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Development of a Socketed Foundation for Cable Barrier Posts - Phase I

John Rohde, Ph.D., P.E.
Associate Professor
Department of Civil Engineering
University of Nebraska-Lincoln

Ryan J. Terpsma, B.S.M.E., E.I.T.
Graduate Research Assistant

Ling Zhu, Ph.D.
Graduate Research Assistant

Benjamin J. Dickey, B.S.C.E., E.I.T
Graduate Research Assistant

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

Ronald K. Faller, Ph.D., P.E.
Resarch Assistant Professor

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Ryan J. Terpsma, B.S.M.E., E.I.T.
Graduate Research Assistant
Midwest Roadside Safety Facility
University of Nebraska-Lincoln

Ling Zhu, Ph.D.
Graduate Research Assistant
Midwest Roadside Safety Facility
University of Nebraska-Lincoln

John Rohde, Ph.D., P.E.
Associate Professor
Department of Civil Engineering
University of Nebraska-Lincoln

Benjamin J. Dickey, B.S.C.E., E.I.T.
Graduate Research Assistant
Midwest Roadside Safety Facility
University of Nebraska-Lincoln

Scott K. Rosenbaugh, M.S.C.E., E.I.T.
Research Associate Engineer
Midwest Roadside Safety Facility
University of Nebraska-Lincoln

Ronald K. Faller, Ph.D., P.E.
Research Assistant Professor
Midwest Roadside Safety Facility
University of Nebraska-Lincoln

MIDWEST ROADSIDE SAFETY FACILITY
University of Nebraska-Lincoln
2200 Vine Street
130 Whittier Building
Lincoln, Nebraska 68583-0853
(402) 472-0965

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16. Abstract

Four socketed foundation designs were evaluated for use as a new reusable base for high-tension, cable barrier systems. Each foundation was a reinforced concrete cylindrical shape. The top of the foundation had an open steel tube to accept the post during installation. The four foundation designs were installed in sand and subjected to dynamic component testing in order to simulate a weak/saturated soil and evaluate maximum displacements during impact events. An S4x7.7 (S102x11.5) post was selected for each test assembly after a review of the current FHWA-accepted, high-tension cable barrier systems revealed the section to be the strongest and most critical post. Both the 24 in. (610 mm) and 36 in. (914 mm) deep foundations rotated through the soil and were deemed too shallow to prevent excessive deformations. The other two assemblies, both 60 in. (1,524 mm) deep, fractured during the impact event. As a result, the 60 in. (1,524 mm) deep configurations were deemed too weak to sustain the full load capacity of the S4x7.7 (S102x11.5) post. Further, the displacement for the 60 in. (1,524 mm) deep foundations could not be determined due to premature fracture. Therefore, none of the four socketed foundation configurations was found to be acceptable and further development and testing was recommended.

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J.C. Holloway, M.S.C.E., E.I.T., Test Site Manager
K.A. Lechtenberg, M.S.M.E., E.I.T., Research Associate Engineer
R.W. Bielenberg, M.S.M.E., E.I.T., Research Associate Engineer
C.L. Meyer, B.S.M.E., E.I.T., Research Associate Engineer
A.T. Russell, B.S.B.A., Shop Manager
K.L. Krenk, B.S.M.A., Maintenance Mechanic
Undergraduate and Graduate Research Assistants

<u>Mid-America Transportation Center</u>

Laurence Rilett, Ph.D., P.E., Professor and MATC Director

<u>Illinois Department of Transportation</u>

David Piper, P.E., Highway Policy Engineer

<u>Iowa Department of Transportation</u>

David Little, P.E., Assistant District Engineer
Deanna Maifield, P.E., Methods Engineer
Chris Poole, P.E., Litigation / Roadside Safety Engineer

Kansas Department of Transportation

Ron Seitz, P.E., Bureau Chief
Rod Lacy, P.E., Metro Engineer
Scott King, P.E., Road Design Leader

Minnesota Department of Transportation

Michael Elle, P.E., Design Standard Engineer

Missouri Department of Transportation

Joseph G. Jones, P.E., Engineering Policy Administrator

Nebraska Department of Roads

Amy Starr, P.E., Road Safety Engineer
Phil TenHulzen, P.E., Design Standards Engineer
Jodi Gibson, Research Coordinator

Ohio Department of Transportation

Michael Bline, P.E., Standards and Geometrics Engineer

South Dakota Department of Transportation

David Huft, Research Engineer
Bernie Clocksin, Lead Project Engineer

Wisconsin Department of Transportation

John Bridwell, P.E., Standards Development Engineer
Erik Emerson, P.E., Standards Development Engineer
Jerry Zogg, P.E., Chief Roadway Standards Engineer

Wyoming Department of Transportation

William Wilson, P.E., Architectural and Highway Standards Engineer

Federal Highway Administration

John Perry, P.E., Nebraska Division Office
Danny Briggs, Nebraska Division Office

Disclaimer Statement

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. Test nos. HTCB-1 through HTCB-4 were non-certified component tests conducted for research and development purposes only.

The Independent Approving Authority (IAA) for the data contained herein was Karla Lechtenberg, Research Associate Engineer.

Abstract

Four socketed foundation designs were evaluated for use as a new reusable base for high-tension, cable barrier systems. Each foundation was a reinforced concrete cylindrical shape. The top of the foundation had an open steel tube to accept the post during installation. The four foundation designs were installed in sand and subjected to dynamic component testing in order to simulate a weak/saturated soil and evaluate maximum displacements during impact events. An S4x7.7 (S102x11.5) post was selected for each test assembly after a review of the current FHWA-accepted, high-tension cable barrier systems revealed the section to be the strongest and most critical post.

Both the 24 in. (610 mm) and 36 in. (914 mm) deep foundations rotated through the soil and were deemed too shallow to prevent excessive deformations. The other two assemblies, both 60 in. (1,524 mm) deep, fractured during the impact event. As a result, the 60 in. (1,524 mm) deep configurations were deemed too weak to sustain the full load capacity of the S4x7.7 (S102x11.5) post. Further, the displacement for the 60-in. (1,524 mm) deep foundations could not be determined due to premature fracture. Therefore, none of the four socketed foundation configurations was found to be acceptable and further development and testing was recommended.

Chapter 1 Introduction

1.1 Background

Thousands of miles of high-tension cable guardrail have been installed on divided highways across the country to prevent median cross-over accidents. Often, these installations include socketed post foundations as opposed to simply driving the barrier's posts into the surrounding soil. Socketed foundation designs allow the posts to slide in and out of a ground socket for easy replacement in the event of system damage during a crash. Thus, the time and cost of system repairs can be held to a minimum. Unfortunately, numerous socketed post foundations have been damaged during real-world real cable barrier crashes. In most cases, foundation damage requires repair crews to either replace the socketed foundation itself or drive a post into the soil adjacent to the damaged component. Either situation defeats the purpose of using sockets, greatly increases the time necessary to restore a damaged barrier, and results in higher maintenance costs and increased risk to repair crews working adjacent to high-speed facilities.

The majority of existing socketed post foundation designs are constructed by drilling a hole in the soil, placing a steel sleeve in the hole, and backfilling with Portland cement concrete. Many of these designs do not have sufficient reinforcement to resist impact loads that are transmitted into the socket in the event of a crash. Further, many of the sockets are too short to resist frost heave that can push the foundations and posts up and out of the ground. Thus, a need exists to develop a general socketed foundation design to assure that cable barrier systems perform as intended when used in the field.

1.2 Objective

The objective of this research project was to develop a new low-maintenance, socketed foundation for cable barrier posts. The new design needed to have sufficient structural capacity to prevent significant damage and displacement during impacts, thus keeping repair costs at a minimum. Further, this study sought to develop guidelines pertaining to the required size of a socketed foundation to prevent both vehicle impact displacements and vertical displacements due to frost heave.

1.3 Research Approach

This research effort began with a review of existing high-tension, cable median barrier systems and their socketed foundations. Next, the critical aspects of the soil surrounding a socketed foundation were identified so that the new foundation designs could be evaluated under a worst-case situation. Four different concrete foundations were then designed, fabricated, and dynamically tested with surrogate vehicles. The results of these bogie tests were then analyzed. Finally, recommendations were made regarding future research on concrete, socketed foundations.

Chapter 2 Design Parameters

2.1 Maximum Loading – Critical Post

During a crash, impact loads are transferred through the barrier posts and into the socketed foundations. Thus, the strength of the system's post will determine the magnitude of load imparted to the foundation. However, each of the high-tension cable barrier systems currently being installed on our nation's roadways use different posts, thus resulting in a wide range of cross-sectional shapes, sizes, and material strengths. Consequently, the load transferred to the socketed foundations can vary greatly between barrier systems.

In order to accommodate posts from all high-tension barrier systems, new socketed foundations need to be evaluated under the worst-case impact scenario, defined here as the strongest cable system post. Currently, Gibraltar Materials, Brifen Limited, Safence, Inc., Nucor Steel Marion, Inc., and Trinity Highway Safety Products, Inc. all have high-tension cable post base designs that have been tested to National Cooperative Highway Research Program (NCHRP) Report 350 [1] conditions and accepted by the Federal Highway Administration (FHWA) [2-6]. The posts used in these systems are listed in Table 2.1 along with their respective material strength and cross-section properties.

The load transferred from a post to the foundation structure is limited by the plastic bending moment of the given post. If the moment between the foundation and the applied load is small (i.e., close to the post base), the magnitude of the lateral shear load transferred to the foundation structure is maximized. As a result, the critical impact height was determined to be the center of the wheel of the 1100C small car vehicle as described in the Manual for Assessing Safety Hardware (MASH) [7]. The height to the center of the wheel of 10.5 in. (266.7 mm) was used to calculate the maximum lateral impact force transferred to a foundation for each of the existing cable posts, as shown in Table 2.1. These calculations identified the S4x7.7 (S102x11.5) post rotating about its strong axis of bending (i.e., moving laterally backward in the barrier system) as the critical post configuration for transferring maximum impact loading to the socketed foundation.

2.2 Critical Soil Selection

Typically, safety barriers requiring soil interaction have been designed, tested, and evaluated while placed in a strong soil, as recommended by both NCHRP Report 350 and MASH. Strong soils are stiffer and help reduce post rotation. Thus, strong soils maximize internal barrier forces and the propensity for both rail rupture and vehicle snag. However, strong soils also minimize system deflections, especially in post foundations, and may not accurately represent foundation displacements in real-world installations. Many cable barrier systems are installed in median ditches where weaker and/or saturated soils can be found. These types of conditions allow the post foundations to rotate and displace a greater amount than if the system was installed in a strong soil. Further, displacements as small as a few inches may require the foundation to be either reset or replaced, effectively eliminating the benefits of using socket foundations to support the posts of a barrier system. Therefore, weak soils were determined to be more critical for the design of a post foundation, and a non-cohesive sand pit was utilized for the testing and evaluation process of this project.

Table 2.1 Calculated Post Strength

Manufacturer	System Name	Crash Test Level	Post Size/Type	Critical Cross-Section Area in^2 (mm^2)	Plastic Section Modulus, Z_x in^3 (mm^3)	Plastic Section Modulus, Z_y in^3 (mm^3)	Yielding Stress ksi (MPa)	Maximum Post Shear Capacity kip (kN)	Ultimate Bending Moment kip-in. (kJ)		Maxium Impact Force from Center of Tire Impacting at 10.5 in. kip (kN)	
									Lateral	Longitudinal	Lateral	Longitudinal
Trinity Highway Safety Products, Inc.	Cable Safety System (CASS)	TL-3 and TL-4	S4x7.7 (S102x11.5)	2.26 (1,458)	3.50 (57,350)	0.97 (15,895)	36.3 (250)	82.0 (365)	126 (14.2)	35.2 (4.0)	12.0 (54.5)	3.4 (15.2)
			4"x2"x5/32" (100x50x4 mm) C Post	1.34 (870)	1.72 (28,173)	0.94 (15,369)		28.3 (126)	62.3 (7.0)	34.0 (3.8)	5.9 (26.4)	3.2 (14.4)
Gibraltar Materials	Gibraltar Cable Barrier	TL-3 and TL-4	3.25"x2.5" (83x64 mm) C Post	1.56 (1006)	1.69 (27,655)	1.49 (24,437)	59.5 (410)	53.8 (239)	100.3 (11.3)	88.7 (10.0)	9.6 (42.5)	8.4 (37.5)
Nucor Steel Marion, Inc.	Nucor Wire Rope Barrier System (Driven)	TL-3 and TL-4	1.5"x5.5" (38x140 mm) U Post	1.11 (717)	0.72 (11,783)	1.05 (17,161)	80.0 (550)	51.6 (230)	57.6 (6.5)	83.8 (9.5)	5.5 (24.4)	8.0 (35.5)
	Nucor Wire Rope Barrier System (Post in Concrete Foundation)	TL-3 and TL-4		1.42 (918)	0.86 (14,129)	1.34 (21,931)		66.1 (294)	69.0 (7.8)	107.1 (12.1)	6.6 (29.2)	10.2 (45.3)
Safence, Inc.	Safence Barrier System	TL-3 and TL-4	IPN-80	0.53 (341)	1.42 (23,285)	0.32 (5,239)	36.3 (250)	11.1 (49)	51.5 (5.8)	11.6 (1.3)	4.9 (21.8)	1.1 (4.91)
		TL-3 and TL-4	C	0.84 (542)	0.27 (4,467)	0.83 (13,545)	79.8 (550)	38.9 (173)	9.88 (1.1)	30.0 (3.4)	1.02 (4.5)	2.9 (12.7)
Brifen Limited	Brifen Safety Fence (Driven Post)	TL-3 and TL-4	4"x2 3/16" (100x55) S/Z Post	1.48 (956)	1.98 (32,497)	0.85 (13,870)	36.3 (250)	31.2 (139)	71.9 (8.1)	30.7 (3.5)	6.8 (30.4)	2.9 (13.0)
	Brifen Safety Fence (Post in Concrete Foundation)	TL-3 and TL-4		1.95 (1261)	2.62 (42,870)	1.12 (18,308)		41.1 (183)	94.9 (10.7)	40.5 (4.6)	9.2 (40.1)	3.9 (17.1)

See References [2-6]

2.3 Frost Heave

Frost heave is a phenomenon in which frozen soils expand and push soil-embedded objects upward. Specifically, the heaving is caused by the formation of ice blocks, or lenses, in the soil below the surface. Once started, ice lenses continue to grow as long as a source of free water is available. Water can migrate through the soil as far as 20 ft (6.1 m) to a forming ice lens by capillary action. It is important to note that water expands nine percent by volume when frozen. Thus, as an ice lens grows, it applies internal stresses to the soil. Since the groundline is the only free surface boundary condition for most soils, these internal stresses often result in vertical soil displacements, or heaving. Over multiple freeze-thaw cycles, objects such as posts and shallow foundations can be pushed up and out of the ground. Therefore, states that routinely observe significant freeze-thaw cycles should take measures to prevent this phenomenon from affecting any shallow foundations.

Frost heave can be prevented using one of two highly-recognized methods. First, the foundation can be extended into the ground below the frost line, which varies in depth depending on geographical region. Setting the foundation deeper than the frost line ensures ice will not form beneath the foundation, thus preventing the foundation from being forced upward from frost heave. Second, the foundation can be set in a frostheave resistant soil. Clean rock and gravel soils provide adequate drainage to minimize water content and contain voids too large to induce capillary action. Thus, replacing silts, clays, and dirty sands with rock and gravel can effectively eliminate frost heave by minimizing the water in the soil.

2.4 Socketed Foundation Design

Initially, two materials were considered for the design of a new socketed foundation - reinforced concrete and steel. However, early analysis illustrated that a steel socketed foundation would be significantly more costly than a concrete foundation. At that point, the development effort focused exclusively on a reinforced concrete foundation. Significant design details are highlighted in the following sections.

2.4.1 Geometry

To simplify the construction and installation process, a circular cross-section was chosen for the socketed foundation. This cylindrical geometry allowed the foundation to be installed without having to backfill around the foundation by using an auger of the same diameter. Basic soil analysis demonstrated that a 12 in. (305 mm) diameter would provide adequate surface area to create the necessary soil resistance and prevent rotation while also providing enough interior space for the placement of the steel rebar cage. Thus, each of the four designs tested during the component testing program, as described in Chapter 0, had a 12 in. (305 mm) diameter.

The socket needed to create a void in the concrete foundation to insert the steel post. The socket also needed to provide a bearing surface, which would distribute impact loads evenly from the post to the concrete foundation in order to prevent concrete cracking. Therefore, the socket was fabricated from a steel sleeve with a bottom end cap. The socket was placed in the center of the top surface of the reinforced concrete foundation. This placement evenly reinforced the socket and provided adequate strength for impacts from any direction, an important feature for barriers placed in roadway medians.

2.4.2 Steel Reinforcement

Steel reinforcement was necessary to prevent the concrete foundation from fracturing during impacts. As such, both shear and bending reinforcement was added to each design option. Shear reinforcement was provided by rebar loops surrounding the socket and the rest of the foundation at various intervals. Bending reinforcement was provided by straight, vertical bars spaced evenly around the socket and extending down to the bottom of the foundation. A minimum clear cover of 2 in. (51 mm) was maintained for all steel reinforcement.

Chapter 3 Component Design Details

Four different post bases were designed and fabricated to evaluate the required strength for a new socketed foundation for cable posts. Each prototype was comprised of a steel post placed into a socketed, reinforced concrete foundation. These components are described in the following sections. Design drawings for the prototypes are shown in figures 3.3 through 3.4. Photographs of the bogie test setup are shown in Figure 3.8.

3.1 S4x7.7 (S102x11.5) Steel Posts

Each test article utilized an S4x7.7 (S102x11.5) steel post, which was identified as the critical post for high-tension cable barrier systems in Chapter **Error! Reference source not found.**. The posts measured 47 in. (1,194 mm) in length and were embedded 14 in. (356 mm) into the socketed foundation for test nos. HTCB-1 through HTCB-3. The post was embedded an extra 2 in. (51 mm) into the socketed foundation for test no. HTCB-4, making the total length of the post 49 in. (1,245 mm). All posts were fabricated using ASTM A36 steel with a minimum yield strength of 36 ksi (248 MPa). A detailed drawing of the posts is shown in Figure 3.5.

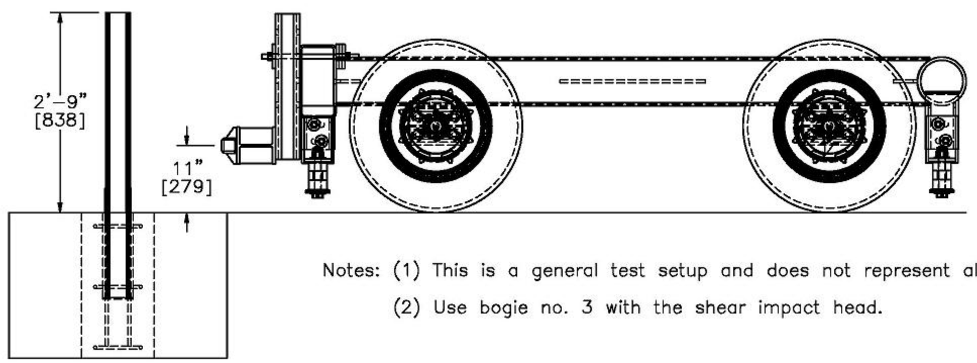
3.2 Socketed Foundation

Each socketed foundation was fabricated from concrete, steel rebar, and a steel socket sleeve. All of the foundations were cylindrical in shape with a 12 in. (305 mm) diameter. The length, or embedment depths, of the foundations for test nos. HTCB-1 through HTCB-4 were 24 in. (610 mm), 36 in. (914 mm), 60 in. (1,524 mm), and 60 in. (1,524 mm), respectively. The steel socket sleeves were located in the center of the top surface of each post base. The concrete was specified to a minimum 28 day compressive strength of 3,500 psi (24 MPa).

A 14 in. (356 mm) long, TS 5x4x⅜ in. (TS 127x102x10 mm) steel tube was used as the post socket for test nos. HTCB-1 through HTCB-3. A 16 in. (406 mm) long, TS 5x4x⅜ in. (TS 127x102x10 mm) steel tube was used in test no. HTCB-4 to accommodate the longer post. For all tests, a 5x4x¼-in. (127x102x6-mm) steel plate was tack-welded to the bottom of the steel tube to enclose the socket void during concrete casting. Both the tubes and plates were ASTM A36 steel. The socket sleeve assembly was then cast into the top of the concrete foundation with the open end of the tube flush with the top surface of the post base. Drawings of the steel tube and plate are shown in figure 3.5.

The post bases were reinforced with both circumferential and vertical ASTM A615 Grade 60 steel rebar. The circumferential rebar was No. 4 (12.7 mm) bars bent into a loop with an inner diameter of 7 in. (178 mm). The spacing of the circumferential steel varied between 4 in. (102 mm) and 10 in. (254 mm), as shown in Figure 3. Four bars, spaced equally around the inside of the circumferential steel, comprised the vertical reinforcement in each of the four designs. Test nos. HTCB-1 through HTCB-3 utilized No. 4 (12.7 mm) rebar for the vertical steel, while test no. HTCB-4 utilized No. 5 (15.9 mm) rebar. Also, the location of the vertical rebar in reference to the post orientation was different in test no. HTCB-4 as compared to the other three tests, as shown in figure 3.4. The lengths of the vertical rebar varied according to the length of the foundation. Additionally, a 5½-in. (140-mm) long No. 4 (12.7 mm) bar was embedded into the top of each assembly in order to attach a string potentiometer line as a means of measuring deflections in the post foundation during testing. All rebar used in the post base was fabricated from ASTM A615 Grade 60 steel.

Test No.	Soil Type	Rebar Configuration	Footing Depth	Speed mph [km/h]	Angle (degrees)
HTCB-1	A-3 Sand	A	24" [610]	20 [32.2]	0
HTCB-2	A-3 Sand	B	36" [914]	20 [32.2]	0
HTCB-3	A-3 Sand	B	60" [1524]	20 [32.2]	0
HTCB-4	A-3 Sand	C	60" [1524]	20 [32.2]	0



Notes: (1) This is a general test setup and does not represent all footing depths.
(2) Use bogie no. 3 with the shear impact head.

Midwest Roadside Safety Facility	MATC High Tension Cable Footing General Test Setup	SHEET: 1 of 7
		DATE: 9/22/2011
		DRAWN BY: EAJ/RJT/DMH
	DWG. NAME. MATC HT Final Test Matrix_v2 / SCALE: 1:25 UNITS: in[mm]	REV. BY: KAL/LZ

Figure 3.1 Bogie Test Matrix

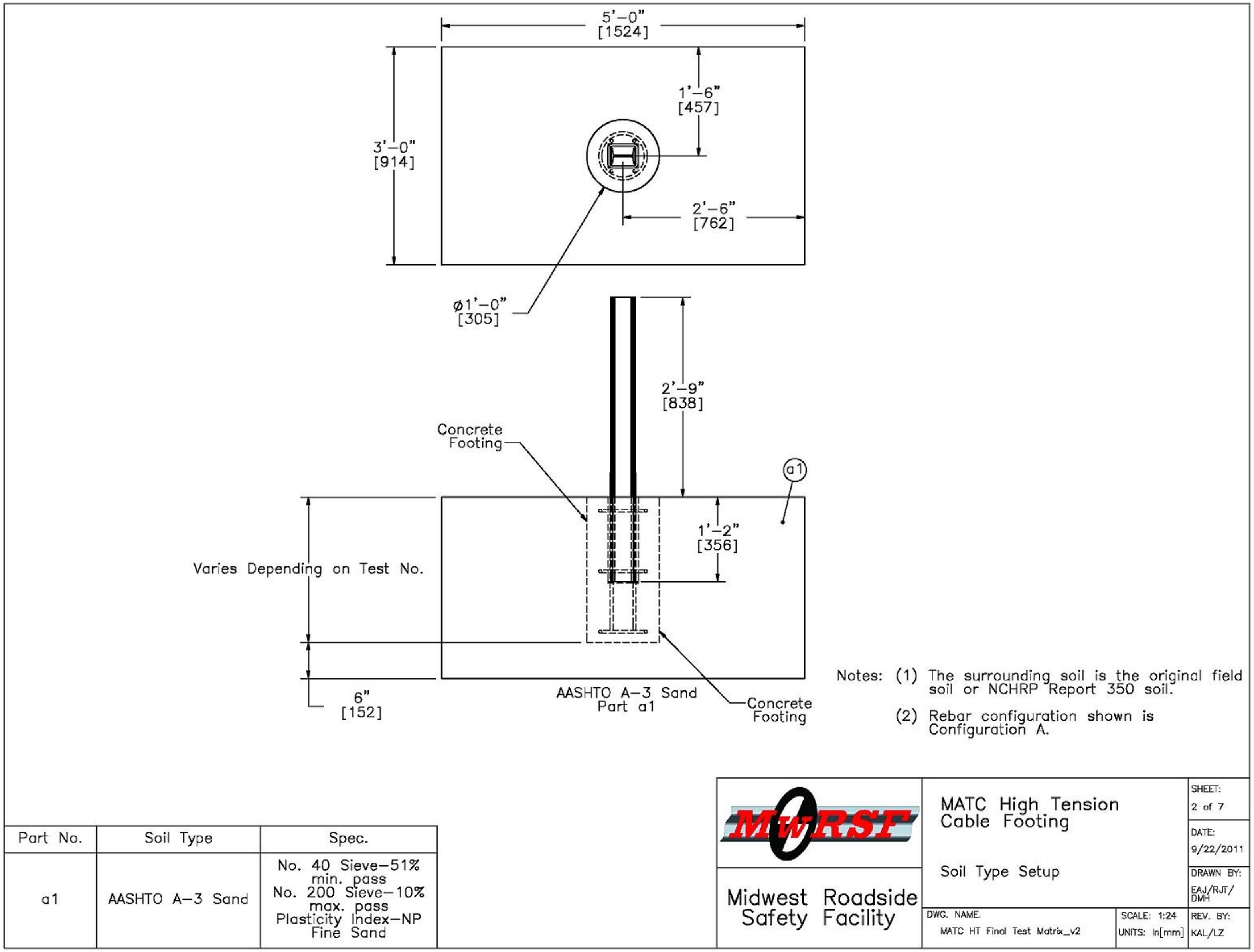


Figure 3.2 Bogie Pit Setup

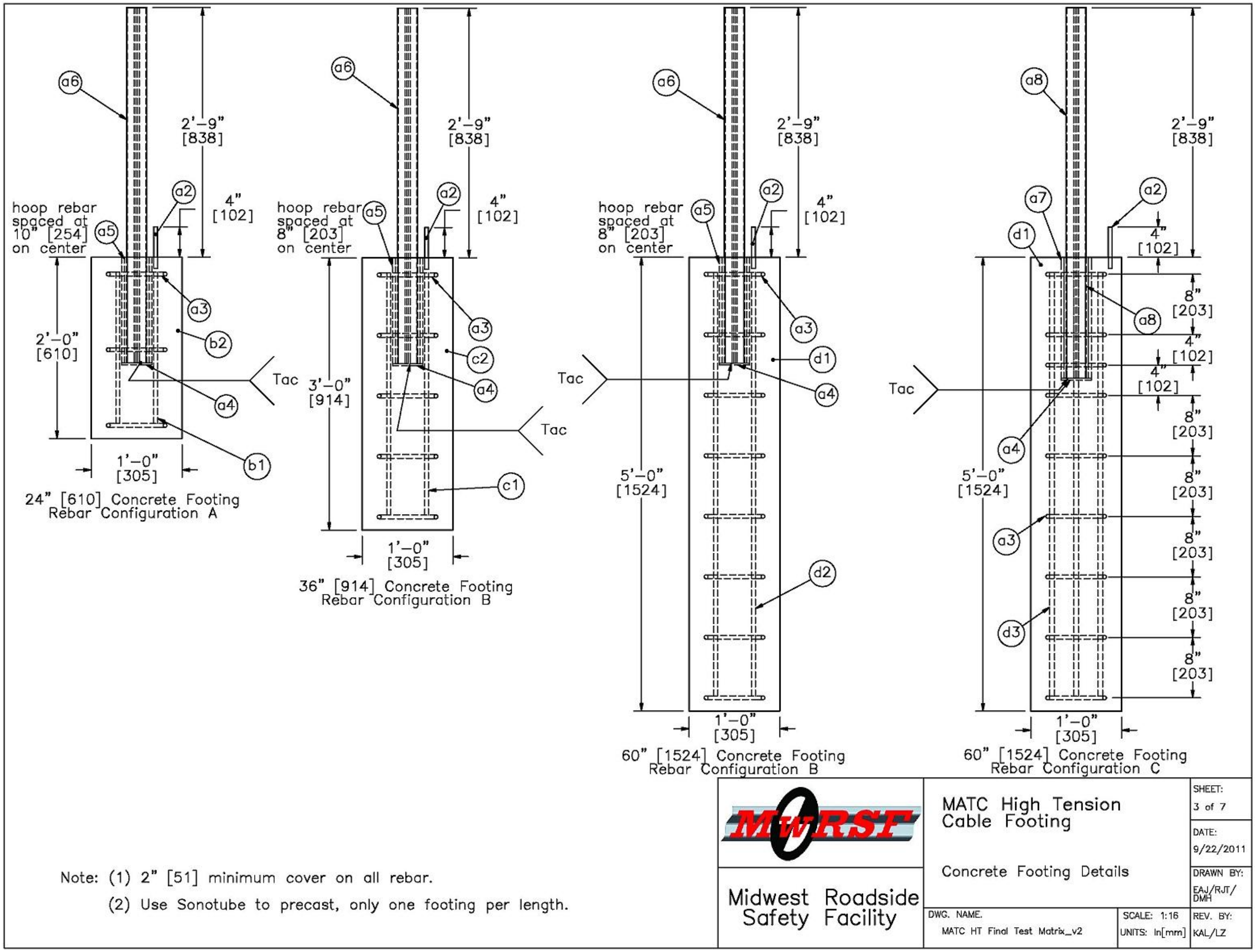
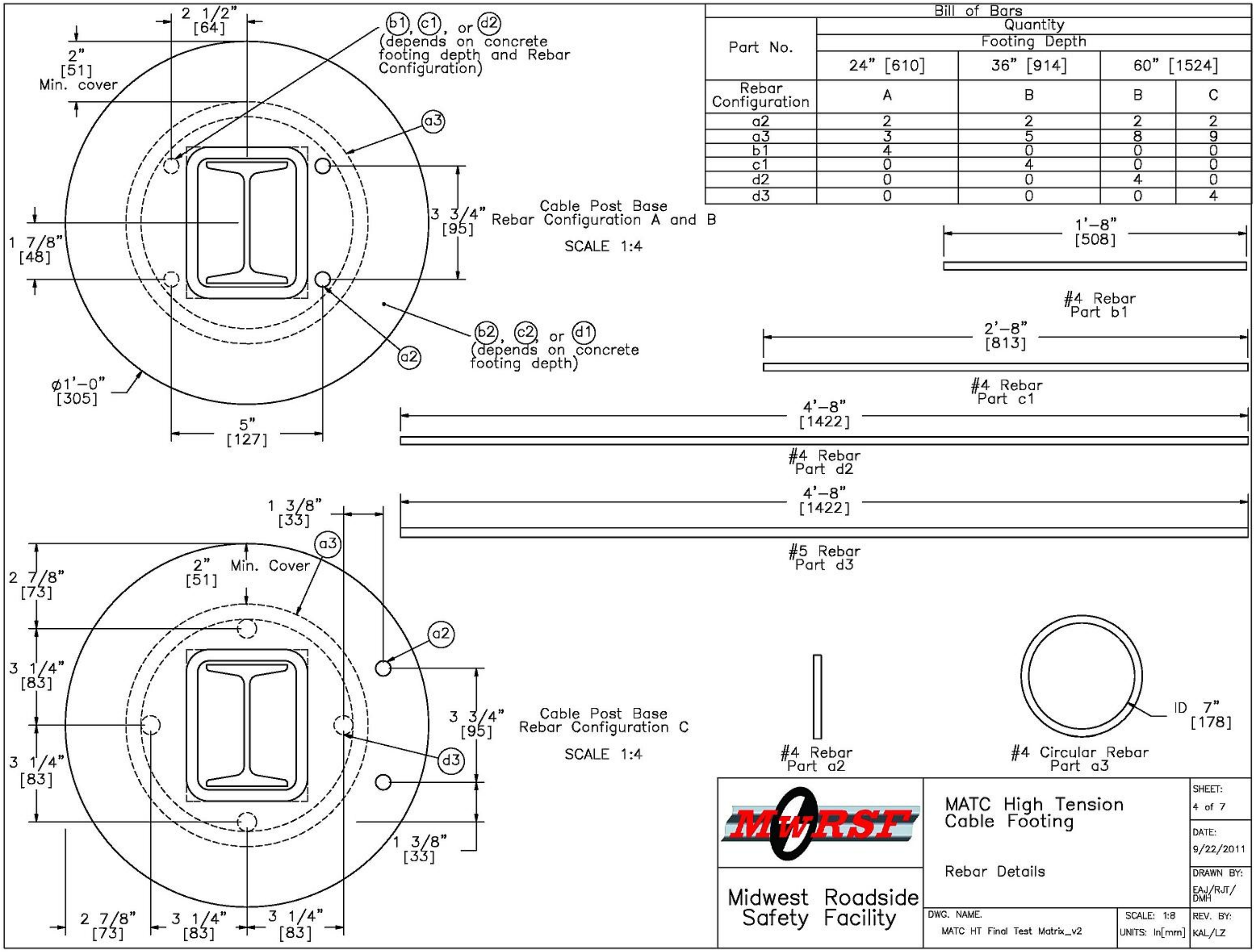


Figure 3.3 Post Assemblies and Reinforcement Configurations



Bill of Bars

Part No.	Quantity			
	Footing Depth			
	24" [610]	36" [914]	60" [1524]	
Rebar Configuration	A	B	B	C
a2	2	2	2	2
a3	3	5	8	9
b1	4	0	0	0
c1	0	4	0	0
d2	0	0	4	0
d3	0	0	0	4

Figure 3.4 Reinforcement Details

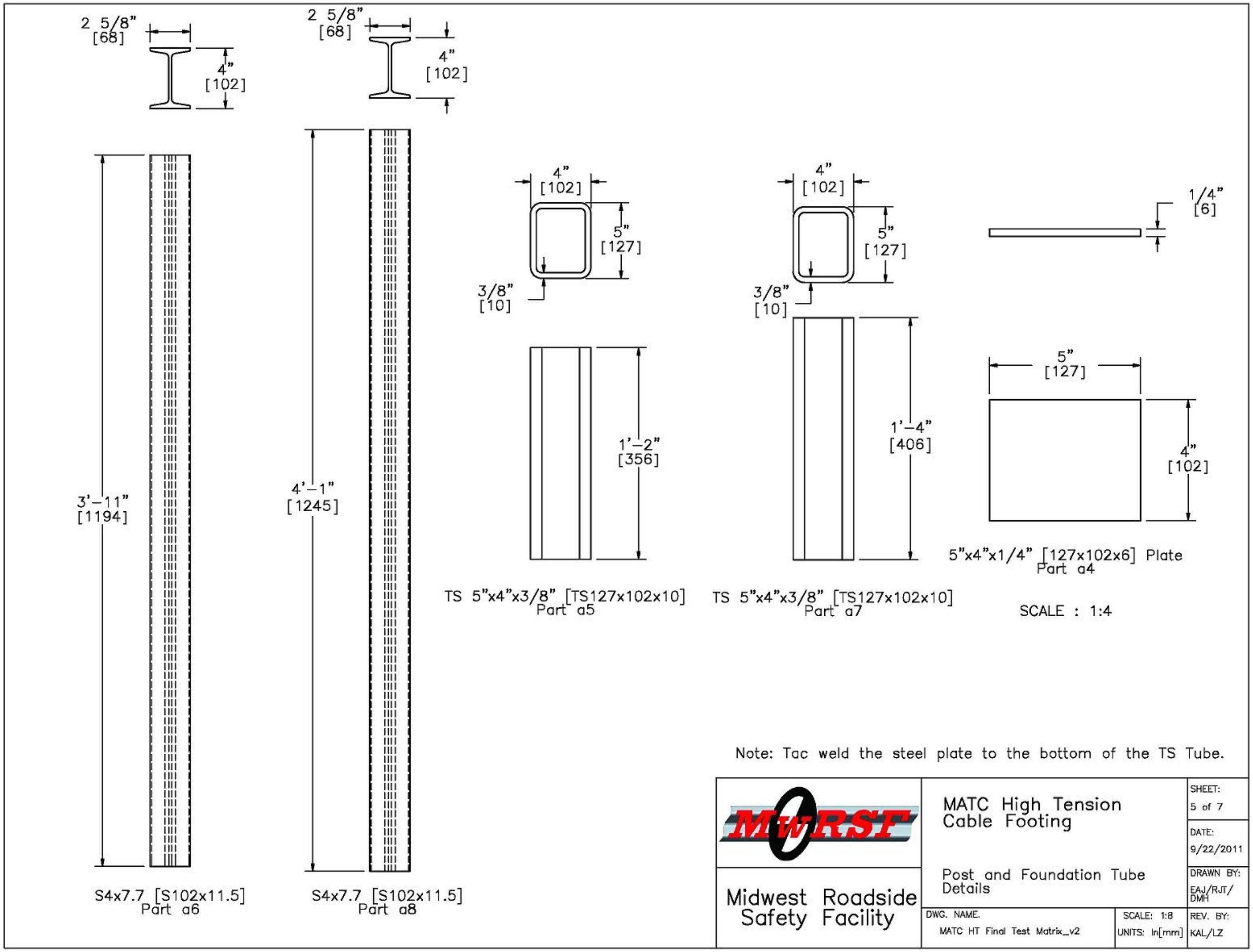


Figure 3.5 Steel Post and Tube Details

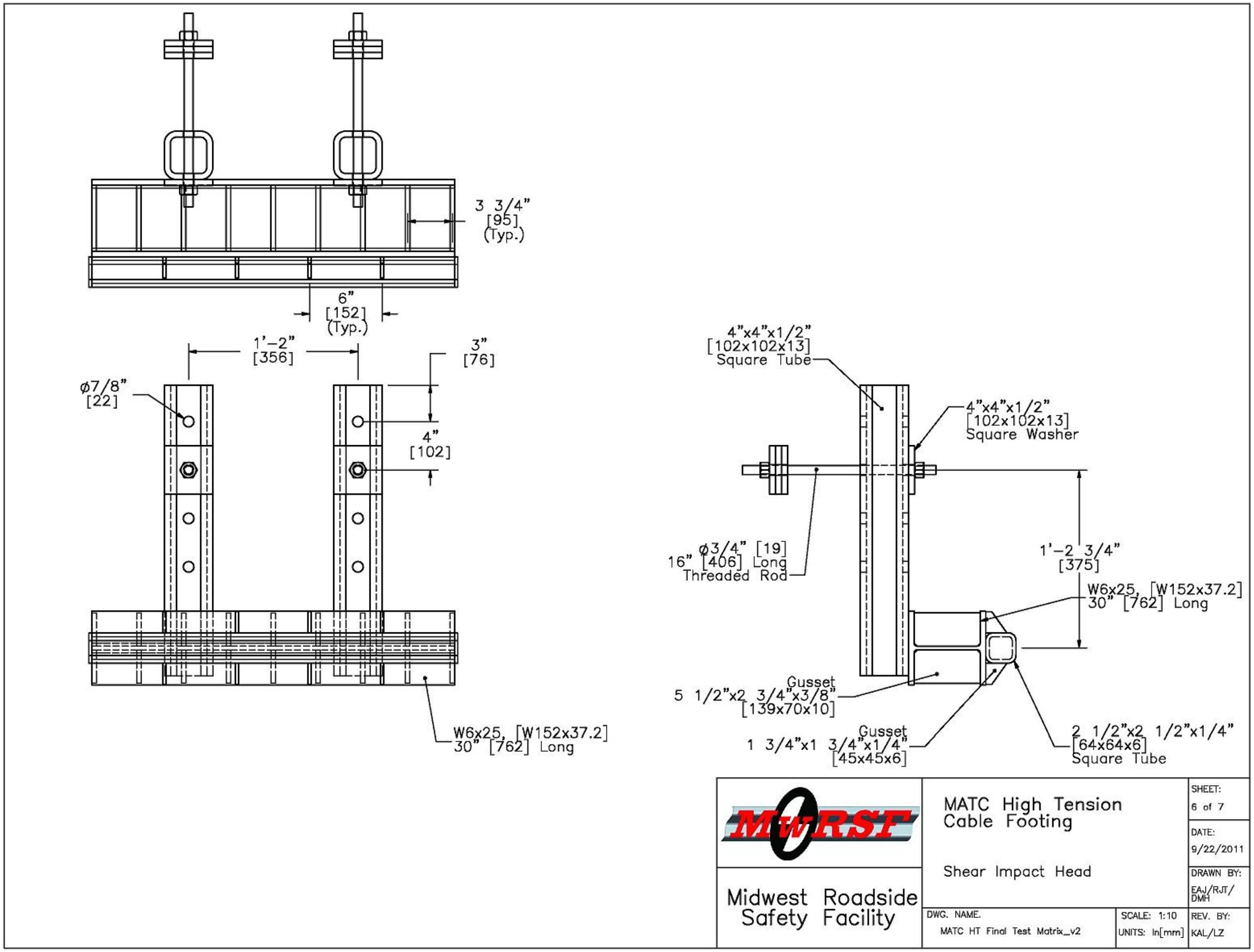


Figure 3.6 Bogie Shear Impact Head Details

MATC High Tension Cable Footing – 24" [610] Depth (Used in A-3 Sand with Rebar Configuration A)			
Item No.	QTY.	Description	Material Spec
a1	1	AASHTO A-3 Sand	See Page 2
a2	2	#4 Rebar 5 1/2" [140] Long	Gr. 60
a3	3	#4 Circular Rebar 7" [178] ID	Gr. 60
a4	1	1/4" [6] Steel Plate	A36
a5	1	TS 5"x4"x3/8" [TS 127x102x10], 14" [356] Long	–
a6	1	S4x7.7 [S102x11.5], 47" [1194] Long	A36
b1	4	#4 Rebar 20" [508] Long	Gr. 60
b2	1	Concrete 24" [610] Long	Min 3500 psi [24 MPa] Comp. Strength
MATC High Tension Cable Footing – 36" [914] Depth (Used in A-3 Sand with Rebar Configuration B)			
Item No.	QTY.	Description	Material Spec
a1	1	AASHTO A-3 Sand	See Page 2
a2	2	#4 Rebar 5 1/2" [140] Long	Gr. 60
a3	5	#4 Circular Rebar 7" [178] ID	Gr. 60
a4	1	1/4" [6] Steel Plate	A36
a5	1	TS 5"x4"x3/8" [TS 127x102x10], 14" [356] Long	–
a6	1	S4x7.7 [S102x11.5], 47" [1194] Long	A36
c1	4	#4 Rebar 32" [813] Long	Gr. 60
c2	1	Concrete 36" [914] Long	Min 3500 psi [24 MPa] Comp. Strength
MATC High Tension Cable Footing – 60" [1524] Depth (Used in A-3 Sand with Rebar Configuration B)			
Item No.	QTY.	Description	Material Spec
a1	1	AASHTO A-3 Sand	See Page 2
a2	2	#4 Rebar 5 1/2" [140] Long	Gr. 60
a3	8	#4 Circular Rebar 7" [178] ID	Gr. 60
a4	1	1/4" [6] Steel Plate	A36
a5	1	TS 5"x4"x3/8" [TS 127x102x10], 14" [356] Long	–
a6	1	S4x7.7 [S102x11.5], 47" [1194] Long	A36
d1	1	Concrete 60" [1524] Long	Min 3500 psi [24 MPa] Comp. Strength
d2	4	#4 Rebar 56" [1422] Long	Gr. 60
MATC High Tension Cable Footing – 60" [1524] Depth (Used in A-3 Sand with Rebar Configuration C)			
Item No.	QTY.	Description	Material Spec
a1	1	AASHTO A-3 Sand	See Page 2
a2	2	#4 Rebar 5 1/2" [140] Long	Grade 60
a3	9	#4 Circular Rebar 7" [178] ID	Gr. 60
a4	1	1/4" [6] Steel Plate	A36
a7	1	TS 5"x4"x3/8" [TS 127x102x10], 16" [406] Long	–
a8	1	S4x7.7 [S102x11.5], 49" [1245] Long	A36
d1	1	Concrete 60" [1524] Long	Min 3500 psi [24 MPa] Comp. Strength
d3	4	#5 Rebar 56" [1422] Long	Gr. 60

Midwest Roadside Safety Facility	MATC High Tension Cable Footing Bill of Materials		SHEET: 7 of 7 DATE: 9/22/2011 DRAWN BY: EAJ/RJT/DMH
	DWG. NAME. MATC HT Final Test Matrix_v2	SCALE: None UNITS: In[mm]	REV. BY: KAL/LZ

Figure 3.7 Bill of Materials

Figure 3.8 Test Installation Setup

Chapter 4 Component Test Conditions

4.1 Purpose

Testing of the socketed foundations for cable guardrail posts was conducted in order to evaluate the structural integrity of the socketed foundations and to measure lateral deflections of the new, variable length, foundation designs placed in weak soil.

4.2 Scope

Four bogie tests were conducted on S4x7.7 (S102x11.5) steel posts inserted into socketed foundations. The socketed foundations were placed in a sand pit satisfying the American Association of State Highway and Transportation Officials (AASHTO) A-3 sand material requirements. The target impact conditions were a speed of 20.0 mph (32.2 km/h) and an angle of 0 degrees, or through the strong-axis of the post bending. All posts were impacted 11 in. (279 mm) above the groundline. A summary of the bogie testing is shown in table 4.1.

4.3 Test Facility

Physical testing of the cable post base was conducted at the Midwest Roadside Safety Facility (MwRSF) outdoor proving grounds, 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.

4.4 Equipment and Instrumentation

Equipment and instrumentation utilized to collect and record data during the dynamic bogie tests included a bogie, accelerometers, pressure tape switches, a string potentiometer, high-speed and standard-speed digital video cameras, and still camera.

Table 4.1 Scope of Physical Testing

Test No.	Post Type	Post Length in. (mm)	Target Impact Velocity mph (km/h)	Impact Orientation	Embedment Depth in. (mm)	Rebar Configuration
HTCB-1	S4x7.7 (S102x11.5)	47 (1,194)	20 (32)	0 deg Strong Axis	24 (610)	A
HTCB-2	S4x7.7 (S102x11.5)	47 (1,194)	20 (32)	0 deg Strong Axis	36 (914)	B
HTCB-3	S4x7.7 (S102x11.5)	47 (1,194)	20 (32)	0 deg Strong Axis	60 (1,524)	B
HTCB-4	S4x7.7 (S102x11.5)	47 (1,194)	20 (32)	0 deg Strong Axis	60 (1,524)	C

4.4.1 Bogie

A rigid-frame bogie equipped with a variable height, detachable impact head was used to strike the posts. The bogie impact 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 head was bolted to the bogie vehicle, creating a rigid frame with an impact height of 11 in. (279 mm). The bogie and impact head are shown in figure 4.1. The weight of the bogie with the addition of the mountable impact head for test no. HTCB-1 was 1,804 lb (818 kg). After the first test, an additional steel section was used to attach the impact head to the bogie frame. Thus, the nominal bogie weight for test nos. HTCB-2 through HTCB-4 was 1,845 lb (837 kg). Approximate bogie weights are listed in their respective test description sections.

Figure 4.1 Rigid Frame Bogie with Impact Head

A pickup truck with a reverse cable tow system was used to propel the bogie to a target impact speed of 20 mph (32 km/h). When the bogie approached the end of the guidance system, it was released from the tow cable, allowing it to be free rolling when it impacted the post. A remote braking system was installed on the bogie allowing it to be brought safely to rest after the test.

4.4.2 Accelerometers

Two accelerometer systems were mounted on the bogie vehicle near its center of gravity to measure the impact accelerations in the longitudinal, lateral, and vertical directions. However, only the longitudinal accelerations were processed and reported. The first accelerometer, Model EDR-3, was a triaxial, piezoresistive accelerometer system developed by Instrumented Sensor Technology (IST) of Okemos, Michigan. The EDR-3 was configured with 256 kB of RAM memory, a range of ±200 g's, a sample rate of 3,200 Hz, and a 1,120 Hz low-pass filter. The "DynaMax 1 (DM-1)" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

A second triaxial piezoresistive accelerometer system, Model EDR-4 6DOF-500/1200, was used. The EDR-4 6DOF-500/1200, also developed by IST of Okemos, Michigan, includes three differential channels as well as three single-ended channels. The EDR-4 6DOF-500/1200 was configured with 24 MB of RAM memory, a range of ±500 g's, a sample rate of 10,000 Hz, and a 1,677 Hz anti-aliasing filter. The "EDR4COM" and "DynaMax Suite" computer software programs and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

4.4.3 Pressure Tape Switches

Three pressure tape switches, spaced at approximately 18 in. (457 mm) intervals and placed near the end of the bogie track, were used to determine the speed of the bogie before the impact. As the right-front tire of the bogie passed over each tape switch, a strobe light was fired sending an electronic timing signal to the data acquisition system. The system recorded the signals and the time each occurred. The speed was then calculated using the spacing between the sensors and the time between the signals. Strobe lights and high-speed video analysis were used only as a backup in the event that vehicle speeds could not be determined from the electronic data.

4.4.4 Photography

One AOS VITcam high-speed digital video camera and two JVC 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 JVC digital video cameras had frame rates of 29.97 frames per second. All three cameras were placed laterally from the post, with a view perpendicular to the bogie's direction of travel. A Nikon D50 digital still camera was also used to document pre- and post-test conditions for all tests.

4.4.5 String Potentionmeters

A linear displacement transducer, or string potentiometer, was installed on the front edge of the sand pit to determine the displacement of the post foundation for each bogie test. The positioning and setup of the string potentiometer are shown in figure 4.2. The string potentiometer used was a UniMeasure PA-50 with a range of 50 in. (1,270 mm). A Measurements Group Vishay Model 2310 signal conditioning amplifier was used to condition and amplify the low-level signals to high-level outputs for multichannel, simultaneous dynamic recording in the "LabVIEW" software. The sample rate of the string potentiometers was 1,000 Hz.

4.4.6 End of Test Determination

During standard bogie-post impact events, the desired test results have been based on force-deflection characteristics. Subsequently, the end of test has typically been defined as the first of three occurrences: (1) fracture of the test article; (2) excessive rotation of the test article; or (3) the bogie vehicle overriding or losing contact with the test article. However, the focus of the four bogie tests conducted herein was to evaluate the structural adequacy of the socketed foundations and to measure the maximum deflections or rotations of the foundations. Since the maximum resistive forces for the post assembly were restricted by the material and section properties of the post, the data recorded by the accelerometers would only be important in measuring the load at fracture. Therefore, the first two end of test criteria were discarded, and the true end of test was defined as the time when the bogie vehicle overrode or lost contact with the post assembly.

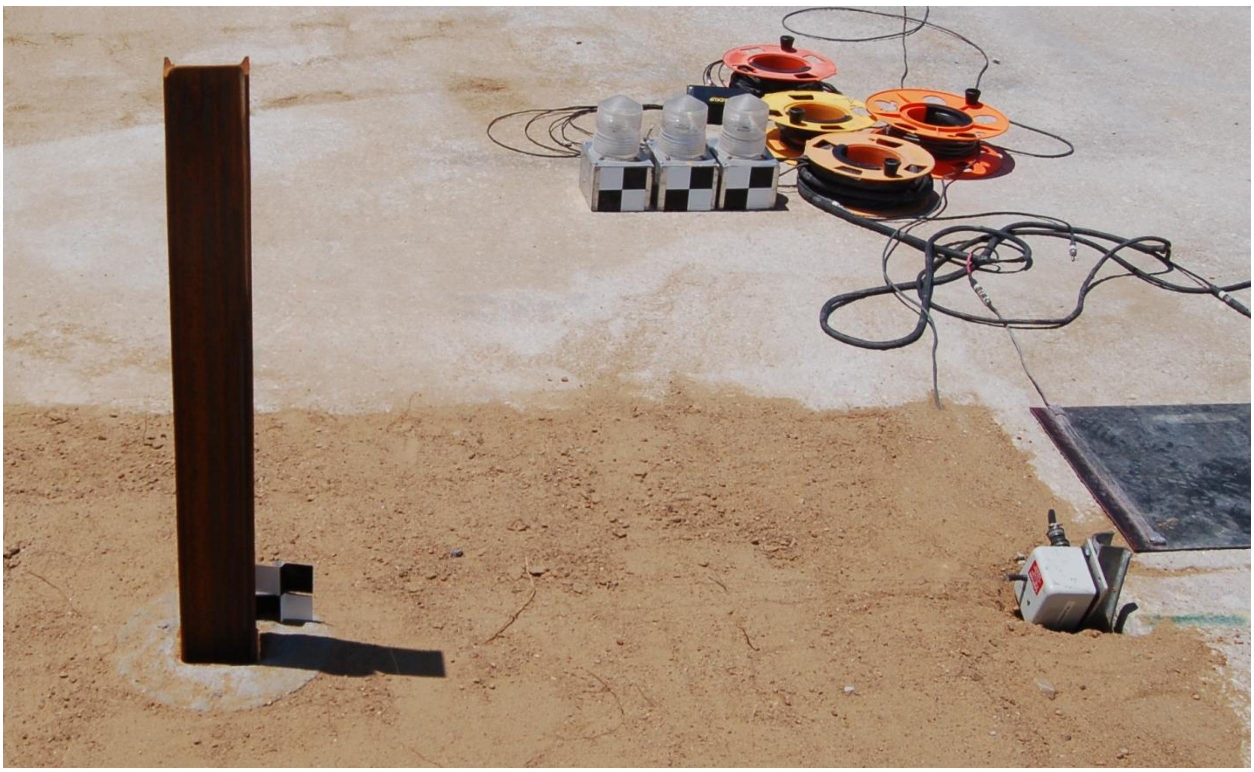


Figure 4.2 Typical String Potentiometer Setup

4.5 Data Processing

The electronic accelerometer data obtained in the dynamic testing was filtered using the SAE Class 60 Butterworth filter conforming to the SAE J211/1 specifications [8]. 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 pressure tape switch data, was used to determine the bogie velocity throughout the impact event. The calculated velocity trace was then integrated to find the bogie's displacement. Combining the previous results, a force versus deflection curve was plotted for each test. These curves only illustrated the lateral resistive force applied at displacements equal to the movement of the bogie vehicle and impact head, not the displacement of the post or the socketed foundation. Finally, integration of the force versus deflection curve produced the energy versus displacement curve for each test. Historically, the EDR-3 unit has provided more accurate data than the EDR-4 unit. Therefore, the graphs and values presented are taken from the data provided by the EDR-3 accelerometer. However, data obtained from both the EDR-3 and EDR-4 units are shown in Appendix A.

Similar to the accelerometer data, the pertinent data from the string potentiometer was extracted from the bulk signal. The extracted data signal was converted to a displacement using the transducers calibration factor. Displacement versus time plots were created to describe the motion of the foundation at groundline. The exact moment of impact could not be determined from the string potentiometer data as impact may have occurred a few milliseconds prior to foundation movement. Thus, the extracted time shown in the displacement versus time plots should not be taken as a precise time after impact, but rather a general time in relation to the impact event.

Chapter 5 Component Testing Results and Discussion

5.1 Results

The information desired from each component test was the performance of each socketed foundation in terms of both structural integrity and the displacement of the foundation in weak soils. Additionally, accelerometer data was used to find the resistance force supplied by the cable barrier post and foundation assembly. The displacements calculated from the acceleration data are related to the motion of the bogie, while the displacements calculated from the string potentiometer are related to the motion of the socketed foundation. Thus, these displacements are in reference to different components and were not expected to be similar. The total force on the post assembly included a vertical component as the post rotated past vertical. However, this vertical component was thought to be negligible when compared to the horizontal force at the beginning of the impact event. Therefore, only the longitudinal forces applied to the bogie (lateral forces on the post assembly) were analyzed and evaluated.

Although the acceleration data was applied to the impact location, the data came from the center of gravity of the bogie. This added error to the data, since the bogie was not perfectly rigid and vibrations in the bogie were recorded. The bogie may have rotated during impact causing differences in accelerations between the bogie center of mass and the bogie impact head. Filtering procedures were applied to the data to smooth out vibrations, and rotations of the bogie during testing were minor. Thus, the data was still deemed appropriate and valid. One useful aspect of using accelerometer data was influences of inertia on the reaction force were included. This was important as the mass of the post, foundation, and soil would affect barrier performance and test results.

5.1.1 Test No. HTCB-1

Test no. HTCB-1 was conducted on June 16, 2009 at approximately 2:45 p.m. The weather conditions as per the National Oceanic and Atmosphere Administration (station 14939/LNK) were reported and are shown in table 5.1.

Table 5.1 Weather Conditions, Test No. HTCB-1

Temperature	82° F
Humidity	53%
Wind Speed	0 mph
Wind Direction	NA
Sky Conditions	Sunny
Visibility	10 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0.29 in.
Previous 7-Day Precipitation	0.74 in.

The 1,804-lb (818-kg) bogie impacted the post and foundation assembly at a speed of 20.7 mph (33.3 km/h). The centerline of the bogie was aligned perpendicular to the strong-axis of the S4x7.7 (S102x11.5) steel post with the impact head centered on the front face of the post at an impact height of 11 in. (279 mm) above the groundline. Test results are described in the following section and sequential photographs are shown in Figure 5.1. Additional post-test photographs are shown in figure 5.2.

Following impacts, the post and socketed foundation assembly rotated through the sand/soil. At 0.158 sec., the bogie overrode and lost contact with the post assembly. The post assembly rotated backward almost a full 90 degrees with the top of the post just above groundline. Both the steel post and the concrete foundation remained intact and undamaged. Time-sequential photographs are shown in figure 5.1. Component damage and post base deflection are shown in figure 5.2.

At the beginning of the impact event, inertial effects resulted in a peak force of 18.8 kips (83.6 kN) at 1.7 in. (43 mm) of deflection. After the initial spike, the force level remained around 5 kips (22 kips) until a deflection of 8 in. (203 mm). After 8 in (203 mm) of deflection, the post and foundation assembly provided minimal resistance; since, the socketed foundation was rotating through the soil, and the bogie vehicle overrode the post. The bogie traveled 49.3 in. (1,252 mm) before overriding and losing contact with the post. A total of 103.8 kip-in. (11.7 kJ) of energy was absorbed by the post and foundation assembly during impact. Force versus deflection and energy versus deflection curves were created from the accelerometer data and are shown in Figure 5.3. According to the string potentiometer, the top of the socketed foundation reached a maximum dynamic and permanent set deflection of 19.8 in. (503 mm) and 19 in. (483 mm), respectively, as shown in Figure 5.4.

0.000 sec

0.114 sec

0.032 sec

0.200 sec

0.044 sec

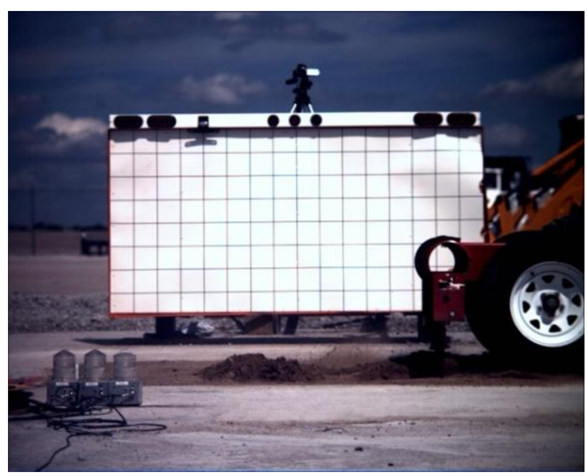


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Figure 5.1 Time-Sequential Photographs, Test No. HTCB-1

Figure 5.2 System Damage, Test No. HTCB-1

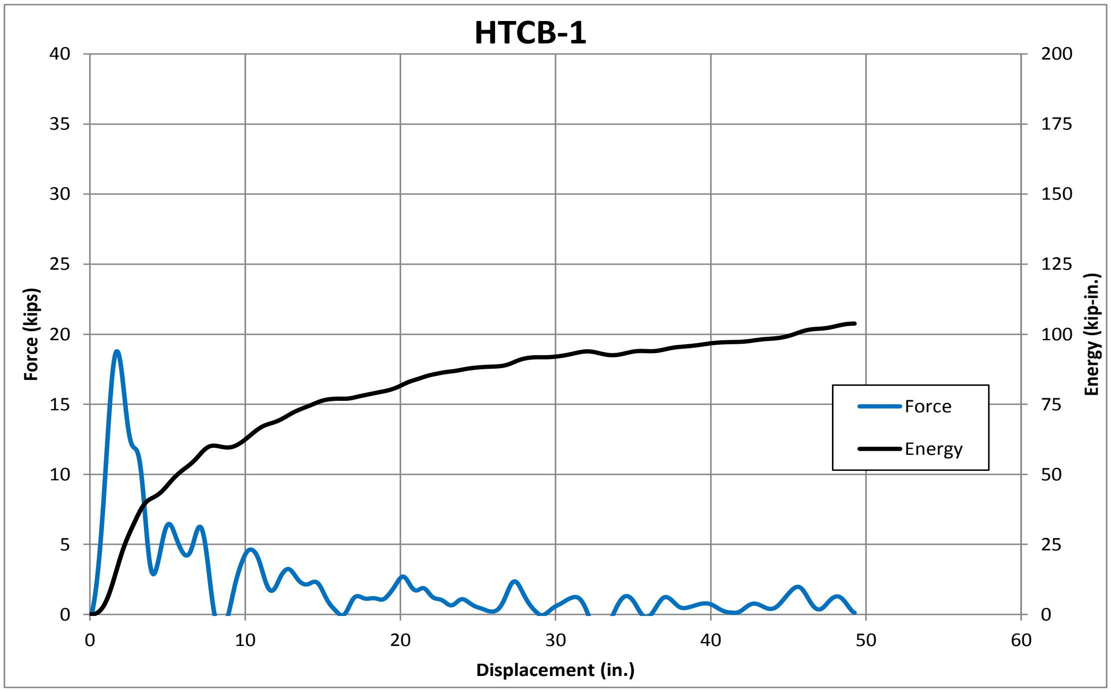


Figure 5.3 Force vs. Deflection and Energy vs. Deflection, Test No. HTCB-1

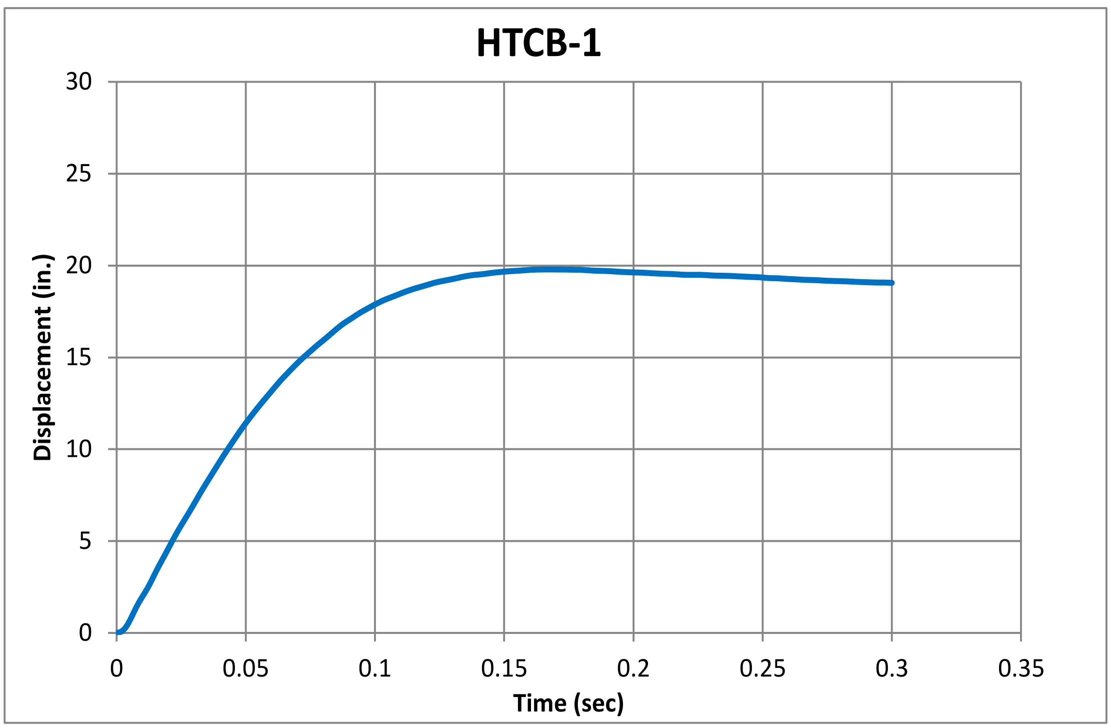


Figure 5.4 Deflection of the Socketed Foundation, Test No. HTCB-1

5.1.2 Test No. HTCB-2

Test no. HTCB-2 was conducted on June 17, 2009 at approximately 1:15 p.m. The weather conditions as per the National Oceanic and Atmosphere Administration (station 14939/LNK) were reported and are shown in table 5.2.

Table 5.2 Weather Conditions, Test No. HTCB-2

Temperature	93° F
Humidity	36 %
Wind Speed	11 mph
Wind Direction	110° from True North
Sky Conditions	Sunny
Visibility	10 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0.29 in.
Previous 7-Day Precipitation	0.70 in.

The 1,845 lb (837 kg) bogie impacted the post and foundation assembly at a speed of 20.4 mph (32.8 km/h). The centerline of the bogie was aligned perpendicular to the strong-axis of the S4x7.7 (S102x11.5) steel post with the impact head centered on the front face of the post at an impact height of 11 in. (279 mm) above the groundline.

Following impact, the post and socketed foundation assembly rotated through the sand/soil. At 0.194 seconds, the bogie overrode and lost contact with the post assembly. The post assembly rotated backward almost a full 90 degrees with the top of the post just above the groundline. The steel post remained undamaged throughout the test, while the concrete foundation received only minor cracking to the top surface downstream of the steel socket and the upstream side 13 in. (330 mm) from the top. The cracks on the upstream side correspond closely with the location of the bottom of the steel socket inside the foundation. Time-sequential photographs are shown in Figure 5.5. Component damage and post base deflection are shown in figures 6 and 6.

At the beginning of the impact event, inertial effects resulted in a peak force of 24.2 kips (107.6 kN) at 1.8 in. (46 mm) of deflection. After the initial spike, the post and foundation assembly provided a relatively constant force level ranging from 3 to 5 kips (13 to 22 kN) until the bogie had traveled 25 in. (635 mm). Only minimal resistance was recorded through the remainder of the test. The bogie traveled 53.4 in. (1,356 mm) before overriding and losing contact with the post. A total of 169.2 kip-in. (19.1 kJ) of energy was absorbed by the post and foundation assembly during impact. Force versus deflection and energy versus deflection curves were created from the accelerometer data and are shown in Figure 5.8. According to the string potentiometer, the top of the socketed foundation reached a maximum dynamic and permanent set deflection of 27.0 in. (686 mm) and 25.5 in. (648 mm), respectively, as shown in Figure 5.9.

0.000 sec

0.030 sec

0.054 sec

0.090 sec

0.120 sec

0.568 sec

Figure 5.5 Time-Sequential Photographs, Test No. HTCB-2

Figure 5.6 System Damage, Test No. HTCB-2

Figure 5.7 Concrete Damage, Test No. HTCB-2

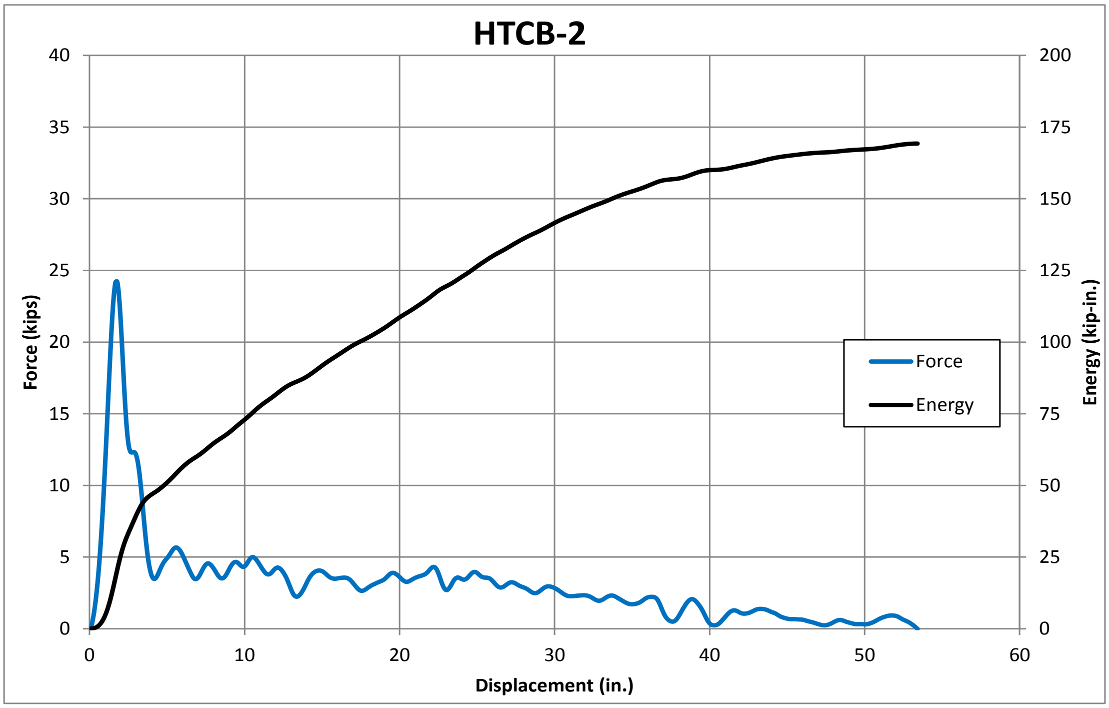


Figure 5.8 Force vs. Deflection and Energy vs. Deflection, Test No. HTCB-2

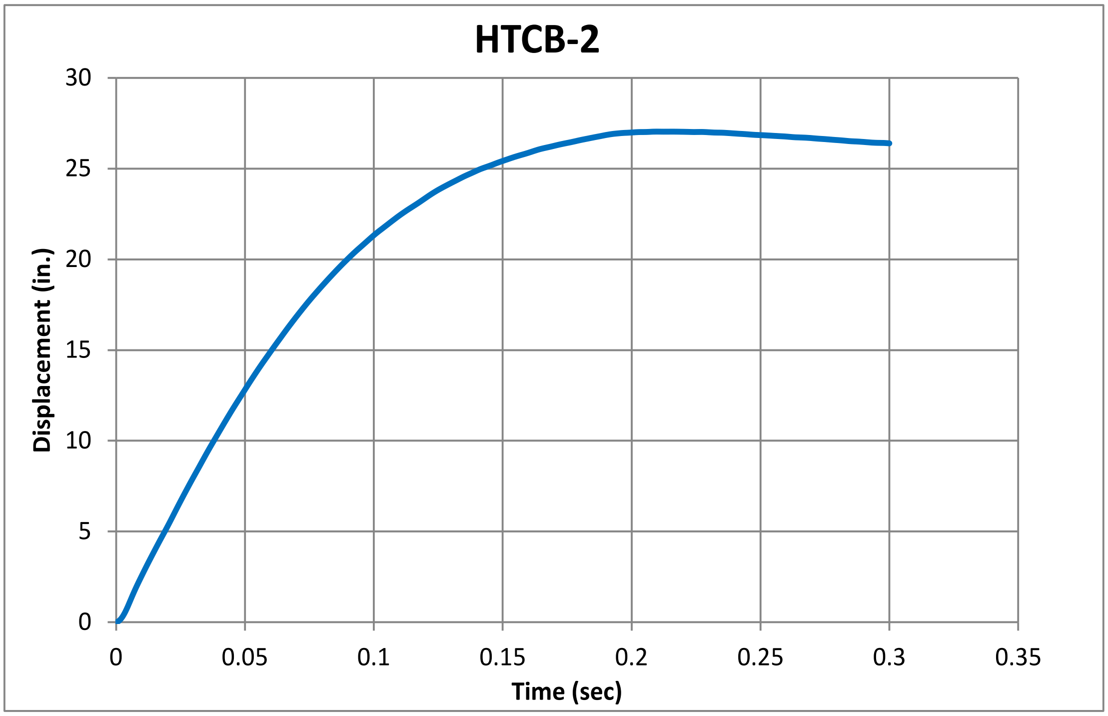


Figure 5.9 Deflections of the Socketed Foundation, Test No. HTCB-2

5.1.3 Test No. HTCB-3

Test no. HTCB-3 was conducted on June 25, 2009 at approximately 9:45 a.m. The weather conditions as per the National Oceanic and Atmosphere Administration (station 14939/LNK) were reported and are shown in table 5.3.

Table 2.3 Weather Conditions, Test No. HTCB-3

Temperature	83° F
Humidity	65%
Wind Speed	0 mph
Wind Direction	NA
Sky Conditions	Sunny
Visibility	10 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0.83 in.
Previous 7-Day Precipitation	2.48 in.

The 1,844 lb (836 kg) bogie impacted the post and foundation assembly at a speed of 21.2 mph (34.1 km/h). The centerline of the bogie was aligned perpendicular to the strong-axis of the S4x7.7 (S102x11.5) steel post with the impact head centered on the front face of the post at an impact height of 11 in. (279 mm).

Upon impact, the post and socketed foundation assembly began to deflect and rotate backward. At 0.012 seconds after impact, the concrete foundation began to fracture apart around the steel socket. By 0.040 seconds, chunks of concrete from the top of the foundation disengaged allowing the socket to rotate without confinement. At 0.148 seconds, the bogie overrode and lost contact with the post. By this time, the rebar serving as the attachment point for the string potentiometer wire had disengaged from the concrete foundation and was being pulled back toward the transducer. Time-sequential photographs are shown in Figure 5.10.

The post sustained only minor plastic deformation at a location coincident with the top of the steel socket. The top of the socketed foundation sustained severe damage as most of the concrete from the top 17 in. (432 mm) had fractured away. The top circumferential rebar loop was bent and both of the longitudinal bars on the upstream side were sheared off near the center of the socket. Post-test photographs documenting the damage sustained by the footing assembly are shown in figures 5.11 and 5.12.

At the beginning of the bogie test, inertial effects resulted in a peak force of 28.0 kips (124.6 kN) at 1.7 in. (43 mm) of deflection. Substantial resistance was only recorded over 7 in. (178 mm) of deflection. After this point, the concrete foundation had fractured and only small force resistances were present until the bogie overrode the post. According to the accelerometer data, a total of 121.9 kip-in. (13.8 kJ) of energy was absorbed during the impact event. Force versus deflection and energy versus deflection curves were created from accelerometer data and are shown in Figure 5.13. The string potentiometer recorded a maximum deflection of 18.1 in. (460 mm) for the socketed foundation before the attachment point rebar disengaged, as shown in Figure. A true deflection could not be quantified due to the concrete foundation fracturing apart.

0.000 sec

0.014 sec

0.040 sec

0.094 sec

0.146 sec

0.472 sec

Figure 5.10 Time-Sequential Photographs, Test No. HTCB-3

Figure 5.11 System Damage, Test No. HTCB-3

Figure 5.12 System Damage, Test No. HTCB-3

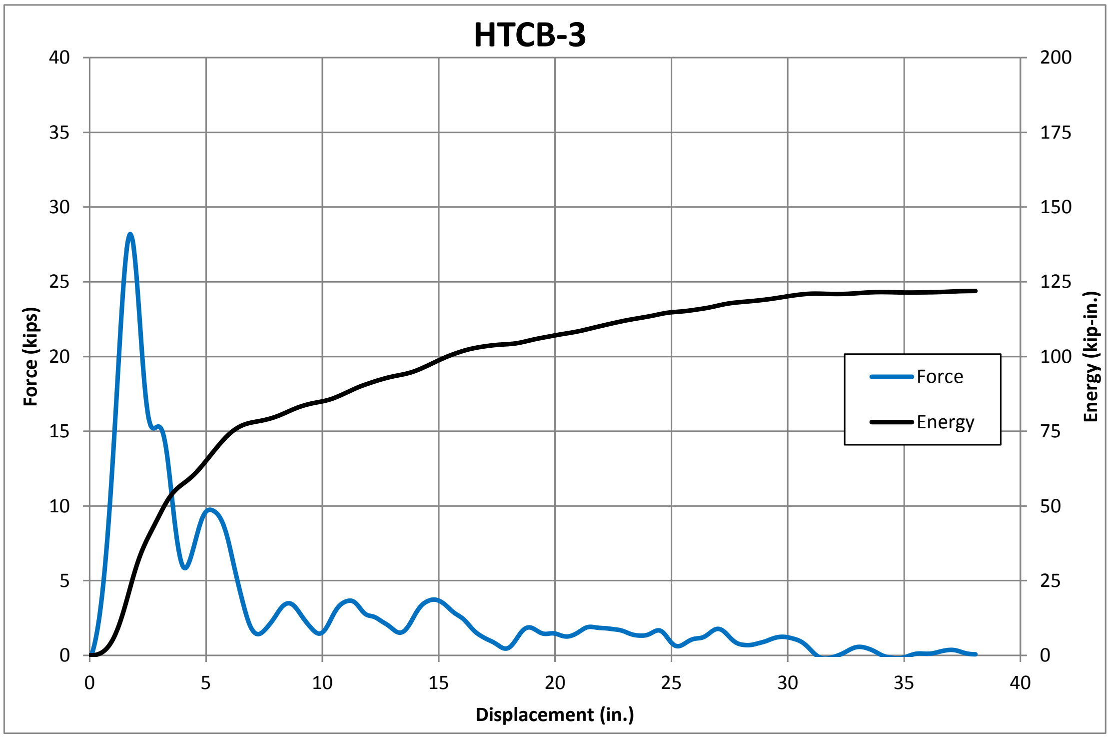


Figure 5.13 Force vs. Deflection and Energy vs. Deflection, Test No. HTCB-3

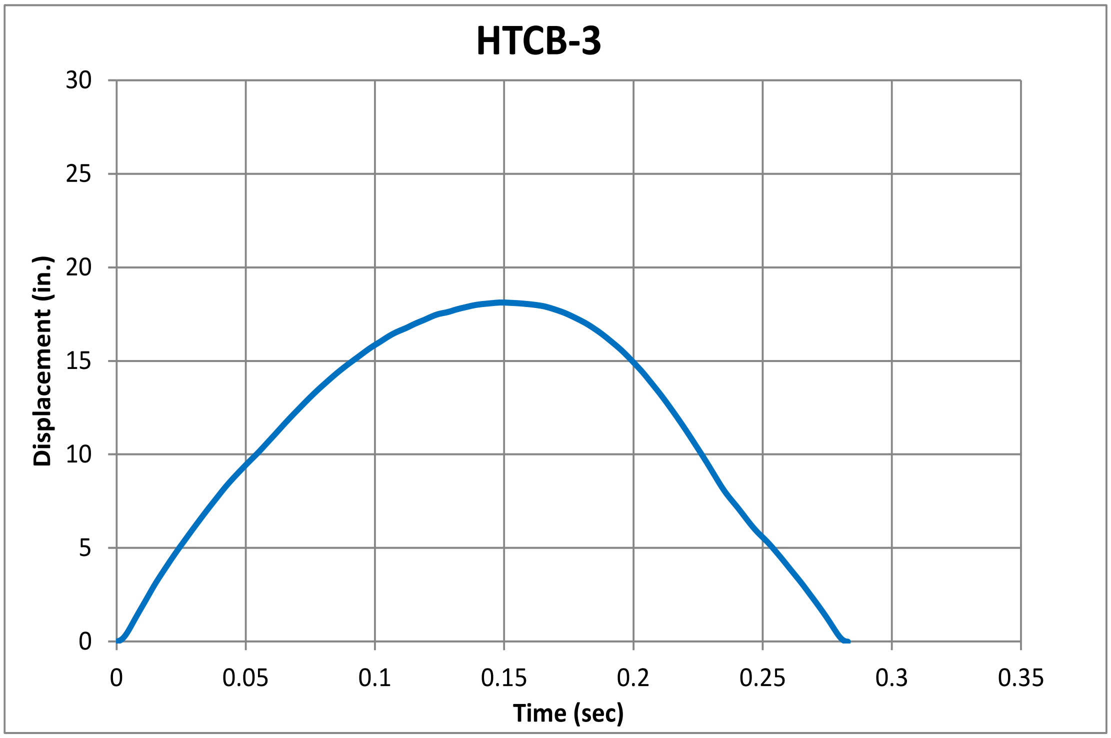


Figure 5.14 Deflection of the Socketed Foundation, Test No. HTCB-3

5.1.4 Test No. HTCB 4

Test no. HTCB-4 was conducted on September 23, 2009 at approximately 10:45 a.m. The weather conditions as per the National Oceanic and Atmosphere Administration (station 14939/LNK) were reported and are shown in **Table 5.4**.

Table 5.4 Weather Conditions, Test No. HTCB-4

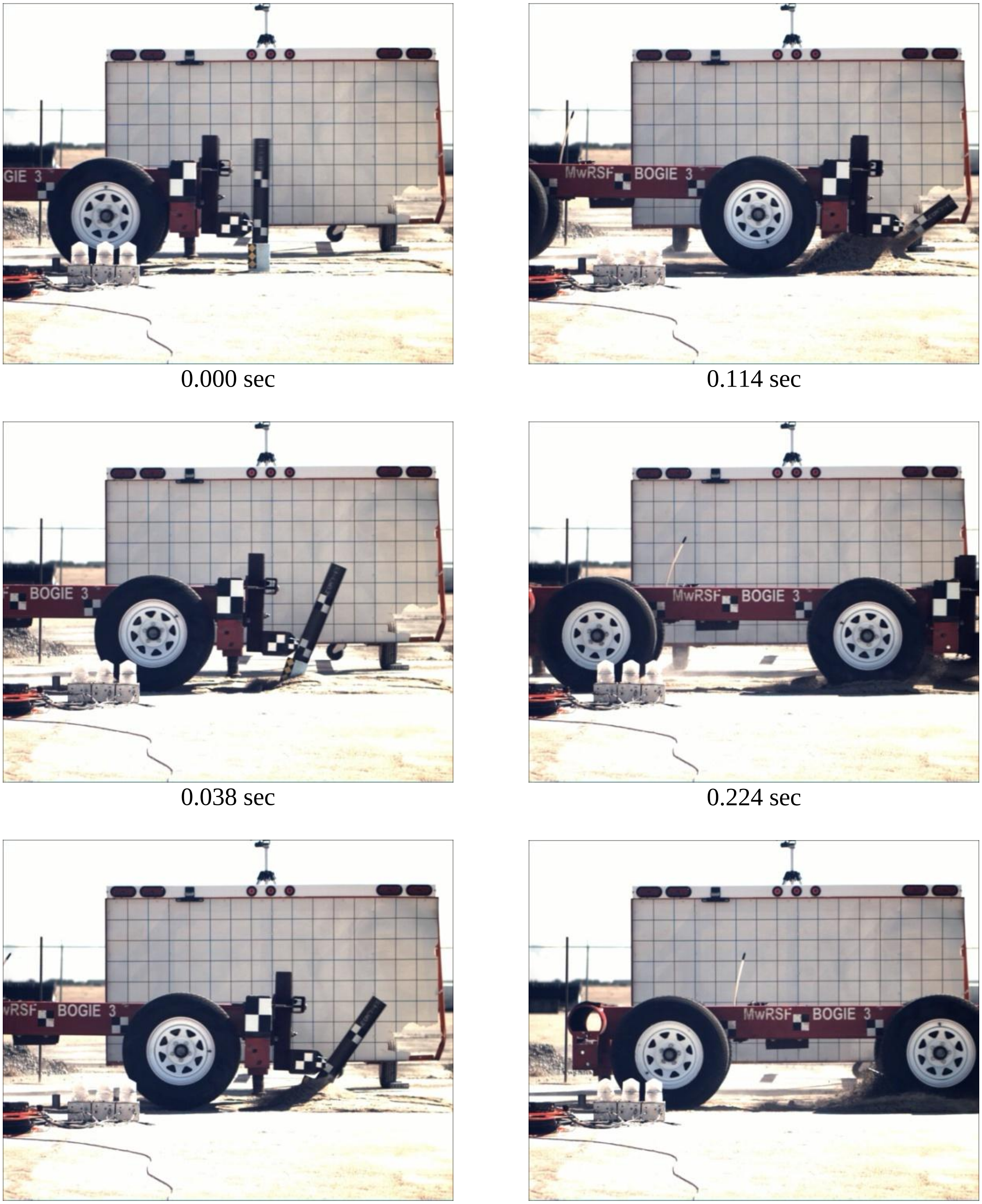
Temperature	63° F
Humidity	65%
Wind Speed	0 mph
Wind Direction	NA
Sky Conditions	Sunny
Visibility	10 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0.27 in.
Previous 7-Day Precipitation	0.27 in.

The 1,839-lb (834-kg) bogie impacted the post and foundation assembly at a speed of 19.6 mph (31.6 km/h). The centerline of the bogie was aligned perpendicular to the strong-axis of the S4x7.7 (S102x11.5) steel post with the impact head centered on the front face of the post at an impact height of 11 in. (279 mm) above the groundline.

Upon impact, the post and socketed foundation assembly began to rotate backward through the sand/soil. By 0.150 seconds after impact, large chunks of concrete had fractured from the socketed foundation. The exact time of fracture could not be determined from the high-speed video due to the displaced debris blocking the view. At 0.200 seconds, the bogie overrode and lost contact with the post. Time-sequential photographs are shown in **Figure 5.15**.

The post sustained no significant damage during the bogie test; however, the concrete foundation was severely damaged. The top 16 in. (406 mm) of concrete on the post base fractured and disengaged, exposing the socket and upper rebar in the assembly. Significant transverse cracking was found lower on the foundation. The steel socket tube rotated backward and the top three pieces of circumferential rebar were exposed. The top two circumferential rebar pieces were bent and deformed. All four of the vertical bars were bent and the vertical rebar on the upstream side fractured near the bottom of the socket. During excavation of the socketed foundation, an air pocket approximately 1 in. (25 mm) in depth was found along the front side of the assembly that may have contributed to the failure in the base. Component damage is shown in figures 5.16 and 5.17.

At the beginning of the bogie test, inertial effects resulted in a peak force of 23.5 kips (104.5 kN) at 1.6 in. (41 mm) of deflection. After this peak, the force steadily decreased until it fell below 5 kips (22 kN) at a deflection of 14 in. (356 mm). Only minor resistance forces were recorded after this point as the bogie overrode the post. According to the accelerometer data, a total of 176.2 kip-in. (19.9 kJ) of energy was absorbed during the impact event. Force versus deflection and energy versus deflection curves were created from accelerometer data and are shown in **Figure 5.18**. The string potentiometer was not used in this test due to concerns of damaging it after the foundation in test no. HTCB-3 fractured. Similar to test no. HTCB-3, a final deflection of the socketed foundation could not be determined due to the concrete foundation fracturing apart.



0.000 sec

0.114 sec

0.038 sec

0.224 sec

0.064 sec

0.300 sec

Figure 5.15 Time-Sequential Photographs, Test No. HTCB-4

Figure 5.16 System Damage, Test No. HTCB-4

Figure 5.17 System Damage, Test No. HTCB-4

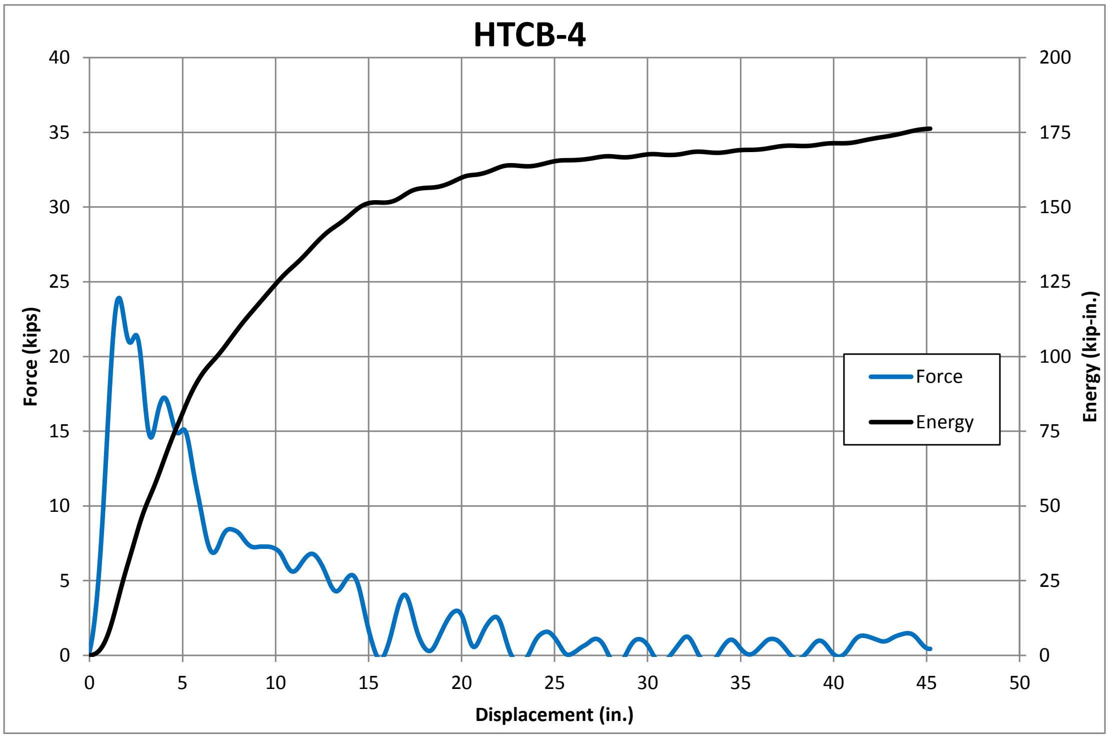


Figure 5.18 Force vs. Deflection and Energy vs. Deflection, Test No. HTCB-4

5.2 Summary of Bogie Tests

The results from the four bogie tests are summarized in Table 5.5. Each test was conducted under nearly identical impact conditions: (1) the same S4x7.7 (S102x11.5) post section; (2) the same bogie impact head; (3) an impact height of 11 in. (280 mm); and (4) an impact velocity near the target velocity of 20 mph (32 km/h). Thus, the variation in results was attributed to the embedment depth of the socketed foundation; since, all concrete foundations had the same 12 in. (305 mm) diameter.

Table 5.5. Dynamic Testing Results

Test No.	Footing Depth in. (mm)	Socket Depth in. (mm)	Impact Velocity mph (km/h)	Permanent Set Deflection in. (mm)	Max. Force kips (kN)	Total Energy kip-in. (kJ)	Notes
HTCB-1	24 (610)	14 (356)	20.7 (33.3)	19 (483)	18.8 (83.7)	104 (11.7)	Excessive Rotation and Displacement
HTCB-2	36 (914)	14 (356)	20.4 (32.8)	25½ (648)	24.2 (107.7)	169 (19.1)	Excessive Rotation and Displacement
HTCB-3	60 (1,524)	14 (356)	21.2 (34.1)	NA	28.2 (125.4)	122 (13.8)	Socketed Foundation Fracture
HTCB-4	60 (1,524)	16 (406)	19.6 (31.5)	NA	23.9 (106.4)	176 (19.9)	Socketed Foundation Fracture

Test nos. HTCB-1 and HTCB-2 had foundations with embedment depths of 24 in. (610 mm) and 36 in (914 mm), respectively. Both socketed foundations rotated through the weak soil (i.e., sand) with no deformation to the post itself. Subsequently, these embedment depths were deemed too shallow to prevent rotation of a 12-in. (305-mm) diameter foundation placed in a weak soil. As expected, the deeper embedment depth of test no. HTCB-2 provided more rotation resistance. However, this magnitude of resistance proved insufficient to prevent excessive deformation of the foundation. Vehicle impacts to either of these socketed foundation designs would likely result in significant dirt work to remove and reset the foundations.

Both test nos. HTCB-3 and HTCB-4 utilized foundations with a 60 in. (1,524 mm) embedment depth. The difference between the two test components was (1) the internal reinforcement configuration and (2) the depth of the socket was increased by 2 in. (51 mm) for test no. HTCB-4, as shown in Table 5.5. However, neither of the internal steel configurations provided adequate strength as the top portions containing the steel socket tube fractured off during testing. These two socketed foundations would likely need to be completely removed and replaced due to severe damage.

The fracturing of the top segment of the foundations prevented the permanent set displacements from being measured. Additionally, sand displaced during the test blocked the view of the high-speed video cameras, so the actual time of fracture could not be determined. Consequently, conclusions regarding the displacement of the 60-in. (1,524-mm) foundations in weak soil could not be made.

Chapter 6 Summary, Conclusions, and Recommendations

The objective of this research project was to develop a socketed foundation for high-tension, cable median barrier posts. The new socketed foundation design was to be compatible with all of the existing, FHWA-accepted, high-tension cable systems. Further, the new foundation had to remain undamaged with minimal displacement during vehicle impacts to make removal and reinstallation of damaged systems quick and easy.

Four socketed foundations were developed utilizing reinforced concrete and a cylindrical geometry. Each socketed foundation measured 12 in. (305 mm) in diameter and utilized a ⅜-in. (10-mm) thick steel tube as the socket for the post. However, each design was configured with differing amounts of vertical and transverse steel reinforcement. The embedment depths varied between 24 in. (610 mm) and 60 in. (1,524 mm).

An initial review of the existing, FHWA-accepted, high-tension cable barrier systems identified the S4x7.7 (S102x11.5) as the strongest of the cable barrier posts. Therefore, this post was selected as the critical post for design and testing as it would provide the highest impact loads to the socketed foundation. Additionally, the foundation displacements would be evaluated while installed in a sand pit to simulate a critically weak, or saturated, soil. Finally, an impact height of 11 in. (279 mm) was selected to represent the center of a small car wheel directly impacting the post.

Results from test nos. HTCB-1 and HTCB-2 illustrated that embedment depths of 24 in. (610 mm) and 36 in. (914 mm), respectively, were too shallow as the entire concrete foundation rotated through the soil. These excessive displacements would require a complete removal and reinstallation, thus negating the benefits of using socketed foundations.

Test nos. HTCB-3 and HTCB-4 both resulted in the foundation fracturing apart as a result of the impact loads. The sustained damage was severe and would require a new foundation during system repair, again negating the purpose of socketed foundations. Both of these test assemblies utilized a 60-in. (1,524-mm) embedment depth, which caused the increased forces in the foundations. However, due to the top sections fracturing the foundation deflections could not be determined.

In conclusion, none of the four socketed foundation configurations satisfied the design criterion established to ensure repeated use without repair to the post base itself. Future design work is necessary to increase the strength and durability of the socketed foundation to prevent structural damage. Increases to the strength of the reinforced concrete foundation could be provided by: (1) additional steel reinforcement; (2) increasing the design strength of the concrete; or (3) increasing the diameter of the foundation. These possible solutions should all be taken into account along with a cost analysis to optimize the design. Additionally, further testing is needed to establish the required embedment depth to prevent excessive deflections.

Another possible solution would be to drive a steel section into the ground as the socketed foundation. This approach was discarded early on in this study due to steel costing much more than concrete. However, the required size of the concrete foundation may be larger than previously anticipated and the cost difference between steel and concrete foundations may not be as different as initially suspected. Thus, the total cost of material and installation should be evaluated for both foundation types in future work.

Finally, it may not be feasible to design a single socketed foundation for all high-tension cable barrier systems. As shown in Table 2.1 of Chapter **Error! Reference source not found.**, the posts used in the current high-tension cable barrier systems cover a wide range of steel sections and strengths. As such, designing only for the most critical (strongest) post may result in a completely overdesigned socketed foundation for the remainder of the cable systems. Thus, it may be more reasonable to consider only a specific system and post when designing socketed foundations for cable barriers.

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Appendices

Appendix A. Bogie Test Results

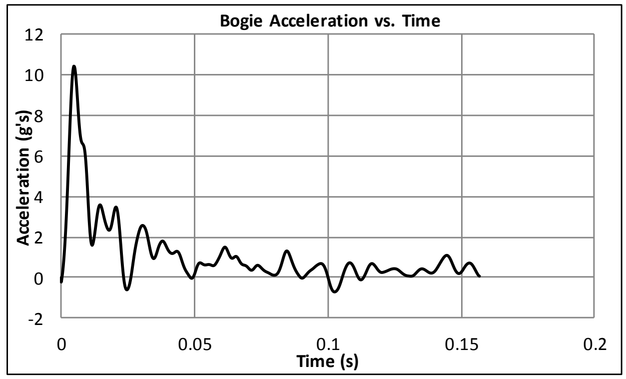
The results of the recorded data from each accelerometer for all four dynamic bogie tests are provided in the summary sheets of this appendix. Summary sheets include acceleration, velocity, and deflection versus time plots as well as force versus deflection and energy versus deflection plots.

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information	HT Cable Post Base Testing	
Test Number:	HTCB-1	
Test Date:	16-Jun-2009	
Failure Type:	foundation rotation through soil	
Post Properties		
Post Type:	S4x7.7 in 12" dia. x 24" deep foundation	
Post Size:	S4x7.7	S100x11.5
Post Length:	47 in.	119.4 cm
Embedment Depth:	24 in.	61 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	AASHTO A-3 Sand	
Moisture Content:	NA	
Compaction Method:	LE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	20.71 mph (30.4 fps)	9.26 m/s
Impact Height:	11 in.	27.9 cm
Bogie Mass:	1803.76 lbs	818.2 kg
Data Acquired		
Acceleration Data:	EDR-3	
Camera Data:	AOS-5 at 100 and 32'-8" inches perp.	

Test Results Summary		
Max. Deflection:	49.3	in.
Peak Force:	18.8	k
Initial Linear Stiffness:	11.1	k/in.
Total Energy:	103.8	k-in.



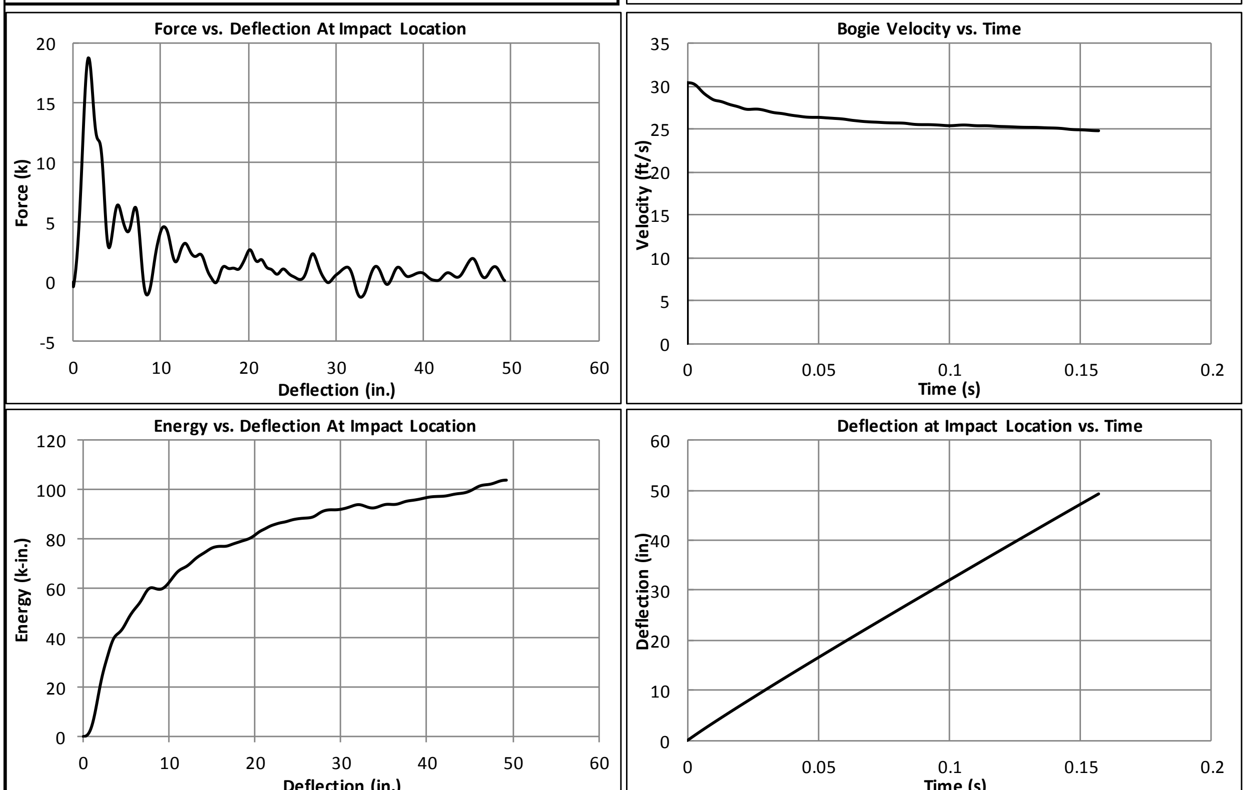


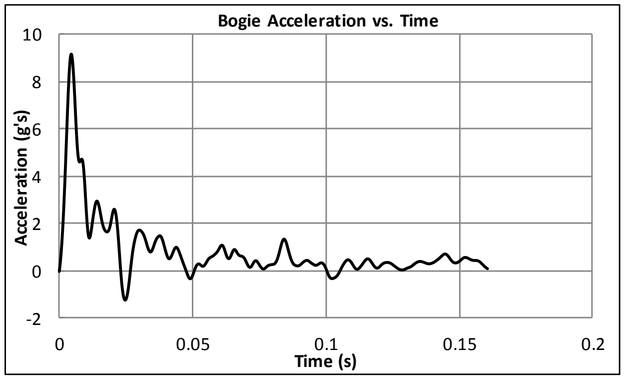
Figure A-1. Results of Test No. HTCB-1 (EDR-3)

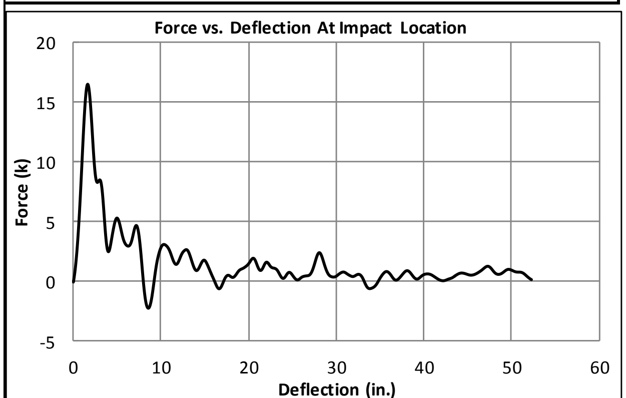
MIDWEST ROADSIDE SAFETY FACILITY

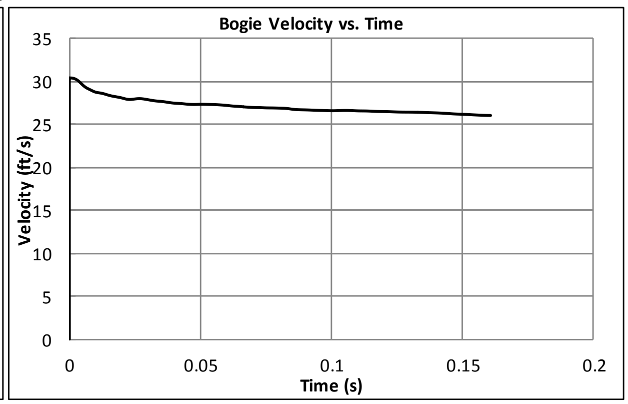
Bogie Test Summary

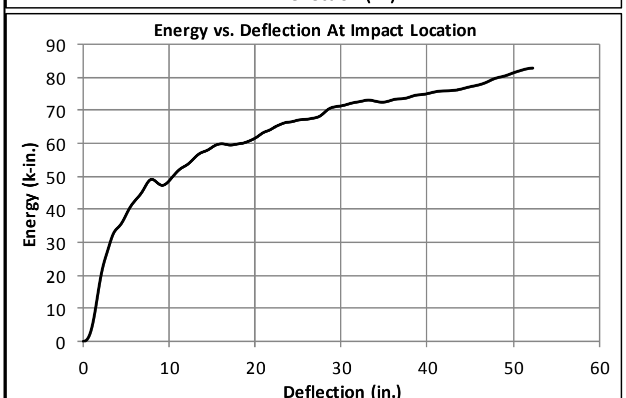
Test Information	HT Cable Post Base Testing	
Test Number:	HTCB-1	
Test Date:	16-Jun-2009	
Failure Type:	foundation rotation through soil	
Post Properties		
Post Type:	S4x7.7 in 12" dia. x 24" deep foundation	
Post Size:	S4x7.7	S100x11.5
Post Length:	47 in.	119.4 cm
Embedment Depth:	24 in.	61 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	AASHTO A-3 Sand	
Moisture Content:	NA	
Compaction Method:	LE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	20.71 mph (30.4 fps)	9.26 m/s
Impact Height:	11 in.	27.9 cm
Bogie Mass:	1803.76 lbs	818.2 kg
Data Acquired		
Acceleration Data:	EDR-4	
Camera Data:	AOS-5 at 100 and 32'-8" inches perp.	

Test Results Summary		
Max. Deflection:	52.3	in.
Peak Force:	16.5	k
Initial Linear Stiffness:	10.1	k/in.
Total Energy:	82.8	k-in.









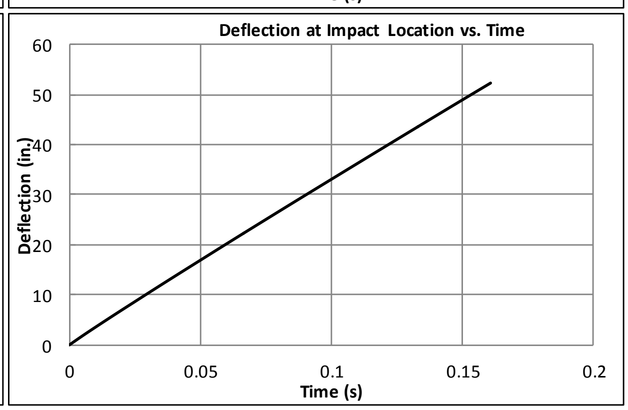


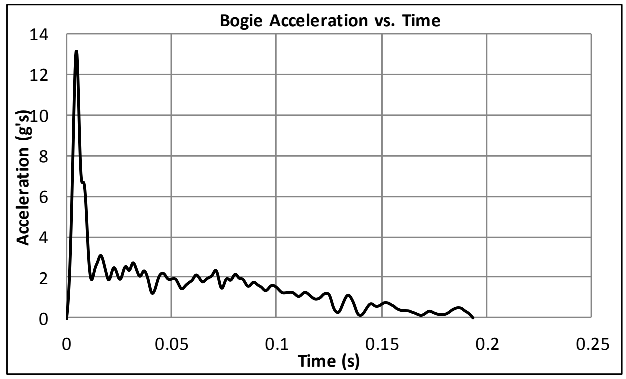
Figure A-2. Results of Test No. HTCB-1 (EDR-4)

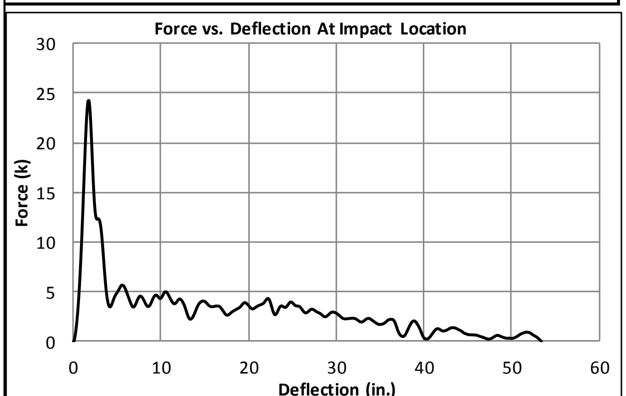
MIDWEST ROADSIDE SAFETY FACILITY

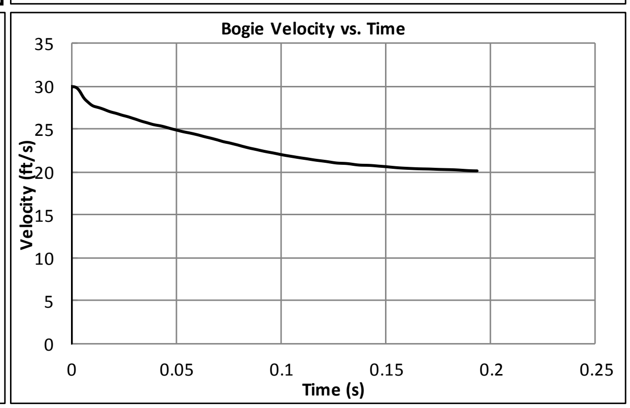
Bogie Test Summary

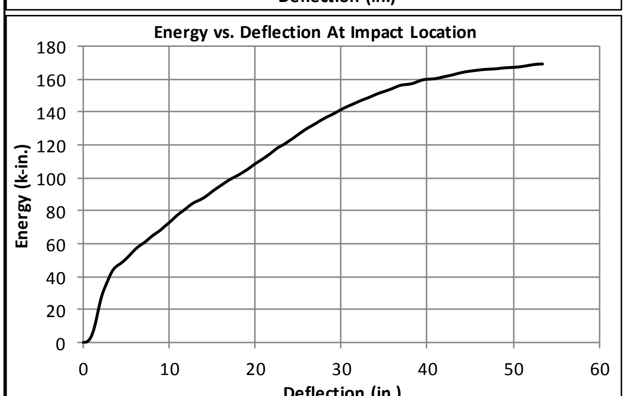
Test Information	HT Cable Post Base Testing	
Test Number:	HTCB-2	
Test Date:	17-Jun-2009	
Failure Type:	foundation rotation through soil	
Post Properties		
Post Type:	S4x7.7 in 12" dia. x 36" deep foundation	
Post Size:	S4x7.7	S100x11.5
Post Length:	47 in.	119.4 cm
Embedment Depth:	36 in.	91.4 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	AASHTO A-3 Sand	
Moisture Content:	4.4%	
Compaction Method:	LE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	20.42 mph (30 fps)	9.13 m/s
Impact Height:	11 in.	27.9 cm
Bogie Mass:	1844.85 lbs	836.8 kg
Data Acquired		
Acceleration Data:	EDR-3	
Camera Data:	AOS-5 w/ S 24-135 lens @100 and 52' perp.	

Test Results Summary		
Max. Deflection:	53.4	in.
Peak Force:	24.2	k
Initial Linear Stiffness:	13.6	k/in.
Total Energy:	169.2	k-in.









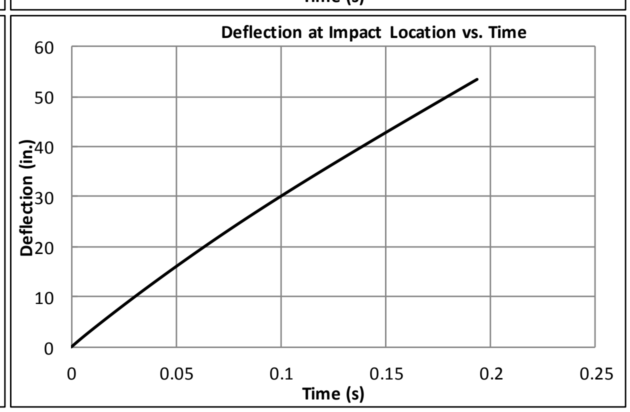


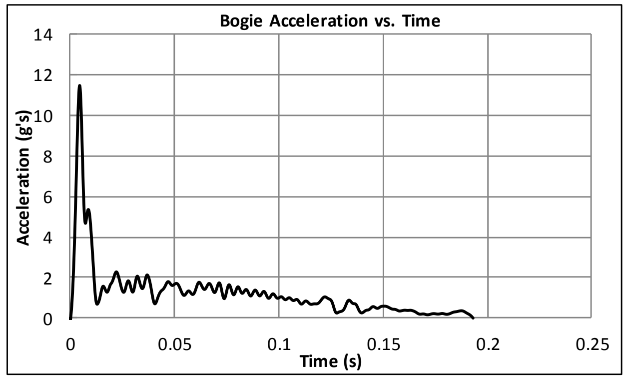
Figure A-3. Results of Test No. HTCB-2 (EDR-3)

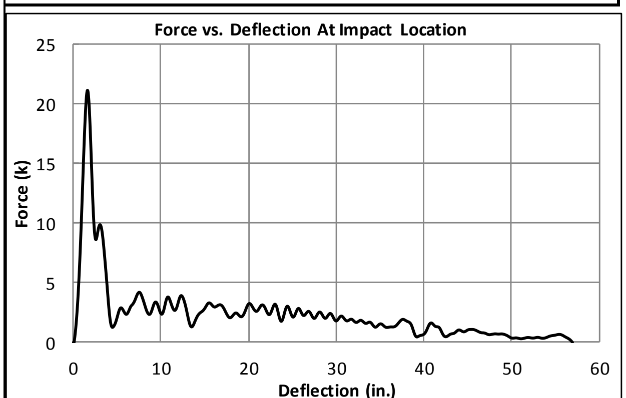
MIDWEST ROADSIDE SAFETY FACILITY

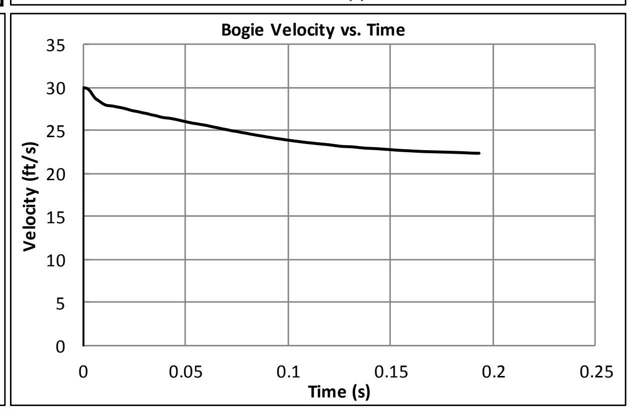
Bogie Test Summary

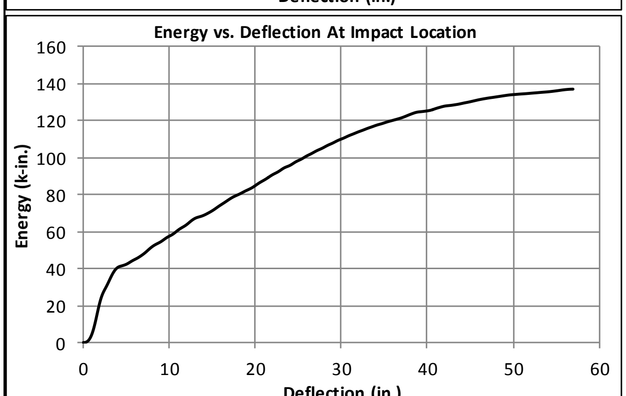
Test Information	HT Cable Post Base Testing	
Test Number:	HTCB-2	
Test Date:	17-Jun-2009	
Failure Type:	foundation rotation through the soil	
Post Properties		
Post Type:	S4x7.7 in 12" dia. x 36" deep foundation	
Post Size:	S4x7.7	S100x11.5
Post Length:	47 in.	119.4 cm
Embedment Depth:	36 in.	91.4 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	AASHTO A-3 Sand	
Moisture Content:	4.4%	
Compaction Method:	LE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	20.42 mph (30 fps)	9.13 m/s
Impact Height:	11 in.	27.9 cm
Bogie Mass:	1844.85 lbs	836.8 kg
Data Acquired		
Acceleration Data:	EDR-4	
Camera Data:	AOS-5 w/ S 24-135 lens @ 100 and 52' perp.	

Test Results Summary		
Max. Deflection:	57.0	in.
Peak Force:	21.1	k
Initial Linear Stiffness:	13.1	k/in.
Total Energy:	136.9	k-in.









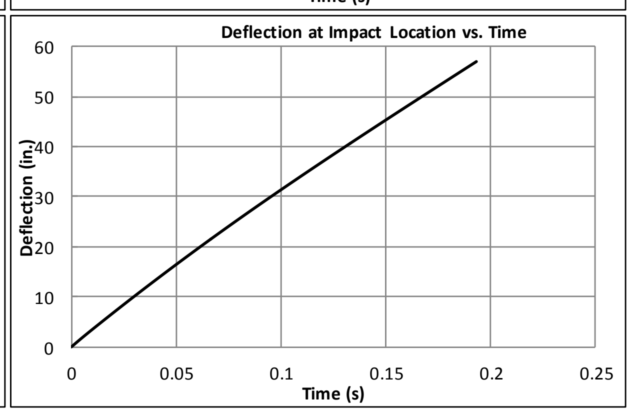


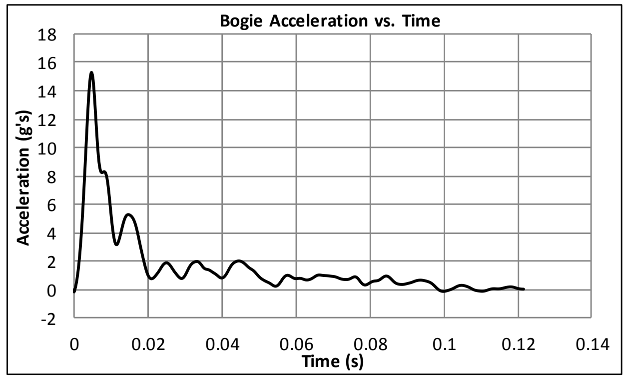
Figure A-4. Results of Test No. HTCB-2 (EDR-4)

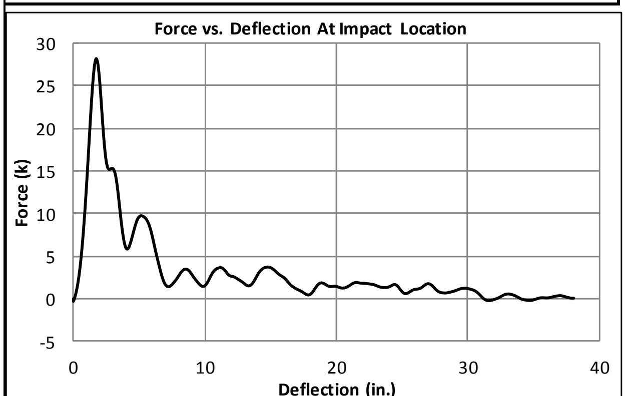
MIDWEST ROADSIDE SAFETY FACILITY

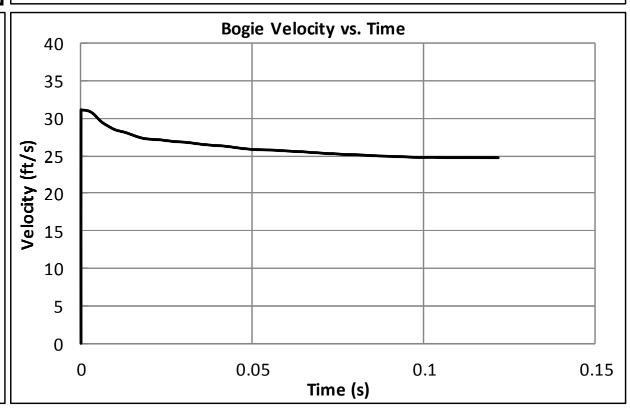
Bogie Test Summary

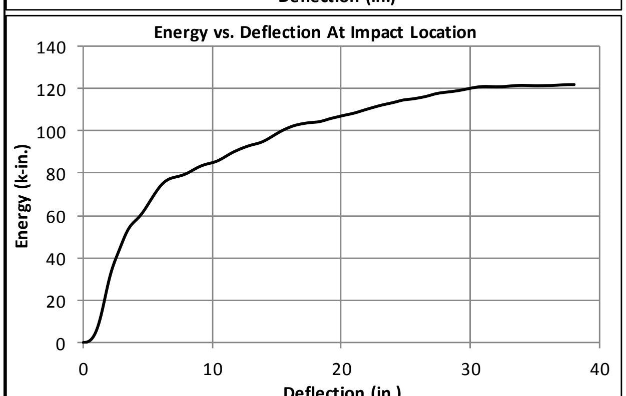
Test Information	HT Cable Post Base Testing	
Test Number:	HTCB-3	
Test Date:	25-Jun-2009	
Failure Type:	Strong axis post and base rotate in soil Fracture of concrete foundation	
Post Properties		
Post Type:	S4x7.7 in 12" dia. x 60" deep foundation	
Post Size:	S4x7.7	S100x11.5
Post Length:	47 in.	119.4 cm
Embedment Depth:	60 in.	152.4 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	AASHTO A-3 Sand	
Moisture Content:	NA	
Compaction Method:	LE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	21.21 mph (31.1 fps)	9.48 m/s
Impact Height:	11 in.	27.9 cm
Bogie Mass:	1843.85 lbs	836.4 kg
Data Acquired		
Acceleration Data:	EDR-3	
Camera Data:	aos 7 w/ sig 50 lens @ 33' perp.	

Test Results Summary		
Max. Deflection:	38.1	in.
Peak Force:	28.2	k
Initial Linear Stiffness:	16.3	k/in.
Total Energy:	121.9	k-in.









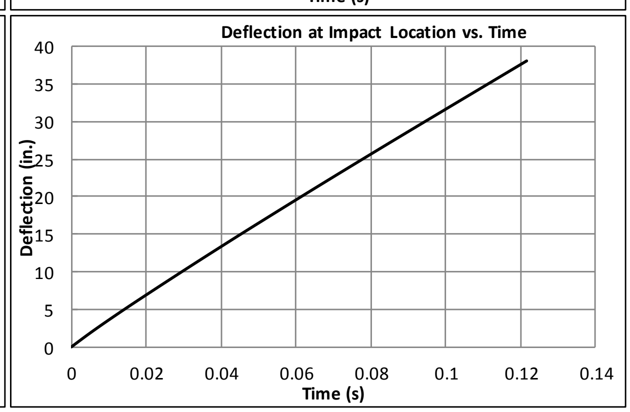


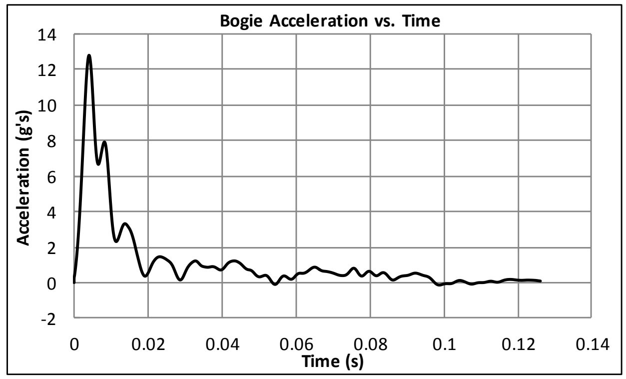
Figure A-5. Results of Test No. HTCB-3 (EDR-3)

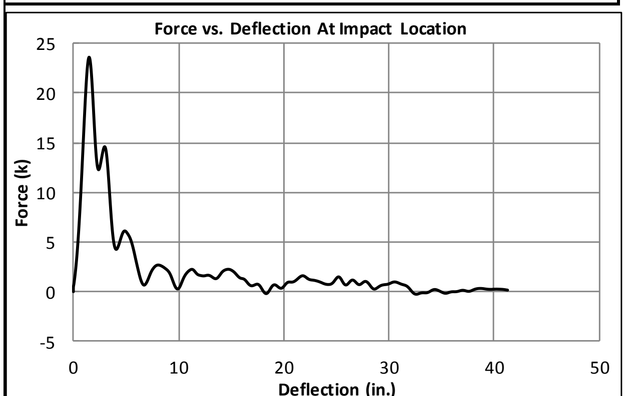
MIDWEST ROADSIDE SAFETY FACILITY

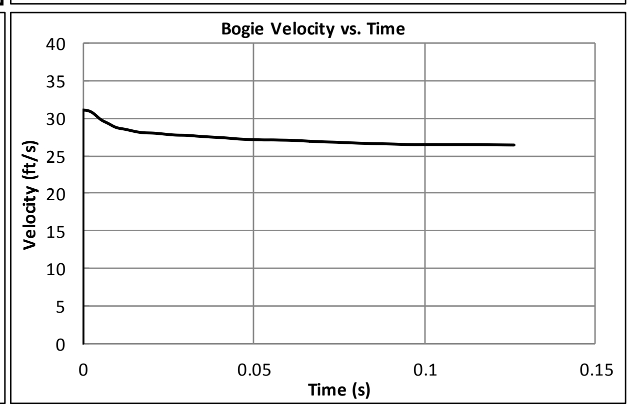
Bogie Test Summary

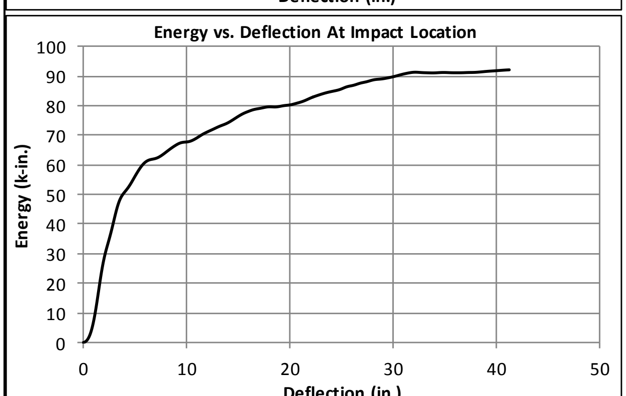
Test Information	HT Cable Post Base Testing	
Test Number:	HTCB-3	
Test Date:	25-Jun-2009	
Failure Type:	Strong axis post and base rotate in soil	
	Fracture of concrete foundation	
Post Properties		
Post Type:	S4x7.7 in 12" dia. x 60" deep foundation	
Post Size:	S4x7.7	S100x11.5
Post Length:	47 in.	119.4 cm
Embedment Depth:	60 in.	152.4 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	AASHTO A-3 Sand	
Moisture Content:	NA	
Compaction Method:	LE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	21.21 mph (31.1 fps)	9.48 m/s
Impact Height:	11 in.	27.9 cm
Bogie Mass:	1843.85 lbs	836.4 kg
Data Acquired		
Acceleration Data:	EDR-4	
Camera Data:	aos 7 w/ sig 50 lens @ 33' perp.	

Test Results Summary		
Max. Deflection:	41.3	in.
Peak Force:	23.6	k
Initial Linear Stiffness:	15.9	k/in.
Total Energy:	92.1	k-in.









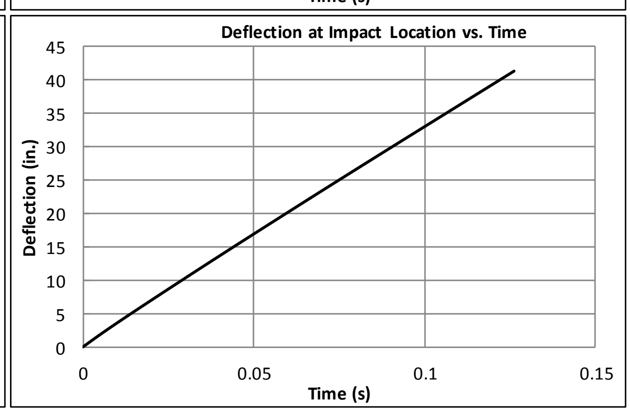


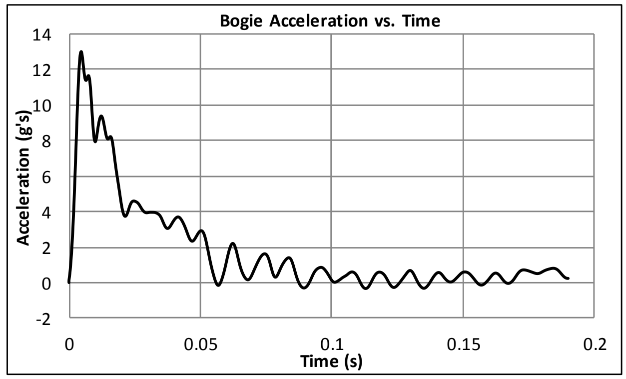
Figure A-6. Results of Test No. HTCB-3 (EDR-4)

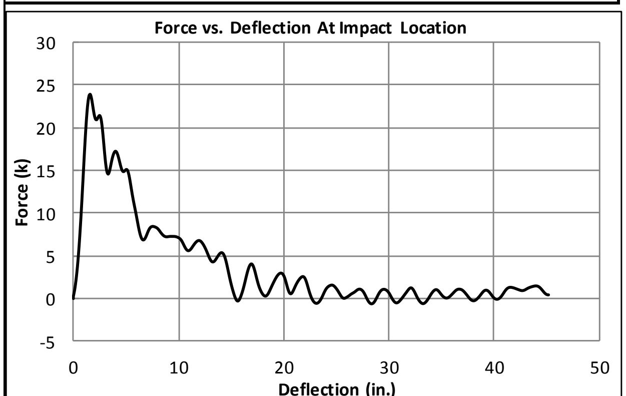
MIDWEST ROADSIDE SAFETY FACILITY

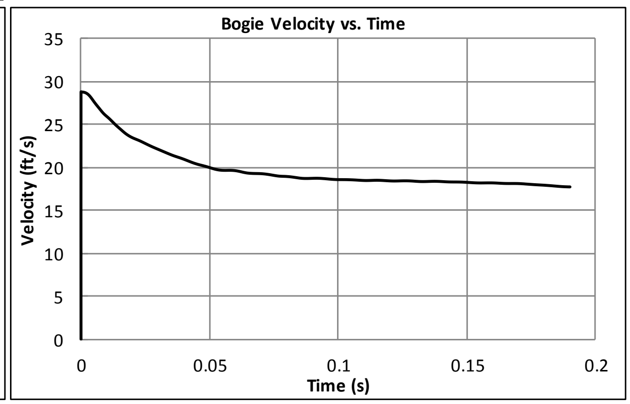
Bogie Test Summary

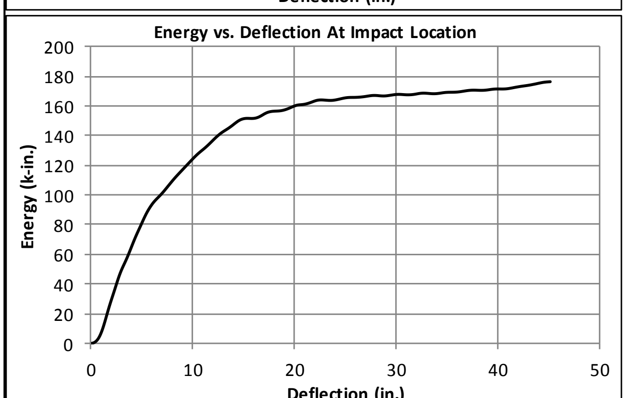
Test Information	HT Cable Post Base Testing	
Test Number:	HTCB-4	
Test Date:	23-Sep-2009	
Failure Type:	Fracture of Concrete Foundation	
Post Properties		
Post Type:	S4x7.7 in 12" dia. x 60" deep foundation	
Post Size:	S4x7.7	S100x11.5
Post Length:	49 in.	124.5 cm
Embedment Depth:	60 in.	152.4 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	AASHTO A-3 Sand	
Moisture Content:	NA	
Compaction Method:	Large Flat Hand Tamp	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	19.62 mph (28.8 fps)	8.77 m/s
Impact Height:	11 in.	27.9 cm
Bogie Mass:	1839.3 lbs	834.3 kg
Data Acquired		
Acceleration Data:	EDR-3	
Camera Data:	AOS-6 @ 41 ft perpendicular	

Test Results Summary		
Max. Deflection:	45.2	in.
Peak Force:	23.9	k
Initial Linear Stiffness:	14.9	k/in.
Total Energy:	176.2	k-in.









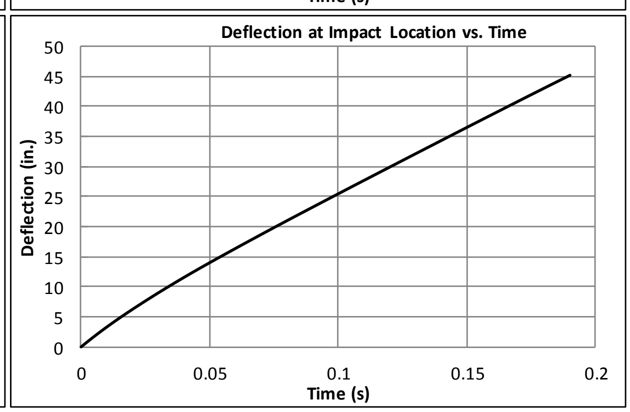


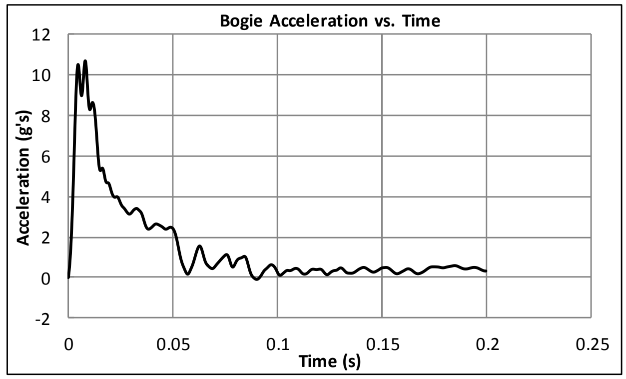
Figure A-7. Results of Test No. HTCB-4 (EDR-3)

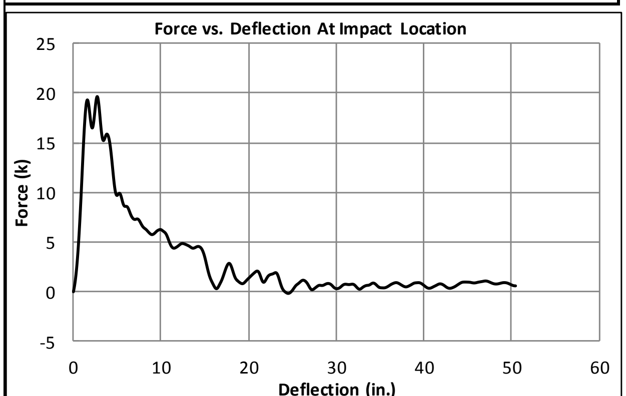
MIDWEST ROADSIDE SAFETY FACILITY

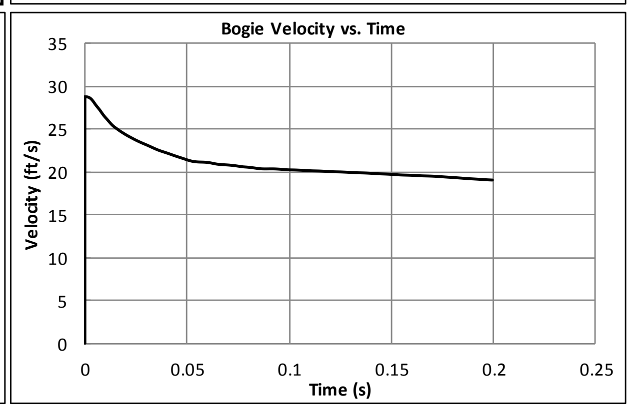
Bogie Test Summary

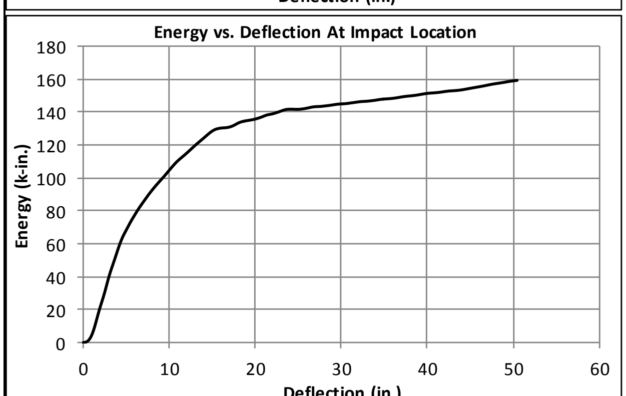
Test Information	HT Cable Post Base Testing	
Test Number:	HTCB-4	
Test Date:	23-Sep-2009	
Failure Type:	Fracture of Concrete Foundation	
Post Properties		
Post Type:	S4x7.7 in 12" dia. x 60" deep foundation	
Post Size:	S4x7.7	S100x11.5
Post Length:	49 in.	124.5 cm
Embedment Depth:	60 in.	152.4 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	AASHTO A-3 Sand	
Moisture Content:	NA	
Compaction Method:	Large Flat Hand Tamp	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	19.62 mph (28.8 fps)	8.77 m/s
Impact Height:	11 in.	27.9 cm
Bogie Mass:	1839.3 lbs	834.3 kg
Data Acquired		
Acceleration Data:	EDR-4	
Camera Data:	AOS-6 @ 41 ft perpendicular	

Test Results Summary		
Max. Deflection:	50.5	in.
Peak Force:	19.6	k
Initial Linear Stiffness:	7.2	k/in.
Total Energy:	159.3	k-in.









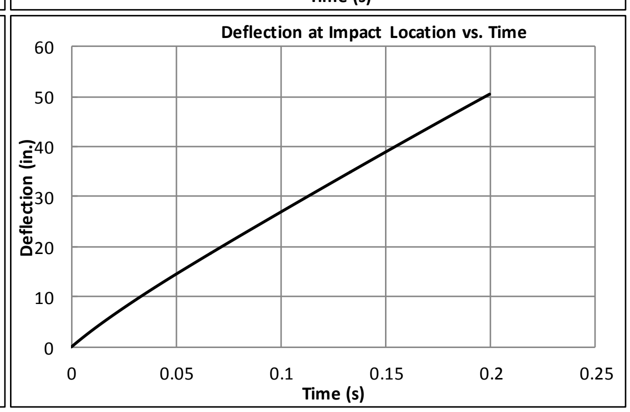


Figure A-8. Results of Test No. HTCB-4 (EDR-4)

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