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DYNAMIC IMPACT TESTING OF S76X8.5 (S3X5.7) STEEL POSTS FOR USE IN CABLE GUARDRAIL SYSTEMS

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16. Abstract (Limit: 200 words)

Dynamic impact testing of S76x8.5 (S3x5.7) steel posts at various embedment depths has been detailed, and the results presented. A total of 10 bogie tests were performed, with post lengths varying from 1,778 mm (5 ft-10 in.) through 2,286 mm (7 ft-6 in.). For each bogie test, raw acceleration data, obtained from the accelerometers, was filtered and used to create force-displacement and energy-displacement plots. From the energy-displacement graphs, the average post-soil forces were calculated for a 1,016-mm (40-in.) displacement at the center cable height. Post-soil forces were then compared to the post capacity of the standard 1,778-mm (70-in.) long cable post with an attached soil plate, and the post-energy relationships analyzed to determine if a suitable length of S76x8.5 (S3x5.7) steel post could replace the more costly standard cable post with attached soil plate. From these comparisons, it was determined that the 1,981-mm (78-in.) long post with 1,067 mm (42 in.) embedment depth had comparable performance to the standard cable post. Therefore, and in order to verify, it was recommended that the S76x8.5 (S3x5.7) cable post with a total length of 1,981 mm (78 in.) be crash tested in a cable barrier system.

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1 INTRODUCTION

1.1 Background

Often hazards located near the travelway, including rigid hazards or slopes, are shielded by guardrail installations. The purpose of the guardrail is to delineate the hazard, capture errant vehicles, and prevent catastrophic collision with fixed objects or vehicle rollovers. Very often, standard W-beam guardrail or the more recent MGS guardrail system is used to shield these hazards. On low-volume roadways, or near locations which allow for large dynamic deflections, cable guardrail has been installed. Cable barriers provide a low initial cost, low-maintenance alternative to standard W-beam guardrail. Cost-effectiveness studies have demonstrated the attractiveness of cable guardrail over standard W-beam in several applications (1). Additionally, in locations where long sections of guardrail are required, including highways with moderately narrow medians, cable barrier installations have been installed with lengths of up to 3,048 m (10,000 ft).

The low initial cost of cable guardrail is due to the post and cable configuration. Standard cable guardrail systems require 1,778-mm (5-ft 10-in.) long S76x8.5 (S3x5.7) section posts with an attached soil plate, often with wide post spacing. These posts have been used in many guardrail testing applications (2), and recent developments in cable end terminal hardware have been tested to the performance recommendations provided in the National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (3, 4).

1.2 Objective

The objective of the research project was to determine the dynamic properties of the post-soil interaction of the S76x8.5 (S3x5.7) steel posts at various embedment depths under impact loading conditions. The results of this research were used for (1) determining the post-soil behavior for steel posts used in cable median barrier systems; (2) determining alternative post options that provide comparable impact behavior to that observed for standard cable median posts; and (3) investigating the strength and energy dissipation capabilities of S76x8.5 (S3x5.7) posts embedded in compacted soil.

2 PHYSICAL TESTING

2.1 Purpose

Physical testing of components is an important aspect of any design process. The researcher is able to gain practical insight and experience for both component and system behavior using this method. Since physical testing is an accurate representation of the design's behavior and if completed properly, the researcher can gain a better understanding of the design and design limits.

2.2 Test Facility

Physical testing of S76x8.5 (S3x5.7) steel cable guardrail posts were performed at the Midwest Roadside Safety Facility's (MwRSF's) outdoor testing facility located at the Lincoln airpark, on the northwest side of the Lincoln Municipal Airport. The test site provided excellent equipment and an advantageous atmosphere to perform physical tests.

2.3 Scope

The research objective was achieved by performing bogie crash tests on the steel posts under various embedment depths with known soil conditions. The target impact conditions for all of the crash tests were a speed of 20.9 km/h (13.0 mph) and an angle of 0.0 degrees relative to the strong axis, creating a classical "head-on" or full-frontal impact. The posts were impacted 683 mm (26.875 in.) above the ground line perpendicular to the post's front face. The test matrix is shown in Table 1.

A total of 10 tests were conducted. The test pit for test nos. CMPB-16 through CMPB-25 was located at the end of a guidance track used to guide the bogie towards impact. The post lengths varied from 1,778 mm (70 in.) to 2,286 mm (90 in.), and the embedment depth varied from 914 mm (36 in.) to 1,372 mm (54 in.).

Table 1. Test Matrix

Test	Embedment Depth		Post Length		Impact Speed		Bending Axis	Soil Plate Utilized?
	mm	in.	mm	in.	kph	mph		
CMPB-18	914	36.5	1778	70	20.7	13.7	Strong Axis	Yes
CMPB-19	914	36.5	1778	70	21.5	12.8	Strong Axis	Yes
CMPB-16	927	36	1829	72	22.1	12.9	Strong Axis	No
CMPB-17	927	36	1829	72	20.6	13.3	Strong Axis	No
CMPB-20	1067	42	1981	78	22.4	13.9	Strong Axis	No
CMPB-21	1067	42	1981	78	21.7	13.5	Strong Axis	No
CMPB-22	1219	48	2134	84	23.0	14.3	Strong Axis	No
CMPB-23	1219	48	2134	84	21.5	13.4	Strong Axis	No
CMPB-24	1372	54	2286	90	20.0	12.4	Strong Axis	No
CMPB-25	1372	54	2286	90	22.4	13.9	Strong Axis	No

3 SYSTEM DETAILS

3.1 Steel Post

The posts tested in this study were S76x8.5 (S3x5.7) beams manufactured using ASTM A36 steel with a cross section in accordance to the A6M standards. The posts consisted of three major components: a rear or compression flange, a front or tensile flange, and a web which connects the two flanges and reacts like a force transmitter. The flanges are called either tensile or compressive based upon the type of loading each flange undergoes during impact. The thickness of the webbing was 4 mm (0.17 in.), while the flanges were sloped at 9.5 degrees, with a nominal average flange width of 59 mm (2.33 in.). The post length varied from 1,778 mm (5 ft-10 in.) to 2,286 mm (7 ft-6 in.). The cross section of an S76x8.5 (S3x5.7) steel post is shown in Figure 1. Various material properties for the post are shown in Table 2.

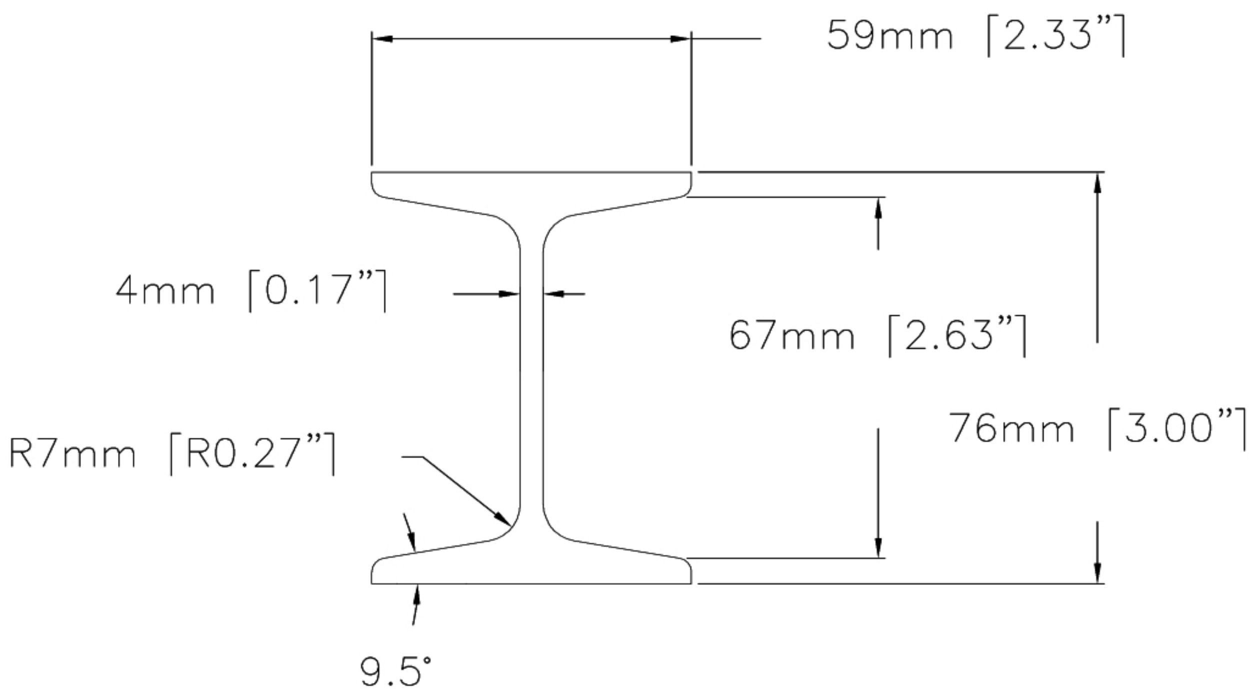


Figure 1. S76x8.5 (S3x5.7) Cross Sectional Dimensions

Table 2. Material Properties of S76x8.5 (S3x5.7) Post

ASTM Designation	Area, A mm^2 ($in.^2$)	Flange Width, b_f mm (in.)	Moment of Inertia, I_x mm^4 ($in.^4$)	Section Modulus, S_x mm^3 ($in.^3$)	Plastic Section Modulus, Z_x mm^3 ($in.^3$)
S76x8.5 (S3x5.7)	1077 (1.67)	59.2 (2.33)	$1.05x10^6$ (2.52)	$2.75x10^4$ (1.68)	$3.20x10^4$ (1.98)

3.2 Soil or Bearing Plate

Steel bearing plates, commonly referred to as soil plates, are welded to standard steel cable posts that are used in both roadside and median cable barrier systems. For a standard cable post using the S76x8.5 (S3x5.7) cross section, a 203-mm (8-in.) wide x 610-mm (24-in.) long x 6-mm (0.25-in.) thick steel plate is rigidly attached to the post, as shown in Figure 2. For this study, post embedment depths were increased from the baseline length to determine the length for which soil plates were no longer required using S76x8.5 (S3x5.7) steel posts. Four additional post lengths and embedment depths were selected for the bogie testing program, as shown in Figure 3.

3.3 Soil Material

The posts were embedded in a coarse aggregate material consisting of gravel and crushed limestone. The soil conformed to the American Association of State Highway Transportation Officials (AASHTO) standard specifications for “Materials for Aggregate and Soil Aggregate Sub-base, Base, and Surface Courses,” designation M 147-55 (1990), grading B. The moisture content was not recorded for any of the steel cable post tests.

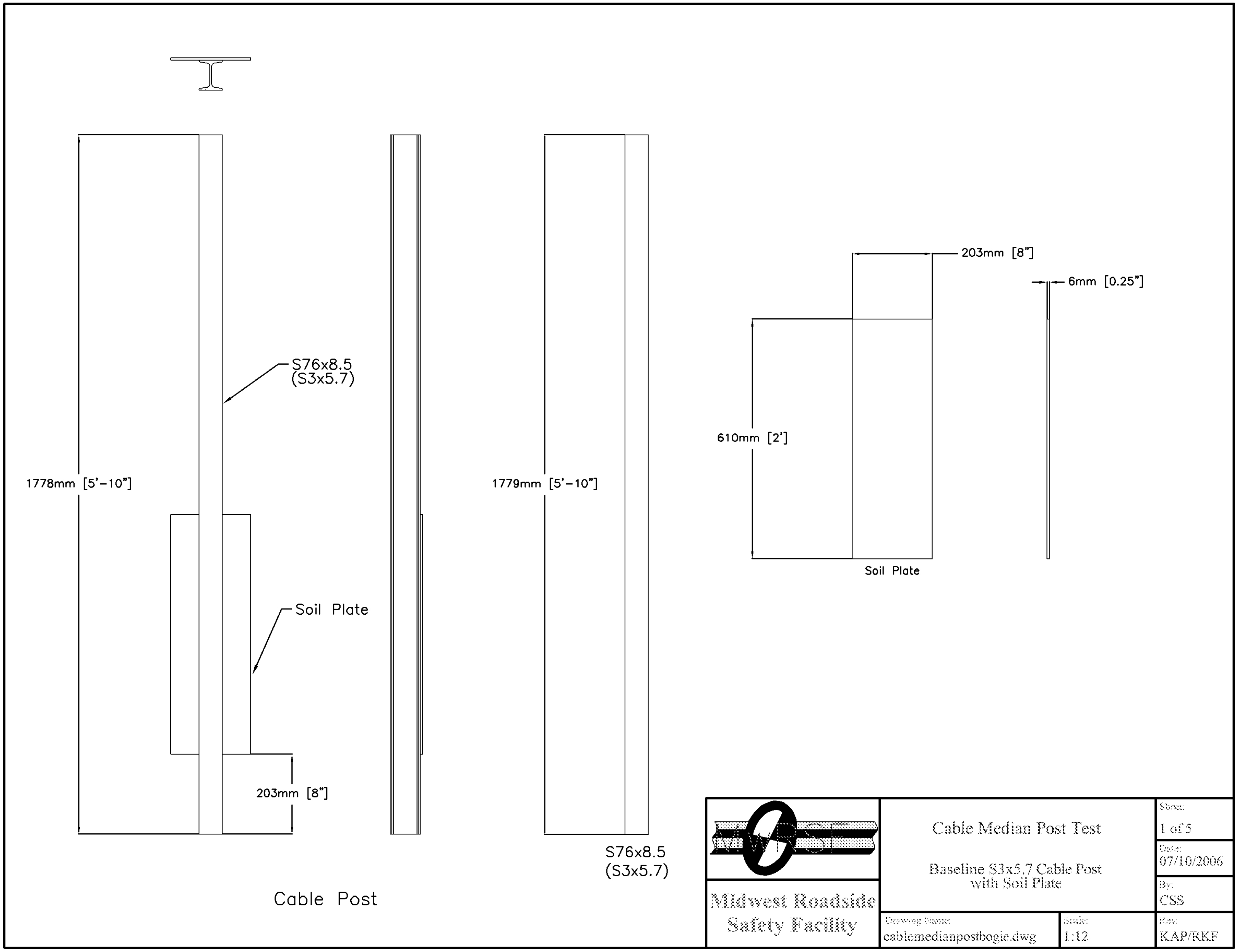


Figure 2. Cable Median Post and Soil Plate, Test Nos. CMPB-18 and CMPB-19

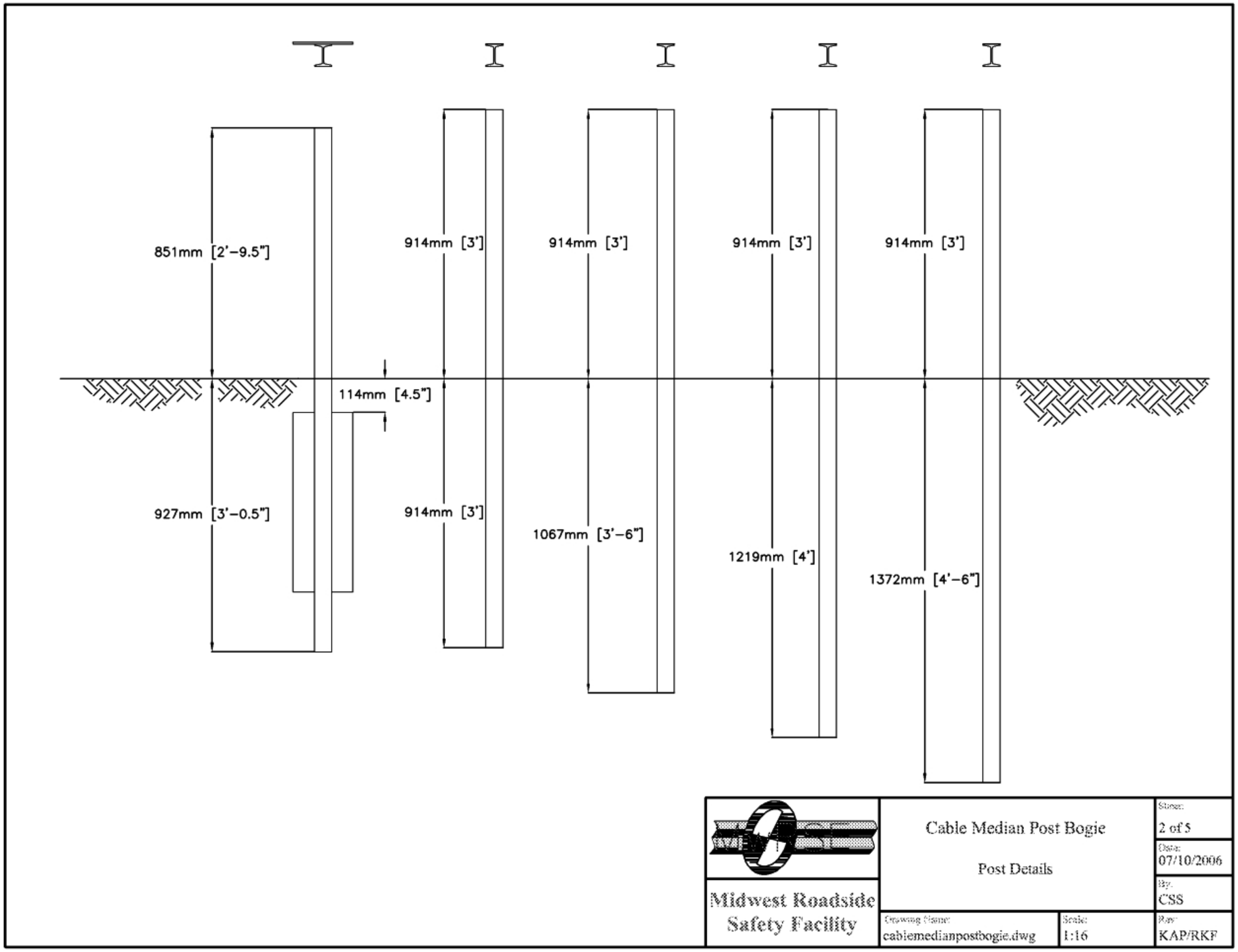


Figure 3. Post Embedment Depth Details

4 TEST PARAMETERS

4.1 Bogie Tow and Guidance System

A reverse cable tow system was used to propel the bogie. The test vehicle was released from the tow cable before impact with the steel posts. A digital speedometer was located on the tow vehicle to increase the accuracy of the bogie's impact speed.

The surrogate vehicle was guided into the steel posts through the use of a steel pipe guide track. The bogie was equipped with two pairs of guide bearings, one pair in the front and one set at the back, to redirect it along the guidance track. The steel pipe used in the guidance system was nominally 76 mm (3 in.) in diameter and 6.4 mm (0.25 in.) thick. When the bogie reached the end of the guide track, the bogie was released from the guidance system to become free-wheeling at impact.

4.2 Bogie Vehicle

A rigid-frame bogie, weighing 726 kg (1,600 lbs), was used to impact the posts. The bogie head was constructed out of 203-mm (8-in.) diameter by 12.5-mm (0.5-in.) thick standard steel pipe with 19-mm (0.75-in.) neoprene belting wrapped around the pipe to prevent local damage to the post from the impact. The rigid impact head, used for numerous bogie testing programs, was bolted to the front of the bogie in six locations. However, slight modifications to the mounting plates were deemed necessary since the load height for the S76x8.5 (S3x5.7) steel I-beam posts was increased from a previous testing height of 632 mm (24.875 in.) to 683 mm (26.875 in.). The mounting plates for the bogie vehicle consisted of two 308-mm (12.125-in.) tall x 286-mm (11.5-in.) wide x 13-mm (0.5-in.) thick steel plates. Three 44-mm (1.75-in.) slots and two 44-mm (1.75-in.) slots were cut on the outward-facing side of the plate and on the side of the plate closer to the centerline of the bogie vehicle, respectively. Three additional 20 mm (0.75 in.)

holes were drilled in the plate and located 64 mm (2.5 in.) below the center of the cut slots in each plate. A schematic of the modified bogie impact head used for test nos. CMPB-16 through CMPB-25 is shown in Figure 4.

4.3 Data Acquisition Systems

4.3.1 Accelerometers

One triaxial piezoresistive accelerometer system with a range of ± 200 G's was used to measure the acceleration in the longitudinal direction at a sample rate of 3200 Hz. The environmental shock and vibration sensor/recorder system, Model EDR-3M6, was developed by Instrumented Sensor Technology (IST) of Okemos, Michigan and includes three differential channels as well as three single-ended channels. The EDR-3 was configured with 256 Kb of RAM memory and a 1,120 Hz lowpass filter. Computer software, "DynaMax 1 (DM-1)" and "DADiSP," was used to analyze and plot the accelerometer data.

4.3.2 High-Speed Photography

For test nos. CMPB-16 through CMPB-25, one high-speed AOS VITcam digital video camera and one JVC MiniDV digital video camera were used. These cameras were placed perpendicular to the location of impact.

The AOS VITcam videos were analyzed using Image Express MotionPlus and Redlake Motion Scope softwares. It should be noted that no high-speed photographic data was captured from test CMPB-25 because of technical difficulties.

4.3.3 Pressure Tape Switches

For all of the bogie tests, three pressure-activated tape switches, spaced at 1-m (3.28-ft) intervals, were used to determine the speed of the vehicle before impact. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the left-front

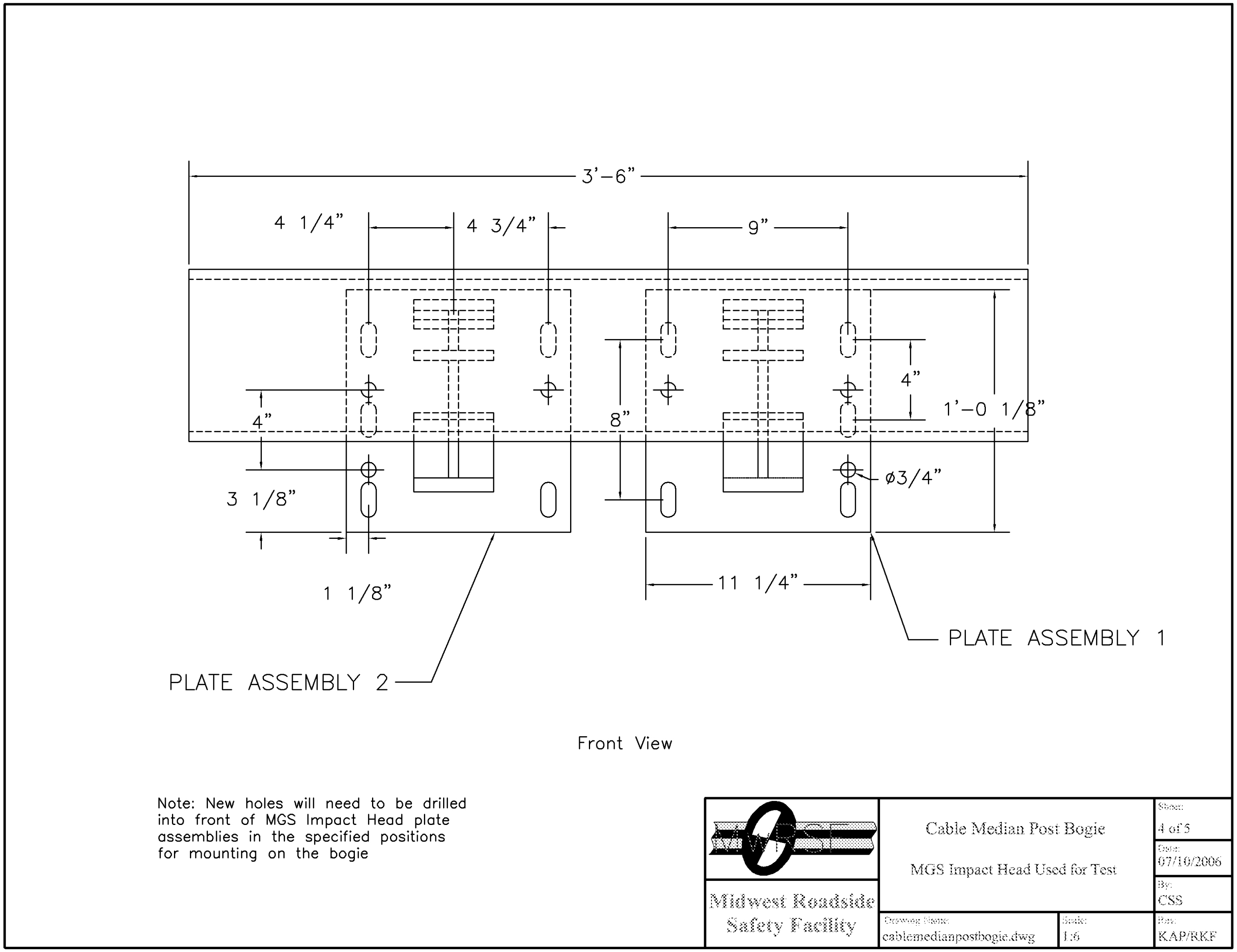


Figure 4. Modified Impact Head Used for Bogie Testing

tire of the test vehicle passed over it. The test vehicle speed was then determined from the electronic timing mark data recorded using Test Point software. Strobe lights and high-speed film analysis are used only as a backup in the event that vehicle speed cannot be determined from the electronic data.

4.4 Methodology of Testing

A total of 10 tests impacted the posts' front flanges with the centerline of the bogie test vehicle aligned with the centerline of the post. The tests were configured with posts buried in a testing pit and the embedment depths varying from 964 mm (36 in.) to 1,372 mm (54 in.). The test parameters are shown in Figure 5.

For the tests, holes measuring 610 mm (24 in.) in diameter and deep enough to accommodate the embedment depth were augered in the test area. These holes were then filled with soil meeting AASHTO standard specification for "Materials and Aggregates and Soil Aggregates Sub-base, Base and Surface Courses", designation M147-65 (1990), grading B and compacted in accordance with AASHTO guide specifications for highway construction, section 304.05 and 304.07.

The test setup used to conduct the post tests is also shown in Figure 5. A schematic of the bogie with the modified impact head along the guidance system is shown in Figure 6.

4.5 End of Test Determination

When the bogie overrode a post, test data could not be analyzed over the period of time equal to the time that the bogie was in contact with the post. This difficulty arose due to the fact that a significant amount of the force applied to the bogie and the post was in the vertical direction as the post rotated in the soil. When the bogie head initially impacted the post, the force exerted by the bogie was directed perpendicular to the face of the post, but as the bogie

Post Type	Post Length (in)	Post Weight (lbs)	Soil Plate Weight (lbs)	Embedment Depth (in)	Test Quantity	Load Direction	Load Height (in)	Bogie No.	Bogie Weight	Bogie Speed (mph)
S3x5.7 with Soil Plate (baseline)	70	33.3	13.6	36.5	2	Strong Axis Bending	27.0	3	1600	13
S3x5.7	72	34.2	N/A	36.0	2	Strong Axis Bending	27.0	3	1600	13
S3x5.7	78	37.1	N/A	42.0	2	Strong Axis Bending	27.0	3	1600	13
S3x5.7	84	39.9	N/A	48.0	2	Strong Axis Bending	27.0	3	1600	13
S3x5.7	90	42.8	N/A	54.0	2	Strong Axis Bending	27.0	3	1600	13

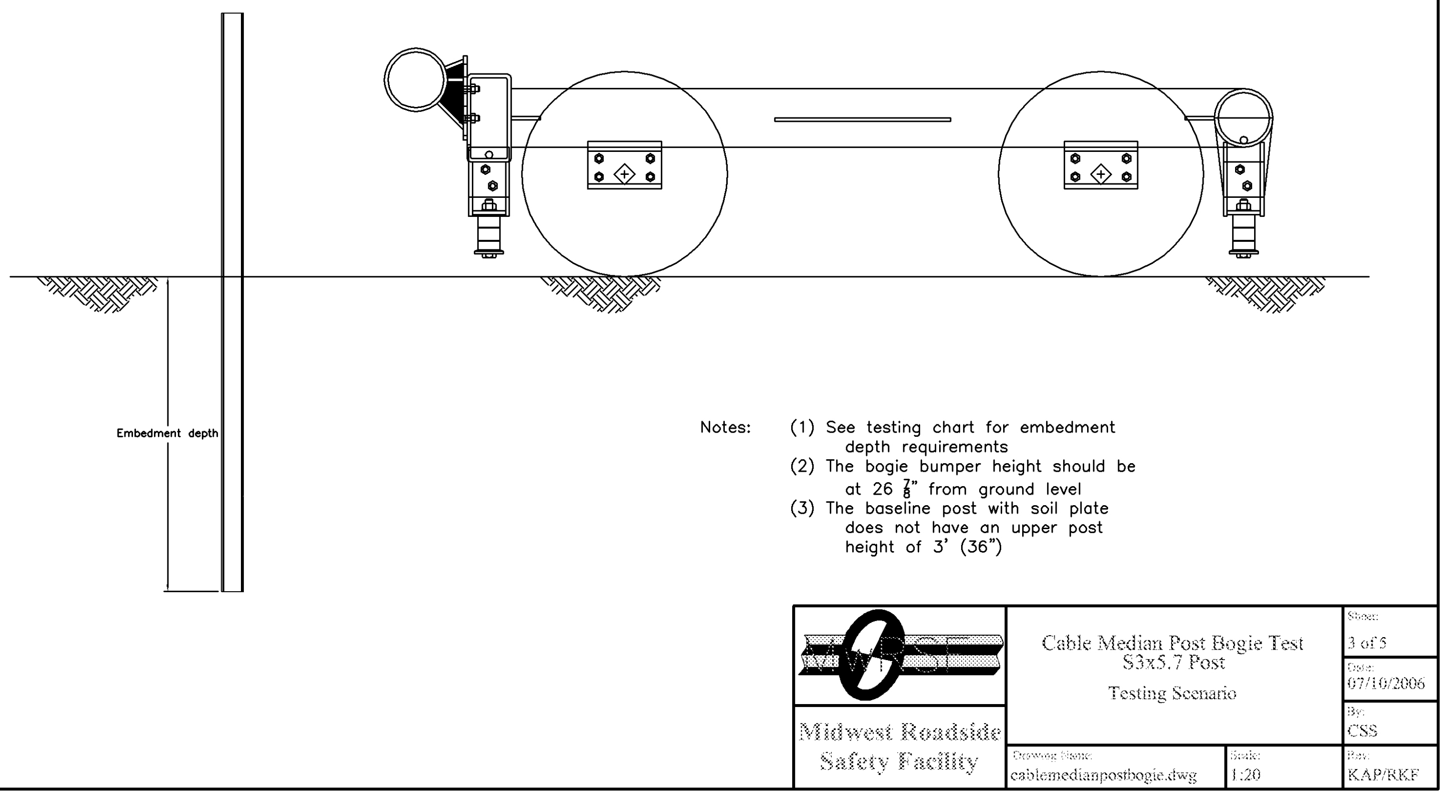


Figure 5. Impact Location

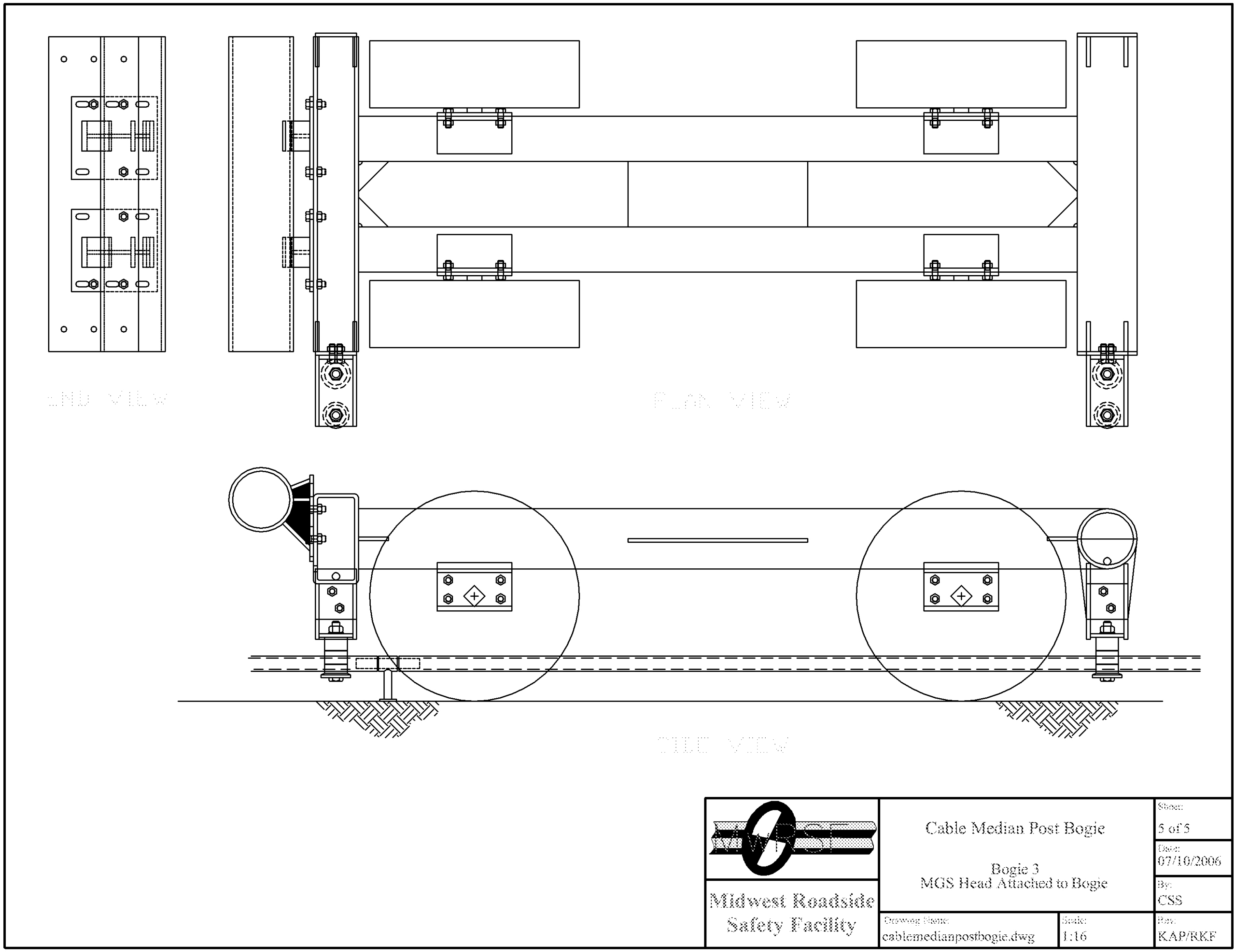


Figure 6. Bogie with Modified Impact Head

progressed forward, the post rotated and allowed the impact head to slide upwards. Thus, by comparing the bogie accelerations with the high-speed digital video, the end of the test was determined as when the bogie tires initially lost contact with the ground. The results of this analysis were then used to determine a standardized post deflection at which further analysis of the post force-deflection and energy-deflection characteristics were no longer valid. This post rotation is shown schematically in Figure 7.

In addition to the variation due to the changing angle of the force direction, the neoprene on the bogie head, which was used to minimize the local stress concentration at the point of impact, increased the frictional forces acting on the surface of the post. Since the accelerometer was used to represent contact forces at the face of the post and not the forces acting at the center of gravity, which are actually observed, additional error was introduced into the data. Consequently, only the initial portion of the accelerometer trace was used in the post analysis.

4.6 Data Processing

Initially, the electronic accelerometer was filtered using the SAE Class 60 Butterworth filter conforming to the SAE J211/1 specifications. The pertinent acceleration signal was extracted from the bulk of the data signal. 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. The calculated velocity trace was then integrated to find the bogie's displacement, which is also the post displacement. Combining the previous results, a force-deflection curve was plotted for each test. Finally, integration of the force-deflection curve provided the energy-displacement curve for each test.

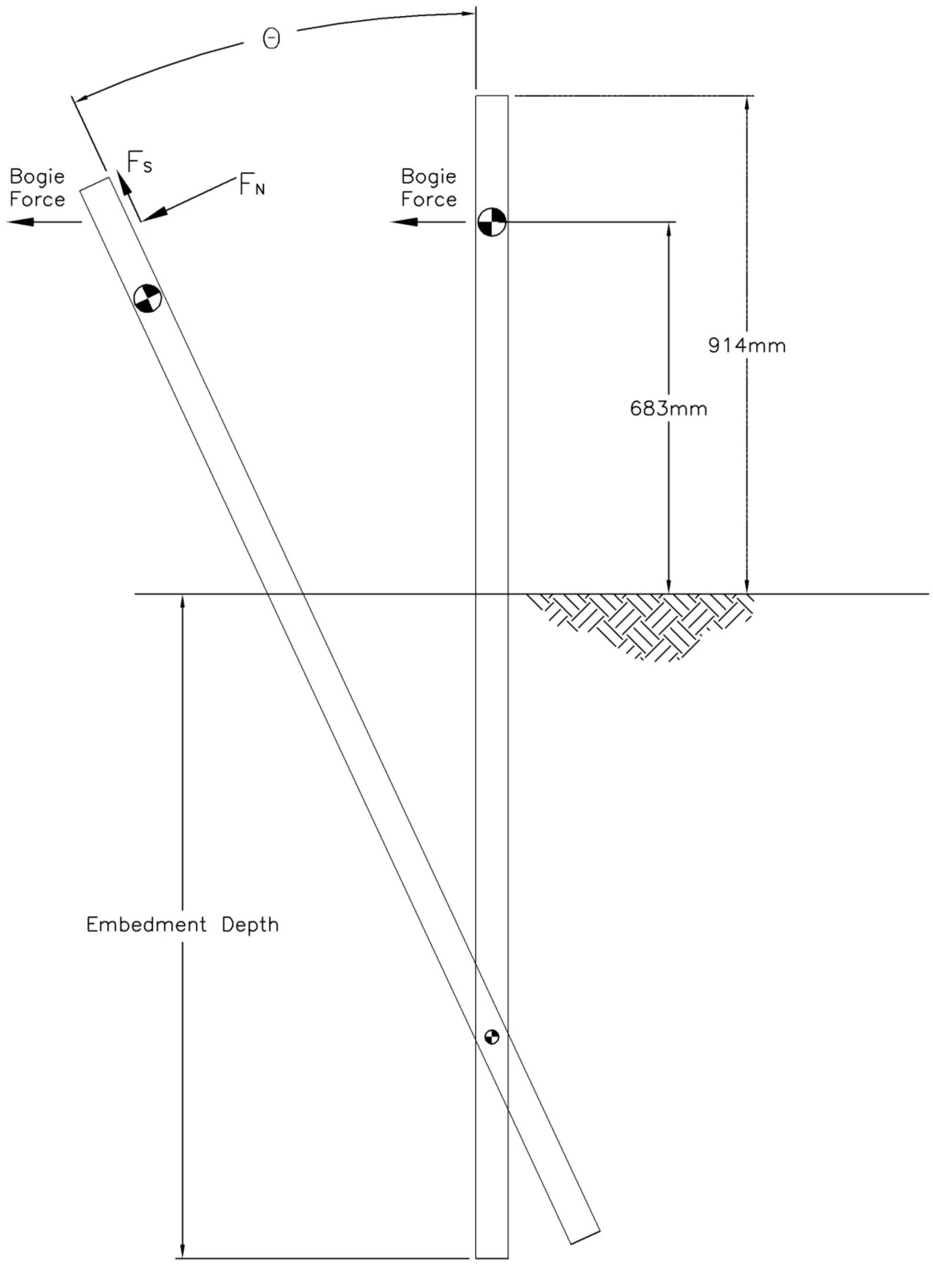


Figure 7. Post Rotation and Force Diagram

5 TEST RESULTS AND DISCUSSION

5.1 Bogie Testing Results

Accelerometer data was processed for each bogie test in order to obtain acceleration, velocity, and displacement curves, as well as force-displacement curves. The data obtained from post-soil interaction was tabulated, and the results were plotted. The bogie test results for the tests with equivalent embedment depths were combined in the subsequent sections.

5.1.1 Test Nos. CMPB-18 and CMPB-19 (Standard Post with Soil Plate)

Two bogie tests were performed on 1,778-mm (5-ft 10-in.) long posts with 610-mm (24-in.) long x 230-mm (8-in.) wide x 6.4-mm (0.25-in.) thick soil plates at an embedment depth of 927 mm (36.5 in.). The test summaries for both tests are given in Tables 3a and 3b. Force-displacement and energy-displacement curves are shown in Figure 8. The sequential photographs at regular time intervals are shown in Figure 9, and photographs of the posts following the tests are shown in Figures 10 and 11. The available photographs of the bogie test and the high-speed video analysis revealed that soil failure was the primary mode of failure in both tests. The posts rotated in the soil for the entire test period, but definite post yielding with visible twisting and buckling of the web around the ground line occurred in test no. CMPB-19. The force displacement curves indicate that an inertial spike, closely documented in many bogie post tests as documented by Hascall, et al. (5), was not present for this testing series. After an initial period of rapidly increasing resisting force, in each test, the bogie underwent a fairly uniform resistive force. The total energy dissipated in test no. CMPB-18 was approximately 18 percent higher than in test no. CMPB-19.

The end of test nos. CMPB-18 and CMPB-19 was determined to be after the posts had rotated in the soil for a distance of 1,016 mm (40 in.). As the post rotated, the impact forces varied from horizontal to a combination of horizontal and vertical components of the post reaction force. Due to this change, the friction between the neoprene bumper pad and the post surface become significant. The 1,016-mm (40-in.) limit was considered to be the maximum displacement at which the bogie accelerations could accurately determine the force and energy reactions in the post tests.

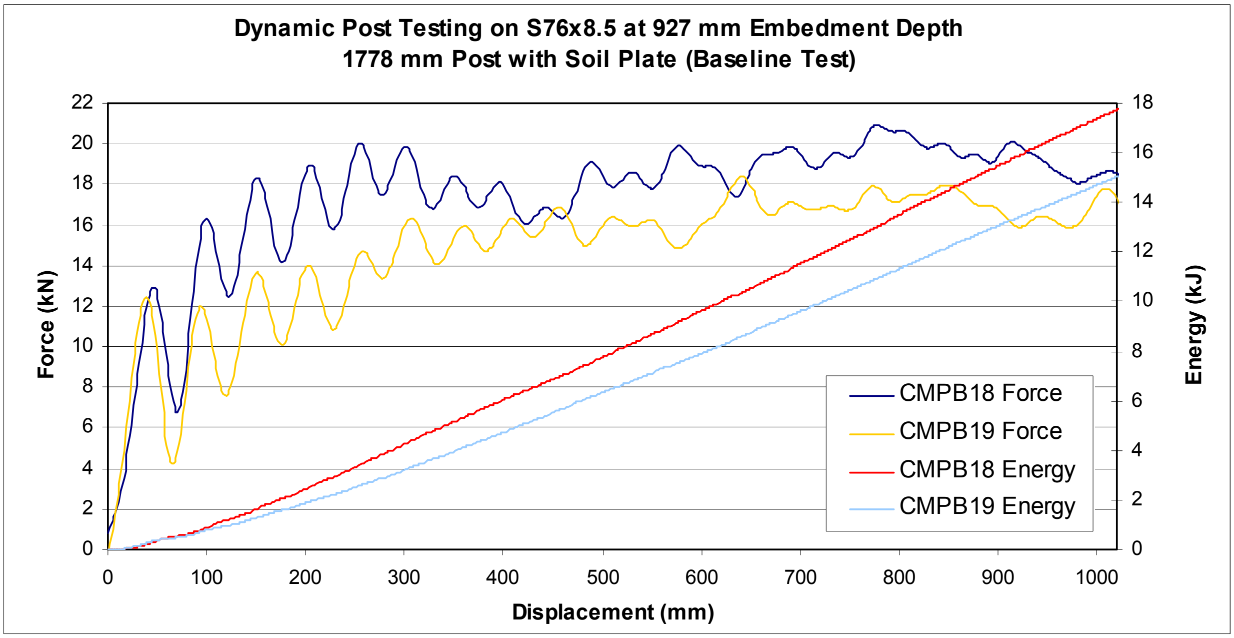
Table 3a. Test Results for Test Nos. CMPB-18 and CMPB-19 (Metric)

Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Effective Force			Total Energy[1] (kJ)	Maximum Displacement[2] (mm)	Primary Failure Type
			457 mm Displacement (kN)	610 mm Displacement (kN)	762 mm Displacement (kN)			
CMPB-18	927	5.75	15.33	16.09	16.68	17.68	1016	Soil Failure
CMPB-19	927	5.96	12.40	13.23	14.01	14.99	1016	Soil Failure

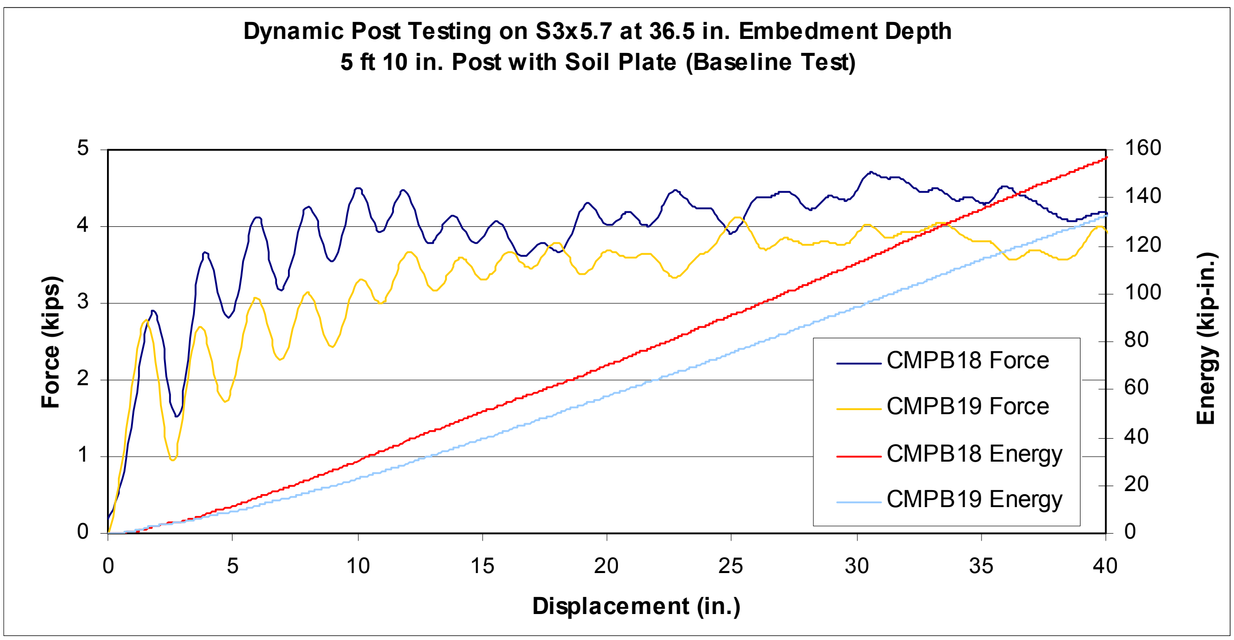
Table 3b Test Results for Test Nos. CMPB-18 and CMPB-19 (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Effective Force			Total Energy[1] (kip*in.)	Maximum Displacement[2] (in.)	Primary Failure Type
			18 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
CMPB-18	36.5	12.87	3.45	3.62	3.75	156.5	40	Soil Failure
CMPB-19	36.5	13.34	2.79	2.97	3.15	132.7	40	Soil Failure

1. The Total Energy category refers to the amount of energy dissipated over the duration of the impact event.
2. The Maximum Displacement category refers to the limiting displacement considered to be applicable for the test study and conclusions for the test. The data collection continued beyond the specified limit, but the extent of the collection was reduced to conform to a reasonable accuracy level. See test discussion for details.

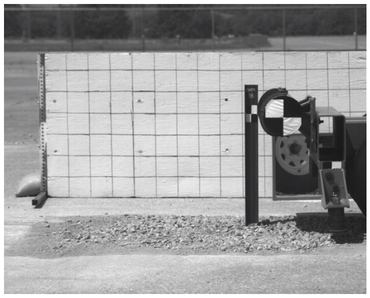


(a)



(b)

Figure 8. Force and Energy vs. Displacement Curves for CMPB-18 and CMPB-19 (a) Metric (b) English



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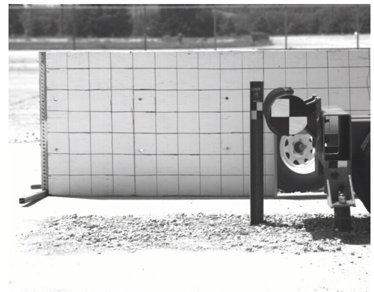

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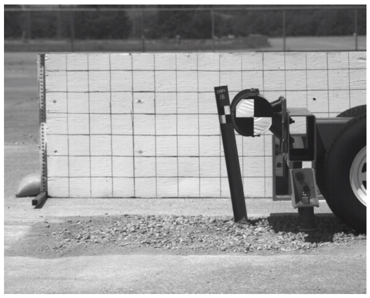

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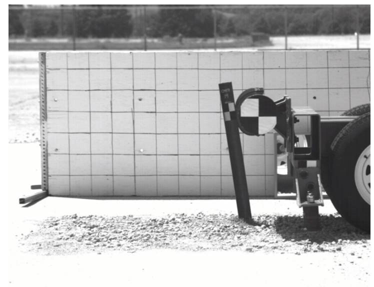

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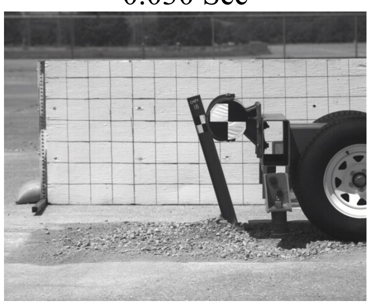

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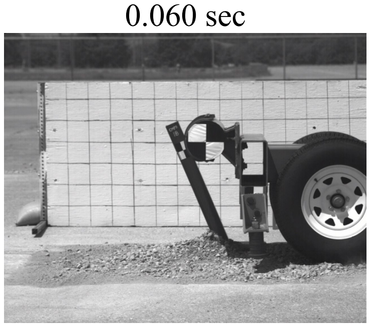

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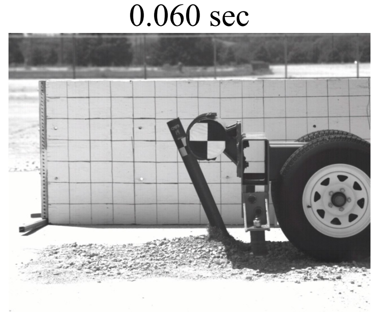

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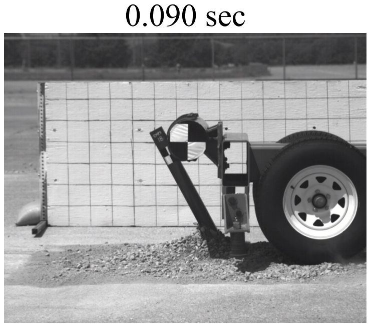

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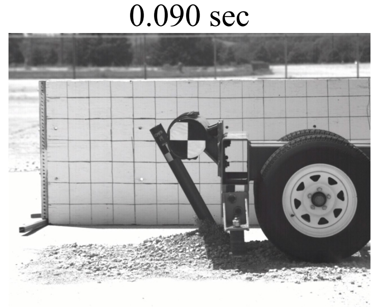

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Figure 9. Sequential Photographs, Test Nos. CMPB-18 and CMPB-19

Figure 10. Post Damage, Test No. CMPB-18

Figure 11. Post Damage, Test No. CMPB-19

5.1.2 Test Nos. CMPB-16 and CMPB-17 (1,829-mm (6-ft) Long Posts)

Two bogie tests were performed on 1,829-mm (6-ft) long posts at an embedment depth of 914 mm (36 in.). The test summaries for both tests are given in Tables 4a and 4b. Force-displacement and energy displacement curves are shown in Figure 12. The sequential photographs at regular time intervals are shown in Figure 13, and photographs of the posts following the tests are shown in Figures 14 and 15. The bogie test photographs and high-speed videos depict soil failure as the primary mode of failure for the tests. For the duration of the tests, negligible buckling, bending or twisting occurred to the posts as the posts rotated in the soil. The force displacement curves for test nos. CMPB-16 and CMPB-17 failed to indicate a large inertial spike at the beginning of the impact, similar to test nos. CMPB-18 and CMPB-19, but showed a period of rapidly increasing force followed by a period of uniform resisting force. The total energy dissipated in each of the two tests was almost identical, unlike the behavior observed during the baseline test nos. CMPB-18 and CMPB-19 with soil plates attached to the posts.

The end of test nos. CMPB-16 and CMPB-17 were determined to be after the posts had rotated in the soil for a distance of 1,016 mm (40 in.). As the post rotated, the impact forces varied from horizontal to a combination of horizontal and vertical components of the post reaction force. Due to this change, the friction between the neoprene bumper pad and the post surface became significant. The 1,016-mm (40-in.) limit was considered to be the maximum displacement at which the bogie accelerations could still accurately determine the force and energy reactions in the post tests. Additionally, since less energy was dissipated during these tests, the bogie had a tendency to ride up the post and introduce further error into the data collected.

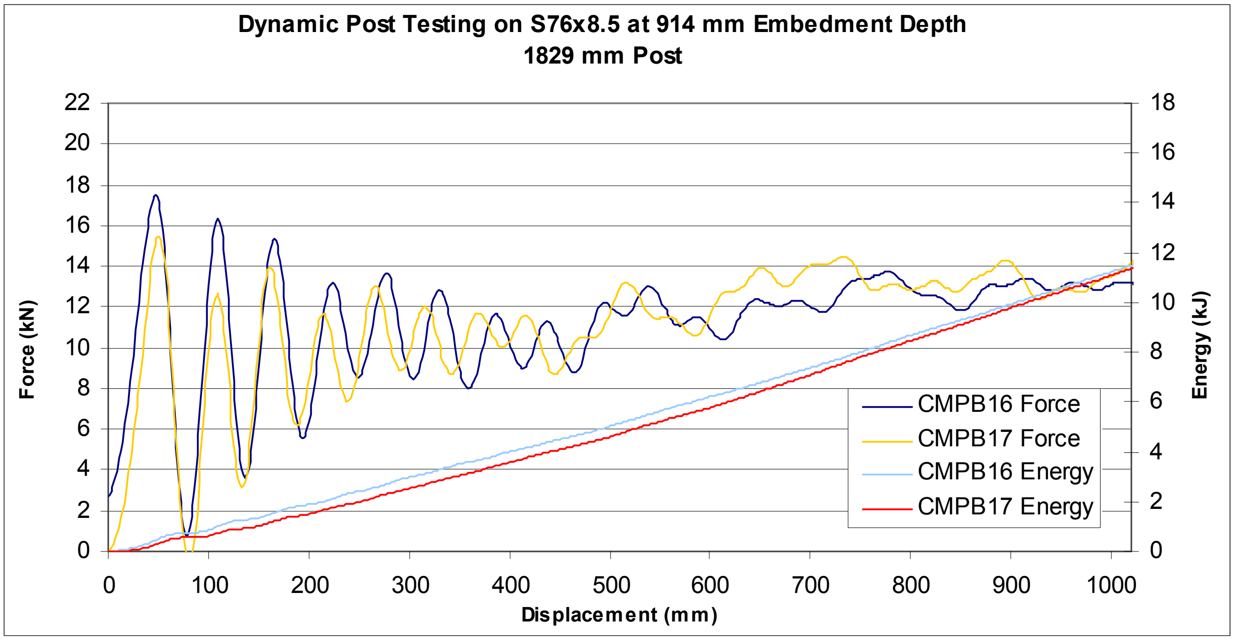
Table 4a. Test Results for Test Nos. CMPB-16 and CMPB-17 (Metric)

Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Effective Force			Total Energy[1] (kJ)	Maximum Displacement[2] (mm)	Primary Failure Type
			457 mm Displacement (kN)	610 mm Displacement (kN)	762 mm Displacement (kN)			
CMPB-16	914	6.12	10.04	10.37	10.75	11.47	1016	Soil Failure
CMPB-17	914	5.71	9.11	9.69	10.46	11.34	1016	Soil Failure

Table 4b. Test Results for Test Nos. CMPB-16 and CMPB-17 (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Effective Force			Total Energy[1] (kip*in.)	Maximum Displacement[2] (in.)	Primary Failure Type
			18 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
CMPB-16	36	13.70	2.26	2.33	2.42	101.5	40	Soil Failure
CMPB-17	36	12.78	2.05	2.18	2.35	100.4	40	Soil Failure

1. The Total Energy category refers to the amount of energy dissipated over the duration of the impact event.
2. The Maximum Displacement category refers to the limiting displacement considered to be applicable for the test study and conclusions. The data collection continued beyond the specified limit, but the extent of the collection was reduced to conform to a reasonable accuracy level. See test discussion for details.



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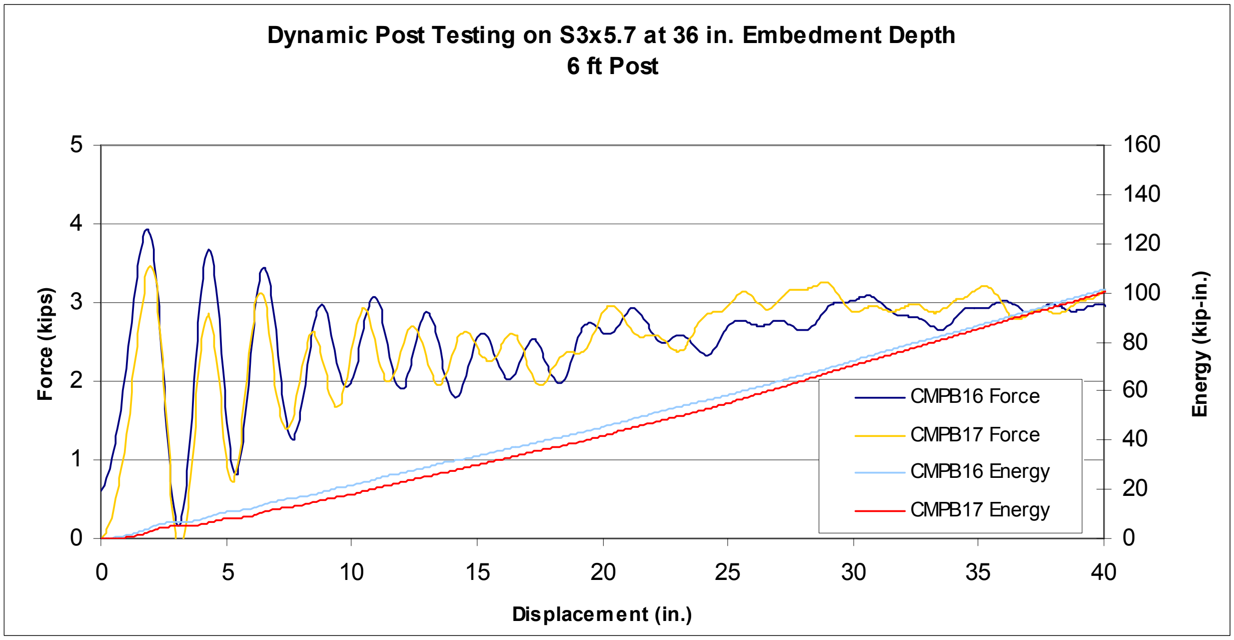

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Figure 12. Force and Energy vs. Displacement Curves for CMPB-16 and CMPB-17 (a) Metric (b) English

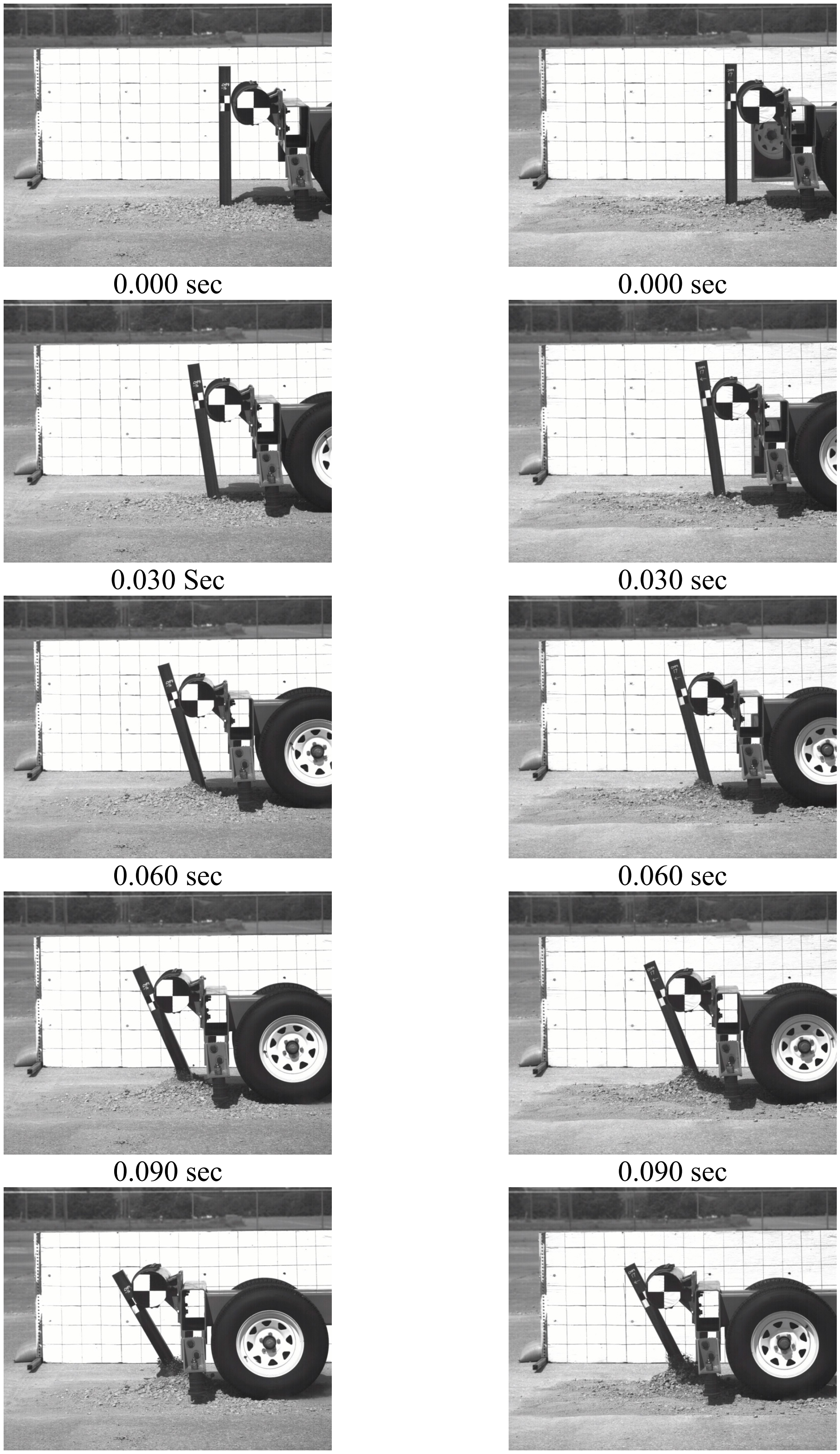

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Figure 13. Sequential Photographs, Test Nos. CMPB-16 and 17

Figure 14. Post Damage, Test No. CMPB-16

Figure 15. Post Damage, Test No. CMPB-17

5.1.3 Test Nos. CMPB-20 and CMPB-21 (1,981-mm (6.5-ft) Long Posts)

Two bogie tests were performed on 1,981-mm (6-ft 6-in.) long posts at an embedment depth of 1,067 mm (42 in.). The test summaries for both tests are given in Tables 5a and 5b. Force-displacement and energy-displacement curves for test no. CMPB-21 are shown in Figure 16. It should be noted that the data acquisition for test no. CMPB-20 failed due to technical difficulties, and no accelerometer data could be obtained for this test. The sequential photographs at regular time intervals are shown in Figure 17, and photographs of the posts out of the ground following the tests are shown in Figures 18 and 19. The bogie test photographs and high-speed videos depict soil failure as the primary mode of failure for the tests. Although the posts rotated in the soil, observable bending of the flanges and twisting in the web occurred slightly below ground level. The force displacement curves for test no. CMPB-21 once again did not indicate a large inertial spike at the beginning of impact, but instead showed a period of rapidly increasing force, followed by a period of uniform resistive force.

The end of test no. CMPB-21 was determined to be after it had rotated in the soil for a distance of 1,016 mm (40 in.). As the post rotated, the impact forces varied from horizontal to a combination of horizontal and vertical components of the post reaction force. Due to this change, the friction between the neoprene bumper pad and the post surface became significant. The 1,016-mm (40-in.) limit was considered to be the maximum displacement at which the bogie accelerations could still accurately reconstruct, through accelerometer traces, the force and energy reactions in the post test. Additionally, since less energy was dissipated during this test, the bogie had a tendency to ride up the post and introduce further error into the data collected.

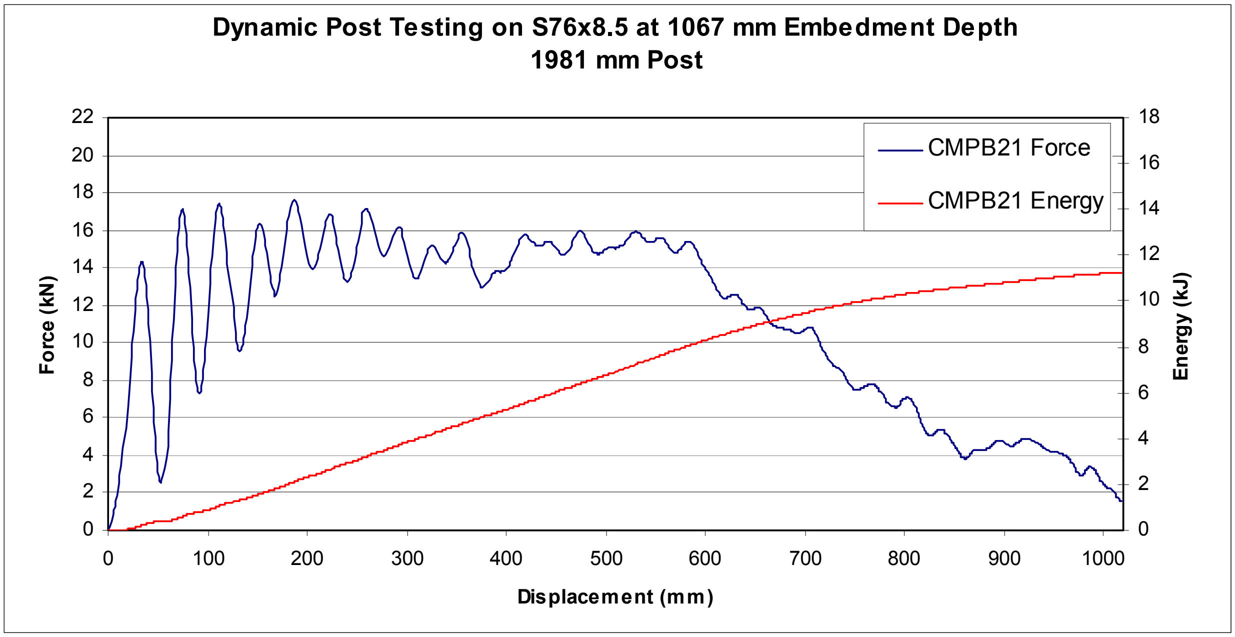
Table 5a. Test Results for Test Nos. CMPB-20 and CMPB-21 (Metric)

Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Effective Force			Total Energy [1] (kJ)	Maximum Displacement[2] (mm)	Primary Failure Type
			457 mm Displacement (kN)	610 mm Displacement (kN)	762 mm Displacement (kN)			
CMPB-20	1067	6.21	NA	NA	NA	NA	NA	Soil Failure
CMPB-21	1067	6.01	13.43	13.85	13.17	11.24	1016	Soil Failure

Table 5b. Test Results for Test Nos. CMPB-20 and CMPB-21 (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Effective Force			Total Energy [1] (kip*in.)	Maximum Displacement[2] (in.)	Primary Failure Type
			18 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
CMPB-20	42	13.89	N/A	NA	N/A	N/A	N/A	Soil Failure
CMPB-21	42	13.45	3.02	3.11	2.96	99.5	40	Soil Failure

1. The Total Energy category refers to the amount of energy dissipated over the duration of the impact event.
2. The Maximum Displacement category refers to the limiting displacement considered to be applicable for the test study and conclusions. The data collection continued beyond the specified limit, but the extent of the collection was reduced to conform to a reasonable accuracy level. See test discussion for details.



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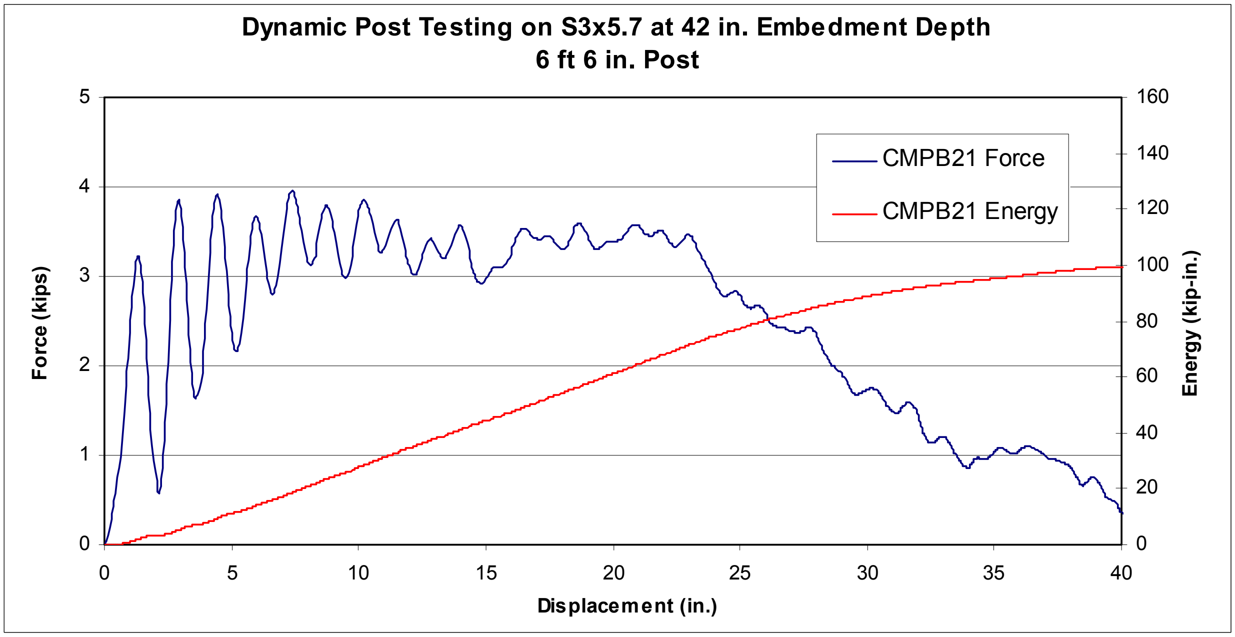

(b)

Figure 16. Force and Energy vs. Displacement Curves for Test Nos. CMPB-21
(a) Metric (b) English

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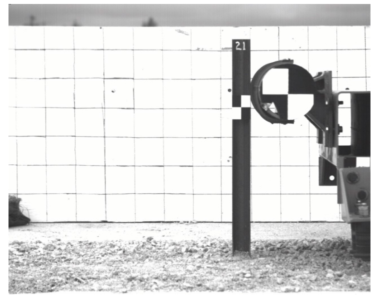

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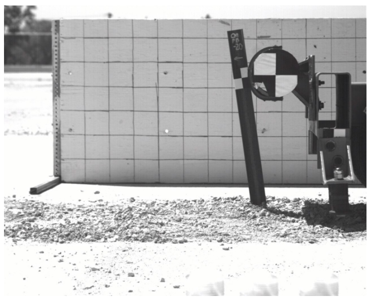

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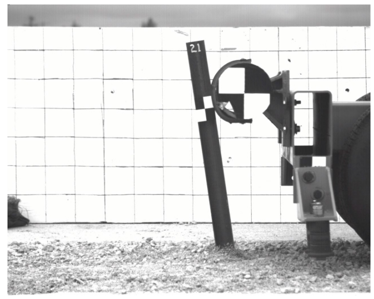

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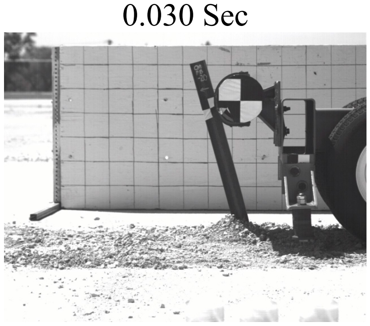

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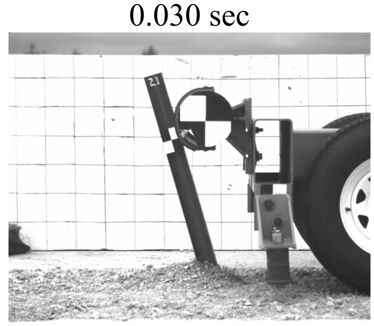

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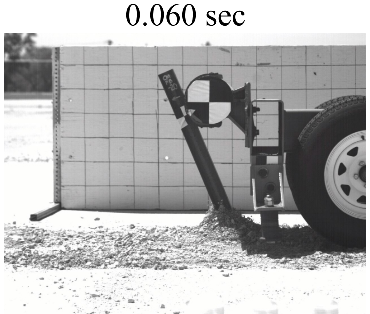

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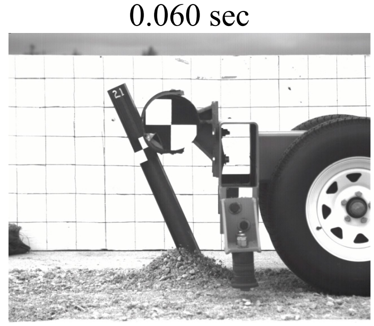

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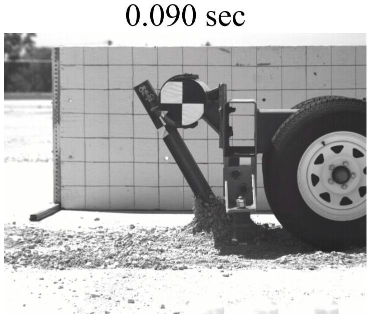

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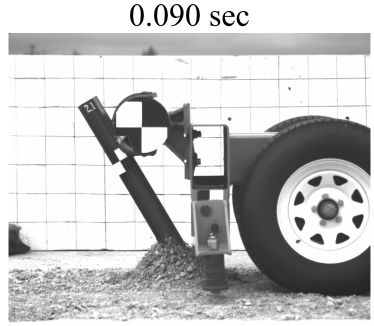

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Figure 17. Sequential Photographs, Test Nos. CMPB-20 and CMPB-21

Figure 18. Post Damage, Test No. CMPB-20

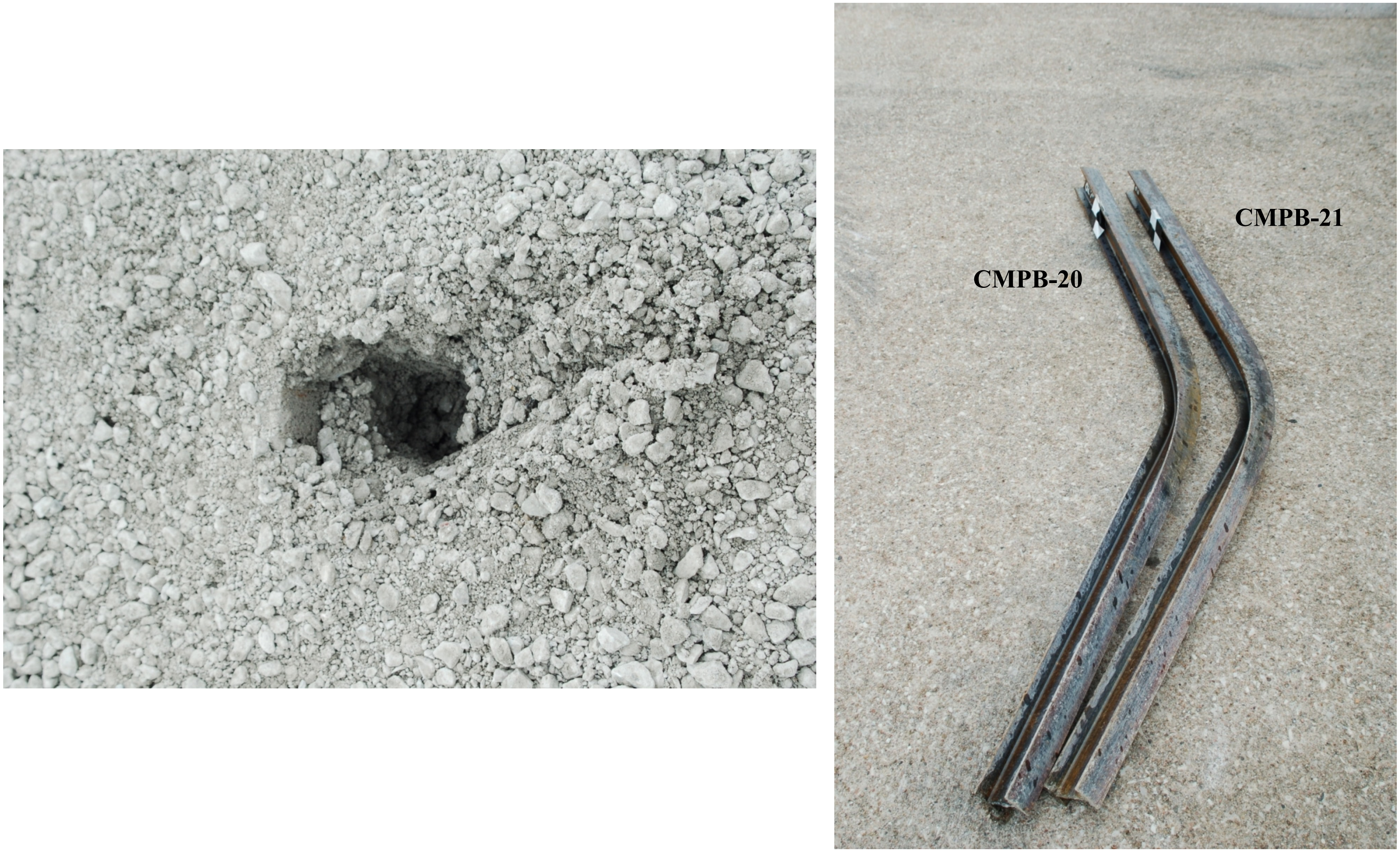


Figure 19. Post and Soil Damage, Test No. CMPB-21 (with Post from Test No. CMPB-20)

5.1.4 Test Nos. CMPB-22 and CMPB-23 (2,134-mm (7-ft) Long Posts)

Two bogie tests were performed on 2,134-mm (7-ft) long posts at an embedment depth of 1,219 mm (48 in.). The test summaries for both tests are given in Tables 6a and 6b. Force-displacement and energy displacement curves are shown in Figure 20. The sequential photographs at regular time intervals are shown in Figure 21, and photographs of the posts out of the ground following the tests are shown in Figures 22 and 23. The bogie test photographs and high-speed videos depict soil failure as the primary mode of failure for test CMPB-23, but the failure mode was determined to be mixed post bending and soil failure for test CMPB-22. Major bending deflections and twisting deformations occurred to the posts following the initial rotation in the soil. The force displacement curves for test nos. CMPB-22 and CMPB-23 once again did not indicate a large inertial spike at the beginning of impact, but showed a period of rapidly increasing force, followed by a period of uniform resistive force. The total energy dissipated in each of the two tests differed significantly. This was due to the rapid deformation of the post in CMPB-22, while the post in test no. CMPB-23 rotated through the soil for a longer duration of time. The relative energy dissipation of test no. CMPB-23 at 810 mm (31.9 in.) was 10.16 kJ (89.9 kip-in.). The 810-mm (31.9 in.) displacement corresponded to the end of test no. CMPB-22, with an energy dissipation of 8.40 kJ (74.3 kip-in.).

The end of test nos. CMPB-23 was determined to be after the post had rotated in the soil for a distance of 1016 mm (40 in.). As the post rotated, the impact forces varied from horizontal to a combination of horizontal and vertical components of the post reaction force. Due to this change, the friction between the neoprene bumper pad and the post surface became significant. The 1,016-mm (40-in.) limit was considered to be the maximum displacement at which the bogie accelerations could still accurately determine the force and energy reactions in the posts tested.

Additionally, as the post rotated, it caused the bogie to climb up and over the posts and introduce further error into the data collected.

In test no. CMPB-22, the bogie began to slide up and over the post, with the bogie's tires becoming airborne at approximately 0.186 sec. As the bogie became airborne, the force directed into the post by the bogie was no longer in the longitudinal direction, and therefore could not be considered an accurate representation of the post-cable forces in an actual installation. Therefore, the test's evaluation period was shortened and was not analyzed to the 1,016-mm (40-in.) displacement condition.

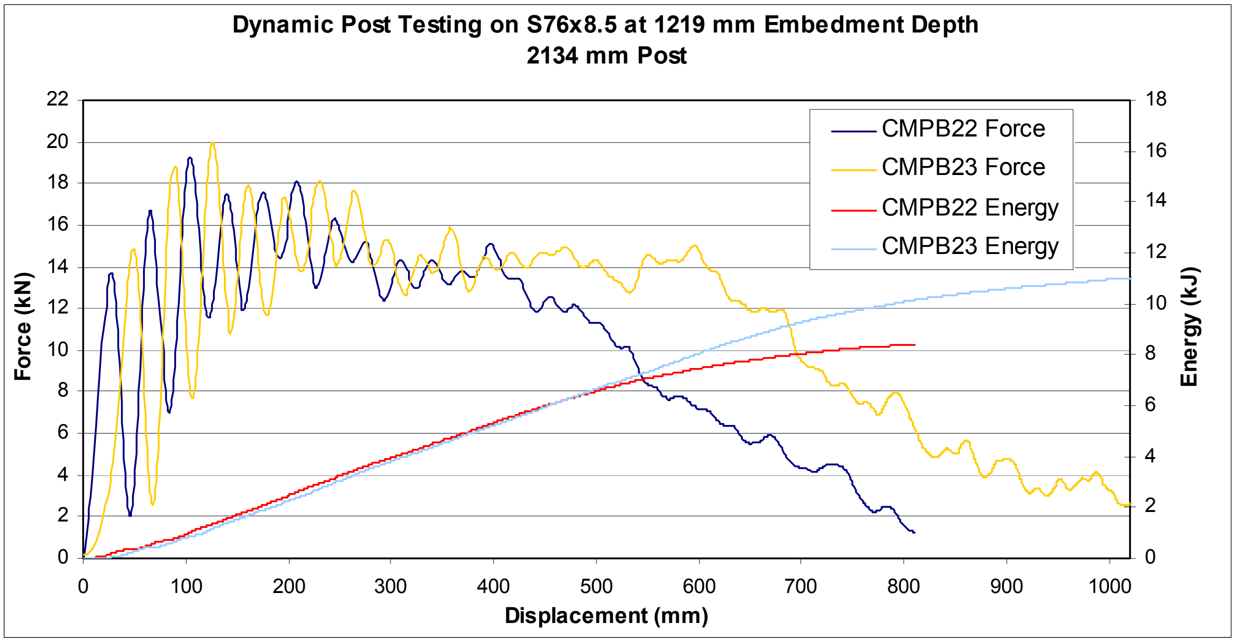
Table 6a. Test Results for Test Nos. CMPB-22 and CMPB-23 (Metric)

Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Effective Force			Total Energy[1] (kJ)	Maximum Displacement[2] (mm)	Primary Failure Type
			457 mm Displacement (kN)	610 mm Displacement (kN)	762 mm Displacement (kN)			
CMPB-22	1219	6.39	13.29	12.35	10.89	8.40	810	Bending
CMPB-23	1219	5.97	13.21	13.46	12.87	11.01	1016	Soil Failure

Table 6b. Test Results for Test Nos. CMPB-22 and CMPB-23 (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Effective Force			Total Energy[1] (kip*in.)	Maximum Displacement[2] (in.)	Primary Failure Type
			18 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
CMPB-22	48	14.30	2.99	2.78	2.45	74.3	31.9	Bending
CMPB-23	48	13.36	2.97	3.03	2.89	97.5	40	Soil Failure

1. The Total Energy category refers to the amount of energy dissipated over the duration of the impact event.
2. The Maximum Displacement category refers to the limiting displacement considered to be applicable for the test study and conclusions. The data collection continued beyond the specified limit, but the extent of the data collected was reduced to conform to a reasonable accuracy level. See test discussion for details.



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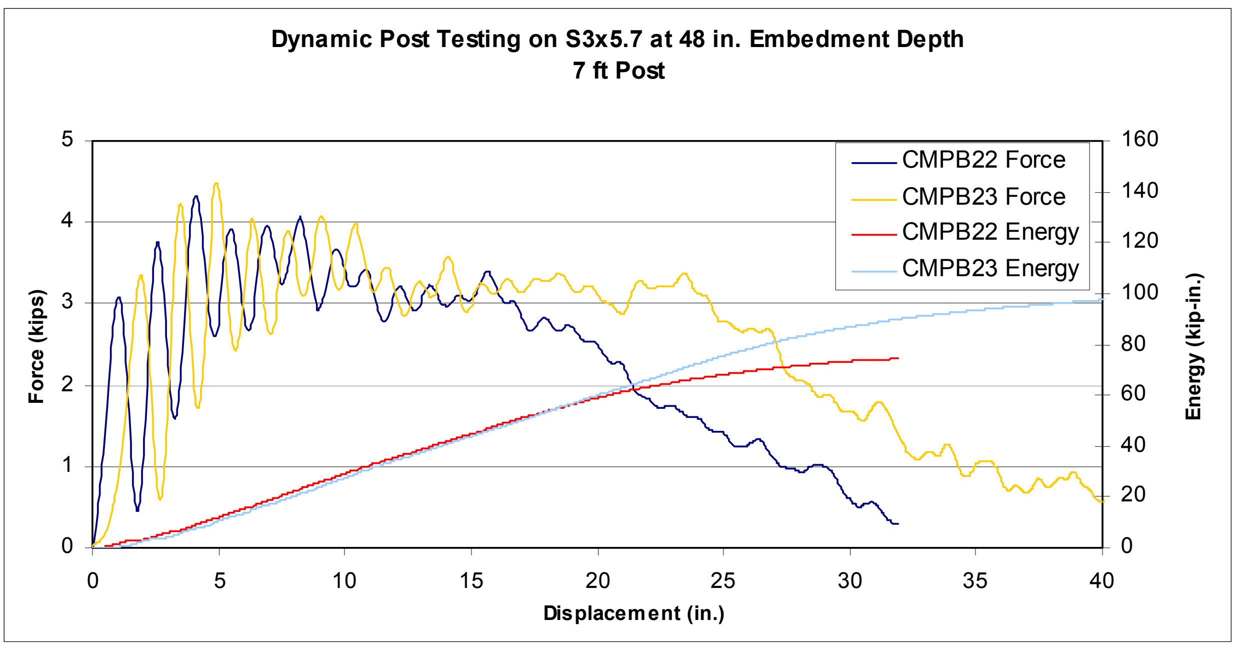
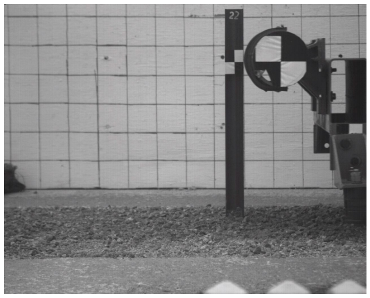


(b)

Figure 20. Force and Energy vs. Displacement Curves for Test Nos. CMPB-22 and CMPB-23 (a) Metric (b) English



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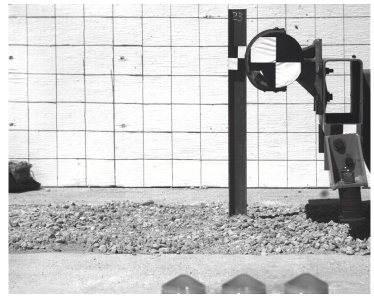

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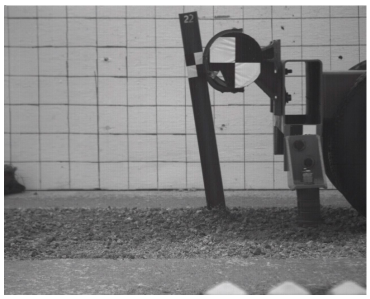

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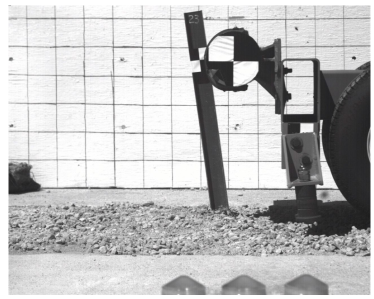

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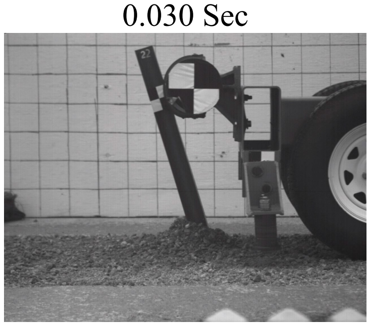

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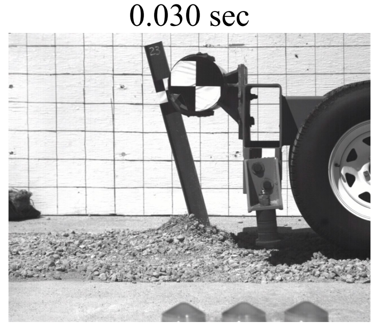

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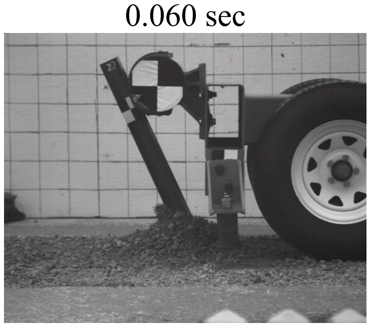

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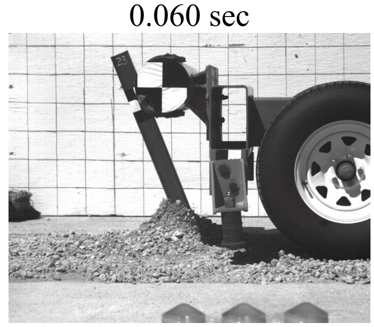

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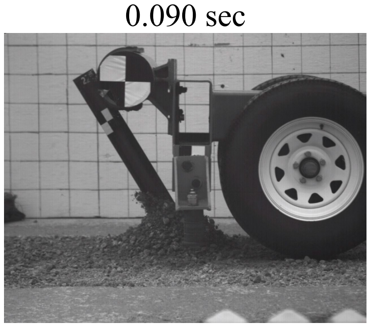

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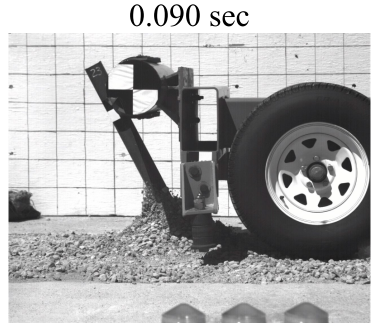

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Figure 21. Sequential Photographs, Test Nos. CMPB-22 and CMPB-23

Figure 22. Post Damage, Test No. CMPB-22

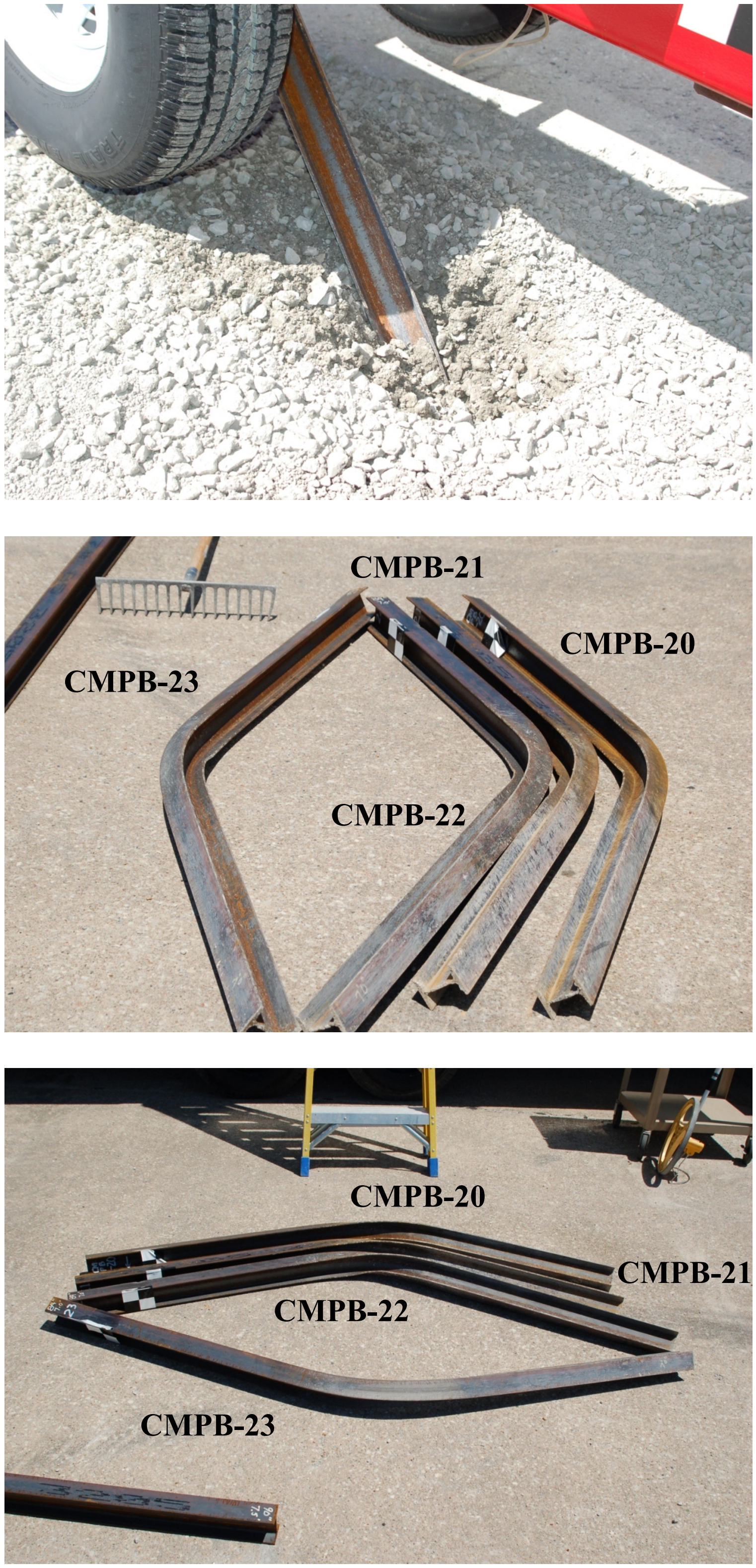


Figure 23. Post Damage, Test No. CMPB-23 (with Posts from Test Nos. CMPB 20 through CMPB-22)

5.1.5 Test Nos. CMPB-24 and CMPB-25 (2,286-mm (7.5-ft) Long Posts)

Two bogie tests were performed on 2,286-mm (7-ft 6-in.) long posts at an embedment depth of 1,372 mm (54 in.). The test summaries for both tests are given in Tables 7a and 7b. Force-displacement and energy displacement curves for test nos. CMPB-24 and CMPB-25 are shown in Figure 24. It should be noted that due to technical difficulties, no high-speed photographic data was obtained for test no. CMPB-25. The sequential photographs for test no. CMPB-24 at regular time intervals are shown in Figure 25, and photographs of the posts are shown in Figures 26 and 27. The bogie test photographs and videos depict post bending and twisting as the primary mode of failure for the tests. Although the posts rotated in the soil, the posts encountered major bending of the flanges and web and twisting slightly below ground level. The force-displacement curves for test nos. CMPB-24 and CMPB-25 once again did not indicate a large inertial spike along the beginning of the impact, but instead showed a period of rapidly increasing force, followed by a period of uniform resistive force.

The end of test nos. CMPB-24 and CMPB-25 was determined to be after the bogie became airborne. The posts twisted shortly after impact and bent along the weak axis, thus creating a ramp for the bogie to vault the post. Also, the impact force varied from horizontal to a combination of horizontal and vertical components of the post reaction force. Due to this change, the neoprene-post frictional force induced large errors into the data collection at deflections of 1,016-mm (40-in.). As such, the duration of the analysis was shortened from the limiting displacement of 1,016-mm (40-in.) to reflect this uncertainty. The deflection limits used for test nos. CMPB-24 and CMPB-25 are provided in the test summary tables given in Tables 7a and 7b.

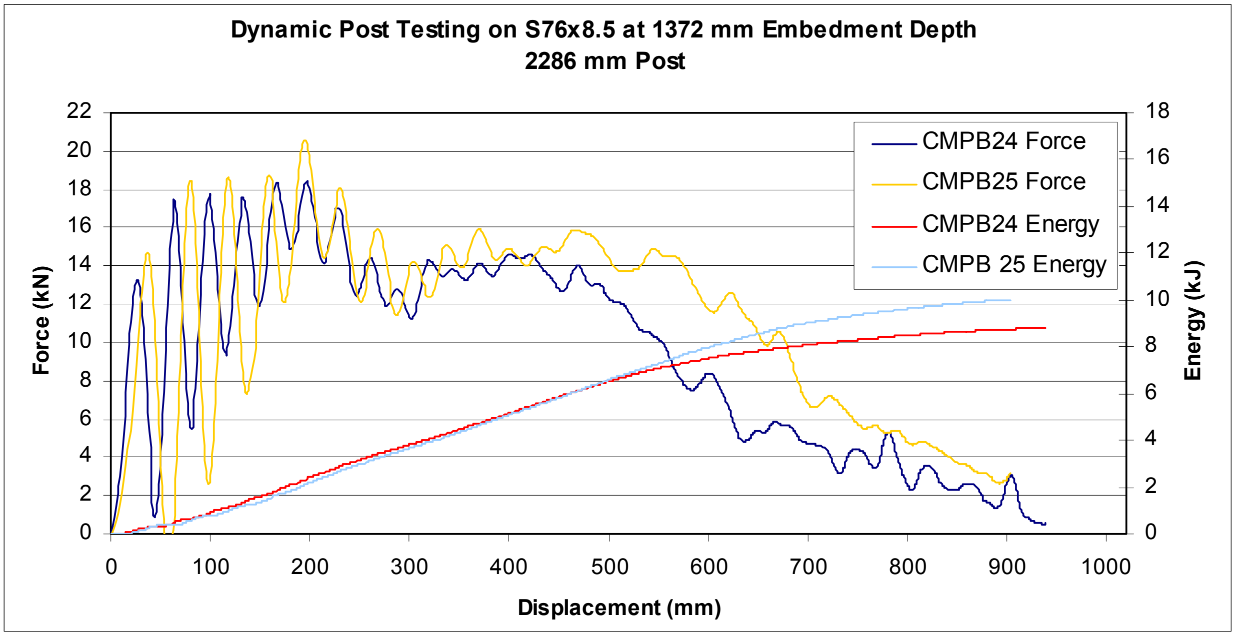
Table 7a. Test Results for Test Nos. CMPB-24 and CMPB-25 (Metric)

Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Effective Force			Total Energy[1] (kJ)	Maximum Displacement[2] (mm)	Primary Failure Type
			457 mm Displacement (kN)	610 mm Displacement (kN)	762 mm Displacement (kN)			
CMPB-24	1372	5.56	13.02	12.44	12.10	8.79	939	Bending
CMPB-25	1372	6.23	12.98	13.27	12.38	10.17	965	Bending

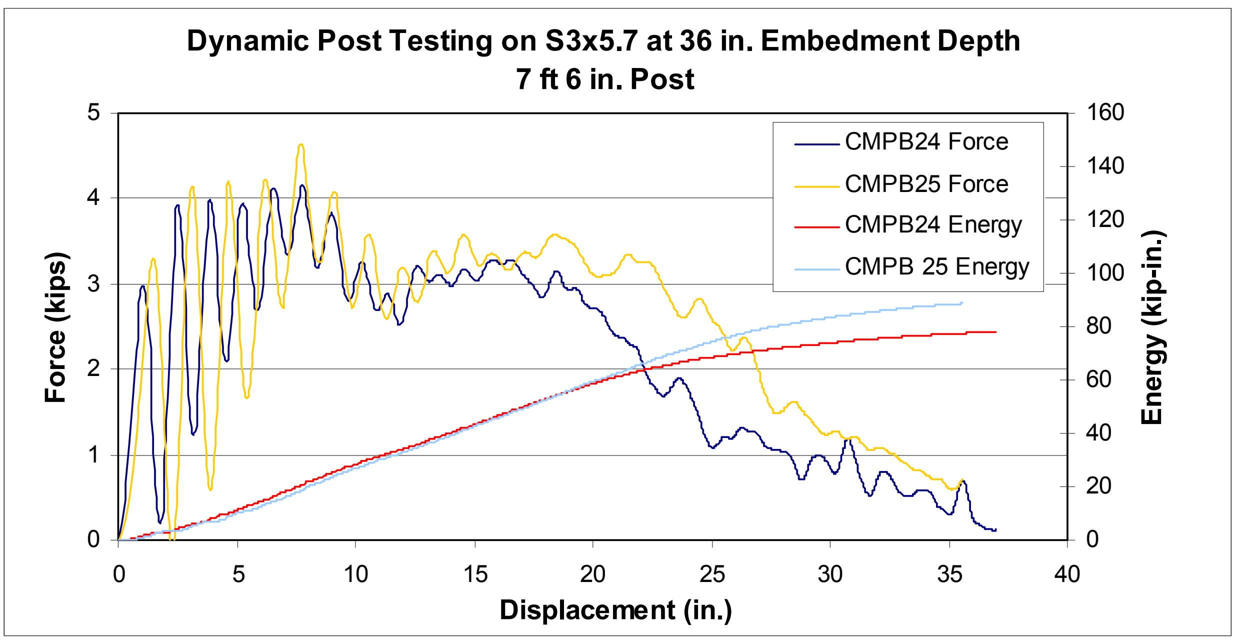
Table 7b. Test Results for Test Nos. CMPB-24 and CMPB-25 (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Effective Force			Total Energy[1] (kip*in.)	Maximum Displacement[2] (in.)	Primary Failure Type
			18 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
CMPB-24	54	12.43	2.93	2.80	2.72	77.8	37.0	Bending
CMPB-25	54	13.94	2.92	2.98	2.78	90.0	38.0	Bending

1. The Total Energy category refers to the amount of energy dissipated over the duration of the impact event.
2. The Maximum Displacement category refers to the limiting displacement considered to be applicable for the test study and conclusions. The data collection continued beyond the specified limit, but the extent of the data collected was reduced to conform to a reasonable accuracy level. See test discussion for details.

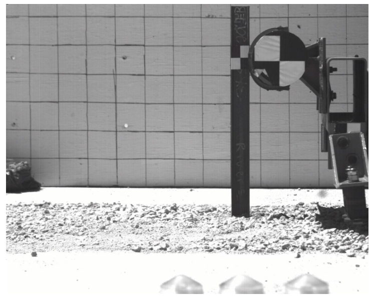


(a)



(b)

Figure 24. Force and Energy vs. Displacement Curves for Test Nos. CMPB-24 and CMPB-25 (a) Metric (b) English



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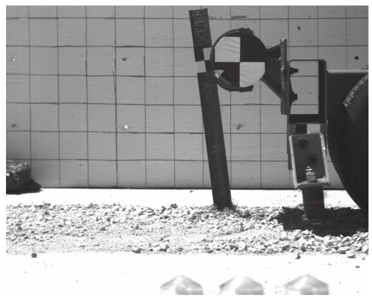

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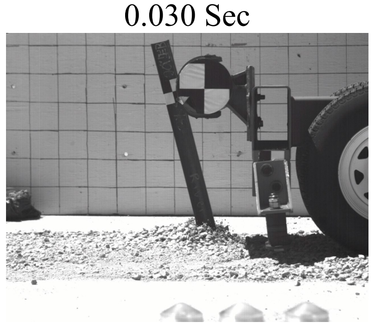

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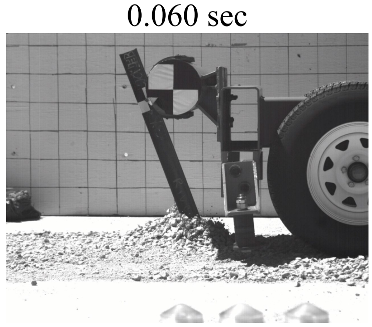

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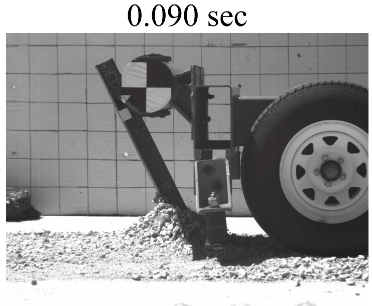


0.120 sec

Figure 25. Sequential Photographs, Test No. CMPB-24

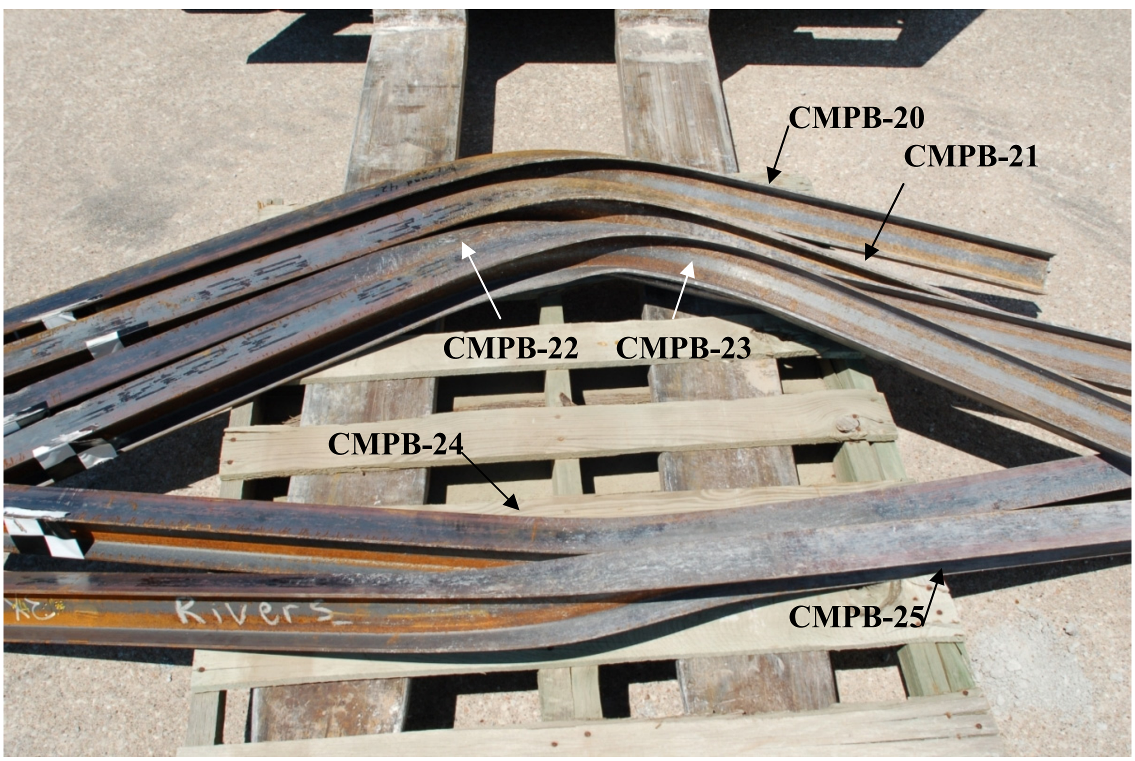


Figure 26. Post Damage, Test No. CMPB-24 (with Posts from Test Nos. CMPB-20 through CMPB-25)

Figure 27. Post Damage, Test No. CMPB-25

5.2 Discussion of Test Results

After the analysis was completed on the ten bogie tests performed at different embedment depths, it became apparent that dramatically increasing the post length of the S76x8.5 (S3x5.7) steel post did not significantly increase the total energy absorbed by the post nor dissipated through the soil displacement. Through derivation of the force-energy relationship, the average force per event could be calculated, using the formula:

$$\text{Average Force} = \frac{\text{Energy}}{\text{Displacement}}$$

The average forces calculated for test nos. CMPB-16 through CMPB-25, using the formula described above, are shown in Tables 8a and 8b.

As shown in Tables 8a and 8b, the test-duration average force for test nos. CMPB-21 through CMPB-25 decreased slightly with increasing embedment depths. The posts with shallower embedment depths were better suited to rotate through the soil and withstand the impact and soil resisting forces with less post deformation. The displacement of soil proved to dissipate more energy than the deformation of the post. This was observed in the results from test nos. CMPB-16 and CMPB-17, which dissipated 11.4 kj (100.9 kip-in.), as compared to those results obtained in test nos. CMPB-24 and CMPB-25, which dissipated 10.0 kJ (88.9 kip-in.) However, the energy absorbed by the post with a shorter embedment was less than posts with longer embedment depths until the post undergoes large deformations, nearly 915 mm (36 in.), as shown in Figure 32. The effect of the S76x8.5 (S3x5.7) post deformation and soil shear was comparable to the results obtained in a similar cable barrier post study with posts embedded in NCHRP 350 strong soil and native soil (6).

As the post embedment depth increased, the soil resistance to post rotation during impact also increased. The increase in soil resistive forces led to large bending and shear stresses in the flanges and web of the post slightly below ground level where the resistive forces were the largest. This was evident in the deformations of the posts tested in test nos. CMPB-20 through CMPB-25, as shown in Figure 28. The posts with shorter embedment depths were better suited to rotate through the soil at nearly constant force without buckling or twisting of the posts. With increasing post lengths, the axis of rotation of the post in the soil was extended below the surface of the ground. As the distance between the axis of rotation and the ground level increased, the bending stresses increased below ground level and caused plastic deformation in the web and flange of the post, and this deformation occurred at a much lower applied impact force level than the soil resistive forces observed in the initial rotation of the post. A comparison of the force-deflection results of test nos. CMPB-17, CMPB-21, CMPB-23 and CMPB-25 are shown in Figure 29.

In order to provide a reasonable comparison between the posts with various embedment depths, the second test in each test scenario was selected and believed to be representative of the post reaction of driven posts at the provided embedment depths. As shown in Figure 29, there are three distinguishable regions in the force-deflection curves derived for each post embedment depth. The first region is a period of rapidly increasing force and momentum transfer between the surrogate test vehicle and the post. During the first region, the baseline posts with attached soil plates and the posts with embedment depths of greater than 914 mm (36 in.) had a nearly identical force-deflection plot, extending through a deflection of 160 mm (6.3 in.). All of the posts experienced a relatively constant resistive force in Region 2 of the force-displacement curves, which extended from 160 mm (6.3 in.) to 572 mm (22.5 in.), as shown in Figure 29. This was verified by the energy-deflection curves in which the slope of the energy-deflection curve is nearly constant for all of the tests in Region 2, as shown in Figure 30. Note, however, that the average force for test no. CMPB-17 was considerably lower than the average force for test nos. CMPB-21, CMPB-23, and CMPB-25 in Region 2. After rotating 572 mm (22.5 in.), the post responses diverged for test no. CMPB-17 and test nos. CMPB-21, CMPB-23 and CMPB-25. In Region 3 of the force-deflection curves, the force exerted on the post increased with increasing deflection for test no. CMPB-17, but there was a nearly uniform decrease in the force-deflection curves for test nos. CMPB-21 through 25, regardless of the embedment depth. The decrease in applied force to the posts in test nos. CMPB-20 through CMPB-25 is due to the twisting and buckling of each post's flanges and web after a deflection of approximately 572 mm (22.5 in.). The posts dissipated considerably less energy while bending than occurred during rotation through the soil. Additionally, the weak axis bending, which was most visible in test nos. CMPB-24 and CMPB-25, caused a severe drop in the reaction forces and energy dissipated after approximately 572 mm (22.5 in.).

A comparison of the initial post reaction force, through Region 2 of the test sequence, is shown in Figure 31, and the energy dissipated in the tests through 572 mm (22.5 in.) is shown in Figure 32. The energy dissipated by a S76x8.5 (S3x5.7) post at a 1,372-mm (54-in.) embedment depth is approximately equal to the energy dissipated by the baseline post with attached soil plate and all posts with embedment depths greater than or equal to 1,067 mm (42 in.). Furthermore, posts with an embedment depth of 1,067 mm (42 in.) dissipated more energy throughout the impact event than posts with deeper embedment depths. These same posts had comparable impact performance to the posts with attached soil plates at a 927 mm (36.5 in.) embedment depth. Therefore, due to the lower cost of the post with the 1,067 mm (42 in.) embedment depth in comparison to the post with welded soil plate, the 1,981-mm (78-in.) post with a 1,067 mm (42 in.) embedment depth is recommended for testing in cable barrier systems.

Table 8a. Average Force and Total Energy Dissipation in Test Nos. CMPB-16 through CMPB-25

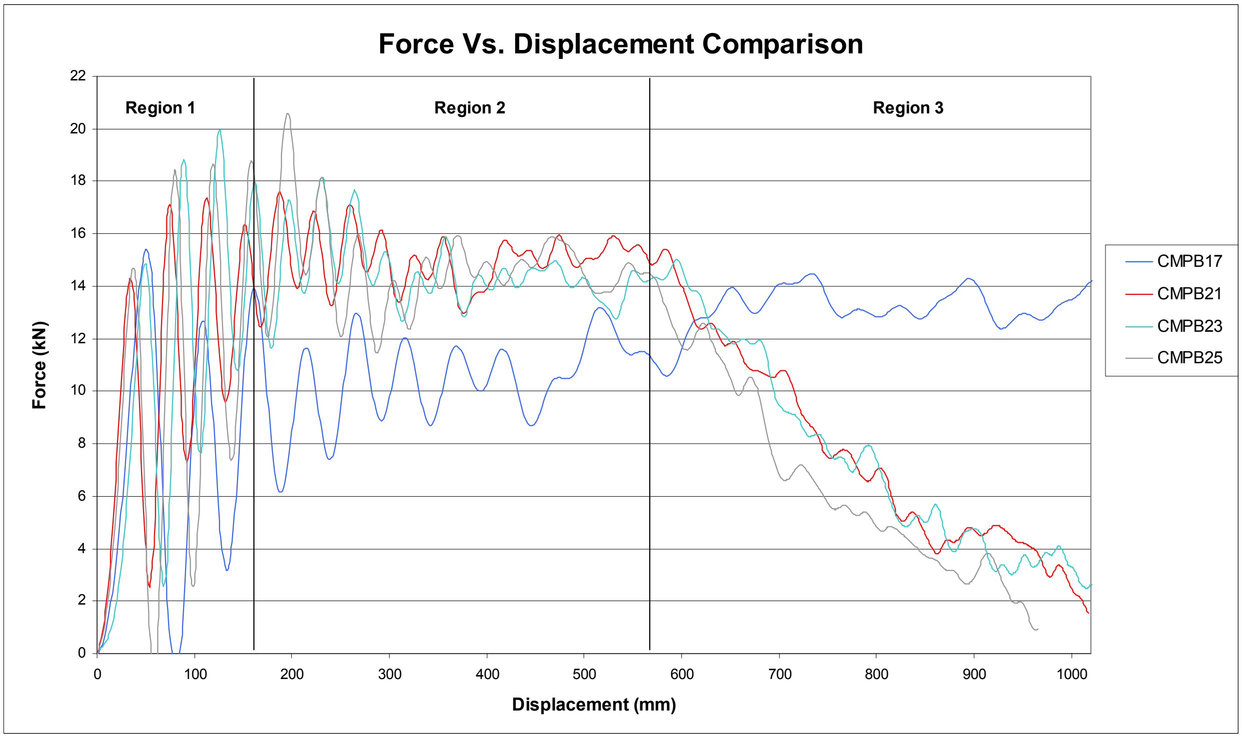
Test No.	Embedment Depth	Impact Velocity	Average Force Calculations		Total Energy	
			610 mm Displacement	End of Test Average	Displacement	Energy
	mm	m/s	kN	kN	mm	kJ
CMPB-18	927	5.75	16.09	17.40	1016	17.7
CMPB-19	927	6.19	13.23	14.75	1016	15.0
Average	**927**	**6.0**	**14.66**	**16.08**	**1016**	**16.3**
CMPB-16	914	6.12	10.37	11.29	1016	11.5
CMPB-17	914	5.71	9.69	11.16	1016	11.3
Average	**914**	**5.9**	**10.03**	**11.22**	**1016**	**11.4**
CMPB-20*	1067	6.21	NA	NA	NA	NA
CMPB-21	1067	6.01	13.85	11.06	1016	11.2
Average	**1067**	**6.1**	**13.85**	**11.06**	**1016**	**11.2**
CMPB-22	1219	6.39	12.35	10.36	810	8.4
CMPB-23	1219	5.97	13.46	10.84	1016	11.0
Average	**1219**	**6.2**	**12.90**	**10.60**	**913**	**9.7**
CMPB-24	1372	5.56	12.44	9.37	940	8.8
CMPB-25	1372	6.23	13.27	10.54	965	10.2
Average	**1372**	**5.9**	**12.86**	**9.95**	**953**	**9.5**

Table 8b. Average Force and Total Energy Dissipation in Test Nos. CMPB-16 through CMPB-25

Test No.	Embedment Depth	Impact Velocity	Average Force Calculations		Total Energy	
			24 in. Displacement	End of Test Average	Displacement	Energy
	in.	mph	kips	kips	in.	kip-in.
CMPB-18	36.5	12.87	3.62	3.91	40.0	156.5
CMPB-19	36.5	13.84	2.97	3.32	40.0	132.7
Average	**36.5**	**13.4**	**3.30**	**3.61**	**40.0**	**144.6**
CMPB-16	36	13.70	2.33	2.54	40.0	101.5
CMPB-17	36	12.78	2.18	2.51	40.0	100.4
Average	**36**	**13.2**	**2.25**	**2.52**	**40.0**	**100.9**
CMPB-20*	42	13.89	NA	NA	NA	NA
CMPB-21	42	13.45	3.11	2.49	40.0	99.5
Average	**42**	**13.7**	**3.11**	**2.49**	**40.0**	**99.5**
CMPB-22	48	14.30	2.78	2.33	31.9	74.3
CMPB-23	48	13.36	3.03	2.44	40.0	97.5
Average	**48**	**13.8**	**2.90**	**2.38**	**36.0**	**85.9**
CMPB-24	54	12.43	2.80	2.11	37.0	77.8
CMPB-25	54	13.94	2.98	2.37	38.0	90.0
Average	**54**	**13.2**	**2.89**	**2.24**	**37.5**	**83.9**

* No accelerometer traces were obtained for test no. CMPB-20

Figure 28. Post Deformation Comparison, Test Nos. CMPB-20 through CMPB-25



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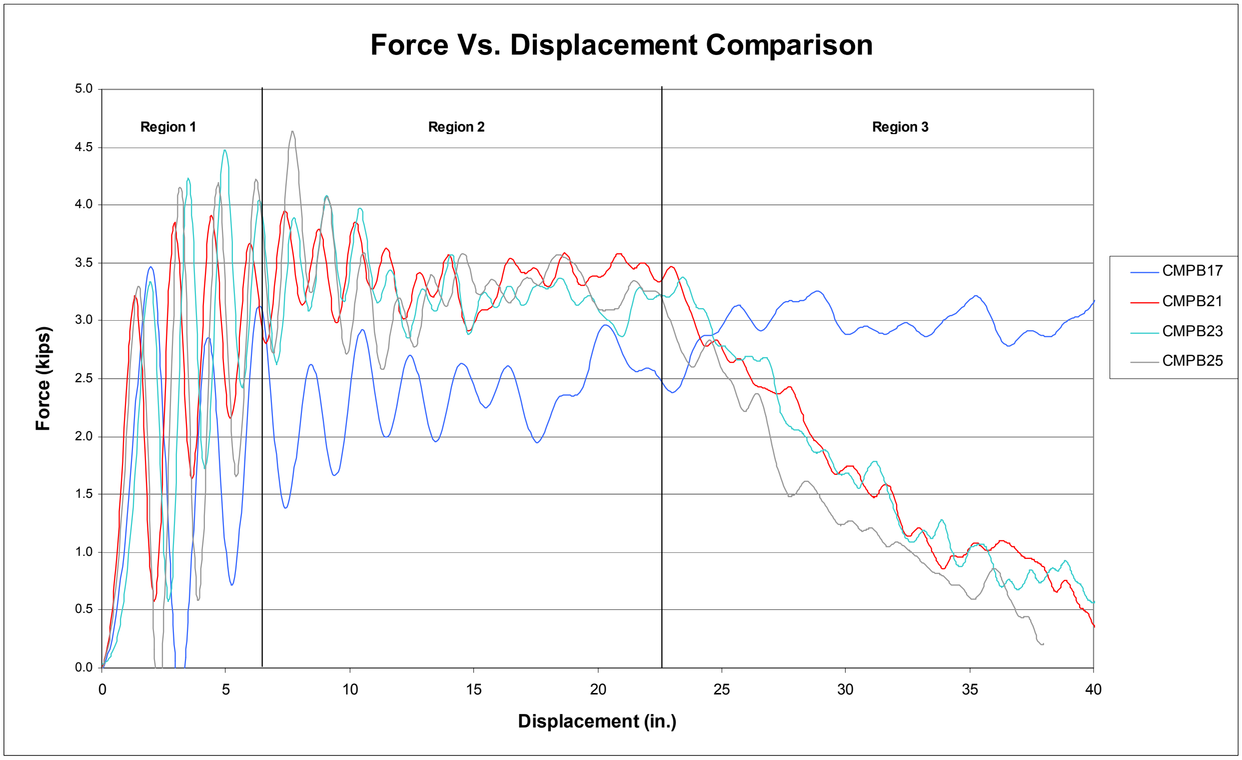
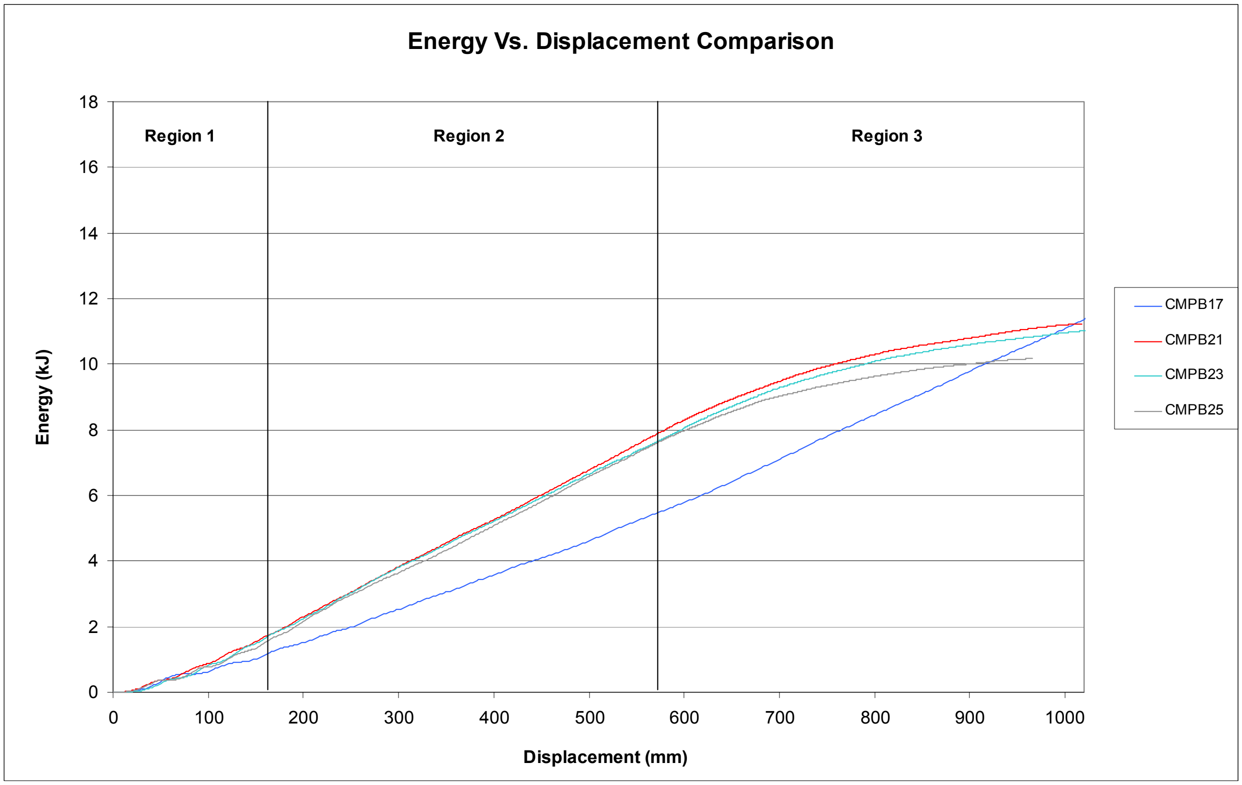
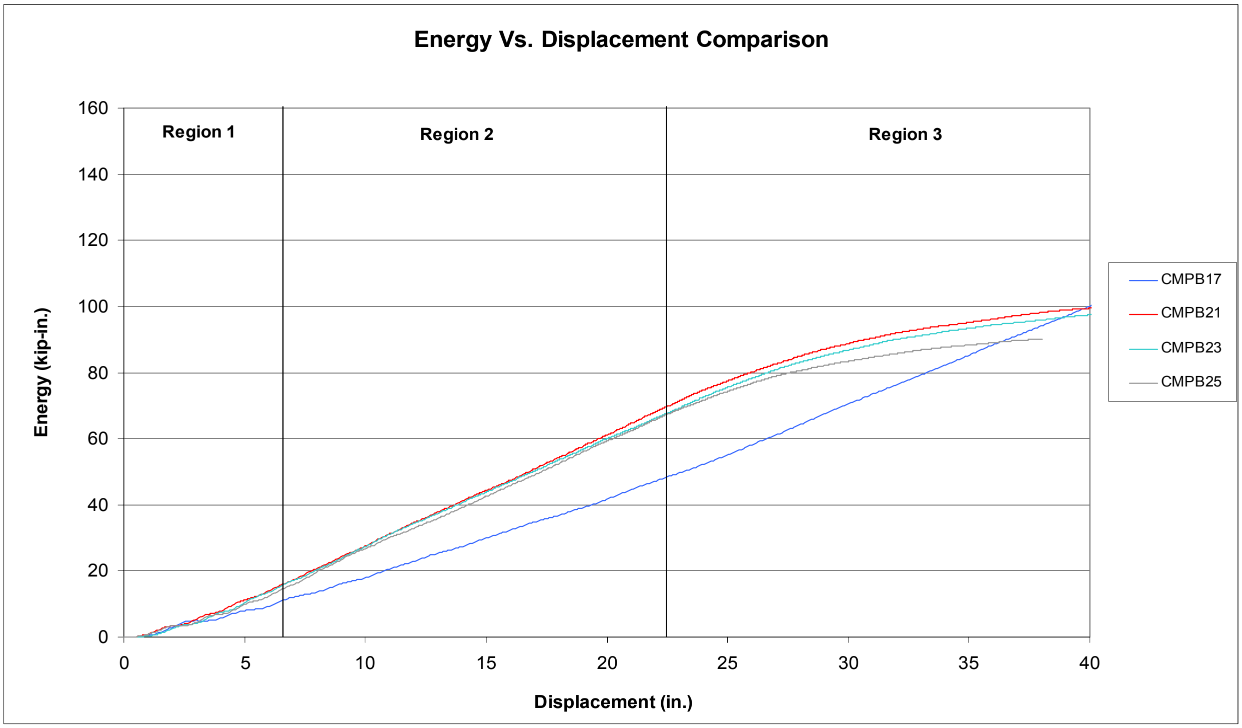


(b)

Figure 29. Force-Displacement Comparison, Test Nos. CMPB-17, CMPB-21, CMPB-23 and CMPB-25 (a) Metric (b) English

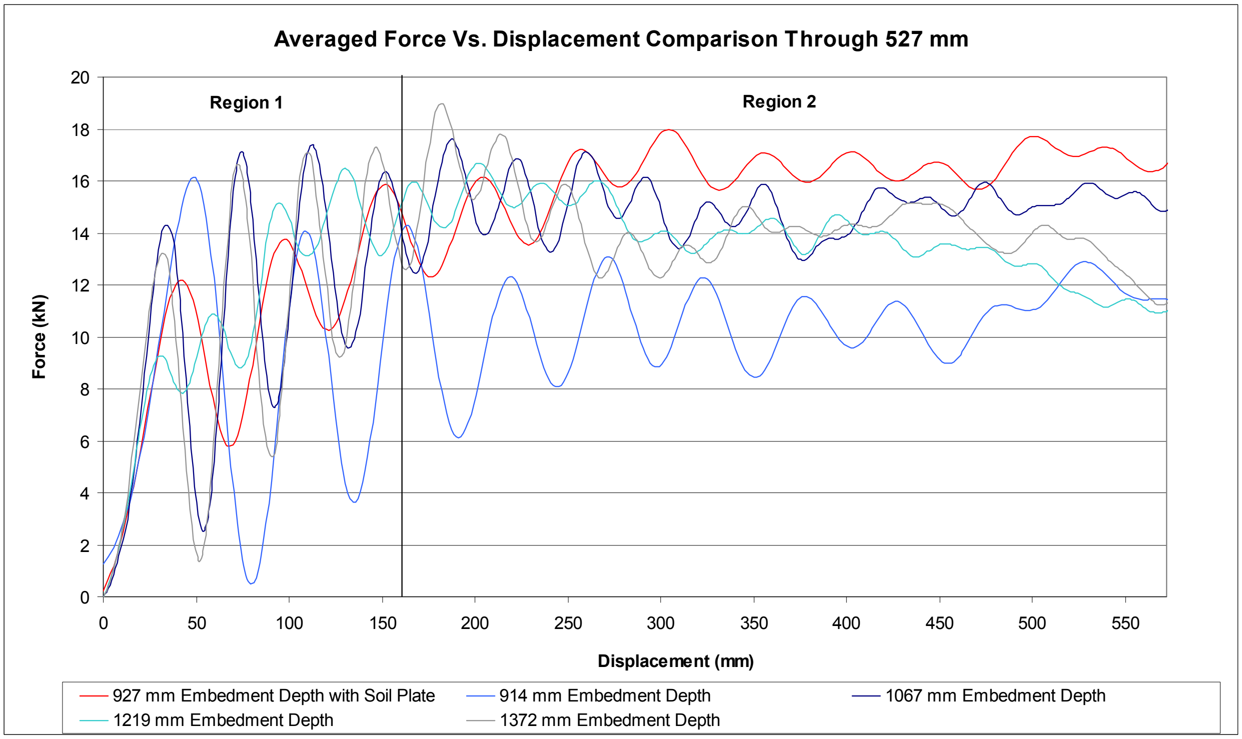


(a)



(b)

Figure 30. Energy-Deflection Comparison for Test Nos. CMPB-17, CMPB-21, CMPB-23, and CMPB-25 (a) Metric (b) English



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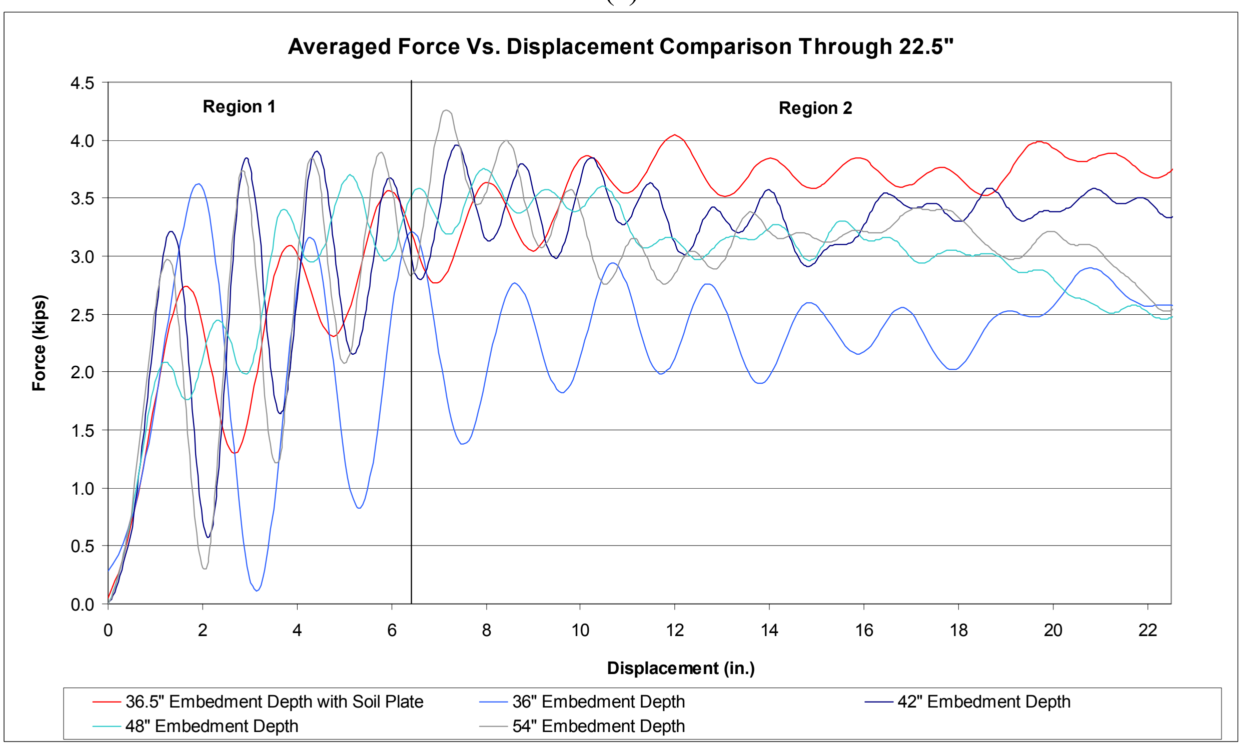
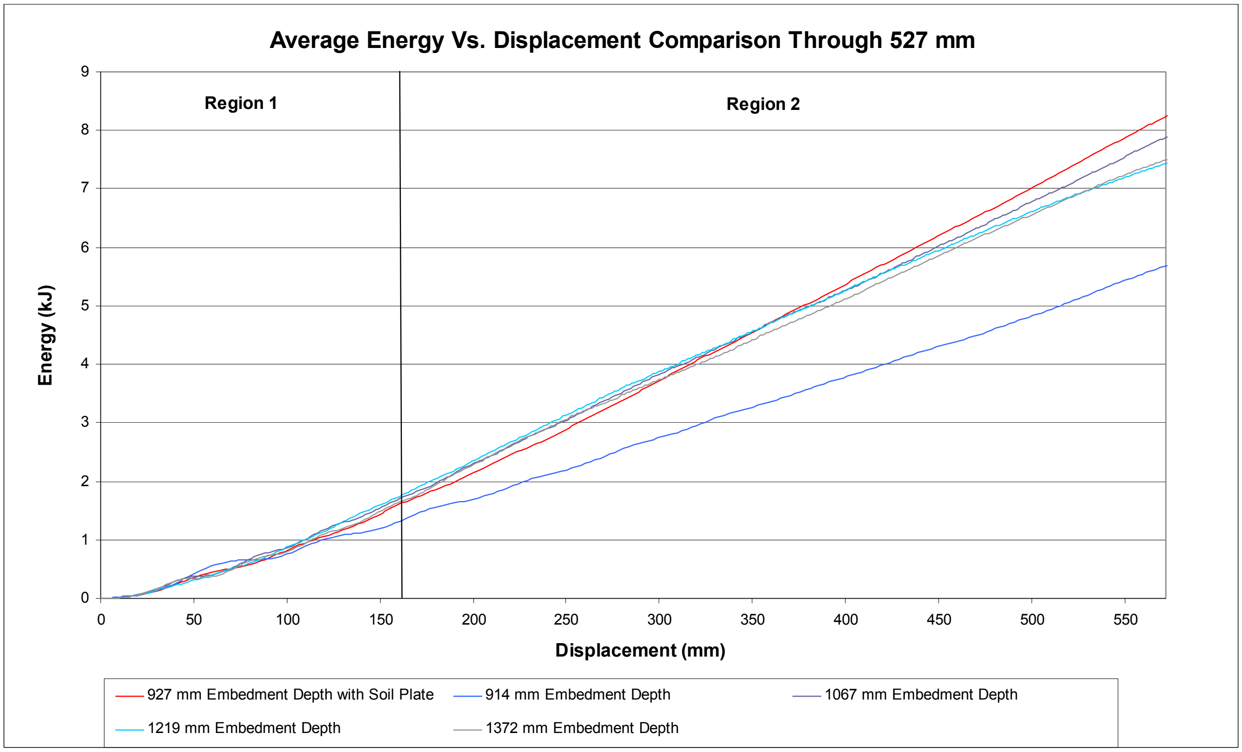


(b)

Figure 31. Force-Displacement Comparison by Embedment Depth (a) Metric (b) English



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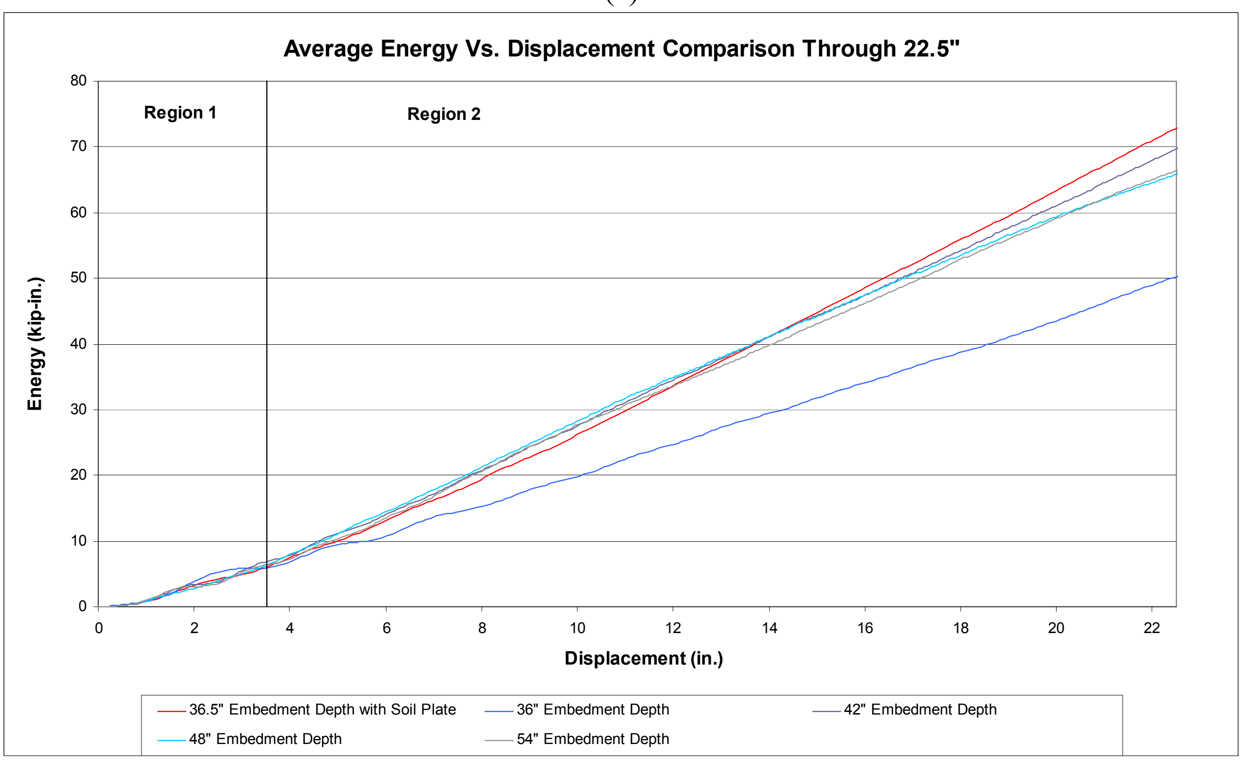


(b)

Figure 32. Energy-Displacement Comparison by Embedment Depth (a) Metric (b) English

6 CONCLUSIONS AND RECOMMENDATIONS

Ten bogie tests were performed on S76x8.5 (S3x5.7) posts of varying lengths in the soil. The embedment depth for the posts varied between 914 mm (36 in.) and 1,372 mm (54 in.), while the overall post lengths varied from 1,778 mm (5 ft-10 in.) to 2,286 mm (7 ft-6 in.). The target impact conditions for these bogie tests were at a speed of 20.9 kph (13.0 mph) and at an angle of 90 degrees to the front flange of the post, creating a classical "head-on" or full frontal impact. The results of these tests were then tabulated and discussed.

In order to measure the repeatability and accuracy of the results, each embedment depth and post length condition was tested twice. To measure the energy absorption capabilities of the posts, a baseline test with a soil plate was used to offer a standard comparison between the alternatives. It was found that the posts with attached soil plates dissipated energy throughout the entire impact event, but the energy absorption of the post depended critically on the deformation of the post. Post deformation dissipated less energy than soil displacement. While more energy was dissipated during impacts of the posts with an embedment depth of 914 mm (36 in.), the displacement of the post required to dissipate the energy exceeded 889 mm (35 in.). Conversely, the 1,981-mm (78-in.) posts with 1,067 mm (42 in.) embedment depths reacted very similarly to the baseline posts with attached soil plates through a deflection of 572 mm (22.5 in.), and dissipated only slightly less energy overall than did the posts with 914 mm (36 in.) embedment depths at a post displacement of 1016 mm (40 in.).

Based on component testing, it is believed that the 1,981-mm (78-in.) posts would have comparable performance to the standard posts with attached soil plates in an impact event. Furthermore, the 1,981-mm (78-in.) posts will be much more cost-effective to use in cable barrier applications than the standard cable post with attached soil plate. Therefore, it is recommended that the 1,981-mm (78-in.) post with a 1,027 mm (42 in.) embedment depth be used in cable barrier applications, after verifying the crash-worthy capabilities of the post through full-scale testing.

7 REFERENCES

1. Post, E.R., and Chastain, P.A., *Cost Effectiveness Comparison of Cable Guardrail vs. W-Beam Guardrail*, MwRSF Research Report TRP-03-007-82, Submitted to the Nebraska Department of Roads, Performed by the University of Nebraska-Lincoln Department of Civil Engineering, University of Nebraska-Lincoln, 1982.

2. Coon, B.A., Faller, R.K. and Reid, J.D., *Cable Barrier Literature Review*, MwRSF Research Report TRP-03-118-02, Submitted to the Midwest States' Regional Pooled Fund Program, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, 1992.

3. Hitz, R.A., et. al, *Design and Evaluation of a Cable Guardrail End Terminal System*, MwRSF Research Report No. TRP-03-133-03, Submitted to the Midwest States' Regional Pooled Fund Program, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, 2007 (draft report in progress).

4. 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.

5. Hascall, J.A., Faller, R.K., Reid, J.D., and Sicking, D.L., *Investigating the Use of Small Diameter Softwood as Guardrail Posts (Dynamic Test Results)*, MwRSF Research Report TRP-03-179-07, Submitted to the Forest Products Laboratory, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, 2007.

6. Fating, R. M., and Reid, J. R., *Dynamic Impact Testing of S75x8.5 Steel Posts (Cable Barrier Posts)*, MwRSF Research Report No. TRP-03-117-02, Submitted to the Midwest States' Regional Pooled Fund Program and the Nebraska Department of Roads, Performed by the Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, November 15, 2002.

8 APPENDICES

APPENDIX A - TEST RESULTS

A summary sheet for each test is provided in this section. Summary sheets include acceleration, velocity, and displacement verses time plots, as well as force and energy verses displacement plots.

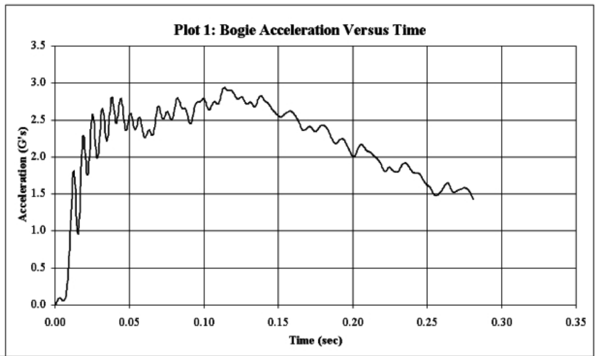
Test Parameters: Bogie Test on Cable Posts in Various Embedment Depths
Test: Strong Axis Impact at 90 Degrees
Bogie Weight: 726 kg (1600 lbs)
Target Speed: 20.9 kph (13.0 mph)
Bumper Height: 683 mm (26.875 in.)
Post Type: S76x8.5 (S3x5.7)
Post Length: Varying from 1,778 mm (5 ft. 10 in.) to 1,778 mm (7 ft. 6 in.)
Accelerometer: EDR-3 Data Recorder
Soil: 2,163 kg/m^3 (135 lbs/ft^3) NCHRP 350 (AASHTO 147-65 (1990) Grade B)

Test	Embedment Depth		Post Length		Impact Speed		Bending Axis	Soil Plate Utilized?
	mm	in.	mm	in.	kph	mph		
CMPB-18	914	36.5	1778	70	20.71	13.70	Strong Axis	Yes
CMPB-19	914	36.5	1778	70	21.47	12.78	Strong Axis	Yes
CMPB-16	927	36	1829	72	22.05	12.87	Strong Axis	No
CMPB-17	927	36	1829	72	20.57	13.34	Strong Axis	No
CMPB-20	1067	42	1981	78	22.35	13.89	Strong Axis	No
CMPB-21	1067	42	1981	78	21.65	13.45	Strong Axis	No
CMPB-22	1219	48	2134	84	23.01	14.30	Strong Axis	No
CMPB-23	1219	48	2134	84	21.49	13.36	Strong Axis	No
CMPB-24	1372	54	2286	90	20.00	12.43	Strong Axis	No
CMPB-25	1372	54	2286	90	22.43	13.94	Strong Axis	No

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	CMPB-18		
Test Date:	19-Jul-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:		Steel Cable Post	
Post Size:	S76x8.5 metric	S3x5.7	
Post Length:	177.8 cm	(70.0 in.)	
Embedment Depth:	92.7 cm	(36.5 in.)	
Category:	0		
Soil Properties			
Gradation:		NA	
Moisture Content:		?	
Compaction Method:		NA	
Soil Density, γ_d:	NA	NA	
Bogie Properties			
Impact Velocity:	6.9 m/s	(15.5 mph)	(22.7 fps)
Impact Location:	68.3 cm	(26.9 in)	above groundline
Bogie Mass:	726 kg	(1600 lbf)	
Data Acquired			
Accelerometer Data:		EDR-3	
Camera Data:		AOS 1	



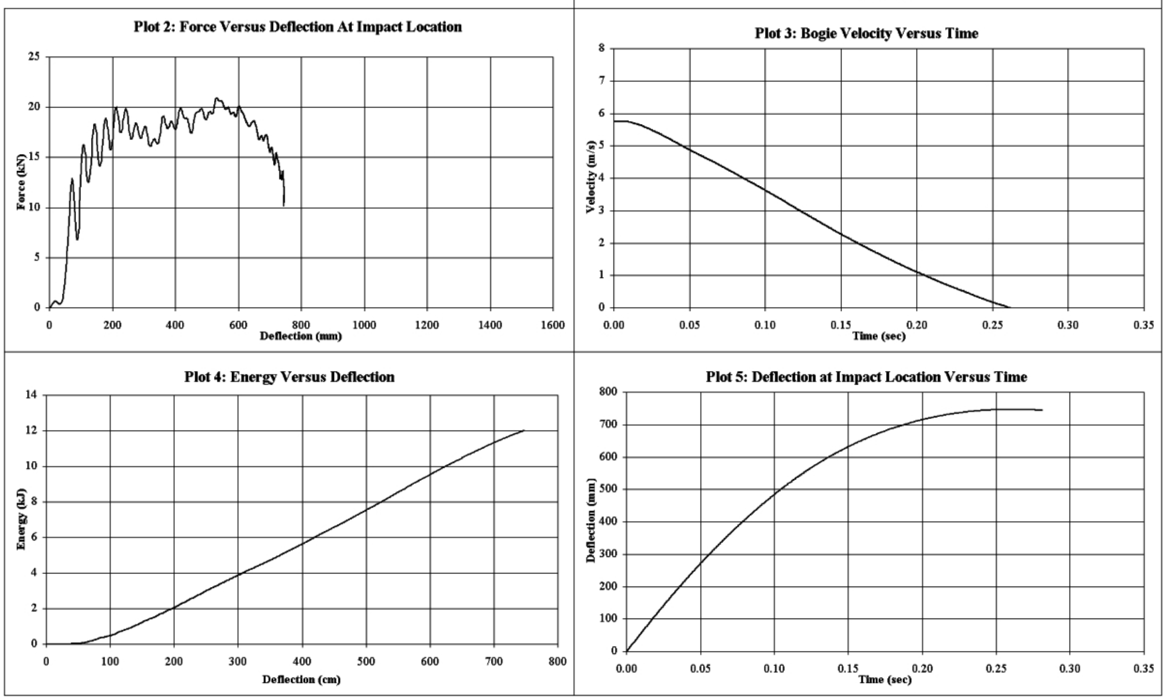


Figure A-1. Test Results – CMPB-18

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information — CL Bogie MGS Height

Test Number:	CMPB-19	
Test Date:	19-Jul-2006	
Failure Type:	Soil Failure	

Post Properties

Post Type:	Steel Cable Post	
Post Size:	S76x8.5 metric	S3x5.7
Post Length:	177.8 cm	(70.0 in.)
Embedment Depth:	92.7 cm	(36.5 in.)
Category:	0	

Soil Properties

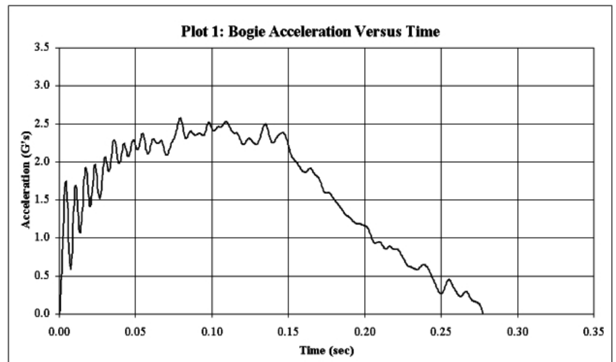
Gradation:	NA	
Moisture Content:	?	
Compaction Method:	NA	
Soil Density, γ_d:	NA	NA

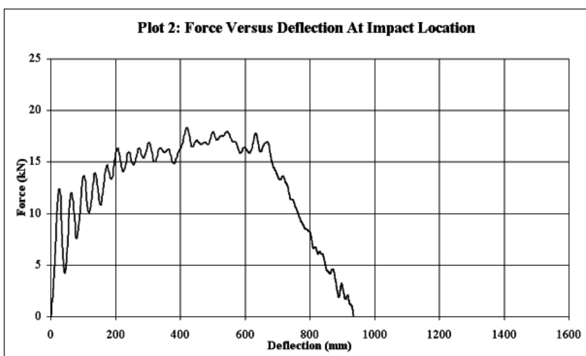
Bogie Properties

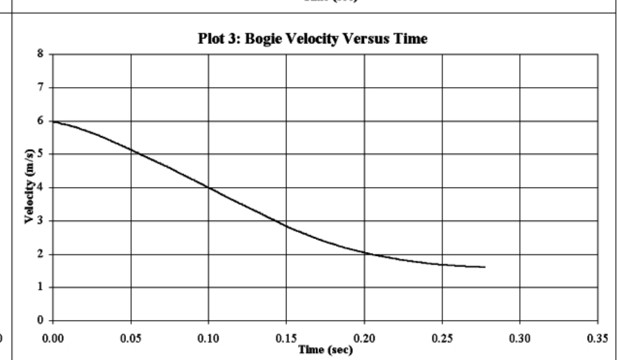
Impact Velocity:	6.9 m/s	(15.5 mph)	(22.7 fps)
Impact Location:	68.3 cm	(26.9 in)	above groundline
Bogie Mass:	726 kg	(1600 lbf)	

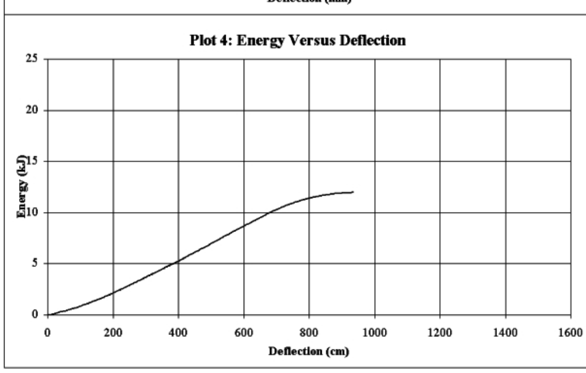
Data Acquired

Accelerometer Data:	EDR-3
Camera Data:	AOS 1









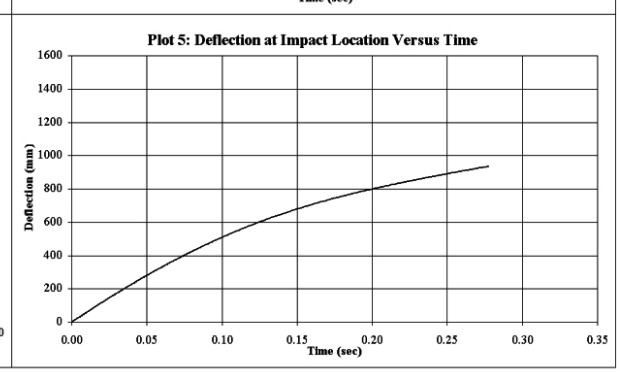
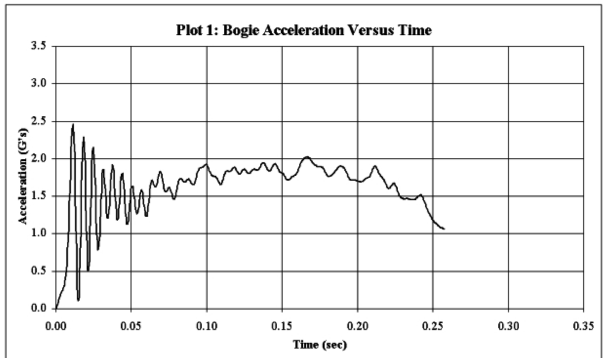


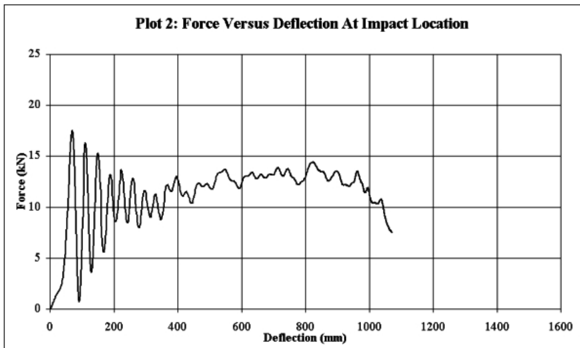
Figure A-2. Test Results – CMPB-19

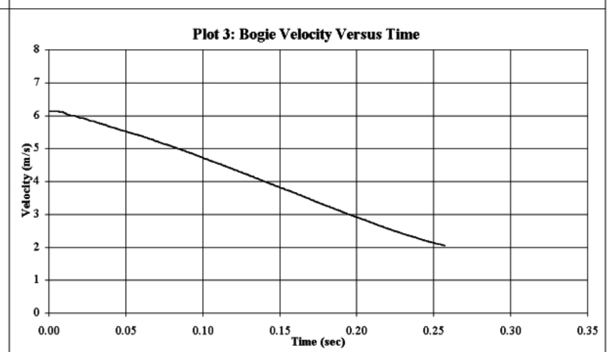
Midwest Roadside Safety Facility

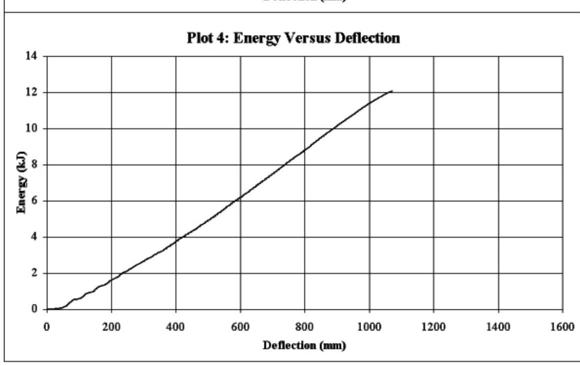
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	CMPB-16		
Test Date:	19-Jul-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:		Steel Cable Post	
Post Size:	S76x8.5	(S3x5.7)	
Post Length:	1828.8 mm	(72.0 in)	
Embedment Depth:	914.4 mm	(36.0 in)	
Category:	0		
Soil Properties			
Gradation:		NA	
Moisture Content:		NA	
Compaction Method:		NA	
Soil Density, γ_d:	NA	NA	
Bogie Properties			
Impact Velocity:	6.9 m/s	(15.5 mph)	(22.7 fps)
Impact Location:	68.3 cm	(26.9 in)	above groundline
Bogie Mass:	726 kg	(1600 lbf)	
Data Acquired			
Accelerometer Data:		EDR-3	
Camera Data:		AOS 1	









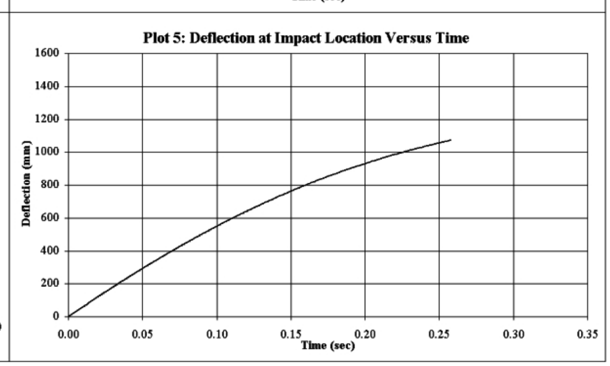
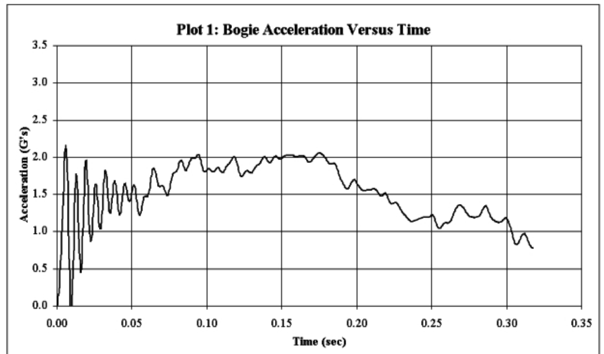


Figure A-3. Test Results – CMPB-16

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	CMPB-17		
Test Date:	19-Jul-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:		Steel Cable Post	
Post Size:	S76x8.5 metric	S3x5.7	
Post Length:	182.9 cm	(72.0 in.)	
Embedment Depth:	91.4 cm	(36.0 in.)	
Category:	0		
Soil Properties			
Gradation:		NA	
Moisture Content:		?	
Compaction Method:		NA	
Soil Density, γ_d:	NA	NA	
Bogie Properties			
Impact Velocity:	6.9 m/s	(15.5 mph)	(22.7 fps)
Impact Location:	68.3 cm	(26.9 in)	above groundline
Bogie Mass:	726 kg	(1600 lbf)	
Data Acquired			
Accelerometer Data:		EDR-3	
Camera Data:		AOS 1	



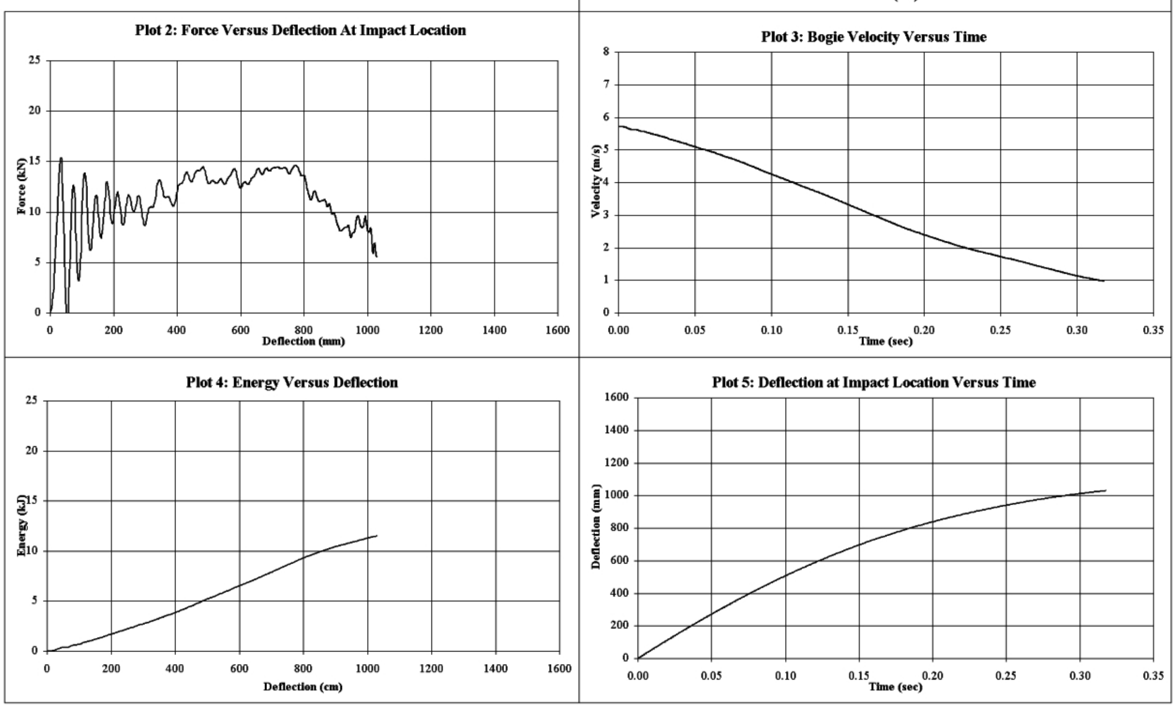


Figure A-4. Test Results – CMPB-17

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information — CL Bogie MGS Height

Test Number:	CMPB-21		
Test Date:	2-Aug-2006		
Failure Type:	Soil Failure		

Post Properties

Post Type:	Steel Cable Post		
Post Size:	S76x8.5 metric	S3x5.7	
Post Length:	198.1 cm	(78.0 in.)	
Embedment Depth:	106.7 cm	(42.0 in.)	
Category:	0		

Soil Properties

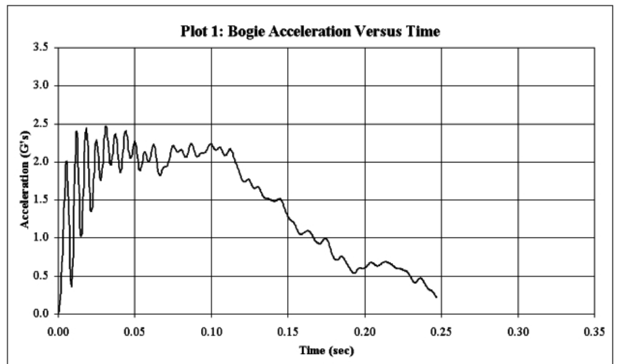
Gradation:		NA	
Moisture Content:		NA	
Compaction Method:		NA	
Soil Density, γ_d:	NA	NA	

Bogie Properties

Impact Velocity:	6.9 m/s	(15.5 mph)	(22.7 fps)
Impact Location:	68.3 cm	(26.9 in)	above groundline
Bogie Mass:	726 kg	(1600 lbf)	

Data Acquired

Accelerometer Data:	EDR-3		
Camera Data:	AOS 1		



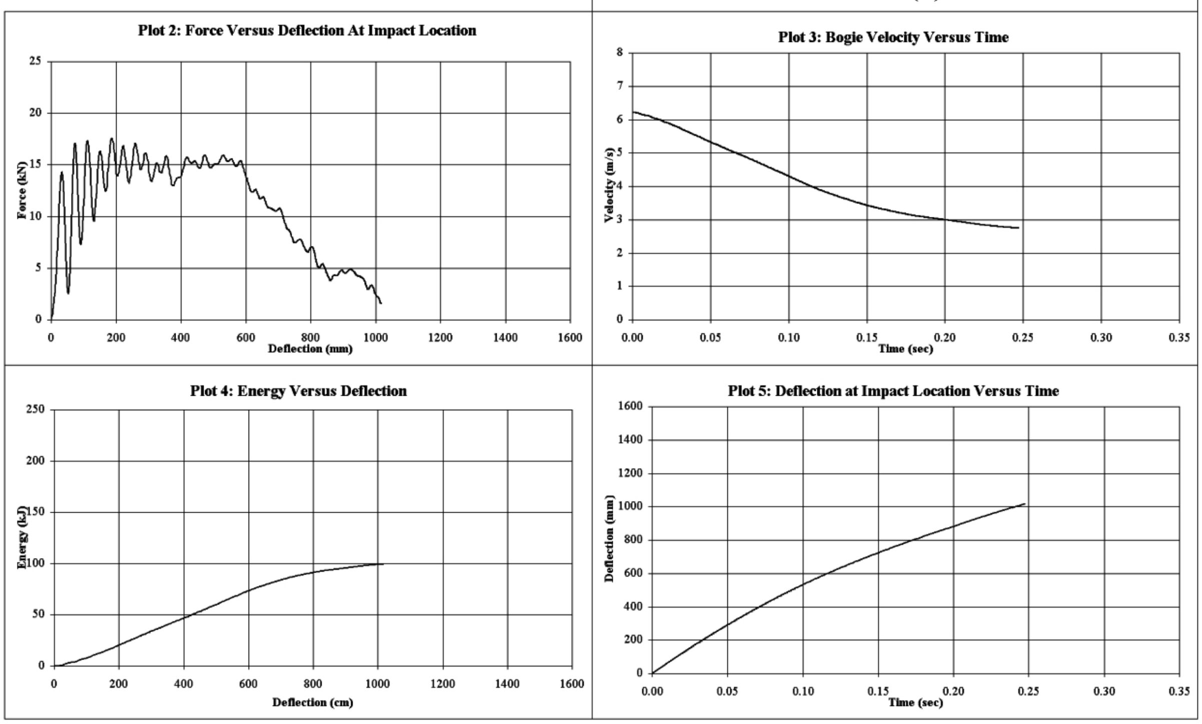


Figure A-5. Test Results – CMPB-21

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information — CL Bogie MGS Height

Test Number:	CMPB-22
Test Date:	2-Aug-2006
Failure Type:	Soil Failure

Post Properties

Post Type:	Steel Cable Post		
Post Size:	S76x8.5	metric	S3x5.7
Post Length:	213.4	cm	(84.0 in.)
Embedment Depth:	121.9	cm	(48.0 in.)
Category:	0		

Soil Properties

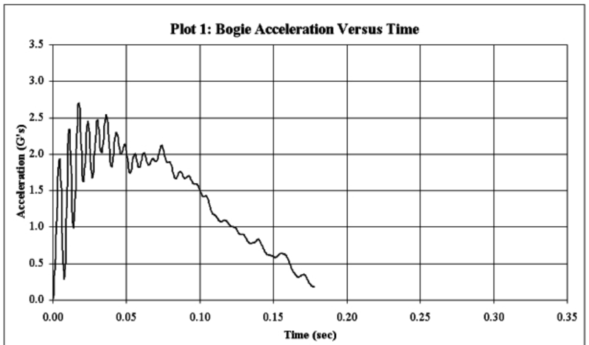
Gradation:		NA
Moisture Content:		NA
Compaction Method:		NA
Soil Density, γ_d:	NA	NA

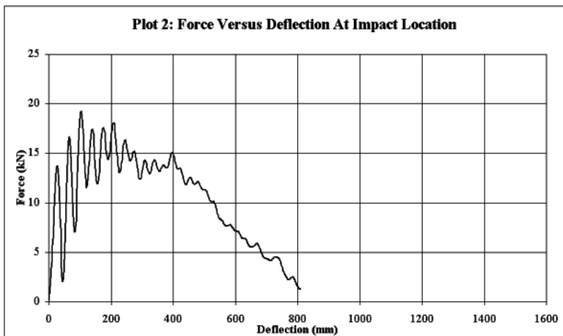
Bogie Properties

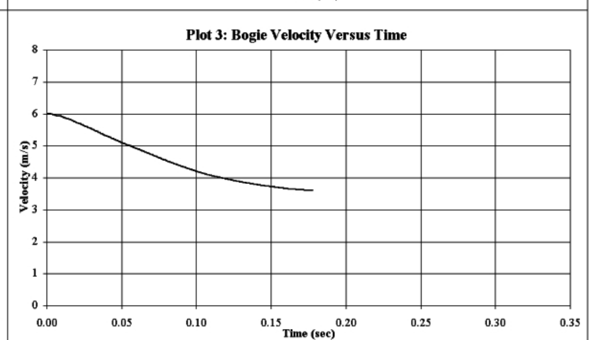
Impact Velocity:	6.9 m/s	(15.5 mph)	(22.7 fps)
Impact Location:	68.3 cm	(26.9 in)	above groundline
Bogie Mass:	726 kg	(1600 lbf)	

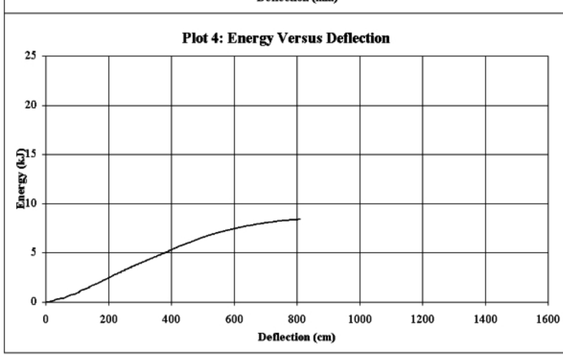
Data Acquired

Accelerometer Data:	EDR-3
Camera Data:	AOS 1









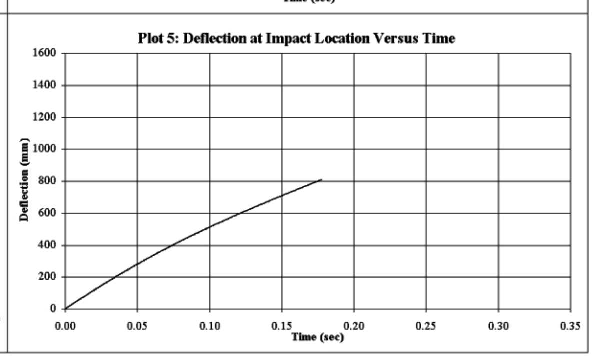


Figure A-6. Test Results – CMPB-22

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information — CL Bogie MGS Height

Test Number:	CMPB-23	
Test Date:	3-Aug-2006	
Failure Type:	Soil Failure	

Post Properties

Post Type:	Steel Cable Post	
Post Size:	S76x8.5 metric	S3x5.7
Post Length:	213.4 cm	(84.0 in.)
Embedment Depth:	121.9 cm	(48.0 in.)
Category:	0	

Soil Properties

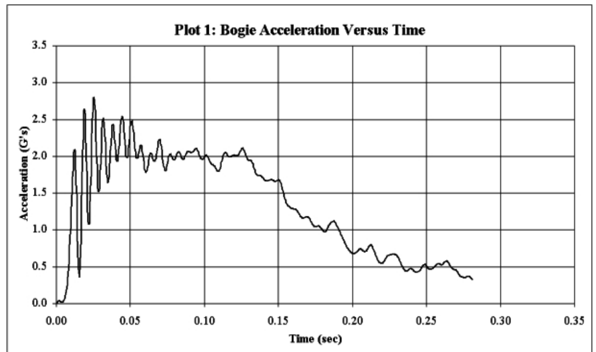
Gradation:		NA
Moisture Content:		NA
Compaction Method:		NA
Soil Density, γ_d:	NA	NA

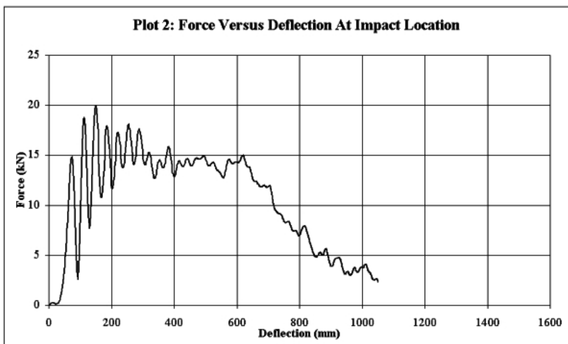
Bogie Properties

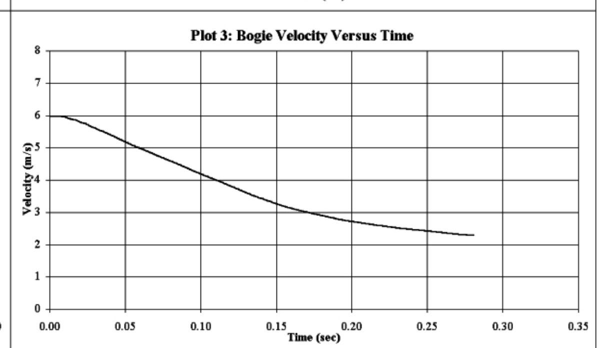
Impact Velocity:	6.9 m/s	(15.5 mph) (22.7 fps)
Impact Location:	68.3 cm	(26.9 in) above groundline
Bogie Mass:	726 kg	(1600 lbf)

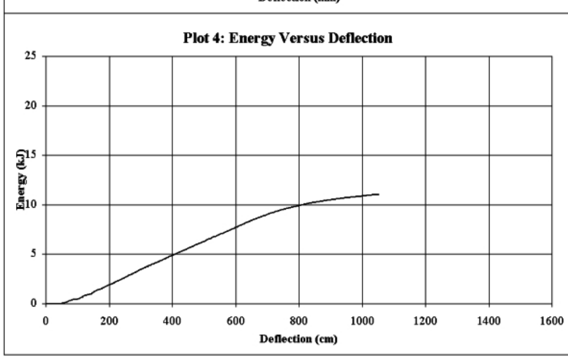
Data Acquired

Accelerometer Data:	EDR-3
Camera Data:	AOS 1









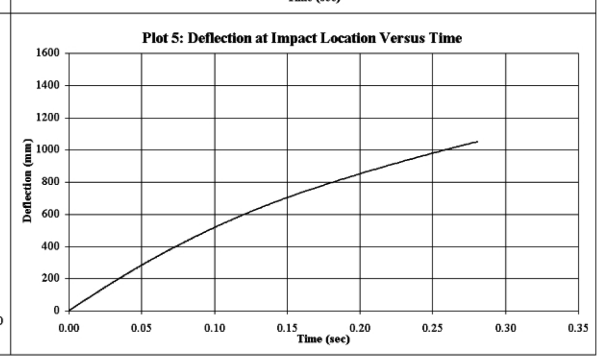
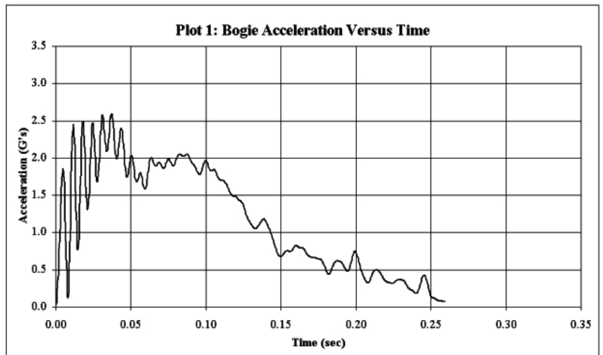


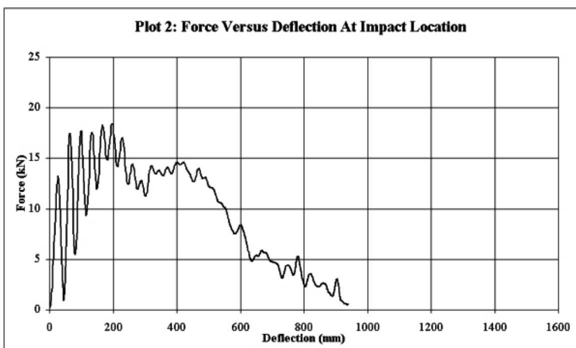
Figure A-7. Test Results – CMPB-23

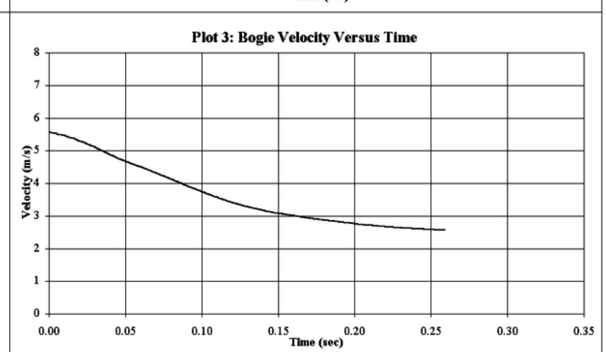
Midwest Roadside Safety Facility

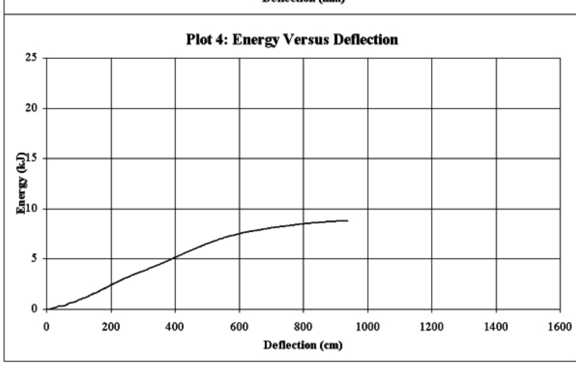
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	CMPB-24		
Test Date:	3-Aug-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:		Steel Cable Post	
Post Size:	S76x8.5 metric		S3x5.7
Post Length:	228.6 cm		(90.0 in.)
Embedment Depth:	137.2 cm		(54.0 in.)
Category:	0		
Soil Properties			
Gradation:		NA	
Moisture Content:		NA	
Compaction Method:		NA	
Soil Density, γ_d:	NA		NA
Bogie Properties			
Impact Velocity:	6.9 m/s	(15.5 mph)	(22.7 fps)
Impact Location:	68.3 cm	(26.9 in)	above groundline
Bogie Mass:	726 kg	(1600 lbf)	
Data Acquired			
Accelerometer Data:		EDR-3	
Camera Data:		AOS 1	









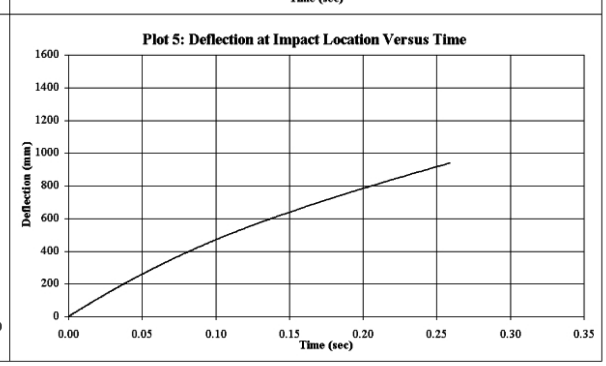


Figure A-8. Test Results – CMPB-24

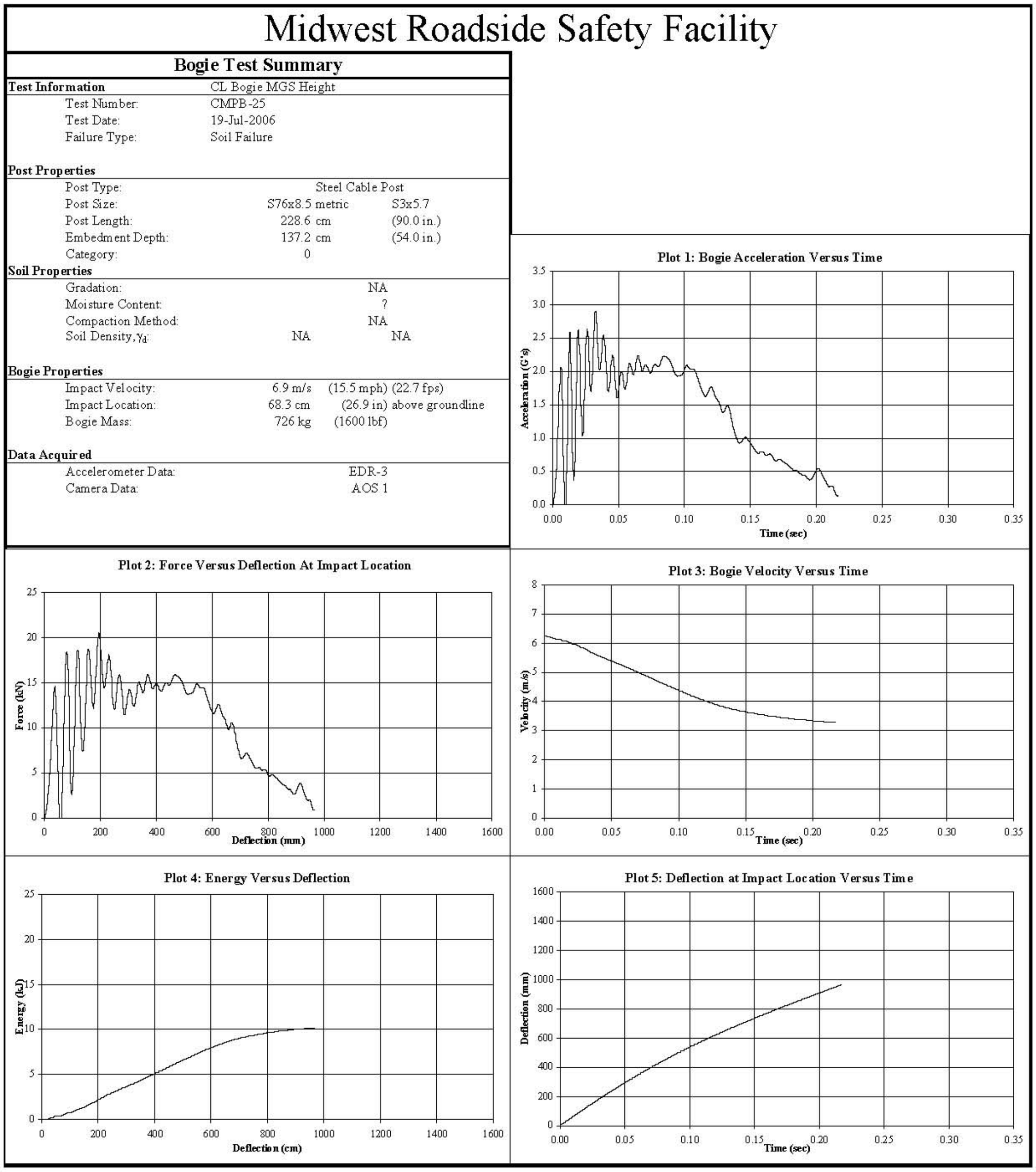


Figure A-9. Test Results – CMPB-25