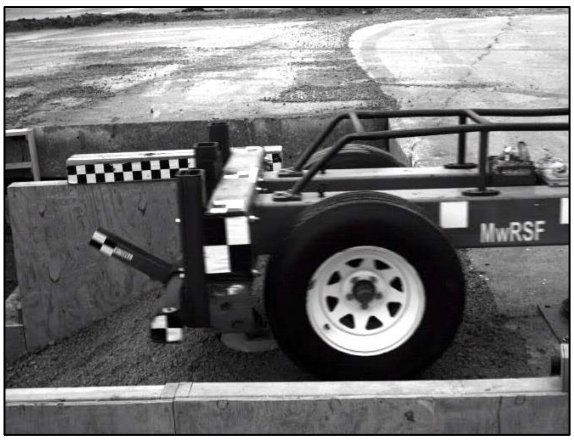

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Figure 64. Time-Sequential Photographs, Test No. TMS-4

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Figure 65. Additional Time-Sequential Photographs, Test No. TMS-4

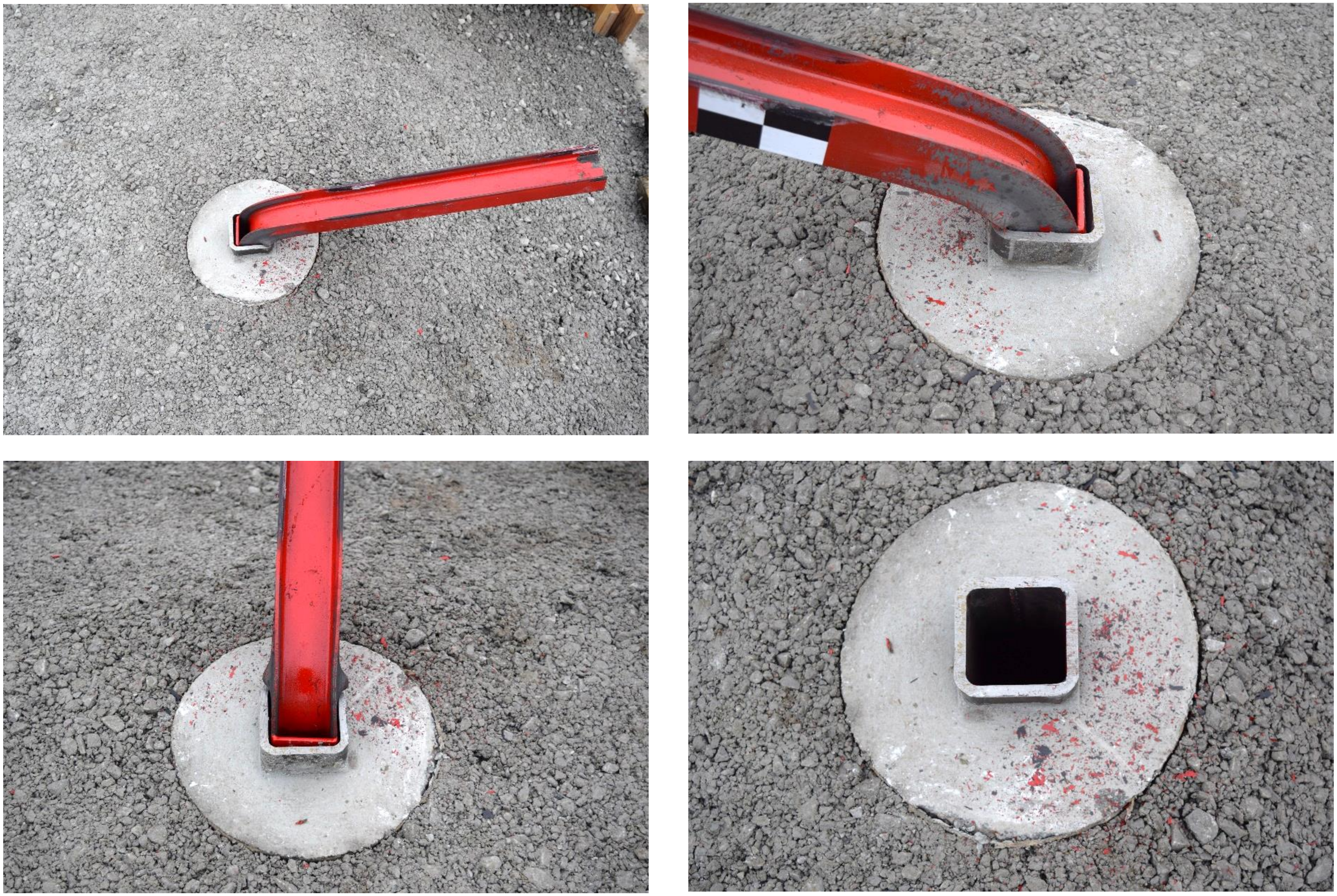

Figure 66. Post-Impact Photographs, Test No. TMS-4

5.1.5 Test No. TMS-5

Test no. TMS-5 was conducted on a dual post installation with the post sockets placed within a 4-in. (102-mm) thick concrete slab. During test no. TMS-5, the bogie impacted the posts at an impact height of 24⅞ in. (632 mm), a speed of 22.9 mph (36.9 km/h), and an angle of 90 degrees, causing strong-axis bending in the posts. At 0.010 s after impact, the concrete slab began to fracture with shear cracks between the sockets. The concrete slab continued to fracture apart as the sockets rotated backward. The posts and sockets continued to rotate until the bogie overrode the posts.

Upon post-test examination, the posts and sockets had sustained only minor plastic deformations. However, the sockets had completely broken free from the concrete slab and rotated 90 degrees backward. The concrete slab was fractured into multiple pieces and would need to be completely replaced if the system were to be repaired. The combined shear loads from the adjacent posts caused a large section of concrete behind the sockets to break off from the slab early in the impact event. Regions of the slab in front of the sockets were then fractured as the socket rotated backward.

Force vs. deflection and energy vs. deflection curves were created from the accelerometer data, as shown in Figure 67. The posts and socket assemblies provided a peak resistance of 13.2 kips (58.7 kN) prior to the slab breaking apart. The test installation absorbed 64.8 k-in. (7.3 kJ) of energy before the bogie overrode the post at a deflection of 15.7 in. (399 mm). Time-sequential photographs are shown in Figure 69, while the post-impact photograph is shown in Figure 70.

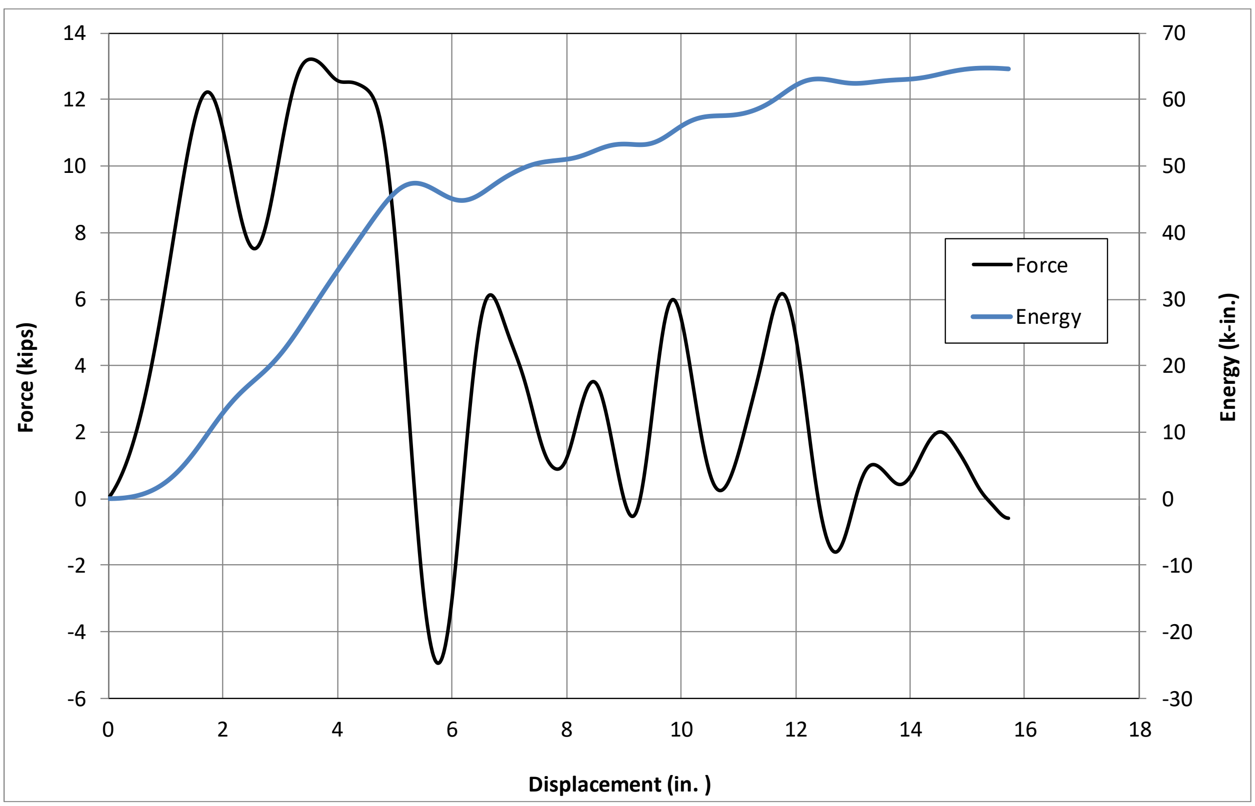

Figure 67. Force vs. Deflection and Energy vs. Deflection, Test No. TMS-5

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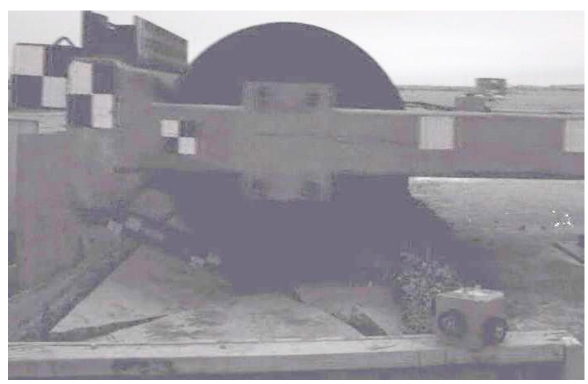

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Figure 68. Time-Sequential Photographs, Test No. TMS-5

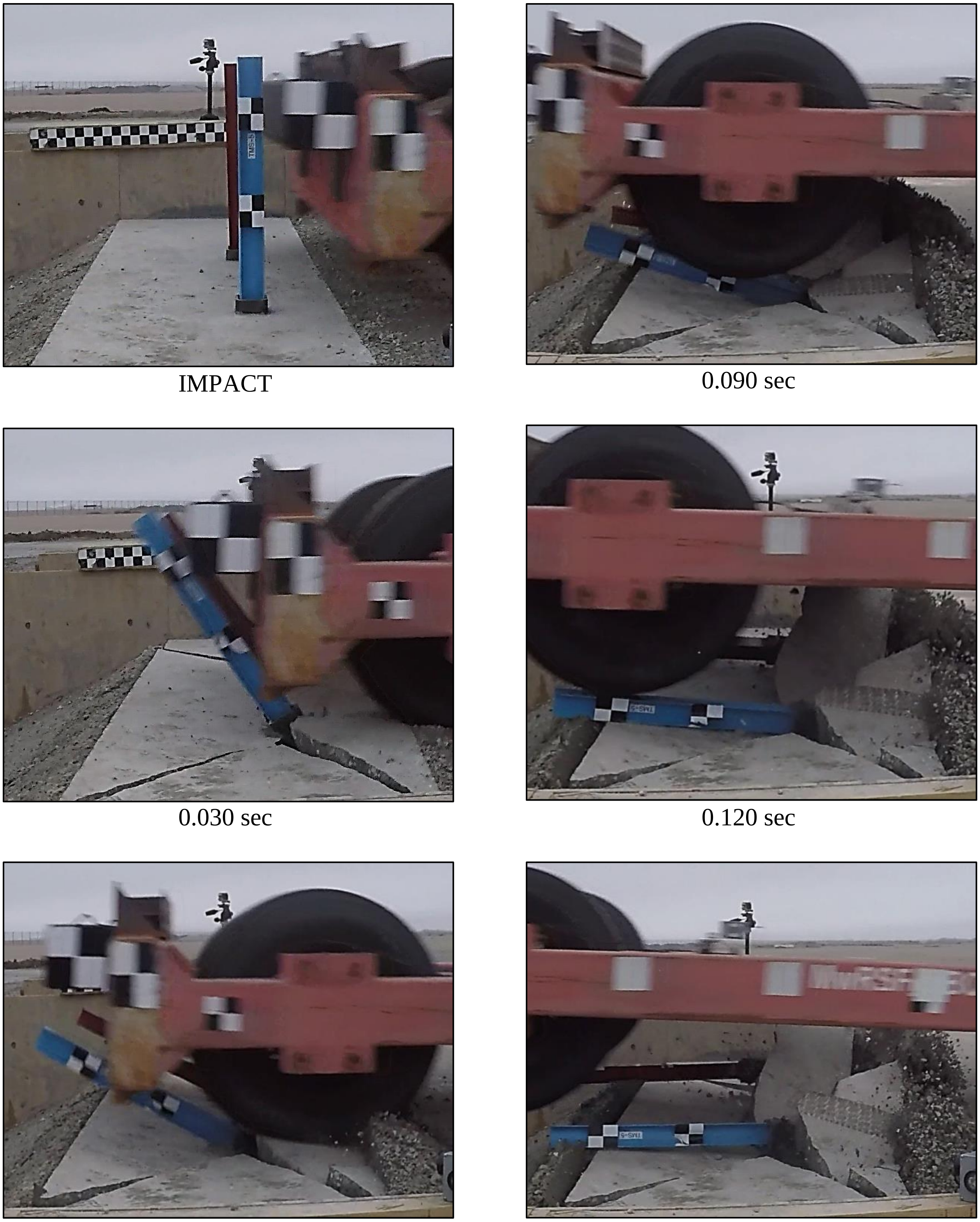

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Figure 69. Additional Time-Sequential Photographs, Test No. TMS-5

Figure 70. Post-Impact Photographs, Test No. TMS-5

5.2 Discussion

A total of five dynamic component tests were conducted on the three design concepts for top-mounted sockets for weak-post MGS on culverts. Testing of both the cylindrical concrete foundations and the steel tube socket assemblies produced favorable results as the test articles received minimal damage, and permanent set displacements were within the desired 1-in. (25-mm) maximum. Testing conducted on the concrete slab design concept resulted in complete failure of the slab as the sockets rotated through and out of the fractured concrete slab. Note, after the tests were conducted, the soil fill was removed to inspect damage below the ground line. No damage was observed to the simulated culverts or socket attachment hardware during any of the tests. A summary of the dynamic component testing is shown in Table 4.

Table 4. Dynamic Component Testing Summary Results

Test No.	Design Concept	Impact Angle	Impact Speed mph (km/h)	Peak Force kips (kN)	Ave. Force (Bogie Dist.) kips (kN)		Total Energy k-in. (kJ)	Max. Deflection of Socket in. (mm)		Failure Mechanism
					@10"	@20"		Dyn.	Perm.	
TMS-1	Concrete Foundation	90° (Lateral)	21.7 (34.9)	7.6 (33.8)	5.6 (24.9)	5.5 (24.5)	125.0 (14.1)	<0.1 (<3)	0 (0)	Post Bending/ Rupture
TMS-2	Steel Socket Assembly	90° (Lateral)	21.1 (33.9)	6.9 (30.7)	5.5 (24.5)	5.5 (24.5)	127.9 (14.5)	1.01 (26)	0.52 (13)	Post Bending
TMS-3	Steel Socket Assembly	0° (Long.)	21.3 (34.3)	12.3 (54.7)	5.9 (26.2)	4.3 (19.1)	99.4 (11.2)	0.85 (22)	0.23 (6)	Post Bending
TMS-4	Concrete Foundation	0° (Long.)	25.2 (40.6)	13.3 (59.2)	6.7 (29.8)	4.9 (21.8)	116.2 (13.1)	0.25 (6)	0.06 (2)	Post Bending
TMS-5	Concrete Slab	90° (Lateral)	22.9 (36.9)	13.2 (58.7)	5.6 (24.9)	-	64.8 (7.3)	-	-	Concrete Slab Fracture

Testing of the cylindrical concrete foundations consisted of a lateral impact with the minimal soil fill depth and a longitudinal impact with the maximum soil fill depth to bracket the behavior of the concrete foundations. These tests resulted in only minor cracking on the top surface of the foundations and negligible permanent set displacements. Thus, these socketed concrete foundations remained essentially rigid and would not require repairs after an impact event.

Testing of the steel tube socket assemblies was conducted with the maximum soil fill depth of 36 in. (914 mm) to maximize the potential for bending and displacement of the sockets. Both the lateral and longitudinal tests resulted in minor deformations to the socket assemblies and displacements of 0.52 in. and 0.23 in. (13 mm and 6 mm), respectively, to the top of the socket. However, these displacements were well within the 1-in. (25-mm) limits and the deformations to the socket were minor. Thus, repairs to the steel tube socket assemblies would not be necessary following an impact event. Note, lower socket displacements than those measured herein would be expected for installations placed on level terrain or adjacent to shallower fill slopes due to the increased soil fill behind the socket.

Testing of the concrete slab was conducted such that the bogie vehicle impacted two posts simultaneously to evaluate the potential for impact loads between adjacent posts to cause shear failure within the slab. Test no. TMS-5 resulted in a catastrophic slab failure that began with concrete shear cracking that ran between the sockets and extended backward at a 45-degree angle. The 4-in. (102-mm) thick slab did not have enough strength to support the S3x5.7 (S76x8.5) posts, as the posts and sockets sustained minimal deformations as they rotated through the fractured concrete slab. Therefore, a 4-in. (102-mm) thick concrete slab is not strong enough to support the weak-post MGS sockets.

Force vs. displacement data curves for all of the lateral tests are shown in Figure 71, while force vs. displacement curves for the longitudinal tests are shown in Figure 72. The force curves between the concrete foundations and the steel tube socket assemblies were very similar in both impact orientations, and they should be as post bending was the main failure mechanism in all four of these tests. The concrete foundation tests did show a slight increase in peak forces, which is likely due to the fact that they remained stiffer and did not displace as far as the steel tube socket assemblies. The recorded force curve for test no. TMS-5 on the concrete slab was divided by two in order to obtain the force resistance attributed to only a single post. Interestingly, the forces observed early in test no. TMS-5 were similar in magnitude to the forces observed in the other two lateral tests. However, once the concrete slab fractured apart, the forces dropped rapidly and the difference in strength between the socket design concepts became very clear.

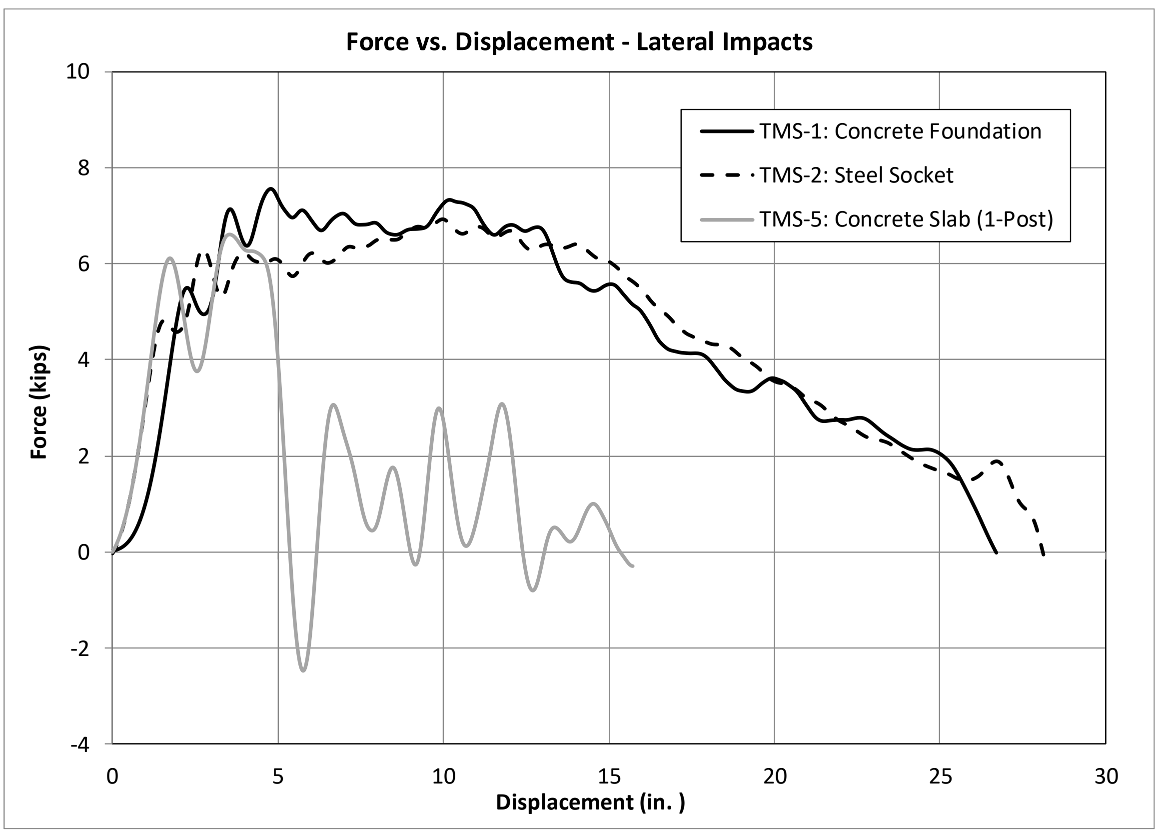


Figure 71. Force vs. Displacement Plots from Lateral Impact Tests

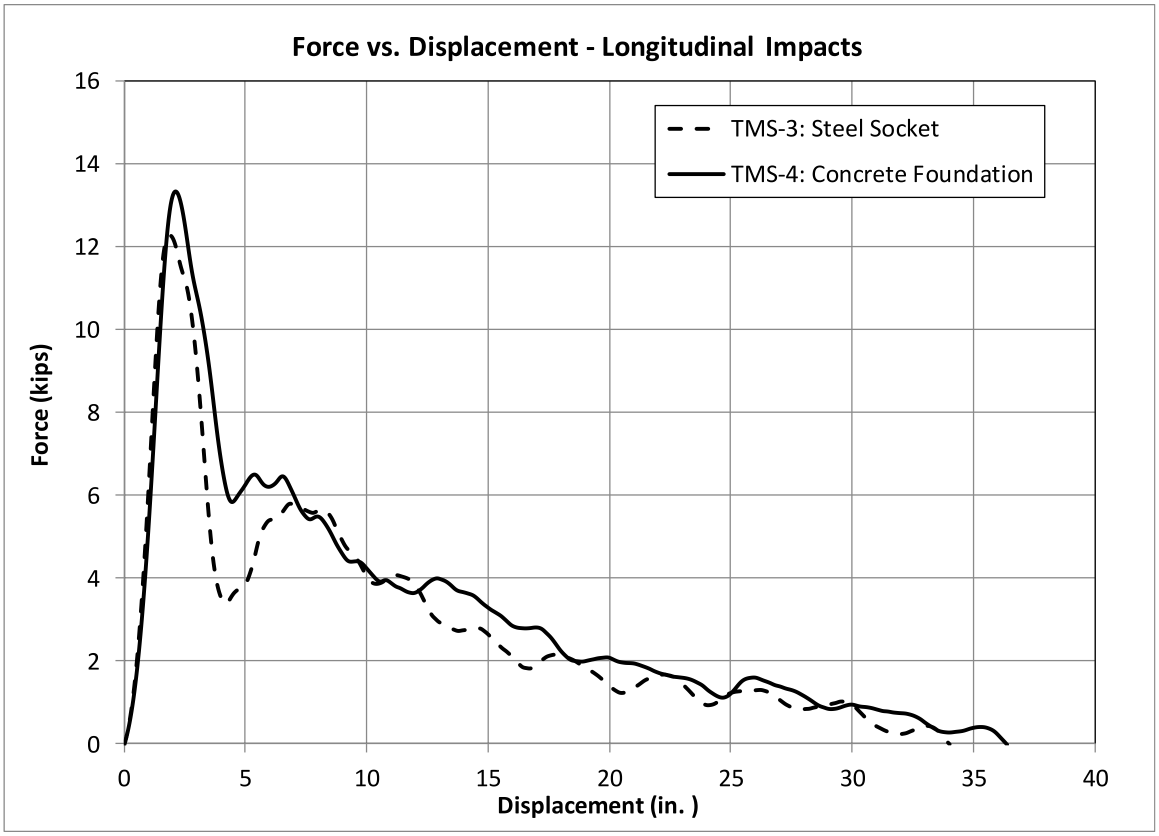


Figure 72. Force vs. Displacement Curves from Longitudinal Impact Tests

6 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The objective of this project was to develop a top-mounted, socketed, weak-post MGS system for concrete box culverts. The new system was to be developed by adapting the weak-post, MGS bridge rail for use as a top-mounted guardrail system. Thus, the system would utilize 31-in. (787-mm) tall W-beam rail, S3x5.7 (S76x8.5) posts spaced at 37.5 in. (953 mm) on center, and HSS 4x4x⅜ steel socket tubes. Specifically, it was desired to utilize the same post assembly as the weak-post MGS bridge rail, as shown in Figures 73 and 74, to avoid confusion and allow agencies to stock only a single post. However, the socket assembly and attachment hardware had to be modified in order for the system to be mounted to the top slab of concrete box culverts. Additionally, the sockets had to be compatible with soil fill depths between 12.5 in. (318 mm) and 36 in. (914 mm).

Three design concepts were explored herein: (1) cylindrical concrete foundations; (2) steel tube socket assemblies; and (3) a 4-in. (102-mm) thick by 36-in. (914-mm) wide concrete slab. Each design concept was evaluated through dynamic component testing of critical soil fill heights and critical impact angles. Lateral tests were conducted with an impact height of 24⅞ in. (632 mm), which corresponded to the center of the W-beam rail, while longitudinal impacts were conducted with an impact height of 12 in. (305 mm), which represented the front bumper of a small car. Each of the test articles were attached to the top of a simulated culvert and placed adjacent to a 2H:1V soil slope as a worst-case scenario for soil backfill.

The concrete foundations and steel tube socket assemblies were subjected to both lateral and longitudinal impacts. Both socket design concepts remained relatively rigid during the tests as they remained largely undamaged and limited permanent set displacements to well within the desired 1-in. (25-mm) limit. Thus, both the cylindrical concrete foundations and the steel tube socket assemblies will provide adequate strength to support the socketed, weak-post MGS when mounted to the top slab of low-fill box culverts.

Testing of the sockets encased within a 4-in. (102-mm) thick concrete slab was conducted with the bogie impacting two posts simultaneously due to concerns that impact loads between adjacent posts may magnify stresses in the slab and lead to concrete shear failure. During the dual post test, concrete shear cracks formed between the two sockets, extended to the back edge of the slab, and eventually resulted in complete fracture of the slab. The sockets rotated through the fractured concrete slab prior to the formation of plastic bending hinges within the posts. Therefore, the 4-in. (102-mm) thick concrete slab is not strong enough to support the S3x5.7 (S76x8.5) posts and is not recommended for use with socketed, weak-post MGS systems.

With the development and successful testing of both the socketed concrete foundations and the steel tube socket assemblies, roadside designers now have two options for installing a top-mounted, socketed, weak-post guardrail system on concrete box culverts. Either of these two socketed systems may be utilized at sites where the culvert headwall is not in line with the adjacent guardrail, and it would be difficult to use the previously-developed weak-post system attached to culvert headwalls [17]. Additionally, these new top-mounted, weak-post guardrail systems are unrestricted in terms of system length, so they may be utilized to span over culverts that are too wide for long-span guardrail systems [11-14], which are currently limited to 25 ft (7.6 m) unsupported span lengths. Finally, these socket assemblies and culvert itself remained undamaged during the critical impact tests. Thus, repair to a damaged system would consist of simply removing damaged rail segments and posts, dropping replacement posts into the undamaged sockets, and bolting on new rail segments. This will significantly reduce repair time and costs compared to top-mounted strong-post systems [2-4, 8], which require the removal of the soil fill to remove damaged posts and attach replacement posts to the culvert.

The top-mounted sockets developed herein were designed to be compatible with soil fill depths between 12.5 in. (318 mm) and 36 in. (914 mm). Thus, the vertical dimensions of the top-mounted sockets will vary with the soil fill depth of each particular site. Details showing how the socketed concrete foundations vary with soil fill depth are shown in Figures 75 through 81, while details for the various steel tube socket assembly heights are shown in Figures 82 through 88. Both socket designs are to remain unchanged within the top 14 in. (356 mm) of the socket, which includes the 2-in. (51-mm) socket extension above the ground line. Changes should only occur to the foundations/socket assemblies below the bottom of the weak-post when it is inserted into the socket. Specifically, only the length of the vertical bars and the number of transverse hoops will vary with the height of the cylindrical concrete foundations. Note, the top of the concrete foundation should always be even with the ground line. For the steel tube socket assemblies, only the length of the HSS square tube and the ¼-in. (6-mm) thick reinforcing plates located on the front and back faces of the tube will change. The reinforcing plates should always extend from the baseplate to 6 in. (152 mm) below the ground line, and the bolt supporting the post should remain $14^{5}/_{16}$ in. (364 mm) from the top of the socket. The anchorages for both socket designs also remain the same regardless of soil fill depth.

The original weak-post MGS bridge rail was developed and evaluated in combination with 6-in. (153-mm) wide W-beam backup plates located behind the rail at every post location. However, multiple full-scale crash tests conducted on similar weak-post guardrail systems [20, 22] following the development of the weak-post MGS bridge rail have resulted in rail tearing due to contact between the W-beam rail and the posts. As such, it is recommended to utilize 12-in. (305 mm) wide backup plates in all weak-post MGS systems, including the top-mounted system developed herein.

To date, all of the socketed, weak-post MGS variations have been evaluated with level terrain in front of the barrier. The introduction of an approach slope may negatively affect the performance of these systems in terms of vehicle capture and stability. Thus, it is recommended that approach slopes of 10H:1V or flatter be placed in front of the top-mounted, socketed, weak-post MGS on culverts. However, soil slopes behind the system should be limited to 2H:1V or flatter. The top-mounted sockets evaluated herein were tested with their back edges adjacent to a 2H:1V slope break point. Steeper soil slopes behind the system would reduce the soil stiffness behind the socket and may lead to excessive deformations. If the use of steeper slopes is desired, the slope break point should be located a minimum of 2 ft (0.6 m) laterally behind the sockets.

The original weak-post MGS bridge rail was full-scale crash tested while mounted to the side of a simulated bridge deck (i.e., it was tested without any ground to support the vehicles as they were being redirected). Additional surface behind the weak-post MGS should not affect the performance of the guardrail system. As such, there are no restrictions on the placement of the top-mounted sockets relative to the culverts, including directly adjacent to the headwall, as long as the socket assembly/foundation is properly anchored to the top slab. However, if the sockets are to be placed adjacent to the headwall, the headwall should not extend more than 2 in. (51 mm) above the ground. Headwalls extending further than 2 in. (51 mm) may act as vertical curbs and could pose a stability hazard. The weak-post MGS has not yet been evaluated in combination with curbed roadways.

The test installations evaluated during this study utilized an epoxy adhesive with a specified minimum bond strength of 1,305 psi (9.0 MPa). Therefore, these top-mounted sockets for culverts may be installed using a wide variety of epoxy adhesives as long as the specified bond strength is at least 1,305 psi (9.0 MPa). Note, the simulated culverts utilized to evaluate the top-mounted sockets had a minimum compressive concrete strength of f'c = 4 ksi (27.6 MPa). Culverts built with a weaker concrete strength may require increased embedment depths for the anchor rods. Finally, if desired, the steel tube socket assemblies may be through-bolted to the top slab of the culvert instead of epoxy anchored. For such installations, a 10-in. x 11-in. x ¼-in. (254-mm x 279-mm x 6-mm) washer plate is recommended for use on the underside of the slab.

Guardrail posts should not be placed too close to the upstream or downstream ends of a culvert as the attachment anchors may not have enough concrete cover to develop the required shear and/or tension loads. Thus, a minimum of 8 in. (203 mm) should be used between the end of a culvert slab and the center of a weak-post/socket. Additionally, to prevent interference with post rotation, the first standard guardrail post adjacent to the culvert should be placed a minimum of 12 in. (305 mm) from the culvert and any wingwalls that may be present. The 12 in. (305 mm) should be measured from the center of the post to the nearest edge of the culvert and/or wingwall.

At some installation sites, there may be a desire to utilize a thin pavement surrounding the guardrail posts as a means of vegetation control or erosion prevention. As shown by test no. TMS-5 herein, a 4-in. (102-mm) thick concrete slab it not strong enough to prevent the sockets from rotating when loaded. However, an asphalt or concrete pavement may be utilized in combination with either the cylindrical concrete foundations or the steel tube socket assemblies since these sockets were designed to prevent movement during impacts. Any pavement around the sockets would only serve to further strengthen the sockets against displacements. Note, the top of the socket must still extend 2 in. (51 mm) above the top surface of any pavement installed around the sockets.

This barrier system was designed as part of a family of non-proprietary, 31-in. (787-mm) high, W-beam guardrail systems commonly referred to as the MGS. This new top-mounted, weak-post guardrail system attached to culverts was designed with a similar lateral stiffness and overall system performance to that observed for the original, strong-post MGS. Therefore, a stiffness transition between the new top-mounted culvert system and adjacent standard MGS installations is unnecessary. A 75-in. (1.9-m) spacing is recommended between the outer S3x5.7 (S76x8.5) weak-post on the culvert and the adjacent W6x8.5 (W152x12.6) strong-post within the standard MGS installation next to the culvert. The adjacent MGS may be either blocked or non-blocked.

Finally, these barrier systems should be installed with the guardrail terminals (or end anchorages) located a sufficient distance from the culvert to prevent the two systems from interfering with the proper performance of one another. As such, the following implementation guidelines should be considered in addition to guardrail length of need requirements:

1. A recommended minimum length of 12 ft – 6 in. (3.81 m) of standard MGS between the first S3x5.7 (S76x8.5) weak post and the interior end of an acceptable TL-3 guardrail end terminal.

2. A recommended minimum barrier length of 50 ft (15.2 m) before the first S3x5.7 (S76x8.5) weak post, which includes standard MGS and a crashworthy guardrail end terminal. This guidance applies to the downstream end as well.

3. For flared guardrail applications, a recommended minimum length of 25 ft (7.6 m) between the first S3x5.7 (S76x8.5) weak post and the start of the flared section (i.e., bend between flared and tangent sections).

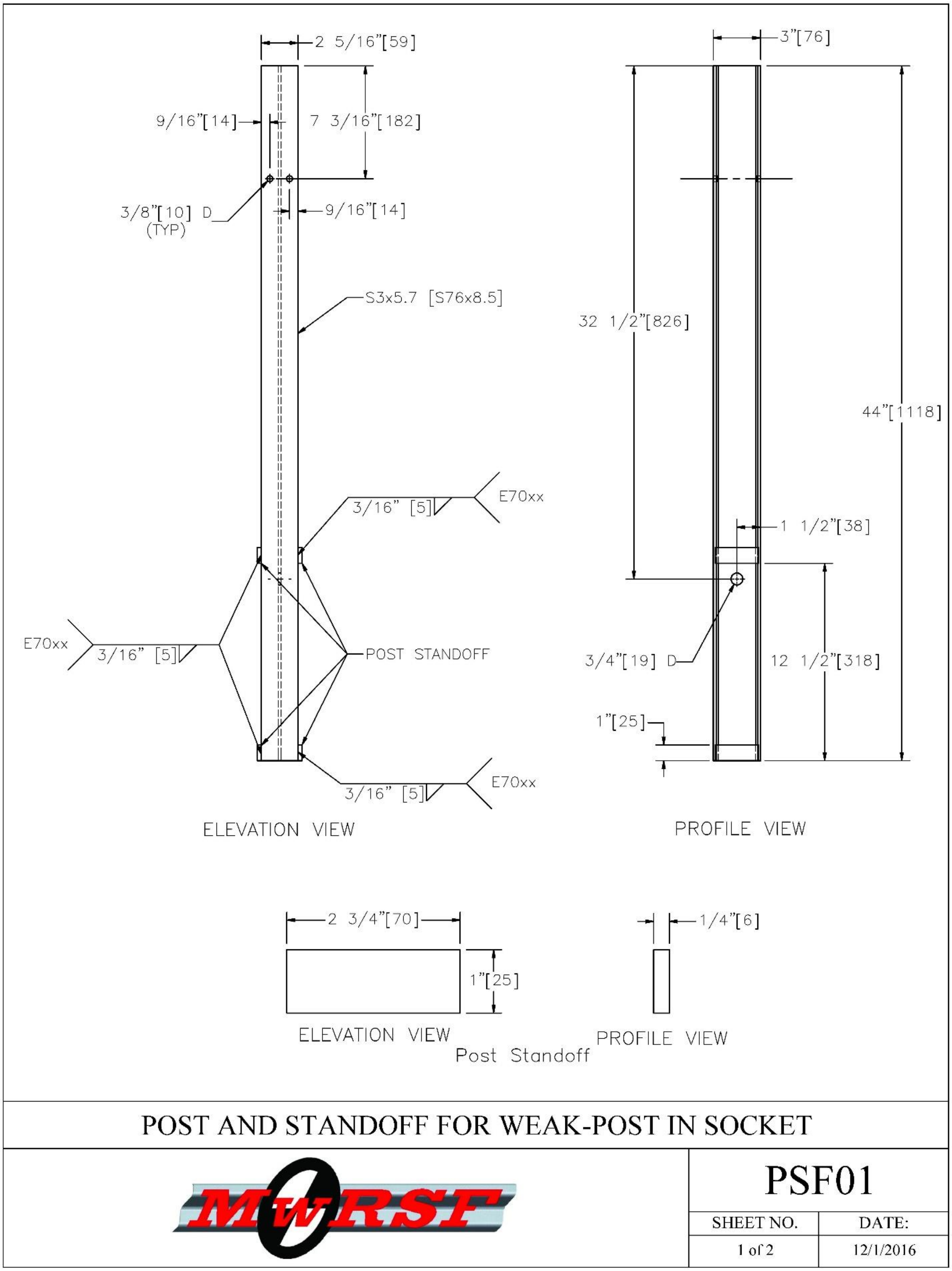


Figure 73. Post and Standoff for Weak-Post in Socket Design Details, Sheet 1 of 2

SPECIFICATIONS

This post shall be manufactured using galvanized ASTM A992 Grade 50 Steel. The section shall be manufactured such that it conforms to the geometry and tolerances of ASTM A992 for an S3x5.7 [S75x8.5] S-section. After all punching, drilling, stamping and welding is complete, the section shall be zinc-coated according to ASTM A123 (AASHTO M111). All holes shall be punched through both flanges (in-line).

Designator	Area in.^{2} [10^3 mm^2]	I_x in.^{4} [10^6 mm^4]	I_y in.^{4} [10^6 mm^4]	S_x in.^{3} [10^3 mm^3]	S_y in.^{3} [10^3 mm^3]
PSF01	1.67 [1.08]	2.52 [1.05]	0.455 [0.189]	1.68 [27.5]	0.391 [6.41]

Dimensional tolerances not shown or implied are intended to be those consistent with the proper functioning of the part, including its appearance and accepted manufacturing practices.

INTENDED USE

The Post and Standoff assembly (PSF01) is designed to be used with MGS Bridge Rail (SBO02c), Top-Mounted Weak-Post Guardrail System Attached to Culvert (SGR52), and Side-Mounted Weak-Post Guardrail System Attached to Culvert (SGR53).

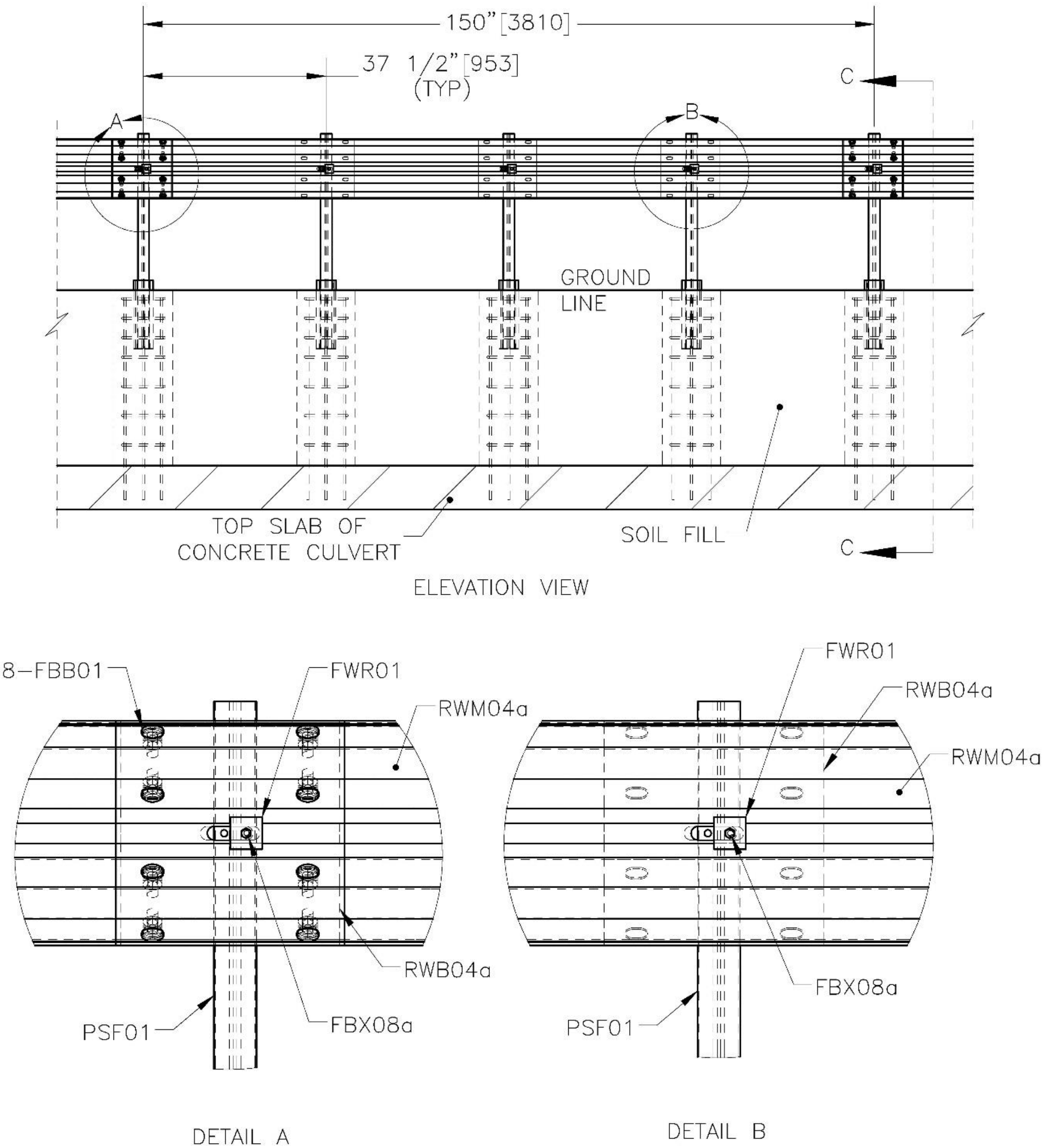
CONTACT INFORMATION

Midwest Roadside Safety Facility
University of Nebraska-Lincoln
130 Whittier Research Center
2200 Vine Street
Lincoln, NE 68583-0853
(402) 472-0965
Email: mwrsf@unl.edu
Website: http://mwrsf.unl.edu/

POST AND STANDOFF FOR WEAK-POST IN SOCKET

PSF01	
SHEET NO.	DATE:
2 of 2	12/1/2016

Figure 74. Post and Standoff for Weak-Post in Socket Design Details, Sheet 2 of 2



TOP-MOUNTED CONCRETE SOCKETS FOR WEAK-POST GUARDRAIL ATTACHED TO CULVERT

SGR68a	
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Figure 75. Top-Mounted Socketed Concrete Foundation, Design Details, Sheet 1 of 7

INTENDED USE

The Top-Mounted Concrete Sockets for Weak-Post Guardrail Attached to Culvert is designed to continue 31-in. [787] W-beam guardrail systems across large box culverts. It is compatible with the Midwest Guardrail System (MGS) with or without blockouts (SGR20a-c or SGR41, respectively), such that an approached transition would not be required between the two barriers. The Top-Mounted Concrete Sockets for Weak-Post Guardrail Attached to Culvert is an adaption of the MGS Bridge Rail (SBW04c) with only the socket assembly and attachment hardware changing. All posts and rail components are identical to the original MGS Bridge Rail (SBW04c). The Top-Mounted Concrete Sockets for Weak-Post Guardrail Attached to Culvert is MASH TL-3 crashworthy based on component testing.

A minimum of 8 in. [203] should be used between the end of a culvert slab and the center of a weak-post/socket. The Top-Mounted Concrete Sockets for Weak-Post Guardrail Attached to Culvert may be installed using a wide variety of epoxy adhesives as long as the specified bond strength is at least 1,305 psi [9.0 MPa].

Approach slopes of 10H:1V or flatter should be placed on traffic-side of the Top-Mounted Concrete Sockets for Weak-Post Guardrail Attached to Culvert. However, soil slopes of 2H:1V or flatter may be utilized behind the system beginning at the back edge of the socket.

A stiffness transition between the new guardrail attached to culvert system and adjacent MGS installation (SGR20a-c or SGR41) is unnecessary. A 75-in. [1905] spacing is recommended between the last S3x5.7 (S76x8.5) culvert post (PSF01) and the first guardrail post of the adjacent MGS installation. The adjacent MGS may be either blocked (SGR20a-c) or non-blocked (SGR41).

A recommended minimum length of 12 ft-6 in. [3810] of standard MGS between the first S3x5.7 (S76x8.5) weak post and the interior end of an acceptable TL-3 guardrail end terminal should be used. A minimum barrier length of 50 ft [15240] before the first S3x5.7 (S76x8.5) weak post is recommended. The 50 ft [15240] length includes standard MGS and a crashworthy guardrail end terminal, and also applies to the downstream end of the system.

For flared guardrail applications, a minimum length of 25 ft [7620] between the first S3x5.7 (S76x8.5) weak post and the start of the flared section is recommended.

COMPONENTS

Unit Length = 150" [3810]

DESIGNATOR	COMPONENT	NUMBER
PSF01	S3x5.7 by 44" Long Post and Standoff	4
RWM04a	12'-6" W-Beam MGS Section 1/2" Post Spacing	1
RWB04a	12" 12-Gauge W-Beam Backup Plate	4
FBX08a	Hex Bolt 5/16"-18x1 1/4"x1 1/4" and Nut	4
FWR01	1 3/4"x1 3/4"x1/8" Square Guardrail Washer	4
FBB01	5/8" Dia., 1 1/4" Long Guardrail Bolt and Nut	8
--------	Concrete Socket	4

ELIGIBILITY

Eligibility will not be pursued.

TOP-MOUNTED CONCRETE SOCKETS FOR WEAK-POST GUARDRAIL ATTACHED TO CULVERT

	SGR68a	
MwRSF	SHEET NO.	DATE:
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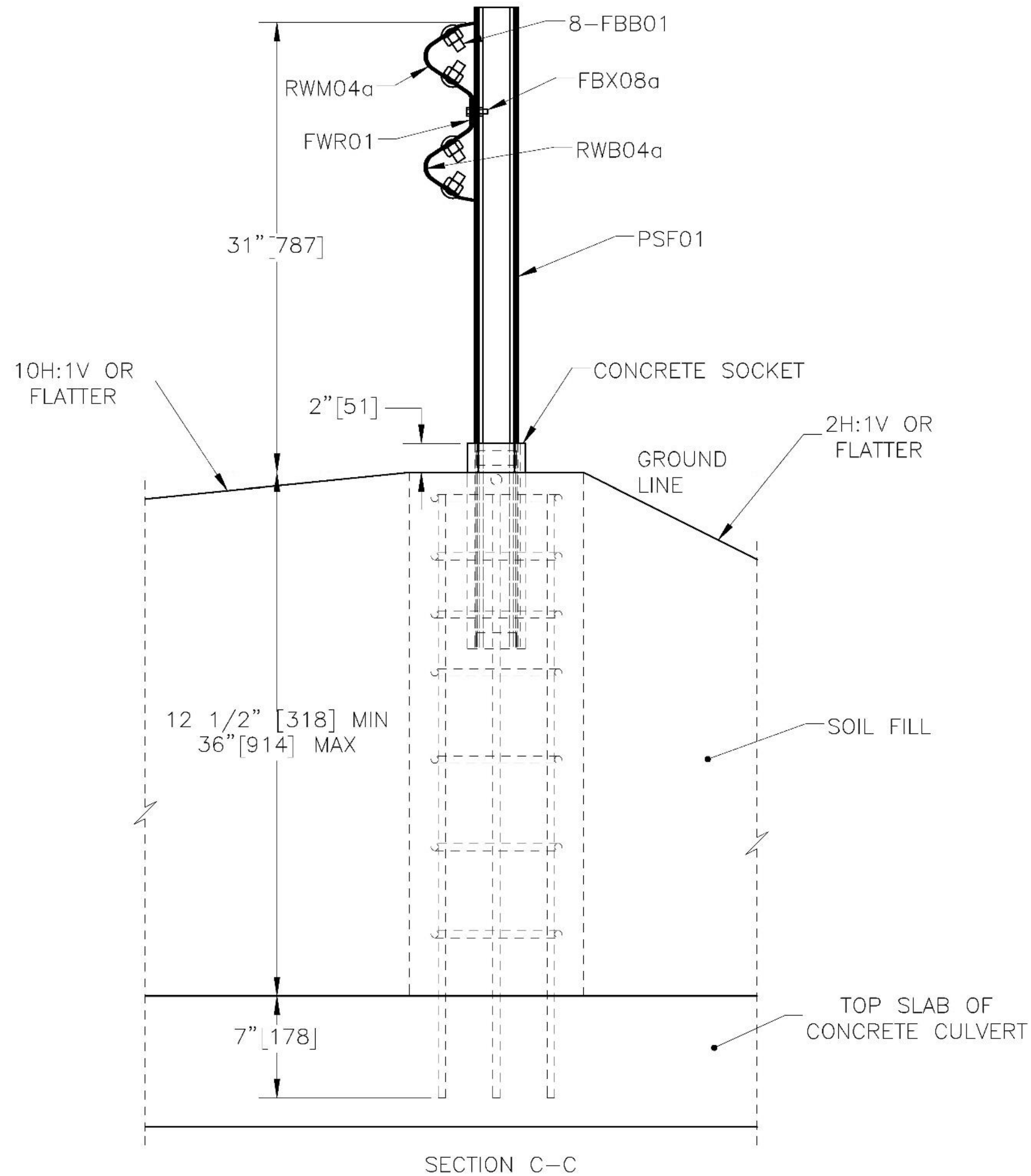
Figure 76. Top-Mounted Socketed Concrete Foundation, Design Details, Sheet 2 of 7



TOP-MOUNTED CONCRETE SOCKETS FOR WEAK-POST GUARDRAIL ATTACHED TO CULVERT

SGR68a	
SHEET NO.	DATE:
3 of 7	10/3/2019

Figure 77. Top-Mounted Socketed Concrete Foundation, Design Details, Sheet 3 of 7

REFERENCES

Rosenbaugh, S.K., Asadollahi Pajouh, M., and Faller, R.K., *Top-Mounted Sockets for Weak-Post MGS on Culverts,* Report No. TRP-03-386-19, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, October 2019.

CONTACT INFORMATION

Midwest Roadside Safety Facility
Nebraska Transportation Center
University of Nebraska-Lincoln
130 Whittier Research Center
2200 Vine Street
Lincoln, NE 68583-0853
(402) 472-0965
Email: mwrsf@unl.edu
Website: https://mwrsf.unl.edu

TOP-MOUNTED CONCRETE SOCKETS FOR WEAK-POST GUARDRAIL ATTACHED TO CULVERT

SGR68a

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Figure 78. Top-Mounted Socketed Concrete Foundation, Design Details, Sheet 4 of 7

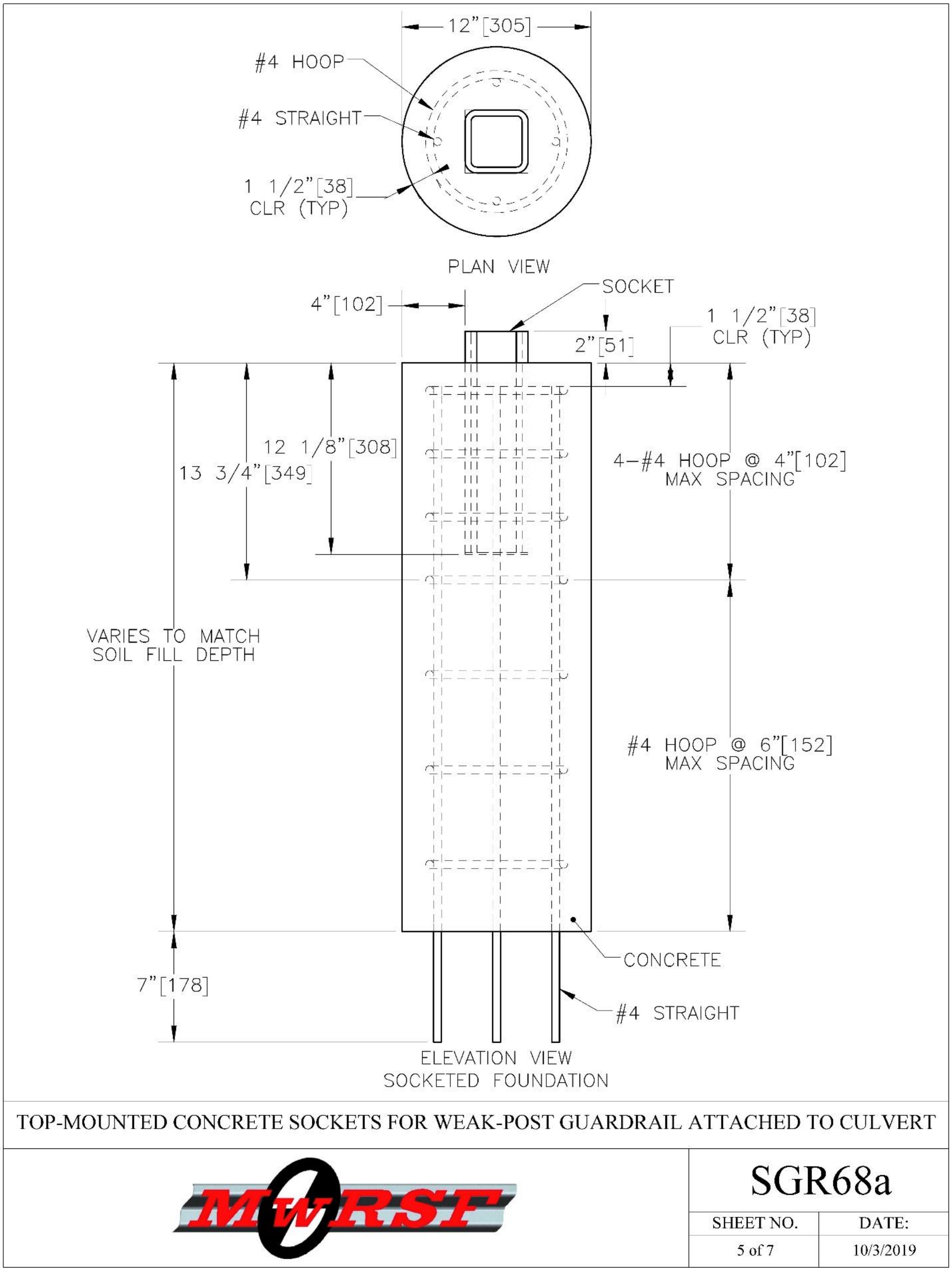
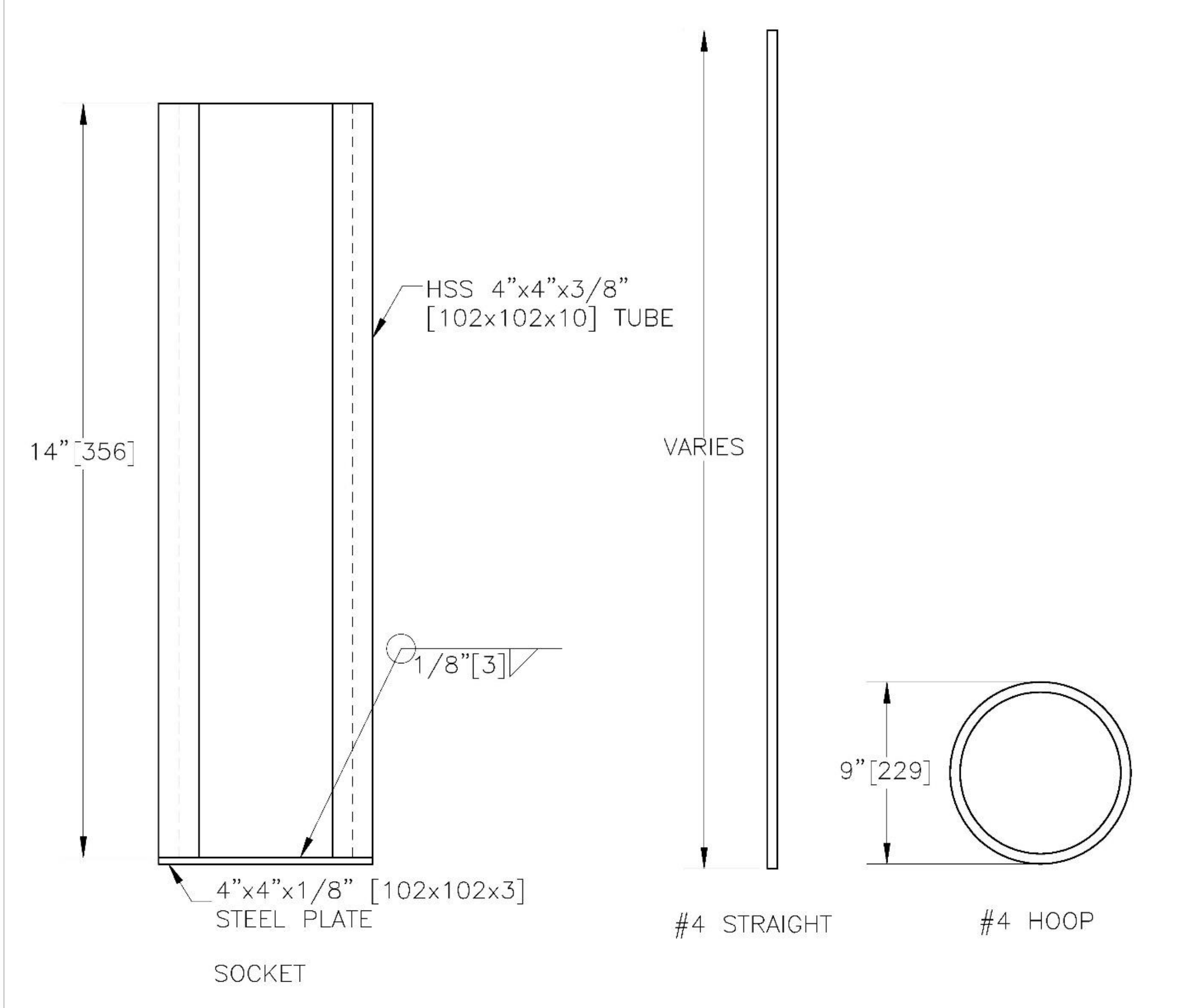


Figure 79. Top-Mounted Socketed Concrete Foundation, Design Details, Sheet 5 of 7



SOCKETED FOUNDATION BILL OF BARS				
ITEM	BAR NO.	QTY. PER UNIT	LENGTH	MATERIAL
#4 HOOP	4	VARIES WITH SOIL DEPTH	32 3/4" [832]	A615 GRADE 60
#4 STRAIGHT	4	4	VARIES = SOIL DEPTH + 5 1/2" [140]	A615 GRADE 60

TOP-MOUNTED CONCRETE SOCKETS FOR WEAK-POST GUARDRAIL ATTACHED TO CULVERT	
SGR68a	
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Figure 80. Top-Mounted Socketed Concrete Foundation, Design Details, Sheet 6 of 7

SPECIFICATIONS

HSS 4"x4"x3/8" [102x102x10] TUBE
The tube shall be ASTM A500 grade B galvanized steel.

4"x4"x1/8" [102x102x3] STEEL PLATE
The steel plate shall be ASTM A572 grade 50 galvanized steel.

TOP-MOUNTED CONCRETE SOCKETS FOR WEAK-POST GUARDRAIL ATTACHED TO CULVERT

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	SHEET NO. 7 of 7	DATE: 10/3/2019

Figure 81. Top-Mounted Socketed Concrete Foundation, Design Details, Sheet 7 of 7

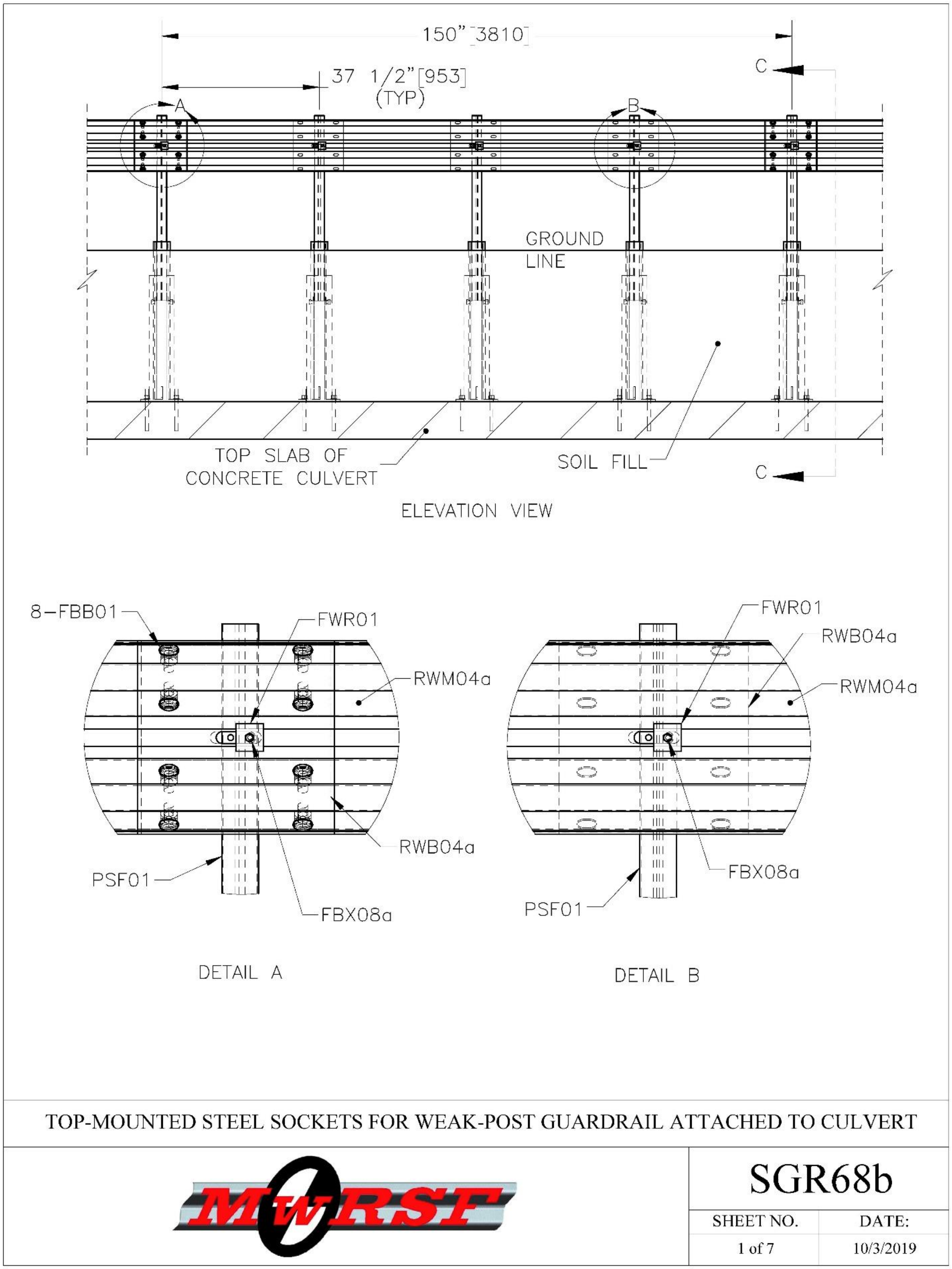

Figure 82. Top-Mounted Steel Tube Socket Assembly Design Details, Sheet 1 of 7

INTENDED USE

The Top-Mounted Steel Sockets for Weak-Post Guardrail Attached to Culvert is designed to continue 31-in. [787] W-beam guardrail systems across large box culverts. It is compatible with the Midwest Guardrail System (MGS) with or without blockouts (SGR20a-c or SGR41, respectively), such that an approached transition would not be required between the two barriers. The Top-Mounted Steel Sockets for Weak-Post Guardrail Attached to Culvert is an adaption of the MGS Bridge Rail (SBW04c) with only the socket assembly and attachment hardware changing. All posts and rail components are identical to the original MGS Bridge Rail (SBW04c). The Top-Mounted Steel Sockets for Weak-Post Guardrail Attached to Culvert is MASH TL-3 crashworthy based on component testing.

A minimum of 8 in. [203] should be used between the end of a culvert slab and the center of a weak-post/socket. The Top-Mounted Steel Sockets for Weak-Post Guardrail Attached to Culvert may be installed using a wide variety of epoxy adhesives as long as the specified bond strength is at least 1,305 psi [9.0 MPa].

Approach slopes of 10H:1V or flatter should be placed on traffic-side of the Top-Mounted Steel Sockets for Weak-Post Guardrail Attached to Culvert. However, soil slopes of 2H:1V or flatter may be utilized behind the system beginning at the back edge of the socket.

A stiffness transition between the new guardrail attached to culvert system and adjacent MGS installation (SGR20a-c or SGR41) is unnecessary. A 75-in. [1905] spacing is recommended between the last S3x5.7 culvert post (PSF01) and the first guardrail post of the adjacent MGS installation. The adjacent MGS may be either blocked (SGR20a-c) or non-blocked (SGR41).

A recommended minimum length of 12 ft-6in. [3810] of standard MGS between the first S3x5.7 (S76x8.5) weak post and the interior end of an acceptable TL-3 guardrail end terminal should be used. A minimum barrier length of 50 ft [15240] before the first S3x5.7 (S76x8.5) weak post is recommended. The 50 ft [15240] length includes standard MGS and a crashworthy guardrail end terminal, and also applies to the downstream end of the system.

COMPONENTS

Unit Length = 150" [3810]

DESIGNATOR	COMPONENT	NUMBER
PSF01	S3x5.7 by 44" Long Post and Standoff	4
RWM04a	12'-6" W-Beam MGS Section 1/2" Post Spacing	1
RWB04a	12" 12-Gauge W-Beam Backup Plate	4
FBX08a	Hex Bolt 5/16"-18x1 1/4"x1 1/4" and Nut	4
FWR01	1 3/4"x1 3/4"x1/8" Square Guardrail Washer	4
FBB01	5/8" Dia., 1 1/2" Long Guardrail Bolt and Nut	8
FBX16b	5/8" Dia., 5" Long Hex Bolt and Nut	4
FRR20b	¾" Dia., 10" Long Threaded Rod	16
FWC20b	¾" Dia., Flat Washer	16
FNX20b	¾" Dia., Heavy Hex Nut	16
--------	Steel Tube Socket	4

TOP-MOUNTED STEEL SOCKETS FOR WEAK-POST GUARDRAIL ATTACHED TO CULVERT

SGR68b

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Figure 83. Top-Mounted Steel Tube Socket Assembly Design Details, Sheet 2 of 7

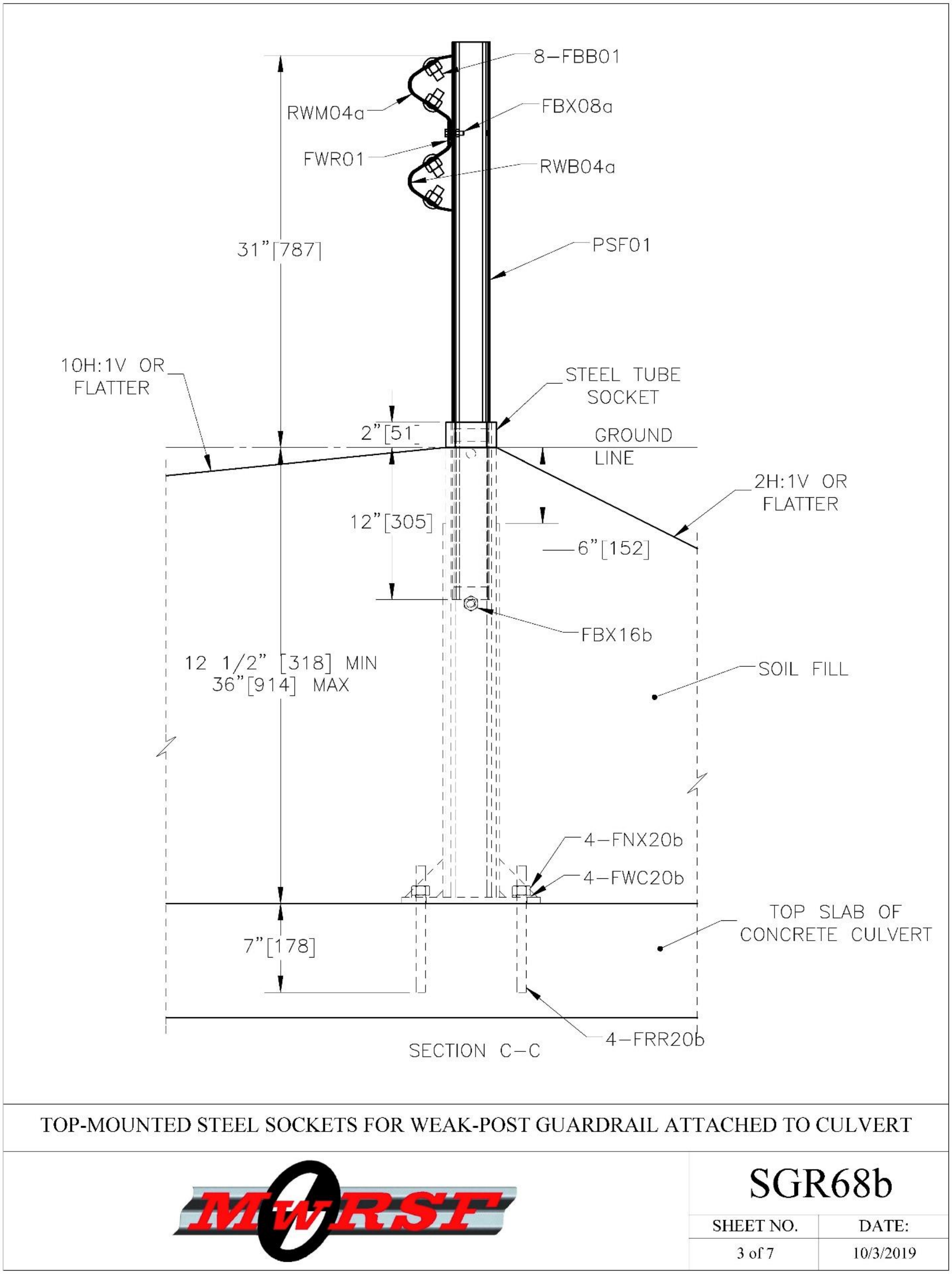

Figure 84. Top-Mounted Steel Tube Socket Assembly Design Details, Sheet 3 of 7

ELIGIBILITY

Eligibility will not be pursued.

REFERENCES

Rosenbaugh, S.K., Asadollahi Pajouh, M., and Faller, R.K., *Top-Mounted Sockets for Weak-Post MGS on Culverts,* Report No. TRP-03-386-19, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, October 2019.

CONTACT INFORMATION

Midwest Roadside Safety Facility
Nebraska Transportation Center
University of Nebraska-Lincoln
130 Whittier Research Center
2200 Vine Street
Lincoln, NE 68583-0853
(402) 472-0965
Email: mwrsf@unl.edu
Website: https://mwrsf.unl.edu

TOP-MOUNTED STEEL SOCKETS FOR WEAK-POST GUARDRAIL ATTACHED TO CULVERT

SGR68b	
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Figure 85. Top-Mounted Steel Tube Socket Assembly Design Details, Sheet 4 of 7

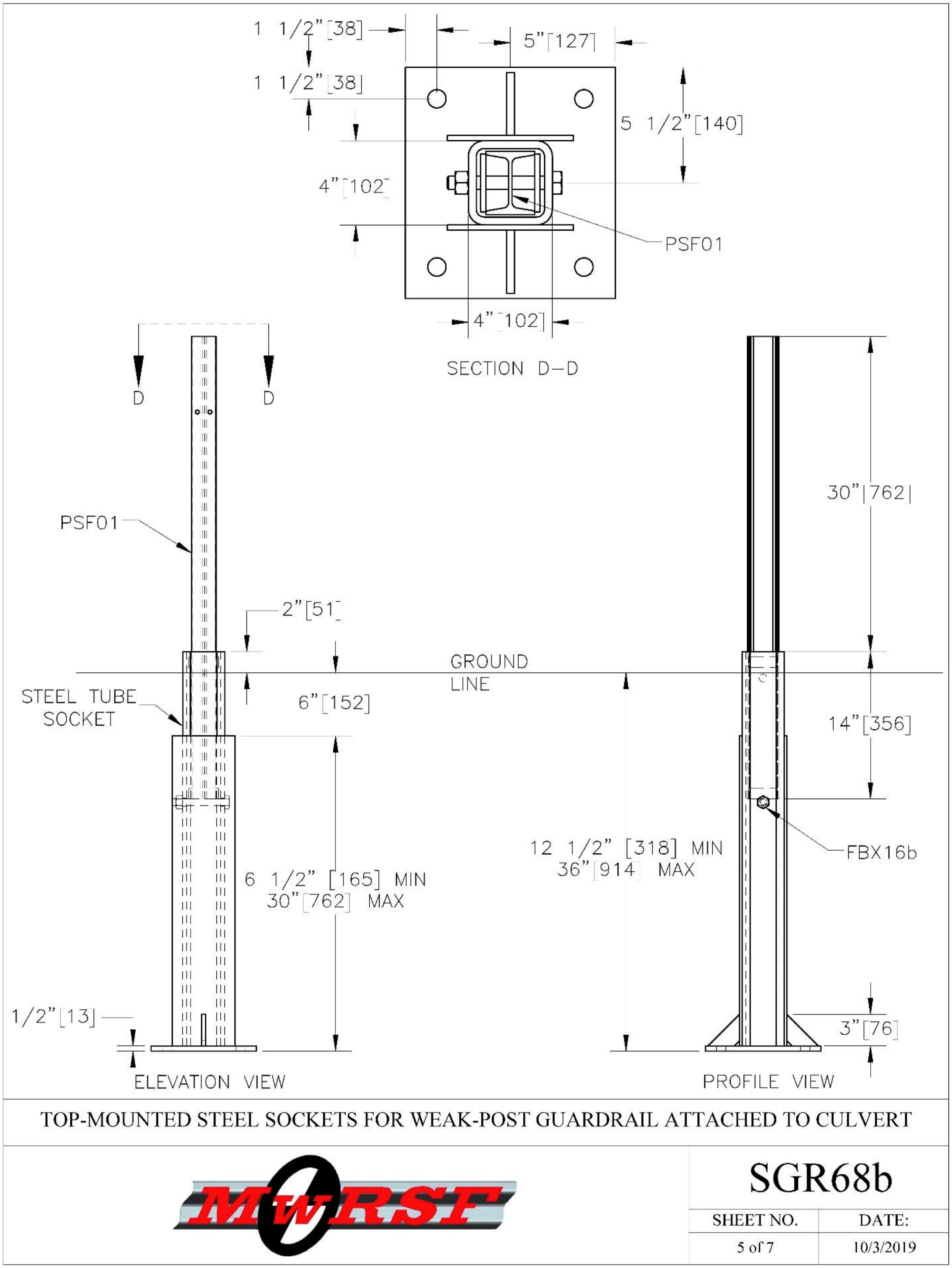

Figure 86. Top-Mounted Steel Tube Socket Assembly Design Details, Sheet 5 of 7

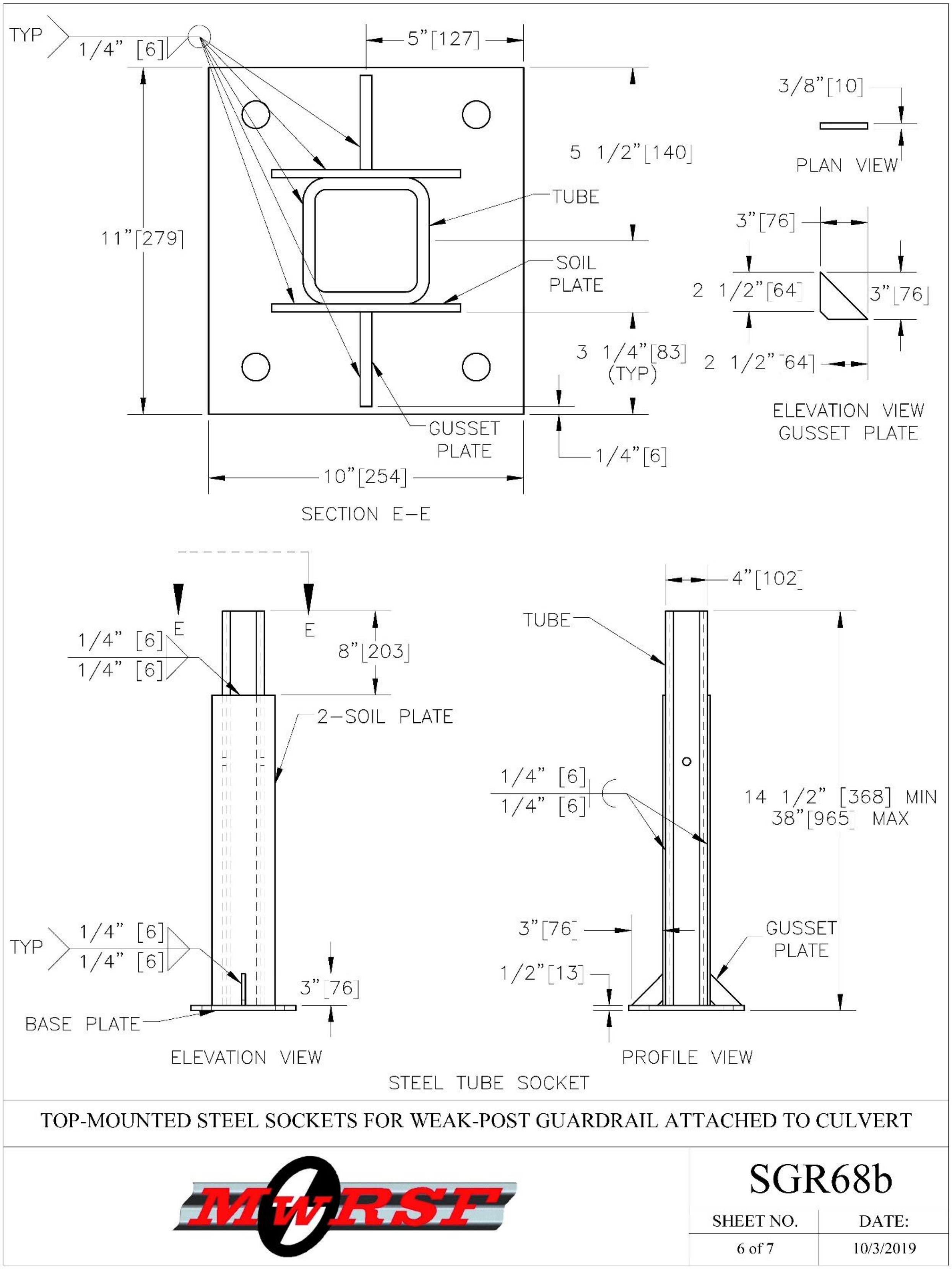

Figure 87. Top-Mounted Steel Tube Socket Assembly Design Details, Sheet 6 of 7

SPECIFICATIONS

HSS 4"x4"x3/8" TUBE
The tube shall be ASTM A500 grade B galvanized steel.

6"xVARIESx1/4" SOIL PLATE
The soil plate shall be ASTM A572 grade 50 galvanized steel. Length of SOIL PLATE is 8" shorter than length of TUBE.

11"x10"x1/2" BASE PLATE
The base plate shall be ASTM A572 grade 50 galvanized steel.

3"x3"x3/8" GUSSET PLATE
The gusset shall be ASTM A572 grade 50 galvanized steel.

TOP-MOUNTED STEEL SOCKETS FOR WEAK-POST GUARDRAIL ATTACHED TO CULVERT

MwRSF

SGR68b	
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Figure 88. Top-Mounted Steel Tube Socket Assembly Design Details, Sheet 7 of 7

7 MASH EVALUATION

The top-mounted, socketed, weak-post MGS for attachment to the top slab of concrete box culverts was evaluated to determine its compliance with MASH 2016 TL-3 evaluation criteria. The system incorporates 31-in. (787-mm) tall W-beam guardrail, 12-in. (305-mm) wide backup plates, S3x5.7 (S76x8.5) weak posts spaced at 37.5 in. (953 mm) on center, and socket assemblies, which support the posts and mount to the top slab of concrete culverts. Two different socket designs have been developed for use with this system: a cylindrical concrete foundation and a steel tube socket assembly.

The cylindrical concrete foundation measures 12 in. (305 mm) in diameter and extends from the top slab of the culvert to the ground line. Each concrete foundation has a minimum concrete strength of f'_c=3,500 psi, is reinforced with both vertical rebar and transverse hoops, and contains a 14-in. (356-mm) long HSS 4x4x⅜ tube embedded down its center with the top extending 2 in. (51 mm) above the top of the concrete foundation. The concrete foundation is anchored by extending the vertical bars 7 in. (178 mm) from the bottom of the foundation and epoxying the bars into the top slab of the culvert.

The steel tube socket assembly is composed of an HSS 4x4x⅜ steel tube extending from a ½-in. (13-mm) thick base plate to 2 in. (51 mm) above ground line. A $^5/_8$-in. (16-mm) dia. bolt is placed through the socket $14^5/_{16}$ in. (356 mm) below the top of the socket to support the post vertically and ensure proper embedment into the socket. The tube is reinforced by 6-in. (152mm) wide by ¼-in. (6-mm) thick steel plates welded to the front and back sides of the tubes. These plates extend from the base plate to 6 in. (152 mm) below the ground line. Two additional ¼-in. (6-mm) thick gusset plates are located on the front and back sides of the assembly to anchor the socket to the base plate. Four ¾-in. (19-mm) diameter threaded rods anchor the base plate to the top slab of the culvert using epoxy and an embedment depth of 7 in. (178 mm).

MASH 2016 requires two full-scale crash tests for the evaluation of longitudinal barrier systems to TL-3. However, full-scale crash testing was not deemed necessary to evaluate the performance of the top-mounted, socketed, weak-post MGS attached to culvert slabs. The top-mounted system was adapted from the weak-post MGS bridge rail, which was designed to have the sockets remain essentially rigid while the posts and W-beam rail deform and absorb energy. During the successful full-scale crash testing of the original weak-post MGS bridge rail to MASH test designation nos. 3-10 and 3-11, the side-mounted sockets remained free from plastic deformations and significant displacements throughout the impact event [15-16]. Thus, all system deflections and energy absorbed by the system were solely attributed to post bending and rail deformations. The top-mounted, socketed, weak-post MGS for attachment to concrete culverts incorporates the same W-beam rail, rail-to-post attachment hardware, mounting height, post assembly, and socket tube as the MGS bridge rail. Therefore, if the new top-mounted socket assemblies could support the full bending strength of the S3x5.7 (S76x8.5) posts under impact conditions, then the guardrail system will perform similarly to the original weak-post MGS bridge rail.

Both of the socket assembly designs described above in combination with S3x5.7 (S76x8.5) weak-posts were evaluated through dynamic impact tests in both the lateral and longitudinal directions. Lateral tests were conducted at an impact height of 24⅞ in. (632 mm) representing the center of the W-beam rail, while longitudinal tests were conducted at a height of

12 in. (305 mm) representing the height of a small car's bumper. The sockets were mounted to the top slab of simulated culverts and placed adjacent to a 2H:1V soil slope break point as a critical worst-case scenario for soil backfill. One test on the concrete foundation was conducted with a soil fill depth of 12.5 in. (318 mm) to evaluate the anchorage to the culvert under critical loading. The second test on the concrete foundation and both tests on the steel tube socket assembly were conducted with a soil fill of 36 in. (914 mm) to evaluate the strength and rigidity of the socket designs under the critical maximum bending loads.

All four of the dynamic component tests resulted in the post bending over with minimal damage and displacements to the sockets. A few hairline cracks were found on the top of one concrete foundation, but they were not determined to affect the structural integrity of the foundation. The steel socket assemblies sustained only very minor localized deformations to the socket. Permanent set displacements to the concrete foundations and steel tube socket assemblies were held to $^{1}/_{16}$ in. (2 mm) and ½ in. (13 mm), respectively, which were well within the desired limit of 1 in. (25 mm). Additionally, no anchorage damage was observed after the soil fill was removed from the test installations. Thus, the sockets would not need to be repaired after an impact event, and system repairs would only include the replacement of damaged posts and rail segments.

Based on the rigidity and robustness illustrated by both top-mounted socket designs during dynamic component testing, it was determined that the use of either socket in combination with socketed, weak-post MGS would result in a system with performance characteristics very similar to the original weak-post MGS bridge rail. Since the weak-post MGS bridge rail was successfully crash tested to the entire MASH TL-3 evaluation matrix, both socket variations of the top-mounted, socketed, weak-post MGS for attachment to low-fill culverts are believed to be crashworthy to TL-3 safety performance standards of MASH 2016.

8 REFERENCES

1. Hirsch, T.J. and Beggs, D., *Use of Guardrails on Low Fill Bridge Length Culverts*, Transportation Research Record No. 1198, Transportation Research Board, National Research Council, Washington D.C., 1988.

2. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Reid, J.D., and Holloway, J.C., *NCHRP 350 Development and Testing of a Guardrail Connection to Low-Fill Culverts*, Research Report No. TRP-03-114-02, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, November 2002.

3. Polivka, K.A., Faller, R.K., and Rohde, J.R., *Guardrail Connection to Low-Fill Culverts*, Transportation Research Record No. 1851, Transportation Research Board, National Research Council, Washington D.C., 2003.

4. Price, C.W., Rosenbaugh, S.K., Faller, R.K., Sicking, D.L., Reid, J.D., and Bielenberg, R.W., *Post Weld and Epoxy Anchorage Variations for W-Beam Guardrail Attached to Low-Fill Culverts*, Research Report No. TRP-03-278-13, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, August 12, 2013.

5. Ross, H.E., Sicking, D.L., Zimmer, R.A., and Michie, J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Research Program (NCHRP) Report No. 350, Transportation Research Board, Washington, D.C., 1993.

6. *Manual for Assessing Safety Hardware (MASH)*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2009.

7. Asadollahi Pajouh, M., Bielenberg, R.W., Faller, R.K., Holloway, J.C., Rosenbaugh, S.R., and Reid, J.D., *Dynamic Testing and Evaluation of Culvert-Mounted, Strong-Post MGS to TL-3 Guidelines of MASH 2016*, DRAFT Report no. TRP-03-383-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, REPORT IN PROGRESS.

8. Williams, W.F. and Menges, W.L., *MASH Test 3-11 of the W-beam Guardrail on Low-Fill Box Culvert*, Test Report No. 405160-23-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, February 2012.

9. *Manual for Assessing Safety Hardware (MASH), Second Edition*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.

10. Polivka, K.A., Bielenberg, R.W., Sicking, D.L., Faller, R.K., and Rohde, J.R., *Development of a 7.62-m Long Span Guardrail System*, Research Report No. TRP-03-72-99, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, April 6, 1999.

11. Polivka, K.A., Bielenberg, R.W., Sicking, D.L., Faller, R.K., Rohde, J.R., and Keller, E.A., *Development of a 7.62-m Long Span Guardrail System - Phase II*, Research Report No. TRP-03-88-99, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, August 13, 1999.

12. Faller, R.K., Sicking, D.L., Polivka, K.A., Rohde, J.R., and Bielenberg, R.W., *A Long-Span Guardrail System for Culvert Applications*, Paper No. 00-0598, Transportation Research Record No. 1720, Transportation Research Board, National Research Council, Washington, D.C., 2000.

13. Bielenberg, R.W., Faller, R.K., Rohde, J.R., Reid, J.D., Sicking, D.L., Holloway, J.C., Allison, E.M., and Polivka, K.A., *Midwest Guardrail System for Long-Span Culvert Applications*, Research Report No. TRP-03-187-07, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, November 16, 2007.

14. Bielenberg, R.W., Faller, R.K., Sicking, D.L., Rhode, J.R., and Reid, J.D., *Midwest Guardrail System for Long-Span Culvert Applications*, Transportation Research Record No. 2025, Transportation Research Board, National Research Council, Washington D.C., 2007.

15. Thiele, J.C., Sicking, D.L., Faller, R.K., Bielenberg, R.W., Lechtenberg, K.A., Reid, J.D., and Rosenbaugh, S.K., *Development of a Low-Cost, Energy-Absorbing Bridge Rail*, Research Report No. TRP-03-226-10, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, August 2010.

16. Thiele, J.C., Sicking, D.L., Lechtenberg, K.A., Reid, J.D., Faller, R.K., Bielenberg, R.W., and Rosenbaugh, S.K., *Development of a Low-Cost, Energy-Absorbing Bridge Rail*, Transportation Research Record No. 2262, Transportation Research Board, National Research Council, Washington D.C., 2011.

17. Schneider, A.J., Rosenbaugh, S.K., Faller, R.K., Sicking, D.L., Lechtenberg, K.A., and Reid, J.D., *Safety Performance Evaluation of Weak-Post, W-Beam Guardrail Attached to Culvert*, Research Report No. TRP-03-277-14, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, February 12, 2014.

18. Rosenbaugh, S.K., Schmidt, T.L., Faller, R.K., and Reid, J.D., *Development of Socketed Foundations for S3x5.7 Posts*, Research Report No. TRP-03-293-15, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, April 2015.

19. Schmidt, T.L., Rosenbaugh, S.K., Faller, R.K., Sicking, D.L., and Reid, J.D., *Development of a Socketed Foundation for the Midwest Weak Post (MWP) V1*, Research Report No. TRP-03-298-14, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, July 2014.

20. Rosenbaugh, S.K., Faller, R.K., Lechtenberg, K.A., and Holloway, J.C., *Development of Weak-Post W-beam Guardrail in Mow Strips*, Research Report No. TRP-03-322-15, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, October 2015.

21. Society of Automotive Engineers (SAE), *Instrumentation for Impact Test – Part 1 – Electronic Instrumentation*, SAE J211/1 MAR95, New York City, New York, July, 2007.

22. Williams, W.F., Bligh, R.P., Menges, W.L., and Kuhn, D.L., *MASH TL-3 Crash Testing and Evaluation of the TxDOT T631 Bridge Rail*, Test Report No. 9-1002-12-12, Texas Transportation Institute, Texas A&M University, College Station, Texas, July 2016.

9 APPENDICES

Appendix A. Material Specifications

Table A-1. Material Certification List, Simulated Concrete Culvert with 36-in. (314-mm) Soil Fill

Part Description	Material Specifications	Material Reference
Concrete	L4000 Type 3 mix, f'c ≥ 4,000 psi	Ticket No. 4185416
#5 Straight Rebar, 289" Long	ASTM A615 Grade 60	Heat No.: 58025756
#4 Straight Rebar, 110" Long	ASTM A615 Grade 60	Heat No.: 58025130
#4 Bent Rebar, Vertical Hoop 68¼" Total Length Unbent	ASTM A615 Grade 60	Heat No.: 586820
#4 Straight Rebar, 289" Long	ASTM A615 Grade 60	Heat No.: 58025130

Table A-2. Material Certification List, Simulated Concrete Culvert – 12.5-in. (318-mm) Fill Culvert

Part Description	Material Specifications	Material Reference
Concrete	L4000 Type 3 mix, f'c ≥ 4,000 psi	Ticket No. 4185416
#4 Bent Rebar, Vertical Hoop 68¼" Total Length Unbent	ASTM A615 Grade 60	Heat No.: 586820
#4 Straight Rebar, 65" Long	ASTM A615 Grade 60	Heat No.: 58025130
#5 Straight Rebar, 72½" Long	ASTM A615 Grade 60	Heat No.: 58025756
#4 Straight Rebar, 72½" Long	ASTM A615 Grade 60	Heat No.: 58025130
#4 Straight Rebar, 16" Long	ASTM A615 Grade 60	Heat No.: 58025130

Table A-3. Material Certification List, Socketed Concrete Foundations, Test Nos. TMS-1 and TMS-4

Part Description	Material Specifications	Material Reference
4"x4"x⅜" Steel Socket Tube	ASTM A500 Grade B	Heat No.: 821T08050
4"x4"x¼" Steel Plate	ASTM A36	Heat No.: A609773
S3x5.7 by 44" Long Steel Post	ASTM A572 Grade 50, ASTM A992	Heat No.: 59079748/02
2¾"x1"x¼" Post Standoff	ASTM A36	Heat No.: 64055041
Concrete	L4000 Type 3 mix, f'c ≥ 4,000 psi	Ticket No. 1209146
#4 Rebar, 18" Long	ASTM A615 Grade 60	Heat No.: KN15106961
#4 Circular Rebar, 8" Long	ASTM A615 Grade 60	Heat No.: KN15106961
Epoxy	Min. Bond Strength 1,305 psi	Tech Data Available Online

Table A-4. Material Certification List, Steel Tube Socket Assemblies, Test Nos. TMS-2 and TMS-4

Part Description	Material Specifications	Material Reference
4"x4"x⅜" Steel Socket Tube	ASTM A500 Grade B	Heat No.: 821T08050
6"x29"x1/4" Steel Plate	ASTM A572 Grade 60	Heat No.: A6H254
10"x11"x1/2" Steel Plate	ASTM A572 Grade 60	Heat No.: 811S07890
3"x3"x3/8" Steel Gusset	ASTM A572 Grade 60	Heat No.: L104606
S3x5.7 by 44" Long Steel Post	ASTM A572 Grade 50, ASTM A992	Heat No.: 59079748
2¾"x1"x¼" Post Standoff	ASTM A36	Heat No.: 64055041
5/8" Dia. UNC Heavy Hex Nut	ASTM A563DH	Heat No.: NF15204037
5/8" Dia. UNC, 5" Long Heavy Hex Bolt	ASTM A325 Type 1	Heat No.: 10382300
3/4" Dia. UNC, 10" Long Threaded Rod	ASTM A449	Heat No.: 10412580
3/4" Dia. Hardened Round Washer	ASTM F436 Type 1	Heat No.: 31602750
3/4" Dia. UNC Heavy Hex Nut	ASTM A563DH	Heat No.: DL16101614
Epoxy	Min. Bond Strength 1,305 psi	Tech Data Available Online

Table A-5. Material Certification List, Concrete Slab, Test No. TMS-5

Part Description	Material Specifications	Material Reference
108"x36"x4" Concrete Pad	f'c ≥ 4,000 psi	Ticket No. 1209146
4"x4"x⅜" Steel Socket Tube	ASTM A500 Grade B	Heat No.: 821T08050
4"x4"x¼" Steel Plate	ASTM A36	Heat No.: A609773
S3x5.7 by 44" Long Steel Post	ASTM A572 Grade 50, ASTM A992	Heat No.: 59079748
2¾"x1"x¼" Post Standoff	ASTM A36	Heat No.: 64055041

CAUTION FRESH CONCRETE

Body and or eye contact with fresh (moist) concrete should be avoided because it contains alkali and is caustic.

Ready Mixed Concrete Company
6200 Cornhusker Highway, P.O. Box 29288
Lincoln, Nebraska 68529
Telephone 402-434-1844

PLANT	MIX CODE	YARDS	TRUCK	DRIVER	DESTINATION	CLASS	TIME	DATE	TICKET
4	24013000	10.00	0227	9516			9:16	08/18/16	4185416

CUSTOMER	JOB	CUSTOMER NAME	TAX CODE	PARTIAL	NIGHT R.	LOADS
00003		CIA—MWRS				10

DELIVERY ADDRESS: 4630 NW 36TH STREET
SPECIAL INSTRUCTIONS: AIRPARK NORTH OF GOODYEAR HANGERS
P.O. NUMBER: JIM 4506250

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UNIT PRICE	AMOUNT
10.00	10.00	10.00	24013000	L4000 SLUMP: 5.00	$113.25	$1,132.50

Ø
WATER ADDED ON JOB AT CUSTOMER'S REQUEST Ø GAL
RECEIVED BY

SUBTOTAL $1,132.5
TAX
TOTAL $1,132.5

$1,132.50

R#17-73 and R#17-77
Concrete Deck and Headwall
Culvert/Top Socket Rebar

Truck	Driver	User	Disp Ticket Num	Ticket ID	Time	Date
0227	9516	SMT user	4185416	4185270	9:16	8/18/16

Load Size	Mix Code	Returned	Qty	Mix Age	Seq	Load ID
10.00 CYDS	24013000				W	10

Material	Description	Design Qty	Required	Batched	% Var	% Moisture	Actual Wat
G47B	47B GRAVEL	2106.0 lb	21270.6 lb	21200.0 lb	-0.33%	1.00% M	25.2 gl
L47B	47B ROCK	916.0 lb	9251.6 lb	9240.0 lb	-0.13%	1.00% M	11.0 gl
CEM1	TYPE I/II CEMENT	611.0 lb	6110.0 lb	6185.0 lb	) 1.23%		
WATER	WATER	31.0 gl	293.8 gl	292.9 gl	-0.31%		292.9 gl
AIR	MB AE 200 air ent	3.0 oz	30.0 oz	30.0 oz	0.00%		

Actual Num Batches: 1 Manual 9:16:37
Load Total: 39071 lb Design 0.423 Water/Cement 0.444 A Design 310.0 gl Actual 329.0 gl To Add: 0.0 gl
Slump: 5.00 in # Water in Truck: 0.0 gl Adjust Water: 0.0 gl / Load Trim Water: 0.0 gl/ CYD

ORIGINAL

Figure A-1. Simulated Culvert Concrete

CERTIFIED MATERIAL TEST REPORT

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GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
NEBCO INC STEEL DIVISION HAVELOCK,NE 68529 USA	CONCRETE INDUSTRIES INC LINCOLN,NE 68529-0529 USA	60 (420)	Rebar / #5 (16MM)	0000000000

LENGTH	WEIGHT	HEAT / BATCH
60'00"	186,248 LB	58025756/02

SALES ORDER	CUSTOMER MATERIAL Nº	SPECIFICATION / DATE or REVISION
3733188/000010		ASTM A615/A615M-15 ASTM A615/A615M-15 E1

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
119213	1327-0000199600	05/19/2016

CHEMICAL COMPOSITION

C %	Mn %	P %	S %	Si %	Cu %	Ni %	Cr %	Mo %	Sn %	V %	Nb %	Al %
0.42	0.85	0.016	0.029	0.22	0.25	0.10	0.15	0.026	0.007	0.017	0.012	0.003

CHEMICAL COMPOSITION

CEqyA706 %
0.58

MECHANICAL PROPERTIES

YS PSI	YS MPa	UTS PSI	UTS MPa	G/L Inch	G/L mm
70156	484	103777	716	8.000	200.0

MECHANICAL PROPERTIES

Elong. %	BendTest
15.40	OK

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of company. We certify that these data are correct and in compliance with specified requirements. This material, including the billets, was melted and manufactured in the USA. CMTR complies with EN 10204 3.1.

Bhaskar — BHASKAR YALAMANCHILI, QUALITY DIRECTOR

Tom Harrington — TOM HARRINGTON, QUALITY ASSURANCE MGR.

Figure A-2. Culvert Reinforcement, No. 5 Bars

CERTIFIED MATERIAL TEST REPORT Page 1/1

GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
NEBCO INC STEEL DIVISION HAVELOCK,NE 68529 USA	CONCRETE INDUSTRIES INC LINCOLN,NE 68529-0529 USA	60 (420)	Rebar / #4 (13MM)	0000000000

LENGTH	WEIGHT	HEAT / BATCH
60'00"	76,714 LB	58025130/03

SALES ORDER	CUSTOMER MATERIAL Nº	SPECIFICATION / DATE or REVISION
3501201/000010		ASTM A615/A615M-15

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
118128	1327-0000193241	03/30/2016

CHEMICAL COMPOSITION

C %	Mn %	P %	S %	Si %	Cu %	Ni %	Cr %	Mo %	Sn %	V %	Nb %	Al %
0.47	0.88	0.010	0.032	0.20	0.31	0.15	0.15	0.037	0.008	0.018	0.000	0.003

CHEMICAL COMPOSITION

CEqyA706 %
0.64

MECHANICAL PROPERTIES

YS PSI	YS MPa	UTS PSI	UTS MPa	G/L Inch	G/L mm
73476	507	108030	745	8.000	200.0

MECHANICAL PROPERTIES

Elong. %	BendTest
13.70	OK

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of company. We certify that these data are correct and in compliance with specified requirements. This material, including the billets, was melted and manufactured in the USA. CMTR complies with EN 10204 3.1.

Bhaskar
BHASKAR YALAMANCHILI
QUALITY DIRECTOR

Tom L Harrington
TOM HARRINGTON
QUALITY ASSURANCE MGR.

Figure A-3. Culvert Reinforcement, No. 4 Bars

EVRAZ ROCKY MOUNTAIN STEEL
A DIVISION OF EVRAZ INC. NA

S. Freeway
lo, CO 81004 USA

MATERIAL TEST REPORT

Date Printed: 25–MAY–16

Date Shipped: 25–MAY–16 **Product: DEF #4 (1/2")** **Specification: ASTM A615/A706 Gr 60**

FWIP: 52825704 **Customer: CONCRETE INDUSTRIES INC** **Cust. PO: 119371**

CHEMICAL ANALYSIS (In Weight %, uncertainty of measurement 0.005%) (Heat cast 05/10/16)

Heat Number	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al	V	B	Cb	Sn	N	Ti
586820	0.26	1.21	0.012	0.024	0.20	0.24	0.09	0.12	0.028	0.002	0.040	0.0004	0.001	0.011	0.0098	0.001

Carbon Equivalent = 0.480

MECHANICAL PROPERTIES **(Tensiles test date 05/18/16)**

Heat Number	Sample No.		Yield (Psi)	Ultimate (Psi)	Elongation (%)	Reduction (%)	Bend	Wt/ft
86820	01		71264	98330	15.4		OK	0.670
		(MPa)	491.3	678.0				
86820	02		70900	98960	15.0		OK	0.669
		(MPa)	488.8	682.3				

All melting and manufacturing processes of the material subject to this test certificate occurred in the United States of America.
ERMS also certifies this material to be free from Mercury contamination.

This material has been produced, tested and conforms to the requirements of the applicable specifications. We hereby certify that the above test results represent those contained in the records of the Company.

Valoree Varick
General Supervisor of Quality

Figure A-4. Culvert Reinforcement, No. 4 Bars, Vertical Hoop

Atlas Tube Corp (Chicago)
1855 East 122nd Street
Chicago, Illinois, USA
60633
Tel: 773-646-4500
Fax: 773-646-6128

Atlas *Tube*
A DIVISION OF ZEKELMAN INDUSTRIES

Ref.B/L: 80732800
Date: 09.23.2016
Customer: 179

MATERIAL TEST REPORT

Sold to

Steel & Pipe Supply Company
PO Box 1688
MANHATTAN KS 66505
USA

Shipped to

Steel & Pipe Supply Company
401 New Century Parkway
NEW CENTURY KS 66031
USA

Material: 4.0x4.0x188x40'0"0(5x4) | Material No: 400401884000 | Made in: USA | Melted in: USA

Sales order: 1121443 | Purchase Order: C450006049 | Cust Material #: 6540018840

Heat No	C	Mn	P	S	Si	Al	Cu	Cb	Mo	Ni	Cr	V	Ti	B	N
U3517	0.190	0.740	0.013	0.002	0.030	0.027	0.170	0.001	0.020	0.070	0.080	0.002	0.001	0.000	0.006

Bundle No	PCs	Yield	Tensile	Eln.2in	Certification	CE
M800654891	20	067564 Psi	079920 Psi	29 %	ASTM A500-13 GRADE B&C	0.35

Material Note:
Sales Or.Note:

Material: 4.0x4.0x188x48'0"0(5x3) | Material No: 400401884800 | Made in: USA | Melted in: USA

Sales order: 1121657 | Purchase Order: 4500273352 | Cust Material #: 6540018848

Heat No	C	Mn	P	S	Si	Al	Cu	Cb	Mo	Ni	Cr	V	Ti	B	N
U3518	0.190	0.750	0.012	0.001	0.040	0.028	0.160	0.001	0.020	0.060	0.090	0.002	0.001	0.000	0.006

Bundle No	PCs	Yield	Tensile	Eln.2in	Certification	CE
M800654887	15	062326 Psi	078685 Psi	31 %	ASTM A500-13 GRADE B&C	0.36

Material Note:
Sales Or.Note:

Material: 4.0x4.0x375x48'0"0(4x2) | Material No: 400403754800 | Made in: USA | Melted in: USA

Sales order: 1121708 | Purchase Order: 4500273356 | Cust Material #: 6540037548

Heat No	C	Mn	P	S	Si	Al	Cu	Cb	Mo	Ni	Cr	V	Ti	B	N
821T08050	0.210	0.780	0.010	0.006	0.009	0.041	0.150	0.002	0.005	0.010	0.020	0.001	0.002	0.000	0.003

Bundle No	PCs	Yield	Tensile	Eln.2in	Certification	CE
M800652529	8	082533 Psi	089040 Psi	31 %	ASTM A500-13 GRADE B&C	0.38

Material Note:
Sales Or.Note:

Authorized by Quality Assurance:
The results reported on this report represent the actual attributes of the material furnished and indicate full compliance with all applicable specification and contract requirements.
D1.1 method.

Steel Tube Institute OF NORTH AMERICA

Page : 2 Of 3

Metals Service Center Institute

Figure A-5. 4-in. x 4-in. x ⅜-in. (107-mm x 107-mm x 10-mm) Steel Socket Tubes, Test Nos. TMS-1 through TMS-5

STEEL AND PIPE SUPPLY
SPS Coil Processing Tulsa
5275 Bird Creek Ave.
Port of Catoosa, OK 74015

METALLURGICAL TEST REPORT

PAGE 1 of 1
DATE 09/13/2016
TIME 09:38:53
USER WILLIAMR

SOLD TO
66031-1127

SHIP TO
13716
Kansas City Warehouse
401 New Century Parkway
NEW CENTURY KS

Order	Material No.	Description	Quantity	Weight	Customer Part	Customer PO	Ship Date
40270331-0010	801148120TM	11GA 48 X 120 A1011-CS-TYB TEMP HS	50	10,000			09/13/2016

Chemical Analysis

Heat No. A609773 Vendor STEEL DYNAMICS COLUMBUS DOMESTIC Mill STEEL DYNAMICS COLUMBUS Melted and Manufactured in the USA

Carbon	Manganese	Phosphorus	Sulphur	Silicon	Nickel	Chromium	Molybdenum	Boron	Copper	Aluminum	Titanium	Vanadium	Columbium	Nitrogen	Tin
0.0700	0.3800	0.0110	0.0020	0.0100	0.0300	0.0600	0.0100	0.0001	0.0900	0.0240	0.0000	0.0020	0.0010	0.0078	0.0040

Mechanical / Physical Properties

Mill Coil No. 16B647062

Tensile	Yield	Elong	Rckwl	Grain	Charpy	Charpy Dr	Charpy Sz	Temperature	Olsen

Batch 0004464962 50 EA 10,000 LB

THE CHEMICAL, PHYSICAL, OR MECHANICAL TESTS REPORTED ABOVE ACCURATELY REFLECT INFORMATION AS CONTAINED IN THE RECORDS OF THE CORPORATION.
The material is in compliance with EN 10204 Section 4.1 Inspection Certificate Type 3.1

Figure A-6. 4-in. x 4-in. x ¼-in. (107-mm x 107-mm x 6-mm) Steel Plate, Test Nos. TMS-1, TMS-4, and TMS-5

GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
STEEL & PIPE SUPPLY CO INC 401 NEW CENTURY PKWY NEW CENTURY,KS 66031-1127 USA	STEEL & PIPE SUPPLY CO INC MANHATTAN,KS 66505-1688 USA	A36/A572-50	Standard I-Beam / 3 X 5.7# / 75 X 8.5	0000050470

LENGTH	WEIGHT	HEAT / BATCH
40'00"	8,208 LB	59070748/02

SALES ORDER	CUSTOMER MATERIAL N°	SPECIFICATION / DATE or REVISION
4082394/000030	000000000035357040	ASME SA36 ASTM A572-15 ASTM A6-14, A36-14 ASTM A709-13A

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
4500271337	1327-0000209580	09/02/2016

CHEMICAL COMPOSITION

C %	Mn %	P %	S %	Si %	Cu %	Ni %	Cr %	Mo %	Sn %	V %	Nb %	Al %
0.14	0.91	0.020	0.035	0.21	0.32	0.17	0.16	0.036	0.009	0.003	0.013	0.002

CHEMICAL COMPOSITION

CEqyA6 %
0.36

MECHANICAL PROPERTIES

YS 0.2% PSI	UTS PSI	YS MPa	UTS MPa	G/L Inch	G/L mm
61464	78321	424	540	8.000	200.0
61487	78301	424	540	8.000	200.0

MECHANICAL PROPERTIES

Elong. %
23.40
21.30

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of company. We certify that these data are correct and in compliance with specified requirements. This material, including the billets, was melted and manufactured in the USA. CMTR complies with EN 10204 3.1.

Bhaskar
BHASKAR YALAMANCHILI
QUALITY DIRECTOR

Tom L Harrington
TOM HARRINGTON
QUALITY ASSURANCE MGR.

Figure A-7. S3x5.7 Weak Posts, Test Nos. TMS-1 through TMS-5

GERDAU

US-ML-WILTON
1500-2500 WEST 3RD STREET
WILTON, IA 52778
USA

CERTIFIED MATERIAL TEST REPORT

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CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
STEEL & PIPE SUPPLY CO INC 401 NEW CENTURY PKWY NEW CENTURY,KS 66031-1127 USA	STEEL & PIPE SUPPLY CO INC MANHATTAN,KS 66505-1688 USA	A36/44W	Flat Bar / 1/4 X 1	0000011110

LENGTH	WEIGHT	HEAT / BATCH
20'00"	19,584 LB	64055041/02

SALES ORDER	CUSTOMER MATERIAL N°
4190352/000010	00000000010810020

SPECIFICATION / DATE or REVISION
ASME SA36
ASTM A6-14, A36-14
ASTM A709-15, AASHTO M270-12
CSA G40.20-13/G40.21-13

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
4500272853	1334-0000034941	09/20/2016

CHEMICAL COMPOSITION

C %	Mn %	P %	S %	Si %	Cu %	Ni %	Cr %	Mo %	V %	Nb %	Al %	Pb %
0.15	0.57	0.007	0.021	0.21	0.26	0.09	0.07	0.020	0.001	0.014	0.002	0.0000

CHEMICAL COMPOSITION

CEqyA529 %	Sn %
0.33	0.018

MECHANICAL PROPERTIES

Elong. %	G/L Inch	UTS PSI	UTS MPa	YS PSI	YS MPa
22.50	8.000	74300	512	58000	400
22.50	8.000	74400	513	57600	397

GEOMETRIC CHARACTERISTICS

R:R
123.14

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of company. We certify that these data are correct and in compliance with specified requirements. This material, including the billets, was melted and manufactured in the USA. CMTR complies with EN 10204 3.1.

Bhaskar
BHASKAR YALAMANCHILI
QUALITY DIRECTOR

Brett Krause
BRETT KRAUSE
QUALITY ASSURANCE MGR.

Figure A-8. Post Standoffs, Test Nos. TMS-1 through TMS-5

CAUTION
FRESH CONCRETE

Body and or eye contact with fresh (moist) concrete should be avoided because it contains alkali and is caustic.

Ready Mixed Concrete Company

6200 Cornhusker Highway, P.O. Box 29288
Lincoln, Nebraska 68529
Telephone 402-434-1844

Top Socket Concrete

R#17-378 January 2017 SMT

LANT	MIX CODE	YARDS	TRUCK	DRIVER	DESTINATION	CLASS	TIME	DATE	TICKET
01	24033000	1.00	0239	3978			9:19	01/11/17	1209146

USTOMER	JOB	CUSTOMER NAME	TAX CODE	PARTIAL	NIGHT R.	LOADS
00003	3	CIA---MWRSS				7

ELIVERY ADDRESS	SPECIAL INSTRUCTIONS	P.O. NUMBER
4630 NW 36TH ST	NORTH OF OLD GOODYEAR HANGERS	JIM 4506250

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UNIT PRICE	AMOUNT
1.00	1.00	1.00	24033000	L4000 TYPE 3	$120.89	$120.89
				SLUMP: 4.00		
				MINIMUM HAUL		60.00
				WINTER SERVICE		4.00

WATER ADDED ON JOB AT CUSTOMER'S REQUEST 3 GAL.

RECEIVED BY Bry Kitn

SUBTOTAL $184.89
TAX
TOTAL $184.89
$184.89

Truck	Driver	User	Disp Ticket Num	Ticket ID	Time	Date
0239	3978	user	1209146	23815	9:19	1/11/17

Load Size	Mix Code	Returned	Qty	Mix Age	Seq	Load ID
1.00 CYDS	24033000				W	7

Material	Description	Design Qty	Required	Batched	% Var	% Moisture	Actual Wat
G47B	47B GRAVEL	2090 lb	2130 lb	2120 lb	-0.46%	1.90% M	5 gl
L47B	47B ROCK	909 lb	909 lb	900 lb	-0.99%		
CEM3	CEMENT TYPE3	611 lb	611 lb	645 lb	+ 5.56%		
WATER	WATER	35.0 GL	31.2 GL	31.2 GL	-0.28%		31.2 gl
AIR	MICRO AIR 200	4.00 oz	4.00 oz	3.00 oz	-25.00%		

Actual Num Batches: 1 Manual
Load Total: 3925 lb Design 0.478 Water/Cement 0.464 A Design 35.0 gl Actual 35.9 gl To Add: 0.0 gl
Slump: 4.00 in # Water in Truck: 0.0 GL Adjust Water: 0.0 GL / Load Trim Water: 0.0 GL/ CYD

ORIGINAL

Figure A-9. Foundation and Slab Concrete, Test Nos. TMS-1, TMS-4 and TMS-5

Concrete Industries
6300 Cornhusker Highway
P.O. Box 29529
Lincoln, NE 68529-
Phone: (402)434-1800 FAX: (402)434-1899

JOB NUMBER	RELEASE NUMBER	REQ. DELIVERY DATE	PAGE
8000MISC.	CORY-861		1 of 1

JOB NAME	CC
JOB COMPLETE	STM

CUSTOMER	BY
MIDWEST ROADSIDE SAFETY	CLR

MATERIAL TYPE	REFERENCE	DRAWING ID	DESCRIPTION
Rebar, Grade 60, Epoxy	epoxy coated		TOP MOUNTED SOCKET

Itm	Qty	Size	Length	Mark	Shape	Lbs	A	B	C	D	E	F/R	G	H	J	K	O	BC
1	3	4	3-00	A2	T3	6			2-041				0-08				0-09	1
2	4	4	1-06	A3		4												0
	7.					10												

Total Weight: 10 Lbs

Longest Length: 3-00

WEIGHT SUMMARY

Rebar, Grade 60, Epoxy

SIZE	TOTAL ITEMS	TOTAL PIECES	TOTAL LBS	STRAIGHT ITEMS	STRAIGHT PIECES	STRAIGHT LBS	LIGHT BENDING ITEMS	LIGHT BENDING PIECES	LIGHT BENDING LBS	HEAVY BENDING ITEMS	HEAVY BENDING PIECES	HEAVY BENDING LBS
4	2	7	10	1	4	4	1	3	6	0	0	0
	2	7	10	1	4	4	1	3	6	0	0	0

Total Weight: 10 Lbs

Longest Length: 3-00

heat number: NUCOR KN15106961

R#17-181 Top Socket Cylinder Rebar

Figure A-10. No. 4 Rebar for Concrete Foundations, Test Nos. 1 and TMS-4

STEEL AND PIPE SUPPLY
SPS Coil Processing Tulsa
5275 Bird Creek Ave.
Port of Catoosa, OK 74015

METALLURGICAL TEST REPORT

PAGE 1 of 1
DATE 10/18/2016
TIME 10:22:43
USER WILLIAMR

Top Socket fabricated parts
R#17-176 October 2016

SOLD TO
66031-1127

SHIP TO
13716
Kansas City Warehouse
401 New Century Parkway
NEW CENTURY KS

Order	Material No.	Description	Quantity	Weight	Customer Part	Customer PO	Ship Date
40272856-0010	72896120A2	1/4 96 X 120 A572GR50 MILL PLATE	11	8,984.800			10/18/2016

Chemical Analysis

Heat No. A6H254 Vendor SSAB - MONTPELIER WORKS DOMESTIC Mill SSAB - MONTPELIER WORKS Melted and Manufactured in the USA

Produced from Coil

Carbon	Manganese	Phosphorus	Sulphur	Silicon	Nickel	Chromium	Molybdenum	Boron	Copper	Aluminum	Titanium	Vanadium	Columbium	Nitrogen	Tin
0.0500	0.9400	0.0140	0.0040	0.0400	0.1300	0.1000	0.0300	0.0000	0.3300	0.0270	0.0010	0.0310	0.0020	0.0000	0.0000

Mechanical / Physical Properties

Mill Coil No. A6H2540774

Tensile	Yield	Elong	Rckwl	Grain	Charpy	Charpy Dr	Charpy Sz	Temperature	Olsen
66700.000	53900.000	30.60			101	Longitudinal	5.0	-20 F	
69300.000	58100.000	29.30			96	Longitudinal	5.0	-20 F	

Batch 0004503098 11 EA 8,984.800 LB

CHEMICAL OR MECHANICAL TESTS REPORTED ABOVE ACCURATELY REFLECT INFORMATION AS CONTAINED IN THE RECORDS OF THE CORPORATION.

Figure A-11. 6-in. x 29-in. x ¼-in. (152-mm x 737-mm x 6-mm) Steel Plate, Test Nos. TMS-2 and TMS-3

ArcelorMittal Burns Harbor Plate
QUALITY ASSURANCE
REPORT OF TEST AND ANALYSES

US HWY 12 Burns Harbor, Indiana

SHIPMENT NO. 804-02594 | DATE SHIPPED 03-24-16 | CAR OR VEHICLE NO. AREA TRANSPORTATIONTRLR 5626 | PAGE 1

SOLD TO: LEECO STEEL LLC
1011 WARRENVILLE RD STE 500
LISLE IL 60532-0933

SHIP TO: LEECO STEEL LLC
1000 E BOUNDARY RD
PORTAGE IN 46368

SERIAL NUMBER	PAT NO.	HEAT NUMBER	NO. PCS.	THICKNESS INCHES	WIDTH OR DIA. INCHES	LENGTH INCHES	WEIGHT POUNDS	YIELD POINT PSI	TENSILE STRENGTH PSI	AF FRAC. ELONG. IN %	RED. %
		823S67580	1	5/8	96	240	4084	60900	86800	8 19	
		811S07890	12	1/2	96	240	39204	53300	73600	8 23	
								52900	73000	8 26	

QUALITY STEEL MELTED & MANUFACTURED IN THE U. S. A.

PLATES - CSA G40.21-13 GR 50W KLD FINE GRAIN PRAC, ASTM A709-13A GR 50 TYPE 2, ASTM A572-13A GR 50 TYPE 2, ASME SA572 GR 50 2013 EDITION --- TEST CERTS ARE PREPARED IN ACCORD WITH PROCEDURES OUTLINED IN EN 10204:2004 TYPE 3.1

CO# V07286-Q116 GH 875-2408

823S67580 1 5/8 96 240 4084 60900 86800 8 19

(M55)MFST REF#:062096240A572-50

PLATES - CSA G40.21-13 GR 50W KLD FINE GRAIN PRAC, ASTM A709-13A GR 50 TYPE 2, ASTM A572-13A GR 50 TYPE 2, ASME SA572 GR 50 2013 EDITION --- TEST CERTS ARE PREPARED IN ACCORD WITH PROCEDURES OUTLINED IN EN 10204:2004 TYPE 3.1

CO# V07376-65315 GH 875-2438

811S07890 12 1/2 96 240 39204 53300 73600 8 23
52900 73000 8 26

(M55)MFST REF#:050096240A572-50

Q-QUENCH TEMPERATURE | T-TEMPER TEMPERATURE | N-NORMALIZE TEMPERATURE

SERIAL NUMBER	PAT NO.	HEAT NUMBER	HARD BHN	BEND	THICKNESS INCHES	TYPE	SIZE	DIR	TEST TEMP F	CHARPY IMPACT ENERGY FT LBS 1	2	3	SHEAR(%) 1	2	3	LAT EXP MILS 1	2	3

HEAT NUMBER	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al	B	Cb	N	Sn	MCQUAID GRAIN SIZE
823S67580	.20	1.26	.016	.004	.300	.027	.01	.03	.006	.061	.002	.037	.0002	.003	.004	.007	
811S07890	.13	1.16	.013	.004	.285	.019	.01	.03	.006	.056	.002	.029	.0002	.002	.003	.002	

I certify that the above results are a true and correct copy of actual results contained in records maintained by ArcelorMittal Burns Harbor and are in full compliance with the requirements of the specification cited above. This test report cannot be altered and must be transmitted intact with any subsequent third party test reports, if required.

R. SPANGLER II PER LSS

BHPLTRPT.TIF SUPV. QUALITY ASSURANCE

Figure A-12. ½-in. (13-mm) Thick Steel Base Plate, Test Nos. TMS-2 and TMS-3

NUCOR
FASTENER DIVISION

LOT NO.
374941A

Post Office Box 6100
Saint Joe, Indiana 46785
Telephone 260/337-1600

CUSTOMER NO/NAME
8061 STRUCTURAL BOLT CO LLC — NUCOR ORDER # 978180
TEST REPORT SERIAL# FB499211 — CUST PART #
TEST REPORT ISSUE DATE 6/27/16
DATE SHIPPED 8/05/16 — CUSTOMER P.O. # 19060
NAME OF LAB SAMPLER: RYAN UNGER, LAB TECHNICIAN

*****************CERTIFIED MATERIAL TEST REPORT*****************

NUCOR PART NO	QUANTITY	LOT NO.	DESCRIPTION
175747C	15300	374941A	5/8-11 GR DH HV H.D.G. HEX NUT HOT DIP GAL.

MANUFACTURE DATE 4/21/16

--CHEMISTRY — MATERIAL GRADE -1026L

**CHEMISTRY COMPOSITION (WT% HEAT ANALYSIS) BY MATERIAL SUPPLIER — NUCOR STEEL - NEBRASKA

MATERIAL NUMBER	HEAT NUMBER	C	MN	P	S	SI
RM030600	NF15204037	.23	.71	.006	.017	.24

--MECHANICAL PROPERTIES IN ACCORDANCE WITH ASTM A563-07a

SURFACE HARDNESS (R30N)	CORE HARDNESS (RC)	PROOF LOAD 33900 LBS	TENSILE STRENGTH DEG-WEDGE (LBS)	STRESS (PSI)
N/A	27.7	PASS	N/A	N/A
N/A	29.0	PASS	N/A	N/A
N/A	26.5	PASS	N/A	N/A
N/A	28.5	PASS	N/A	N/A
N/A	29.4	PASS	N/A	N/A

AVERAGE VALUES FROM TESTS
28.2
PRODUCTION LOT SIZE 204000 PCS

--VISUAL INSPECTION IN ACCORDANCE WITH ASTM A563-07a — 160 PCS. SAMPLED — LOT PASSED

--COATING - HOT DIP GALVANIZED TO ASTM F2329-13 - GALVANIZING PERFORMED IN THE U.S.A.
1. 0.00372 2. 0.00230 3. 0.00269 4. 0.00418 5. 0.00426 6. 0.00286 7. 0.00258
8. 0.00417 9. 0.00345 10. 0.00341 11. 0.00295 12. 0.00314 13. 0.00267 14. 0.00237
15. 0.00228
AVERAGE THICKNESS FROM 15 TESTS .00314
HEAT TREATMENT - AUSTENITIZED, OIL QUENCHED & TEMPERED (MIN 800 DEG F)

--DIMENSIONS PER ASME B18.2.6-2010

CHARACTERISTIC	#SAMPLES TESTED	MINIMUM	MAXIMUM
Width Across Corners	8	1.187	1.193
Thickness	32	0.599	0.614

ALL TESTS ARE IN ACCORDANCE WITH THE LATEST REVISIONS OF THE METHODS PRESCRIBED IN THE APPLICABLE SAE AND ASTM SPECIFICATIONS. THE SAMPLES TESTED CONFORM TO THE SPECIFICATIONS AS DESCRIBED/LISTED ABOVE AND WERE MANUFACTURED FREE OF MERCURY CONTAMINATION. NO INTENTIONAL ADDITIONS OF BISMUTH, SELENIUM, TELLURIUM, OR LEAD WERE USED IN THE STEEL USED TO PRODUCE THIS PRODUCT.
THE STEEL WAS MELTED AND MANUFACTURED IN THE U.S.A. AND THE PRODUCT WAS MANUFACTURED AND TESTED IN THE U.S.A. PRODUCT COMPLIES WITH DFARS 252.225-7014. WE CERTIFY THAT THIS DATA IS A TRUE REPRESENTATION OF INFORMATION PROVIDED BY THE MATERIAL SUPPLIER AND OUR TESTING LABORATORY. THIS CERTIFIED MATERIAL TEST REPORT RELATES ONLY TO THE ITEMS LISTED ON THIS DOCUMENT AND MAY NOT BE REPRODUCED EXCEPT IN FULL.

ACCREDITED

MECHANICAL FASTENER
CERTIFICATE NO. A2LA 0139.01
EXPIRATION DATE 12/31/17

NUCOR FASTENER
A DIVISION OF NUCOR CORPORATION

John W. Ferguson
JOHN W. FERGUSON
QUALITY ASSURANCE SUPERVISOR

Figure A-13. ⅝-in. (16-mm) Dia. UNC Heavy Hex Nut, Test Nos. TMS-2 and TMS-3

CHARTER STEEL
A Division of
Charter Manufacturing Company, Inc.

EMAIL

1658 Cold Springs Road
Saukville, Wisconsin 53080
(262) 268-2400
1-800-437-8789
Fax (262) 268-2570

CHARTER STEEL TEST REPORT

Melted in USA Manufactured in USA

Cust P.O.	111389
Customer Part #	955311627A1
Charter Sales Order	10154705
Heat #	10382300
Ship Lot #	4347362
Grade	LEBA3 M SKFG RHQ 41/64
Process	HRCC
Finish Size	41/64
Ship date	07-JUN-15

Fontana Fasteners Inc
3595 West State Road 28
Frankfort,IN-46041

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed below and that it satisfies these requirements. The recording of false, fictitious and fraudulent statements or entries on this document may be punishable as a felony under federal statute.

Test results of Heat Lot# 10382300

Lab Code: 7388

CHEM	C	MN	P	S	SI	NI	CR	MO	CU	SN	V
%Wt	.32	.88	.009	.013	.210	.05	.16	.02	.08	.007	.004
	AL	N	B	TI	NB						
	.024	.0070	.0026	.022	.001						

JOMINY(HRC)

J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J11	J12
53	52	51	50	47	36	27	23	22	21	20	20
J13											
20											

JOMINY LAB-0358-01 JOMINY SAMPLE TYPE ENGLISH-R DI-2.68

Test results of Rolling Lot # 1157865

	# of Tests	Min Value	Max Value	Mean Value	
TENSILE (KSI)	1	88.1	88.1	88.1	TENSILE LAB = 0358-02
REDUCTION OF AREA (%)	1	60	60	60	RA LAB = 0358-02
ROCKWELL B (HRBW)	1	85	85	85	RB LAB = 0358-02
ROD SIZE (Inch)	4	.640	.645	.643	
ROD OUT OF ROUND (Inch)	1	.005	.005	.005	

NUMDECARB-1
REDUCTION RATIO=94:1

AVE DECARB (Inch)-.003

Specifications: Manufactured per Charter Steel Quality Manual Rev Date 9/12/12
Meets customer specifications with any applicable Charter Steel exceptions for the following customer documents:
Customer Document = LE 1.1 Revision = 9 Dated = 27-NOV-07

Additional Comments: GRADE 30 Min B3

Charter Steel
Saukville, WI, USA

Rem: Load1,Fax0,Mail0

ACCREDITED
Testing Laboratory

Page 1 of 2

This MTR supersedes all previously dated MTRs for this order

Janice Barnard
Manager of Quality Assurance
Printed Date : 06/07/2015

Figure A-14. ⅝-in. (16-mm) UNC Heavy Hex Bolt, Test Nos. TMS-2 and TMS-3

Portland Bolt
& MANUFACTURING COMPANY

Phone: 800-547-6758 | Fax: 503-227-4634
3441 NW Guam Street, Portland, OR 97210
Web: www.portlandbolt.com | Email: sales@portlandbolt.com

For: CASH SALE
PB Invoice#: 94373
Cust PO#: MIDWEST ROADSIDE
Date: 11/07/2016
Shipped: 11/08/2016

CERTIFICATE OF CONFORMANCE

We certify that the following items were manufactured and tested in accordance with the chemical, mechanical, dimensional and thread fit requirements of the specifications referenced.

Product:
ASTM A449 ALL THRD RODS

By:
Certification Department Quality Assurance
Dane McKinnon

R#17-184 Top Socket Threaded Rods material
H#10412580 November 2016 SMT

Figure A-15. ¾-in. (19-mm) Diameter Threaded Rod, Test Nos. TMS-2 and TMS-3

TSI EST. 1991 TECHNICAL STAMPING

TECHNICAL STAMPING, INC.

50600 E. RUSSELL SCHMIDT BLVD.
CHESTERFIELD TWP., MI 48051
PH(586)948-3285 / FX(586)948-3286

MATERIAL CERTIFICATION

CUSTOMER NAME	CUSTOMER ORDER NUMBER	DATE
Brighton-Best International	U32267	5/9/2016

PART NUMBER - CUSTOMER LOT NO.	LOT NUMBER	QUANTITY
3/4" F436 Hdg 257086	0216-175	24,300

STEEL GRADE	HEAT	C	MN	P	S	SI	AL	REVISION
1050	31602750	.54	.75	.008	.000	.22	.022	ASTM F-436-10

SPECIFICATION		ACTUAL	GAUGE
O.D -	1.436 - 1.500	1.441 - 1.444	CALIPER
I.D -	.813 - .845	.822 - .825	CALIPER, PIN GAUGE
THICKNESS-	.122 - .177	.125 - .128	MICROMETER
FLAT-	Max .010	.002	CALIPER
HEAT TREAT -	38 - 45 HRC	38 - 45	
PLATING-		See Attached Cert	
OTHER		N/A	

WE HEARBY CERTIFY THIS PRODUCT WAS PRODUCED UNDER A ISO-9001:2008 QUALITY ASSURANCE SYSTEM. ISO-9001:2008 CERTIFICATION NUMBER-1265 - DATE OF REGIS. JAN. 3, 2003 ALL MATERIALS ARE MADE AND MELTED IN THE U.S.A. THIS PRODUCT WAS MANUFACTURED IN CHESTERFIELD, MICHIGAN, U.S.A. THIS PRODUCT CONFORMS TO ALL REQUIREMENTS FOR WASHERS AS PRODUCED ACCORDING TO A.S.T.M. F-436-10. THE ABOVE TEST RESULTS APPLY ONLY TO THE ITEMS TESTED. THIS TEST REPORT MUST NOT BE REPRODUCED EXCEPT IN FULL WITHOUT PRIOR WRITTEN APPROVAL.

Sherrie Michon

AUTHORIZED SIGNATURE

CERTIFIED ISO 9001:

Qlty 2008 Rev. 2 11/26/01

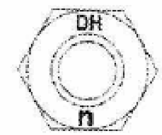
Figure A-16. ¾-in. (19-mm) Dia. Hardened Round Washer, Test Nos. TMS-2 and TMS-3

NUCOR
FASTENER DIVISION

LOT NO.
375522C

Post Office Box 6100
Saint Joe, Indiana 46785
Telephone 260/337-1600

CUSTOMER NO/NAME
8061 STRUCTURAL BOLT CO LLC NUCOR ORDER # 983384
TEST REPORT SERIAL# FB497915 CUST PART #
TEST REPORT ISSUE DATE 6/13/16
DATE SHIPPED 9/20/16 CUSTOMER P.O. # 19285
NAME OF LAB SAMPLER: RYAN UNGER, LAB TECHNICIAN



****************CERTIFIED MATERIAL TEST REPORT****************

NUCOR PART NO	QUANTITY	LOT NO.	DESCRIPTION
175657	8100	375522C	3/4-10 GR DH HV H.D.G. HEX NUT HDG/GREEN LUBE

MANUFACTURE DATE 4/26/16

--CHEMISTRY MATERIAL GRADE -1045L
**CHEMISTRY COMPOSITION (WT% HEAT ANALYSIS) BY MATERIAL SUPPLIER NUCOR STEEL - SOUTH CAROL

MATERIAL NUMBER	HEAT NUMBER	C	MN	P	S	SI
RM030767	DL16101614	.45	.66	.010	.021	.21

--MECHANICAL PROPERTIES IN ACCORDANCE WITH ASTM A563-07a

SURFACE HARDNESS (R30N)	CORE HARDNESS (RC)	PROOF LOAD 50100 LBS	TENSILE STRENGTH DEG-WEDGE (LBS)	STRESS (PSI)
N/A	29.1	PASS	N/A	N/A
N/A	28.4	PASS	N/A	N/A
N/A	27.4	PASS	N/A	N/A
N/A	31.6	PASS	N/A	N/A
N/A	27.6	PASS	N/A	N/A
AVERAGE VALUES FROM TESTS				
	28.8			

PRODUCTION LOT SIZE 200000 PCS

--VISUAL INSPECTION IN ACCORDANCE WITH ASTM A563-07a 160 PCS. SAMPLED LOT PASSED

--COATING - HOT DIP GALVANIZED TO ASTM F2329-13 - GALVANIZING PERFORMED IN THE U.S.A.
1. 0.00320 2. 0.00259 3. 0.00289 4. 0.00300 5. 0.00288 6. 0.00276 7. 0.00238
8. 0.00244 9. 0.00300 10. 0.00488 11. 0.00464 12. 0.00268 13. 0.00275 14. 0.00500
15. 0.00506
AVERAGE THICKNESS FROM 15 TESTS .00334
HEAT TREATMENT - AUSTENITIZED, OIL QUENCHED & TEMPERED (MIN 800 DEG F)

--DIMENSIONS PER ASME B18.2.6-2010

CHARACTERISTIC	#SAMPLES TESTED	MINIMUM	MAXIMUM
Width Across Corners	8	1.404	1.407
Thickness	32	0.731	0.746

ALL TESTS ARE IN ACCORDANCE WITH THE LATEST REVISIONS OF THE METHODS PRESCRIBED IN THE APPLICABLE SAE AND ASTM SPECIFICATIONS. THE SAMPLES TESTED CONFORM TO THE SPECIFICATIONS AS DESCRIBED/LISTED ABOVE AND WERE MANUFACTURED FREE OF MERCURY CONTAMINATION. NO INTENTIONAL ADDITIONS OF BISMUTH, SELENIUM, TELLURIUM, OR LEAD WERE USED IN THE STEEL USED TO PRODUCE THIS PRODUCT.
THE STEEL WAS MELTED AND MANUFACTURED IN THE U.S.A. AND THE PRODUCT WAS MANUFACTURED AND TESTED IN THE U.S.A. PRODUCT COMPLIES WITH DFARS 252.225-7014. WE CERTIFY THAT THIS DATA IS A TRUE REPRESENTATION OF INFORMATION PROVIDED BY THE MATERIAL SUPPLIER AND OUR TESTING LABORATORY. THIS CERTIFIED MATERIAL TEST REPORT RELATES ONLY TO THE ITEMS LISTED ON THIS DOCUMENT AND MAY NOT BE REPRODUCED EXCEPT IN FULL.

ACCREDITED

MECHANICAL FASTENER
CERTIFICATE NO. A2LA 0139.01
EXPIRATION DATE 12/31/17

NUCOR FASTENER
A DIVISION OF NUCOR CORPORATION

John W. Ferguson
JOHN W. FERGUSON
QUALITY ASSURANCE SUPERVISOR

Figure A-17. ¾-in. (19-mm) Diameter Heavy Hex Nut, Test Nos. TMS-2 and TMS-3

Appendix B. Bogie Test Results

The results of the recorded data from each accelerometer for every dynamic bogie test are provided in the summary sheets found in this appendix. Summary sheets include acceleration, velocity, and deflection vs. time plots as well as force vs. deflection and energy vs. deflection plots.

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

Test Description:	S3.7x5.7 Post in Concrete Foundation
Test Number:	TMS-1
Test Date:	12/12/2016
Failure Type:	Post bending and rupture

Post Properties

Post Type:	Steel
Post Size:	S3.7x5.7 Post
Post Length:	44
Embedment Depth:	14 in. - into steel socket
Orientation:	90° - Strong-Axis

Soil Properties

Gradation:	N/A
Moisture Content:	N/A
Compaction Method:	N/A

Bogie Properties

Impact Velocity:	21.71 mph	(31.85 ft/s)
Impact Height:	24.875 in.	
Bogie Mass:	1778 lb	

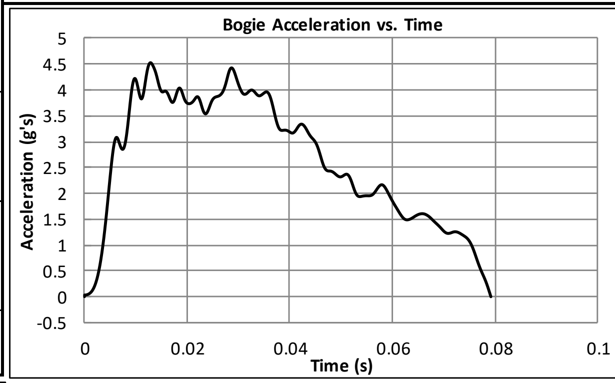
Data Acquired

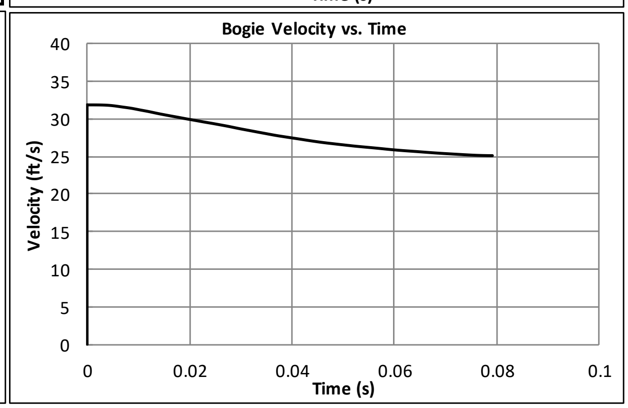
Accelerometer:	SLICE-1
Camera Data:	AOS-8, gp9, gp10

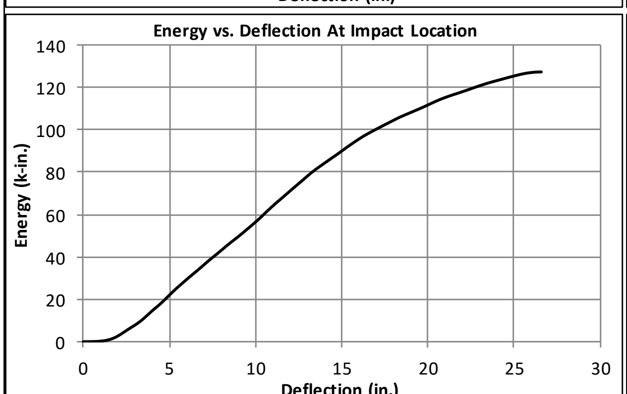
Test Results Summary

Event Duration:	0.0792	sec
Max. Deflection:	26.6	in.
Peak Force:	8.0	k
Initial Linear Stiffness:	1.6	k/in.
Total Energy:	127.3	k-in.

	@ 5"	@ 10"	@ 15"	@20"
Average Force (k)	4.38	5.63	5.99	5.58
Energy (k-in.)	21.9	56.3	89.8	111.7







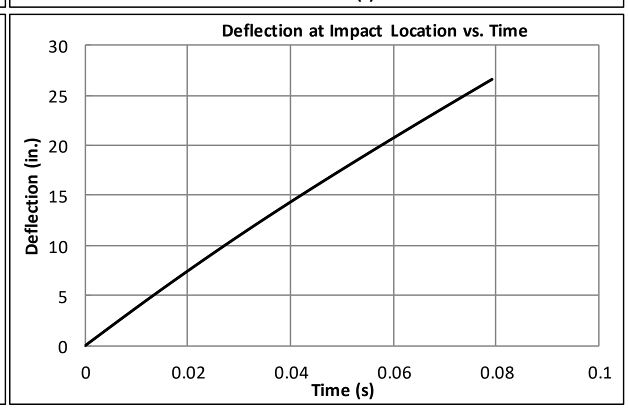


Figure B-1. Test No. TMS-1 Results (SLICE-1)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

Test Description:	S3x5.7 Post in 36" concrete foundation
Test Number:	TMS-1
Test Date:	12/12/2016
Failure Type:	Post bending and rupture

Post Properties

Post Type:	Steel
Post Size:	S3.7x5.7 Post
Post Length:	44
Embedment Depth:	14 in. - in socket
Orientation:	90° - Strong-Axis

Soil Properties

Gradation:	N/A
Moisture Content:	N/A
Compaction Method:	N/A

Bogie Properties

Impact Velocity:	21.71 mph	(31.85 ft/s)
Impact Height:	24.875 in.	
Bogie Mass:	1778 lb	

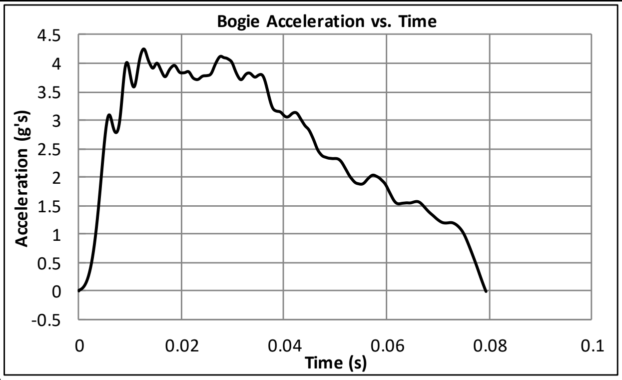
Data Acquired

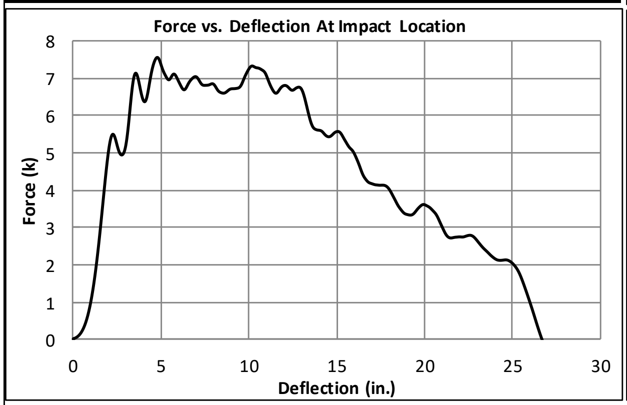
Accelerometer:	SLICE-2
Camera Data:	AOS-8, gp9, gp10

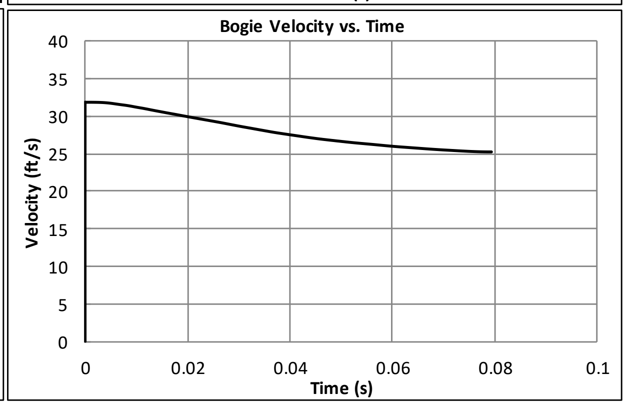
Test Results Summary

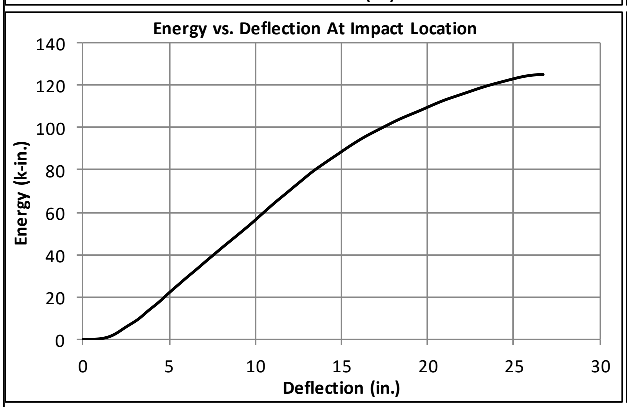
Event Duration:	0.0794	sec
Max. Deflection:	26.7	in.
Peak Force:	7.6	k
Initial Linear Stiffness:	1.6	k/in.
Total Energy:	125.0	k-in.

	@ 5"	@ 10"	@ 15"	@20"
Average Force (k)	4.39	5.62	5.90	5.48
Energy (k-in.)	21.9	56.2	88.5	109.5









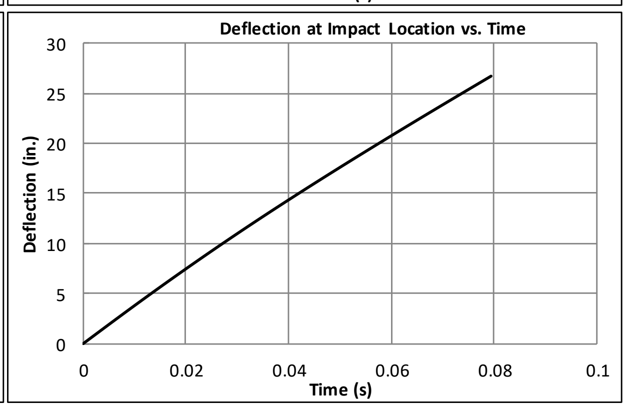


Figure B-2. Test No. TMS-1 Results (SLICE-2)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

Test Description:	S3x5.7 Post in steel socket assembly
Test Number:	TMS-2
Test Date:	12/12/2016
Failure Type:	Post Bending

Post Properties

Post Type:	Steel
Post Size:	S3x5.7
Post Length:	44 in.
Embedment Depth:	14 in. into steel socket
Orientation:	90 deg. - Strong Axis

Soil Properties

Gradation:	N/A
Moisture Content:	N/A
Compaction Method:	N/A

Bogie Properties

Impact Velocity:	21.09 mph	(30.93 ft/s)
Impact Height:	24.875 in.	
Bogie Mass:	1778 lb	

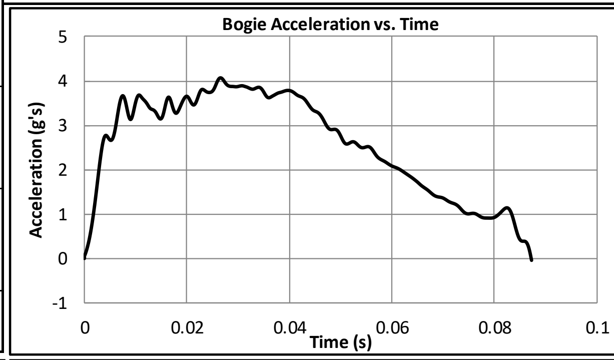
Data Acquired

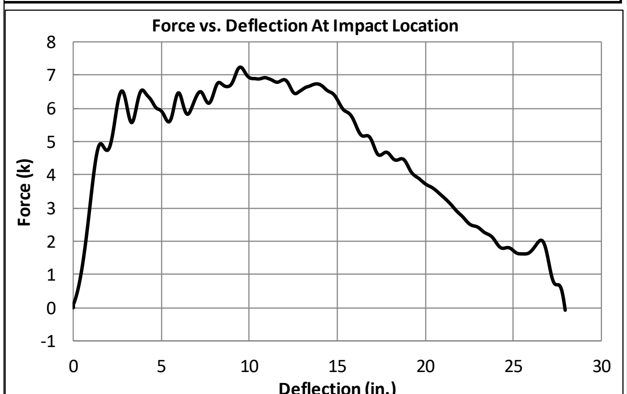
Accelerometer:	SLICE-1
Camera Data:	AOS-8, gp9, gp10

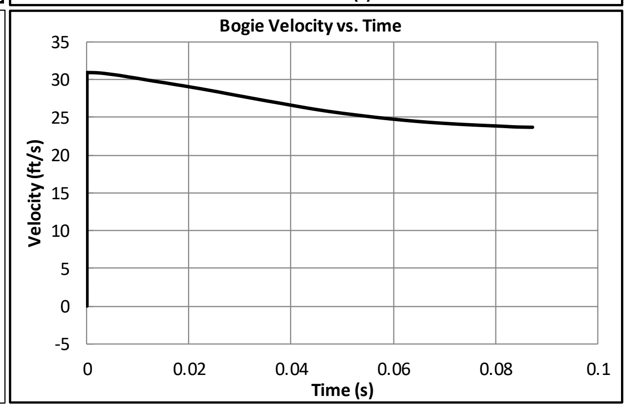
Test Results Summary

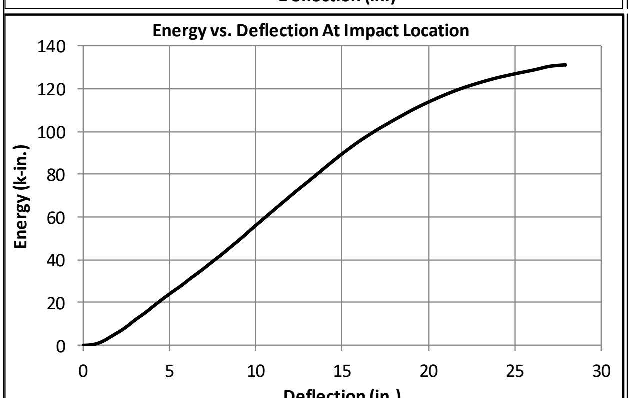
Event Duration:	0.0873	sec
Max. Deflection:	27.9	in.
Peak Force:	7.2	k
Initial Linear Stiffness:	0.8	k/in.
Total Energy:	131.1	k-in.

	@ 5"	@ 10"	@ 15"	@20"
Average Force (k)	4.77	5.59	5.97	5.69
Energy (k-in.)	23.8	55.9	89.5	113.7









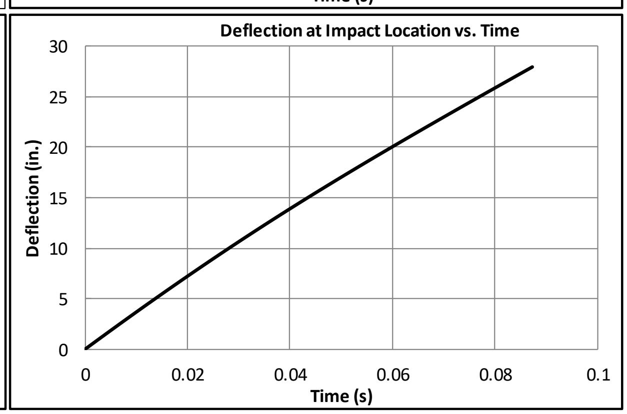


Figure B-3. Test No. TMS-2 Results (SLICE-1)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

Test Description:	S3x5.7 Post in steel socket assembly
Test Number:	TMS-2
Test Date:	12/12/2016
Failure Type:	Post Bending

Post Properties

Post Type:	Steel
Post Size:	S3x5.7
Post Length:	44 in.
Embedment Depth:	14 in. into steel socket
Orientation:	90 deg. - Strong Axis

Soil Properties

Gradation:	N/A
Moisture Content:	N/A
Compaction Method:	N/A

Bogie Properties

Impact Velocity:	21.09 mph	(30.93 ft/s)
Impact Height:	24.875 in.	
Bogie Mass:	1778 lb	

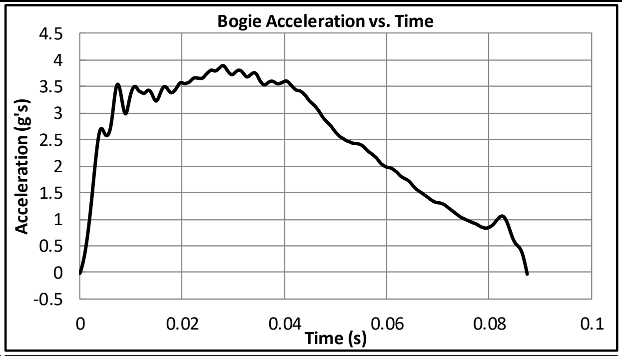
Data Acquired

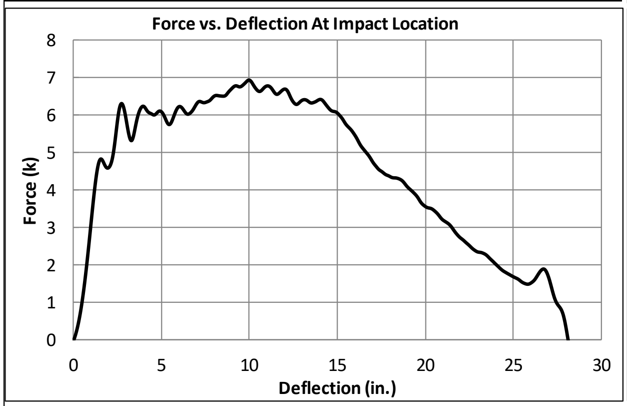
Accelerometer:	SLICE-2
Camera Data:	AOS-8, gp9, gp10

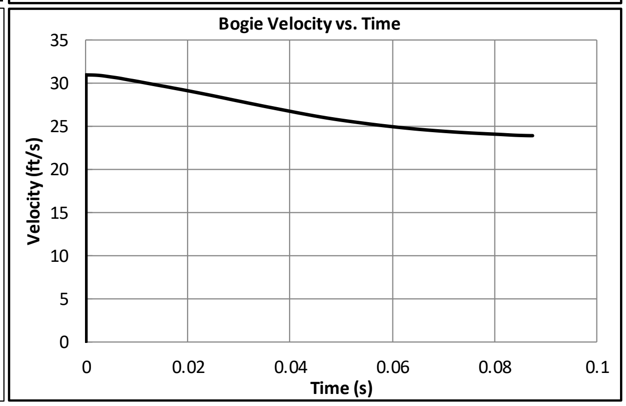
Test Results Summary

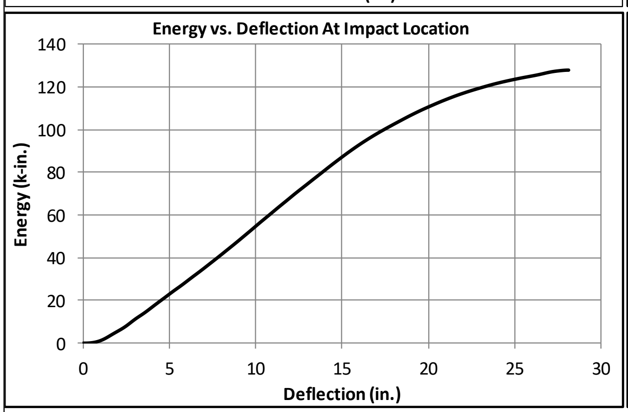
Event Duration:	0.0875	sec
Max. Deflection:	28.1	in.
Peak Force:	6.9	k
Initial Linear Stiffness:	0.7	k/in.
Total Energy:	127.9	k-in.

	@ 5"	@ 10"	@ 15"	@20"
Average Force (k)	4.57	5.47	5.80	5.53
Energy (k-in.)	22.9	54.7	87.1	110.6









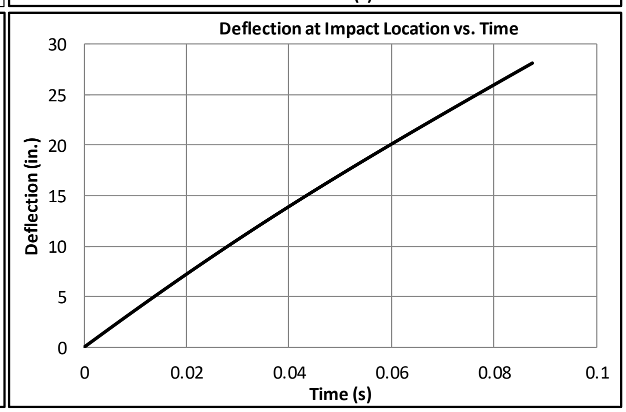


Figure B-4. Test No. TMS-2 Results (SLICE-2)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

Test Description:	S3x5.7 post in steel socket assembly
Test Number:	TMS-3
Test Date:	12/13/2016
Failure Type:	Post bending

Post Properties

Post Type:	Steel
Post Size:	S3x5.7
Post Length:	44 in.
Embedment Depth:	14 in. - in to steel socket
Orientation:	0 deg. - weak axis

Soil Properties

Gradation:	N/A
Moisture Content:	N/A
Compaction Method:	N/A

Bogie Properties

Impact Velocity:	21.28 mph	(31.22 ft/s)
Impact Height:	12 in.	
Bogie Mass:	1688 lb	

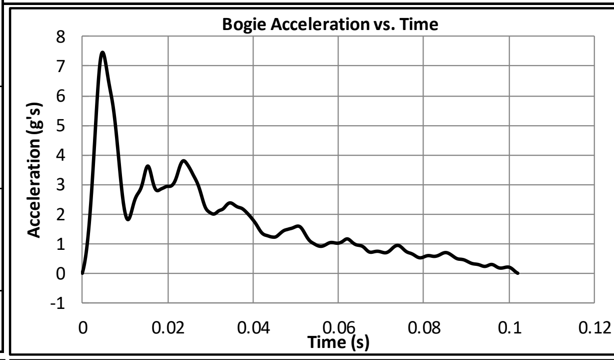
Data Acquired

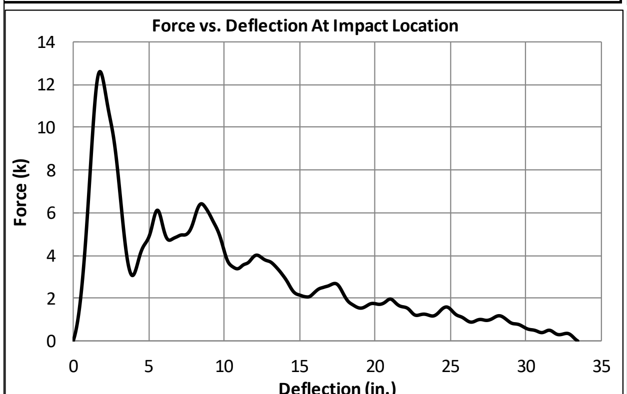
Accelerometer:	SLICE-1
Camera Data:	AOS-8, gp9, gp10

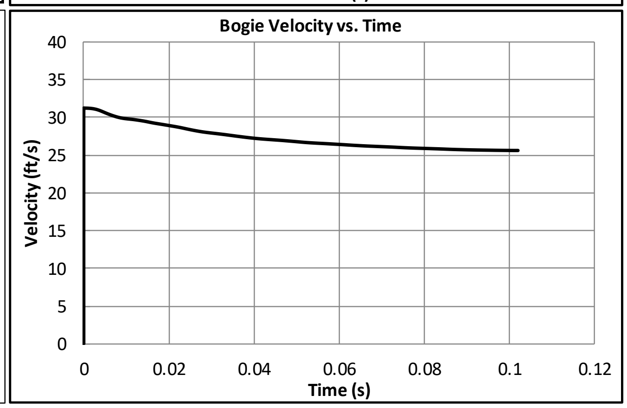
Test Results Summary

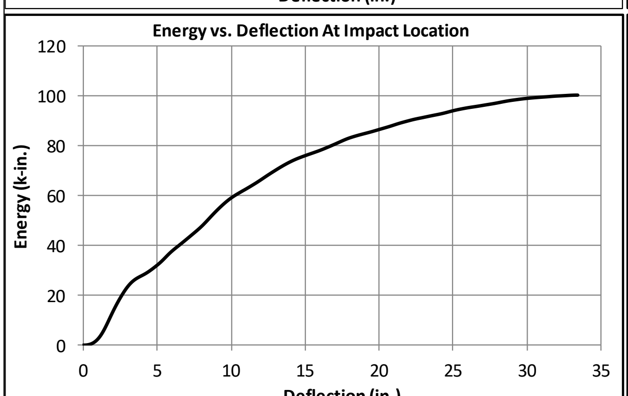
Event Duration:	0.1021	sec
Max. Deflection:	33.4	in.
Peak Force:	12.6	k
Initial Linear Stiffness:	7.2	k/in.
Total Energy:	100.4	k-in.

	@ 5"	@ 10"	@ 15"	@20"
Average Force (k)	6.41	5.91	5.07	4.33
Energy (k-in.)	32.1	59.1	76.0	86.5









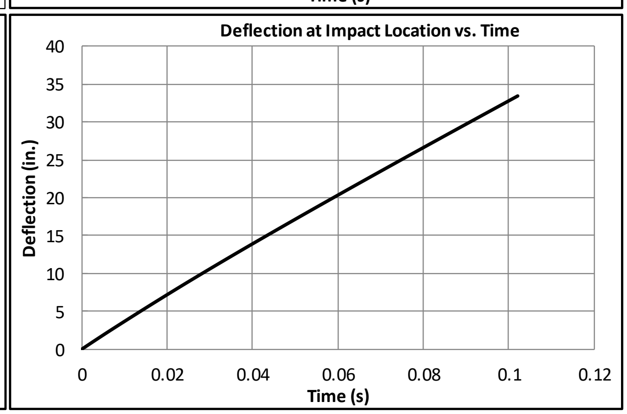


Figure B-5. Test No. TMS-3 Results (SLICE-1)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

Test Description:	S3x5.7 post in steel socket assembly
Test Number:	TMS-3
Test Date:	12/13/2016
Failure Type:	Post bending

Post Properties

Post Type:	Steel
Post Size:	S3x5.7
Post Length:	44 in.
Embedment Depth:	14 in. - into steel socket
Orientation:	0 deg. - weak axis

Soil Properties

Gradation:	N/A
Moisture Content:	N/A
Compaction Method:	N/A

Bogie Properties

Impact Velocity:	21.28 mph	(31.22 ft/s)
Impact Height:	12 in.	
Bogie Mass:	1688 lb	

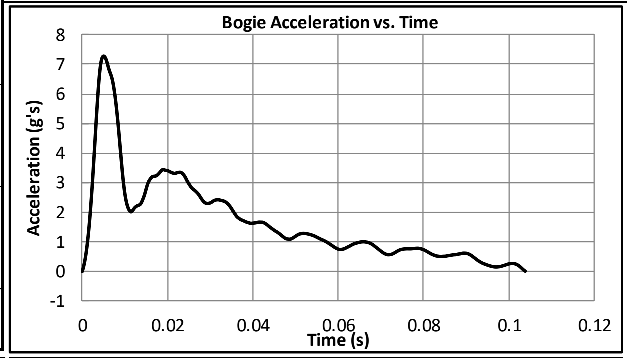
Data Acquired

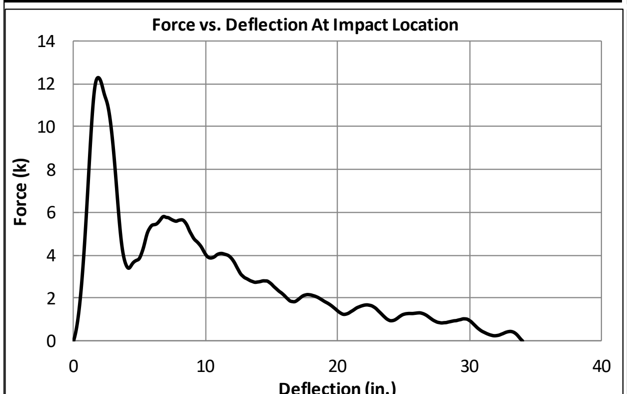
Accelerometer:	SLICE-2
Camera Data:	AOS-8, gp9, gp10

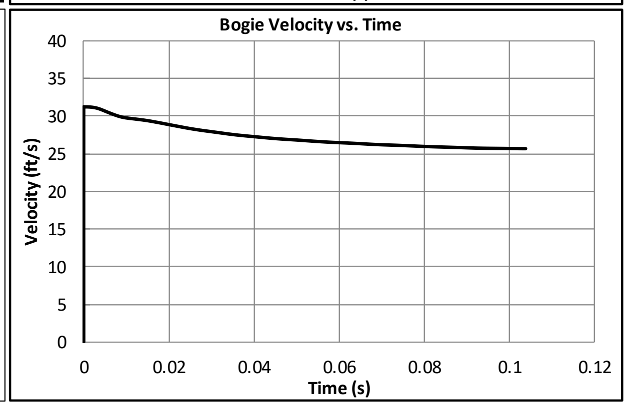
Test Results Summary

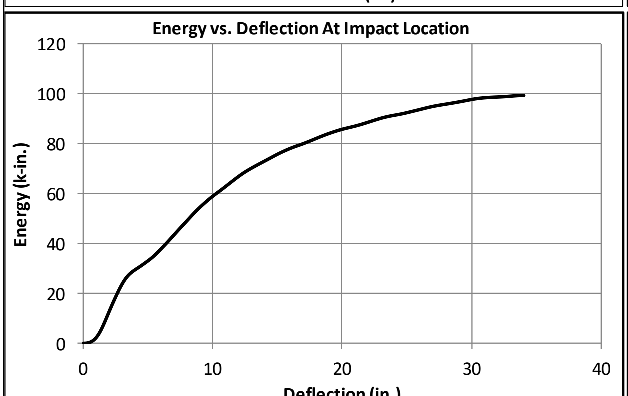
Event Duration:	0.1039	sec
Max. Deflection:	34.0	in.
Peak Force:	12.3	k
Initial Linear Stiffness:	6.6	k/in.
Total Energy:	99.4	k-in.

	@ 5"	@ 10"	@ 15"	@20"
Average Force (k)	6.60	5.89	5.05	4.29
Energy (k-in.)	33.0	58.9	75.7	85.8









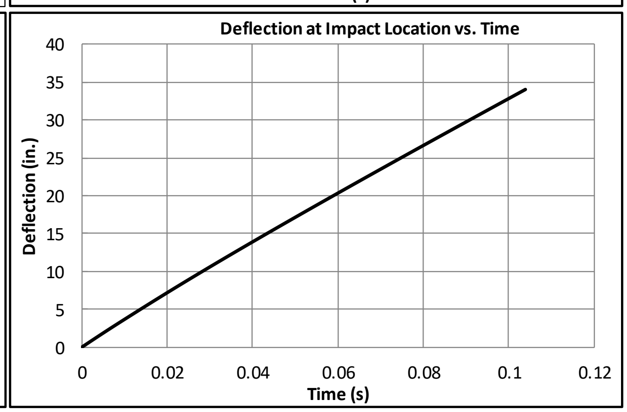


Figure B-6. Test No. TMS-3 Results (SLICE-2)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

Test Description:	S3x5.7 Post in socketed concrete footing
Test Number:	TMS-4
Test Date:	1/20/2017
Failure Type:	Post Bending

Post Properties

Post Type:	Steel
Post Size:	S3x5.7
Post Length:	44 in.
Embedment Depth:	14 in. - into socket
Orientation:	0 deg. - weak axis

Soil Properties

Gradation:	na
Moisture Content:	na
Compaction Method:	na

Bogie Properties

Impact Velocity:	25.23 mph	(37 ft/s)
Impact Height:	12 in.	
Bogie Mass:	1699 lb	

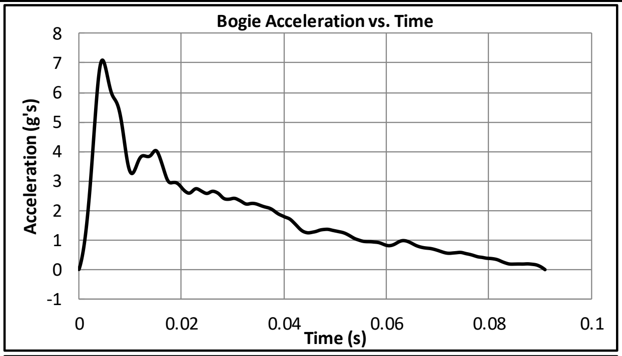
Data Acquired

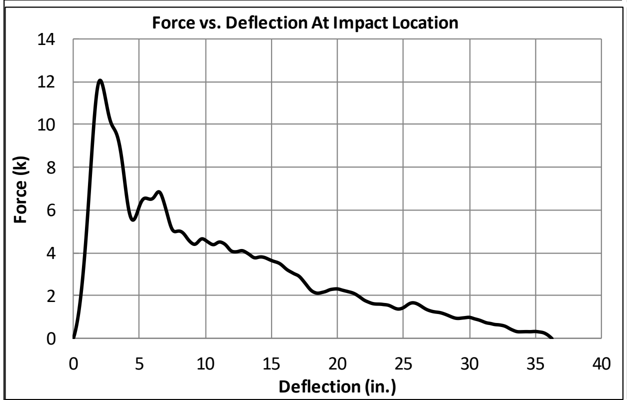
Accelerometer:	TDAS
Camera Data:	aos9, gp7, gp10

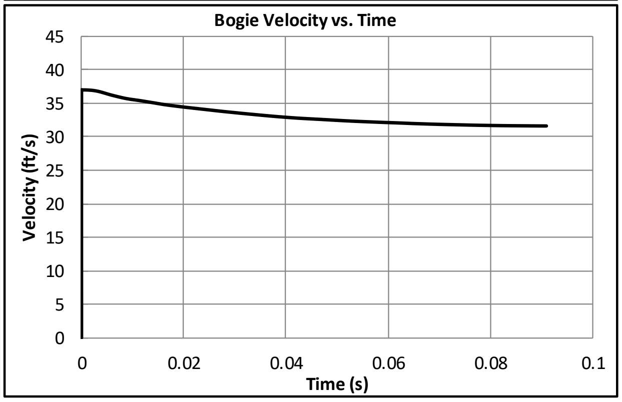
Test Results Summary

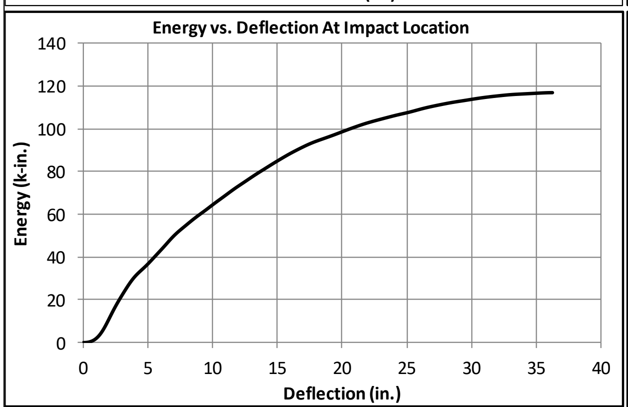
Event Duration:	0.0910	sec
Max. Deflection:	36.3	in.
Peak Force:	12.1	k
Initial Linear Stiffness:	5.9	k/in.
Total Energy:	116.9	k-in.

	@ 5"	@ 10"	@ 15"	@20"
Average Force (k)	7.31	6.43	5.66	4.93
Energy (k-in.)	36.6	64.3	84.8	98.5









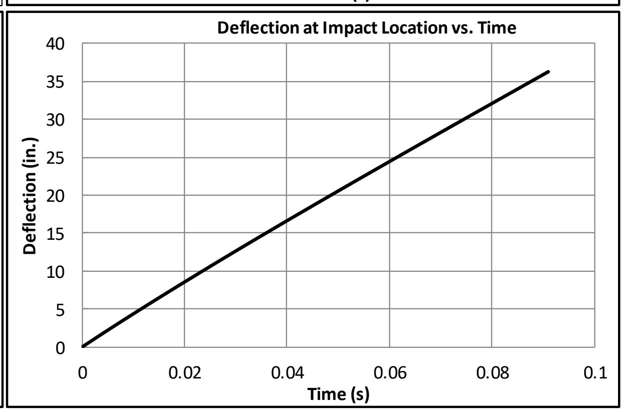


Figure B-7. Test No. TMS-4 Results (TDAS)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

Test Description:	S3x5.7 Post in socketed concrete foundation
Test Number:	TMS-4
Test Date:	1/20/2017
Failure Type:	Post Bending

Post Properties

Post Type:	Steel
Post Size:	S3x5.7
Post Length:	44 in.
Embedment Depth:	14 in. into socket
Orientation:	0 deg. - weak axis

Soil Properties

Gradation:	na
Moisture Content:	na
Compaction Method:	na

Bogie Properties

Impact Velocity:	25.23 mph	(37 ft/s)
Impact Height:	12 in.	
Bogie Mass:	1699 lb	

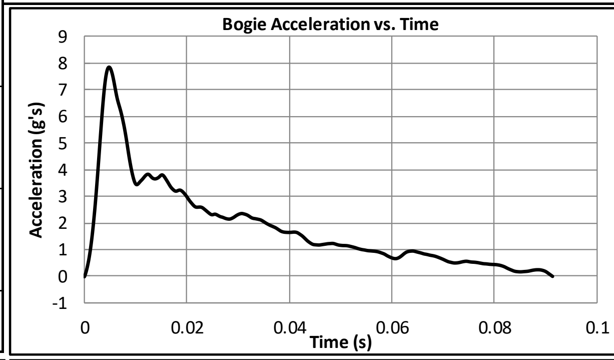
Data Acquired

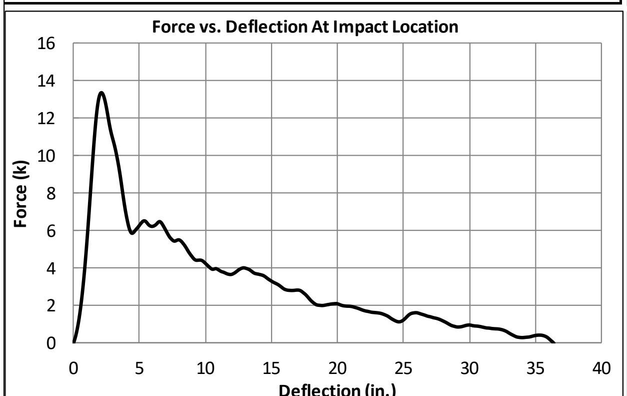
Accelerometer:	SLICE-2
Camera Data:	aos9, gp7, gp10

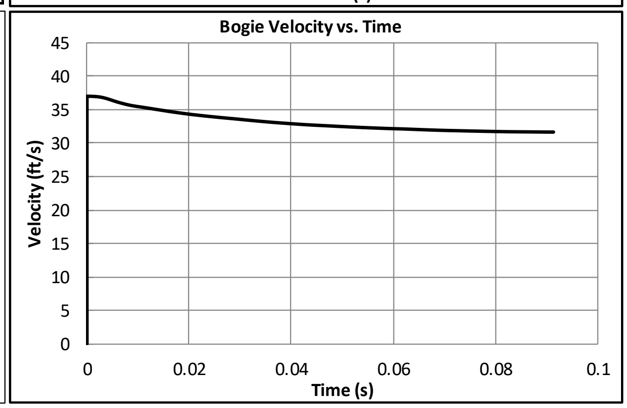
Test Results Summary

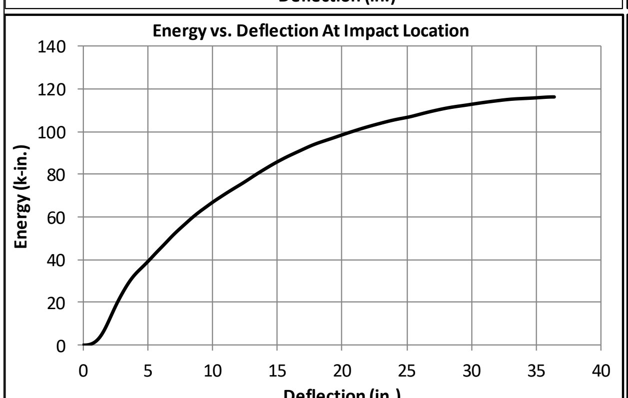
Event Duration:	0.0914	sec
Max. Deflection:	36.4	in.
Peak Force:	13.3	k
Initial Linear Stiffness:	6.3	k/in.
Total Energy:	116.2	k-in.

	@ 5"	@ 10"	@ 15"	@20"
Average Force (k)	7.84	6.69	5.72	4.92
Energy (k-in.)	39.2	66.9	85.8	98.4









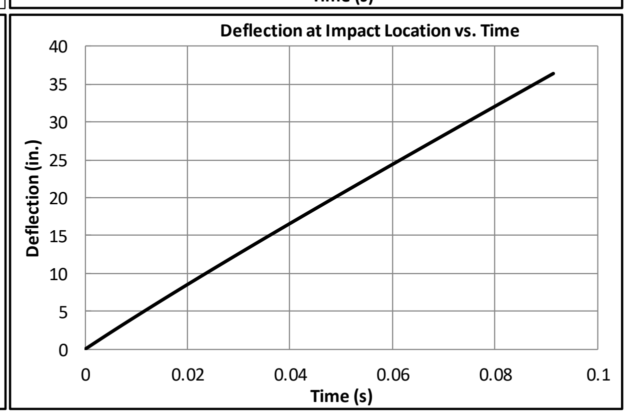


Figure B-8. Test No. TMS-4 Results (SLICE-2)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

Test Description:	Dual S3x5.7 Posts in concrete slab
Test Number:	TMS-5
Test Date:	1/20/2017
Failure Type:	Concrete slab fracture

Post Properties

Post Type:	Dual Steel
Post Size:	S3x5.7
Post Length:	44 in.
Embedment Depth:	14 in. - into socket
Orientation:	90 deg. - strong axis

Soil Properties

Gradation:	na
Moisture Content:	na
Compaction Method:	na

Bogie Properties

Impact Velocity:	22.93 mph	(33.63 ft/s)
Impact Height:	24 7/8 in.	
Bogie Mass:	4965 lb	

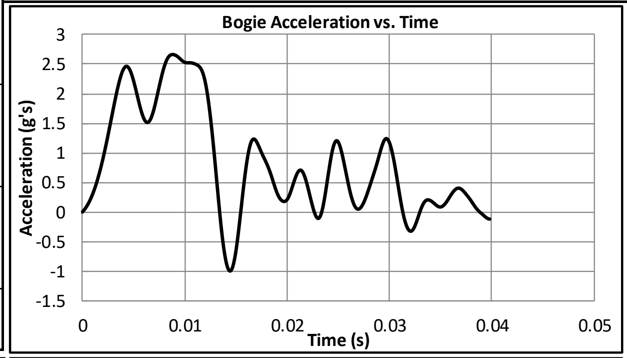
Data Acquired

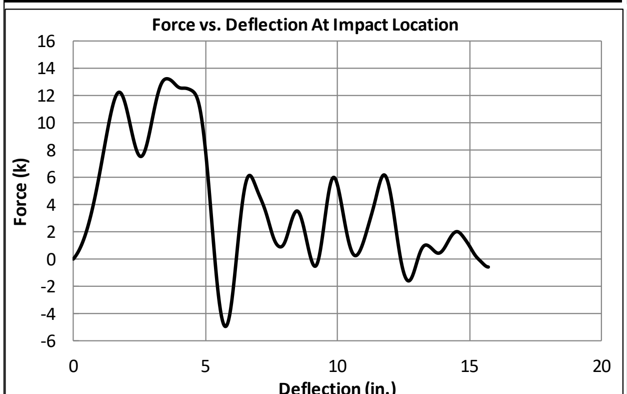
Accelerometer:	TDAS
Camera Data:	aos-9, gp-7, gp-8

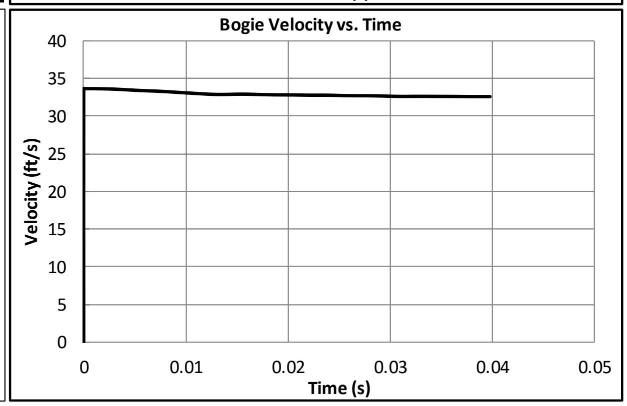
Test Results Summary

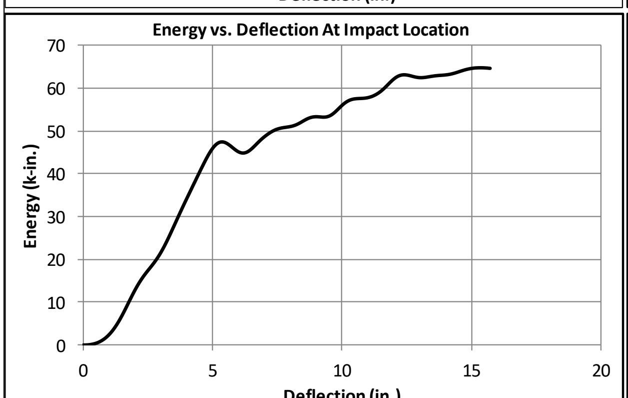
Event Duration:	0.0398	sec
Max. Deflection:	15.7	in.
Peak Force:	13.2	k
Initial Linear Stiffness:	7.1	k/in.
Total Energy:	64.8	k-in.

	@ 5"	@ 10"	@ 15"	@20"
Average Force (k)	9.19	5.58	4.31	NA
Energy (k-in.)	46.0	55.8	64.6	NA









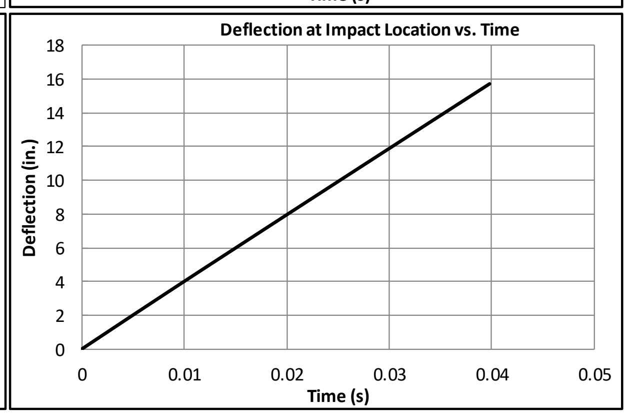


Figure B-9. Test No. TMS-5 Results (TDAS)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

Test Description:	Dual S3x5.7 Posts in concrete slab
Test Number:	TMS-5
Test Date:	1/20/2017
Failure Type:	Concrete slab fracture

Post Properties

Post Type:	Dual Steel
Post Size:	S3x5.7
Post Length:	44 in.
Embedment Depth:	14 in. - into socket
Orientation:	90 deg. - strong axis

Soil Properties

Gradation:	na
Moisture Content:	na
Compaction Method:	na

Bogie Properties

Impact Velocity:	22.93 mph	(33.63 ft/s)
Impact Height:	24 7/8 in.	
Bogie Mass:	4965 lb	

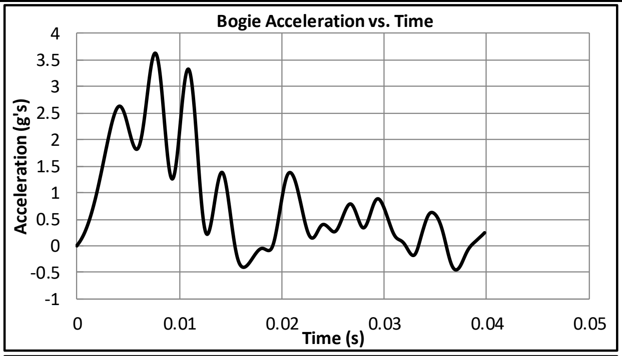
Data Acquired

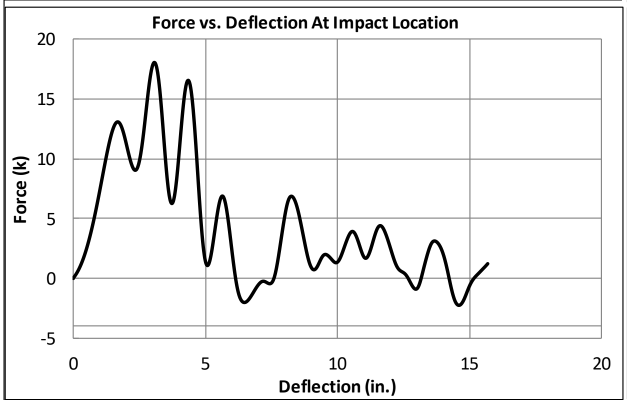
Accelerometer:	SLICE-2
Camera Data:	aos-9, gp-7, gp-8

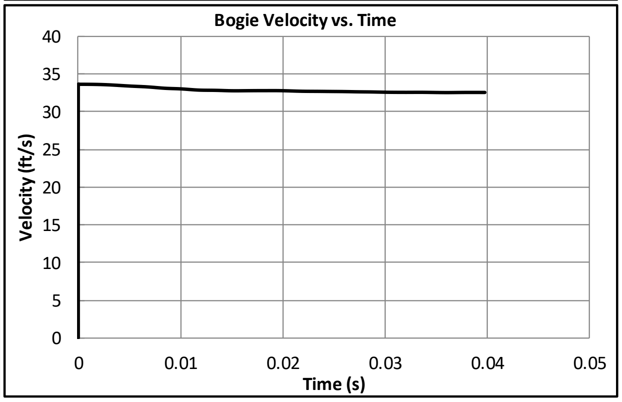
Test Results Summary

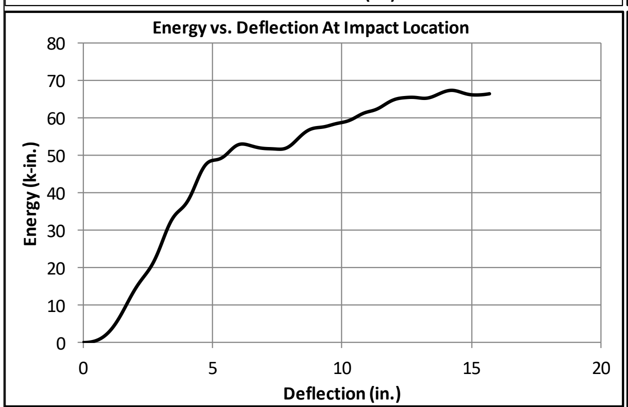
Event Duration:	0.0398	sec
Max. Deflection:	15.7	in.
Peak Force:	18.0	k
Initial Linear Stiffness:	5.9	k/in.
Total Energy:	67.4	k-in.

	@ 5"	@ 10"	@ 15"	@20"
Average Force (k)	9.74	5.88	4.42	NA
Energy (k-in.)	48.7	58.8	66.2	NA









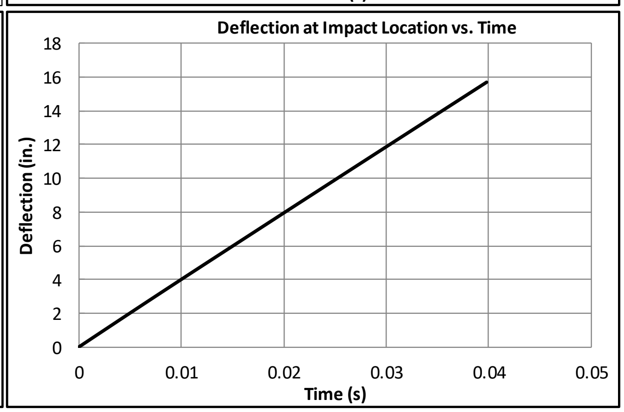


Figure B-10. Test No. TMS-5 Results (SLICE-2)

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