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DYNAMIC IMPACT TESTING OF W152x13.4 (W6x9) STEEL POSTS ON A 2:1 SLOPE

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16. Abstract (Limit: 200 words)

Dynamic impact testing of W152x13.4 (W6x9) steel posts at various embedment depths has been detailed, and the results stated. A total of 17 bogie tests have been performed on a 2:1 slope, with post lengths varying from 1,829 mm (6 ft) through 2,743 mm (9 ft). A total of four bogie tests were performed on level terrain using 1,829-mm (6-ft) long steel posts at two different impact speeds. For each bogie test, raw acceleration data, obtained from accelerometers, was filtered and then force-displacement and energy-displacement graphs were plotted. From the energy-displacement graphs, the average post-soil forces were calculated for a 381-mm (15-in.) displacement at the center rail height. Post-soil forces were then compared to the required post capacity of 28.5 kN (6.4 kips), including energy dissipation characteristics, for the MGS placed on level terrain. From these comparisons, a recommended post length was selected for standard post spacing. A 2,743-mm (9-ft) long post with a 1,930-mm (76-in.) embedment depth was found to best meet the post requirements, while providing an average force of 28.42 kN (6.39 kips). As such, this post configuration was recommended for evaluation using computer simulation modeling.

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1 INTRODUCTION

1.1 Background

The original strong-post, W-beam guardrail system, developed for use on the break line of a 2:1 fill slope, utilized a ½-post spacing and 2,134-mm (7-ft) long guardrail posts [1-2]. A full-scale crash test was performed with a ¾-ton pickup truck on the guardrail system and was determined to be acceptable according to the TL-3 safety performance criteria presented in NCHRP Report No. 350 [3].

From 2000-2002, the Midwest Roadside Safety Facility (MwRSF) developed a new strong-post, W-beam guardrail system, now known as the Midwest Guardrail System (MGS) [4-6]. Through testing, the MGS guardrail system has proven to significantly reduce the propensity for vehicle instabilities during redirection, vehicle snag, as well as rail rupture. Hence, further research was recommended in order to develop the MGS barrier for use on a 2:1 slope. However, any further efforts should be aimed at reducing the number of guardrail posts and hence the overall installation cost.

For this study, it will be necessary to conduct several dynamic bogie tests of steel posts placed at the slope break point of a 2:1 fill slope and using varying embedment depths. The results from these post-soil bogie tests will later be used to create input data for use in studying vehicle-to-barrier impacts into the MGS barrier as well as to aid in the new barrier design. Following any computer simulation modeling, it is anticipated that the modified barrier system will be subjected to full-scale vehicle crash testing according to the new impact safety standards contained in the Update to NCHRP Report No. 350 [7].

1.2 Objective

The objective of the research project was to determine the dynamic properties of the post-soil interaction for W152x13.4 (W6x9) posts at various embedment depths or under different impact speeds. Once completed, the test results can be used to: (1) determine the appropriate embedment depth for the Midwest Guardrail System when placed on a 2:1 slope and (2) prepare input data for use in BARRIER VII computer simulation modeling [8].

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 insights for both component and system behavior using this tool. If used properly, the researcher can better understand the practicality of the design, since physical testing often gives an accurate representation of the behavior of the design.

2.2 Testing Facility

Physical testing of W152x13.4 (W6x9) steel posts on a 2:1 slope and flat terrain was performed at the MwRSF's outdoor testing facility located at the Lincoln airpark, on the northwest side of the Lincoln Municipal Airport. The testing 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 tests MGS2-1B1 through MGS2-1B14 were at a speed of 24.14 km/h (15 mph), tests MGS2-1B15 through MGS2-1B17 at 27.39 km/h (17 mph), tests MGS2-1B18 and MGS2-1B19 were at 24.14 km/h (15 mph), and tests MGS2-1B20 and MGS2-1B21 were at 32.19 km/h (20 mph). All tests were at an angle of 0.0 degrees (strong axis), creating a classical "head-on" or full frontal impact. The posts were impacted 632 mm (24.875 in.) above the ground line perpendicular to the face of the post. This impact height was chosen since it represents the center rail height of the MGS. The scope of the physical testing is listed in Table 1.

A total of 21 tests were conducted. The post testing pit for test nos. MGS2-1B1 through MGS2-1B14 was determined to be not large enough. For these tests, the posts were found to contact the backslope of the testing pit, as shown in Figure 1. This post contact was not desired and resulted in compromised data for the initial tests. Therefore, three additional tests (MGS2-1B15 through MGS2-1B17) were conducted with a different test setup which eliminated the propensity for the posts to contact the back side of the test pit. Finally, four additional tests (MGS2-1B18 through MGS2-1B21) were conducted to evaluate post-soil behavior at two different impact speeds on level terrain.

Through the years, bogie testing of guardrail posts placed in soil has been performed at a speed of approximately 8.93 m/s (20 mph). More recently, bogie impact speeds have been reduced to 6.71 m/s (15 mph) in order to reduce inertial effects from the test results. As such, the four additional bogie tests were performed to determine whether or not the reduced bogie speed significantly influenced post performance.

Diagrams for all three test layouts are given in Section 3.4. The post length varied from 1,829 mm (6 ft) to 2,743 mm (9 ft), and the embedment depth varied from 1,016 mm (40 in.) to 1,930 mm (76 in.). The results for identical embedment depths are over-plotted and shown graphically in Section 4.1.

Table 1. Scope of Physical Testing

Test No.	Post Size		Embedment Depth		Speed		Bending Axis
	(ft)	(mm)	(in.)	(mm)	(mph)	(m/s)	
MGS2-1B1	6.0	1829	40.0	1016	15.40	6.88	Strong
MGS2-1B2	6.5	1981	46.0	1168	15.08	6.74	Strong
MGS2-1B3	7.0	2134	52.0	1321	15.59	6.97	Strong
MGS2-1B4	7.5	2286	58.0	1473	15.51	6.93	Strong
MGS2-1B5	8.0	2438	64.0	1626	15.47	6.92	Strong
MGS2-1B6	8.5	2591	70.0	1778	14.81	6.62	Strong
MGS2-1B7	9.0	2743	76.0	1930	15.10	6.75	Strong
MGS2-1B8	7.0	2134	52.0	1321	15.31	6.84	Strong
MGS2-1B9	6.5	1981	46.0	1168	15.32	6.85	Strong
MGS2-1B10	6.0	1829	40.0	1016	16.06	7.18	Strong
MGS2-1B11	7.5	2286	58.0	1473	15.51	6.93	Strong
MGS2-1B12	8.0	2438	64.0	1626	15.41	6.89	Strong
MGS2-1B13	8.5	2591	70.0	1778	15.89	7.10	Strong
MGS2-1B14	9.0	2743	76.0	1930	15.75	7.04	Strong
MGS2-1B15	8.0	2438	64.0	1626	17.34	7.75	Strong
MGS2-1B16	9.0	2743	76.0	1930	17.22	7.70	Strong
MGS2-1B17	9.0	2743	76.0	1930	17.58	7.86	Strong
MGS2-1B18	6.0	1829	40.0	1016	15.40	6.88	Strong
MGS2-1B19	6.0	1829	40.0	1016	15.91	7.11	Strong
MGS2-1B20	6.0	1829	40.0	1016	19.33	8.64	Strong
MGS2-1B21	6.0	1829	40.0	1016	19.82	8.86	Strong

Figure 1. Impacted Post Contacting Backslope of Testing Pit

3 SYSTEM DETAILS

3.1 Steel Post

The posts under study were W152x13.4 (W6x9) beams manufactured using ASTM A36 steel with a cross-section in accordance with the A6M standards. The posts consisted of the three major components: a rear or compression flange, a front or tensile flange, and a web which connects the two flanges and act like a force transmitter. The flanges are called either tensile or compressive depending on the type of loading it undergoes upon impact. The thickness of the webbing was 4.32 mm (0.17 in.) while the thicknesses of the flanges were generally 5.46 mm (0.215 in.). The post length varied from 1,829 mm (6 ft) to 2,743 mm (9 ft). The cross-section of a W152x13.4 (W6x9) post is shown in Figure 2, and various material properties for the posts are provided in Table 2.

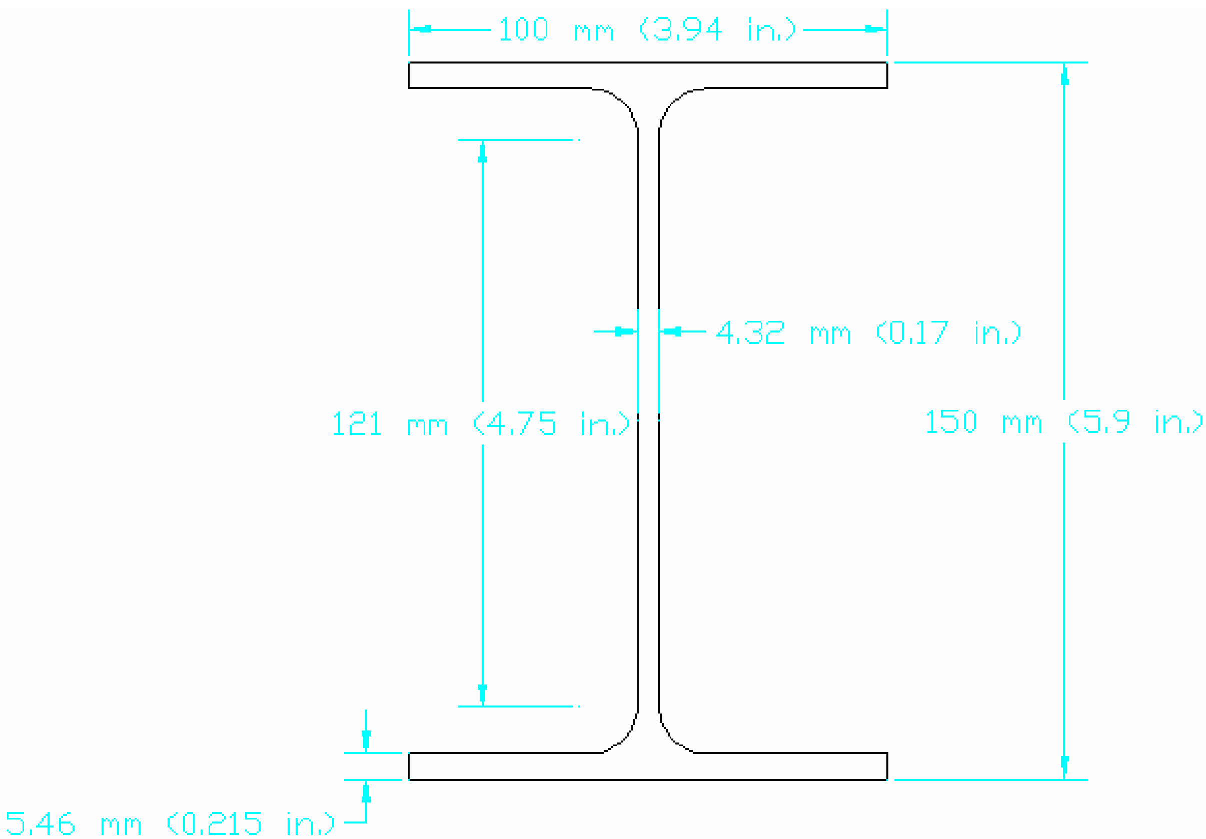


Figure 2. W152x13.4 (W6x9) Cross-Section Dimensions

Table 2. Material Properties of W152x13.4 (W6x9) Post

ASTM Designation	Area, A mm^2 ($in.^2$)	Flange Width, bf mm (in.)	Moment of Inertia, Ix mm^4 ($in.^4$)	Section Modulus, Sx mm^3 ($in.^3$)	Plastic Section Modulus, Zx mm^3 ($in.^3$)
W152x13.4 (W6x9)	1,729 (2.68)	100 (3.94)	$6.83x10^6$ (16.40)	$9.11x10^4$ (5.56)	$1.02x10^5$ (6.23)

3.2 Soil Material

A crusher run coarse aggregate material consisting of gravel and crushed limestone was used for filling the excavated pit area. The soil conformed to AASHTO standard specifications for "Materials for Aggregate and Soil Aggregate Sub-base, Base, and Surface Courses," designation M 147-65 (1990), grading B. The moisture content was 4.7 percent for test no. MGS2-1B1, 4.43 percent for test nos. MGS2-1B2 through MGS2-1B4, 4.5 percent for test nos. MGS2-1B5 through MGS2-1B14, and 5.5 percent for test no. MGS2-1B17. For test nos. MGS2-1B18 through MGS2-1B21 moisture measurements were taken and were deemed optimum for the soil used.

3.3 Equipment and Instrumentation

A variety of equipment and instrumentation was used to record and collect data. It was important to gather correct data using affordable instrumentation in order to understand and derive meaningful conclusions from the physical tests. The main equipment and instruments used for the tests were:

- Bogie
- Accelerometer
- Pressure Tape Switches
- Photography Cameras

3.3.1 Bogie Vehicle

A rigid-frame bogie was used to impact the posts. The bogie head was constructed of 203-mm (8-in.) diameter, 12.5-mm (0.5-in.) thick standard steel pipe, with 19-mm (0.75-in.) thick neoprene belting wrapped around the pipe to prevent local damage to the post from the impact. The impact head was bolted to the bogie vehicle, thus creating a rigid frame. The bogie with the impact head is shown in Figure 3. The weight of the bogie, with the addition of the mountable impact head, was 728 kg (1,605 lbs). The impact height was 632 mm (24.875 in.) above the ground. The target speed was either 24.14 km/h (15 mph), 27.39 km/h (17 mph), or 32.19 km/h (20 mph).

For test nos. MGS2-1B1 through MGS2-1B14 and test nos. MGS2-1B18 through MGS2-1B21, a pickup truck with a reverse cable tow system was used to propel the bogie. When the bogie reached the end of the guidance system, it was released from the tow cable, allowing it to be free rolling when it impacted the post. For test nos. MGS2-1B15 through MGS2-1B17, the bogie was pushed along a guardrail track. A remote braking system was installed on the bogie, thus allowing it to be safely brought to rest after the test.

Figure 3. Bogie and Test Setup

3.3.2 Accelerometer

The initial velocity and the accelerometer data were used to determine the forces, velocity, displacement, and energy absorbed by the post during the impact. Although the accelerometer was located at the center of gravity of the bogie and measured the acceleration of the bogie's center of gravity, this data was used to approximate the post-soil forces at the point of impact using Newton's Second Law.

A tri-axial piezo-resistive accelerometer system with a range of ± 200 G's was mounted on the frame of the bogie at approximately the center of gravity. It measured the accelerations in the longitudinal, lateral, and vertical directions. The accelerometer system, known as the Model EDR-3, was developed by Instrumented Sensor Technology (IST) of Okemos, Michigan.

The EDR-3 is a self-contained, user programmable acceleration sensor/recorder with a 74dB dynamic range. During active recording, acceleration signals are digitized to 10-bit resolution and stored in digital memory onboard the unit. The EDR-3 was configured with 256 KB of RAM and was set to sample data at 3,200 Hz. The EDR-3 offers recording capability from three input channels simultaneously. Analog low-pass filtering was used internally in the EDR-3 to condition the input signal. A Butterworth low-pass filter with a –3dB cut-off frequency of 1120 Hz was used for anti-aliasing. The EDR-3 had a maximum cross axis sensitivity of ±3%.

A laptop computer downloaded the raw acceleration data immediately following each test. The computer made the use of "DynaMax 1.75" accelerometer software [9] and then loaded into "DADiSP 4.0" data processing program [10]. The data was processed as per the SAE J211/1 specifications [11]. The details of these specifications are discussed in the subsequent chapter of data processing.

3.3.3 Pressure Tape Switches

For test nos. MGS2-1B1 through MGS2-1B17 three pressure tape switches, spaced at 1-meter (3.3-ft) intervals, were used to determine the speed of the bogie before the impact. For test nos. MGS2-1B18 through MGS2-1B21 five pressure tapes switches, spaced at 0.457 meters (1.5-ft) intervals were used. As the bogie's left-front tire passed over each tape switch, a strobe light was fired, sending an electronic timing signal to the data acquisition system. Test speeds were determined using the time between these signals and the distance between the switches.

3.3.4 Photography Camera

One high-speed digital VITcam video camera, with a Sigma 24-70 mm lens and an operating speed of 500 frames/sec, was located perpendicular to the post impact direction. One JVC digital video camera, with an operating speed of 29.97 frames/sec, was also used to film the bogie test.

3.4 Methodology of Testing

A total of 21 impact tests were carried out with respect to the strong axis of bending and at different embedment depths, varying from 1,016 mm (40 in.) to 1,930 mm (76 in.). The test parameters are shown below.

Test Parameters: MGS Bogie Test on 2:1 Slope
Test: Strong-Axis Impact at 0 degrees
Bogie Weight: 728.0 kg (1605.0 lbs)
Target Speed: 24.14 km/h (15 mph)
Bumper Height: 635 mm (25 in.)
Post Type: W152x13.4 (W6x9)
Post Length: Varying from 1,829 mm (6 ft) to 2,743 mm (9 ft)
Accelerometer: EDR-3 Data Recorder
Soil: 2,163 kg/m^3 (135 lbs/ft^3) NCHRP 350 (AASHTO 147-65 (1990) Grade B)

Three different test setups were used to conduct the tests. The test setup for test nos. MGS2-1B1 through MGS2-1B14 is shown in Figure 4. The test setup for test nos. MGS2-1B15 through MGS2-1B17 is shown in Figure 5. As previously noted, the test setup was changed following the completion of the data analysis of the first 14 tests. This change, consisting of an increased size of the sloped fill section behind the posts, eliminated the propensity for the posts to contact the back side of the test pit. All other parameters remained the same. The test setup for test nos. MGS2-1B18 through MGS2-1B21 is shown in Figure 6. This test setup is different from the first two setups in that the posts were installed in level terrain. As previously noted, these additional four tests were conducted in order to evaluate post-soil behavior at both 6.71 and 8.93 m/s (15 and 20 mph) impact speeds.

3.5 End of Test Determination

When the bogie overrode the post, the end of the test could not be the entire duration of the contact between the post and the bogie head. This is because a portion of the force is consumed to lift the bogie in the vertical direction. When the bogie head initially impacts the post, the force exerted by the bogie is directed perpendicular to the face of the post. As the post begins to rotate, however, the bogie head is no longer perpendicular to the face of the post and begins to slide along the face of the post as shown in Figure 7**.**

In addition to the variation due to the changing angle of impact, the neoprene on the bogie head, used to minimize 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 the contact forces rather than the actual center of gravity forces it truly observes, additional error was induced into the data. Consequently only the initial portion of the accelerometer trace was used.

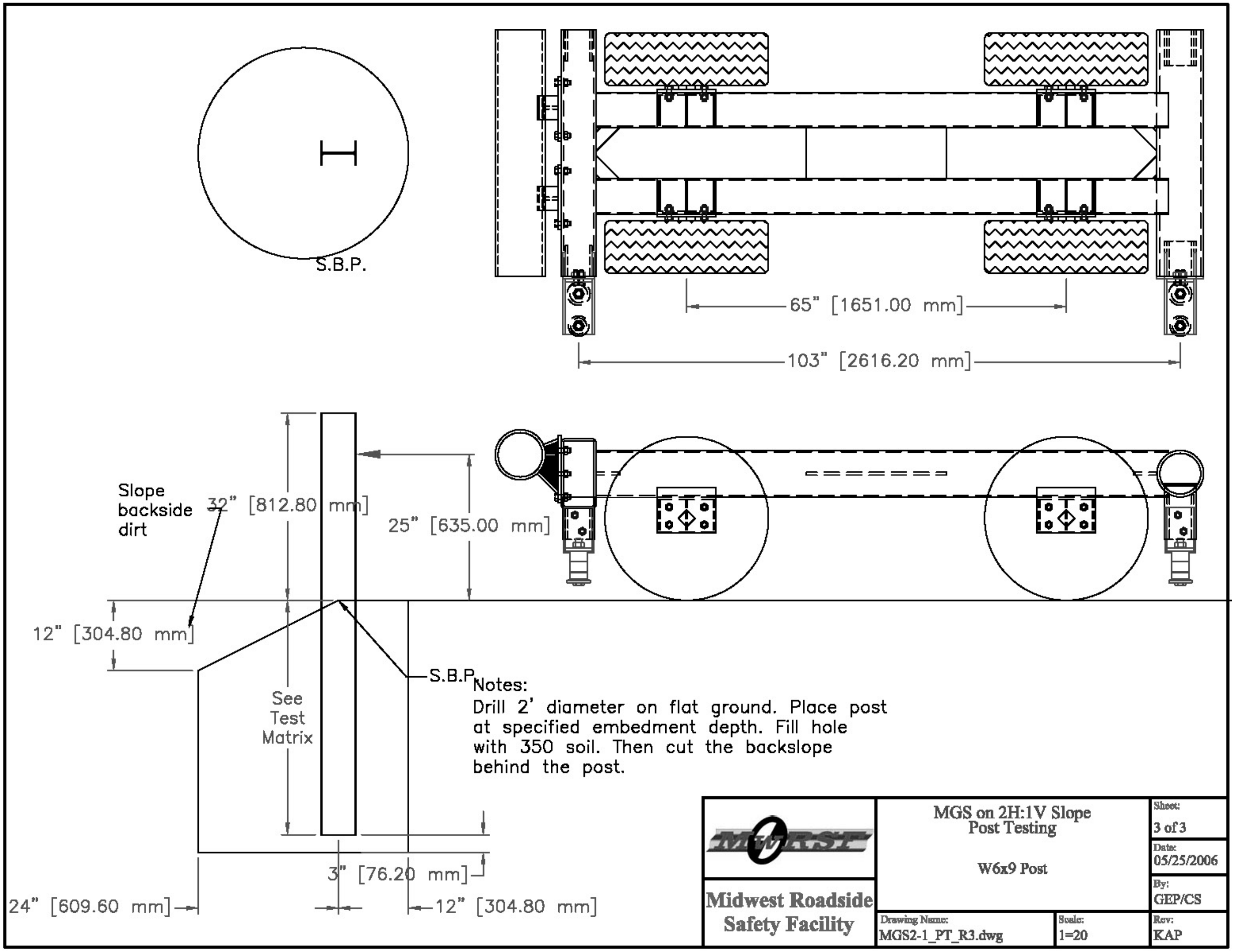


Figure 4. Test Setup for Test Nos. MGS2-1B1 to MGS2-1B14

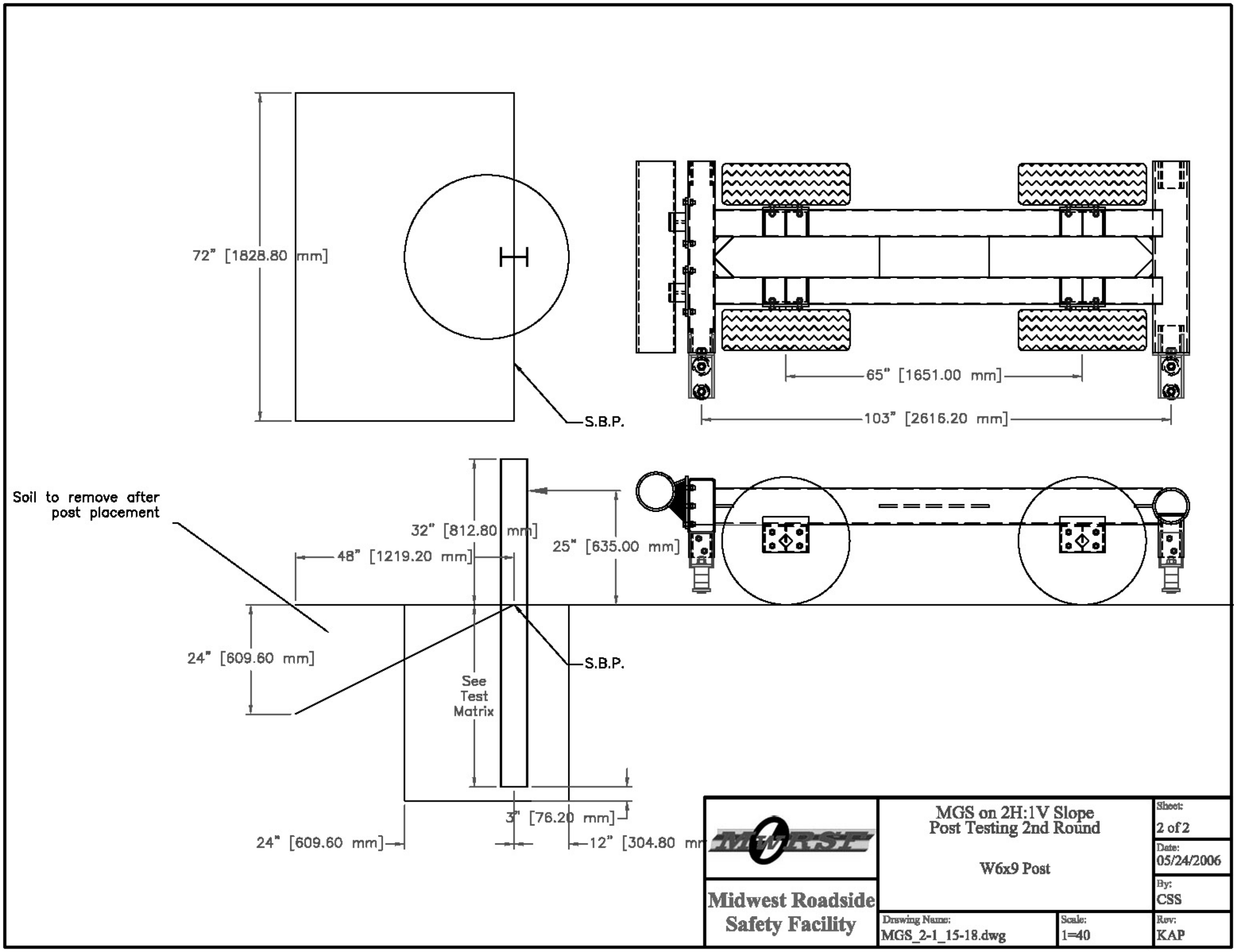
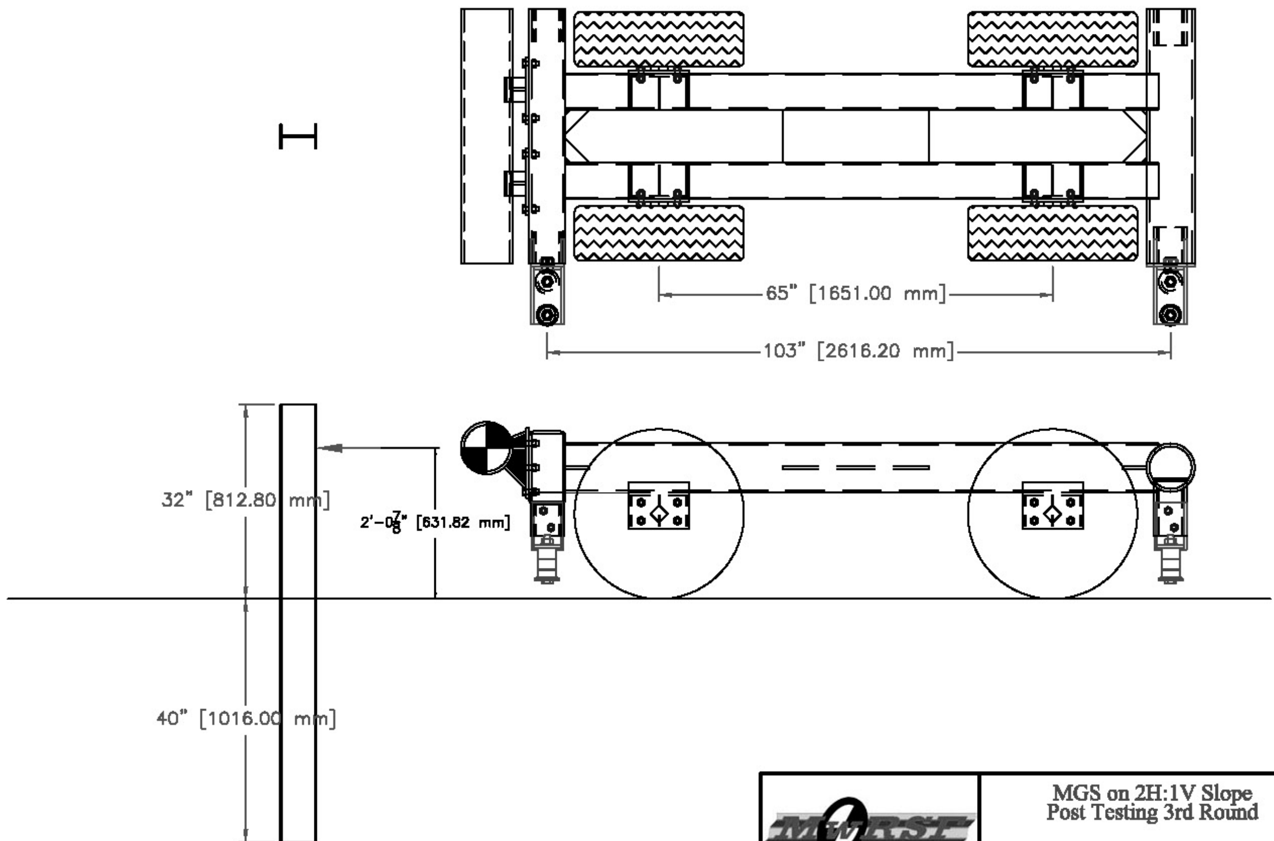


Figure 5. Test Setup for Test Nos. MGS2-1B15 to MGS2-1B17

Number of Tests	Impact Speed (km/h)	Impact Orientation	Post Placement	Post Length (mm)	Embedment Depth (mm)	Post Specifications
2	24.14	Strong Axis	Strong Soil	1828.8	1016	W152x13.4
2	32.19	Strong Axis	Strong Soil	1828.8	1016	W152x13.4



Midwest Roadside Safety Facility

MGS on 2H:1V Slope
Post Testing 3rd Round

Post Details &
Test Matrix

Sheet: 1 of 2
Date: 09/22/2006
By: CSS
Drawing Name: MGS_2-1speed.dwg
Scale: 1=25
Rev: KAP/RKF

Figure 6. Test Setup for Test Nos. MGS2-1B18 to MGS2-1B21

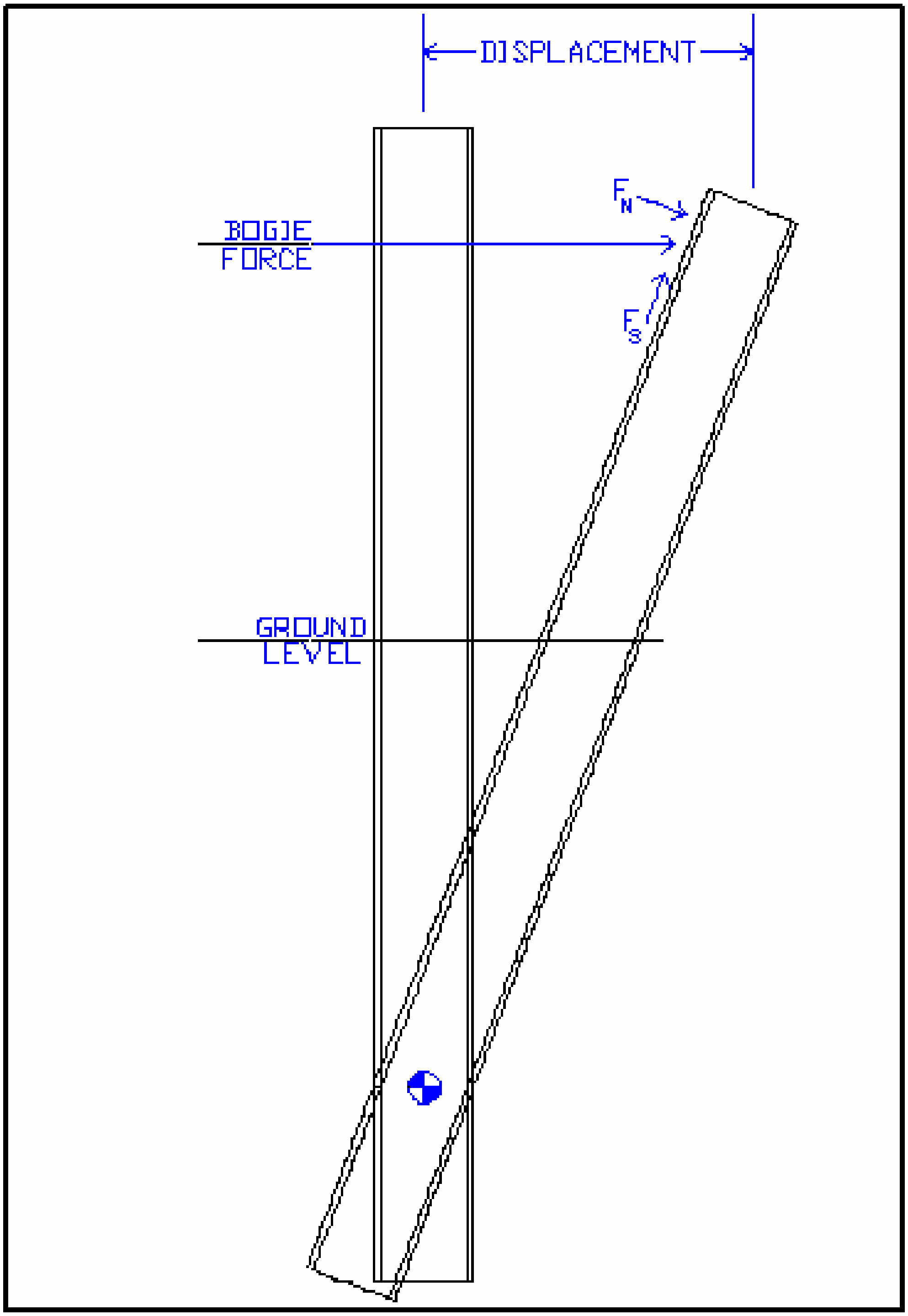


Figure 7. Forces Acting on the Post

3.6 Data Processing

Initially the electronic accelerometer data was filtered using the SAE Class 60 Butterworth filter conforming to the SAE J211/1 specifications. 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 using the data from the pressure tape switches, was then used to determine the bogie velocity, and the calculated velocity trace was integrated to find the bogie’s displacement, which is also the 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.

4 TEST RESULTS AND DISCUSSION

4.1 Results

Accelerometer data was processed for each bogie test in order to obtain acceleration, velocity, and displacement curves, as well as force-deflection curves. The data obtained from the post-soil interaction was tabulated, and results were plotted. The bogie test results for the first test setup with like embedment depths were combined together in Sections 4.1.1 through 4.1.7. The results for the second and third test setups with tests having similar embedment depths are combined in Sections 4.1.8 through 4.1.9 and 4.1.10, respectively.

4.1.1 Test Nos. MGS2-1B1 and MGS2-1B10

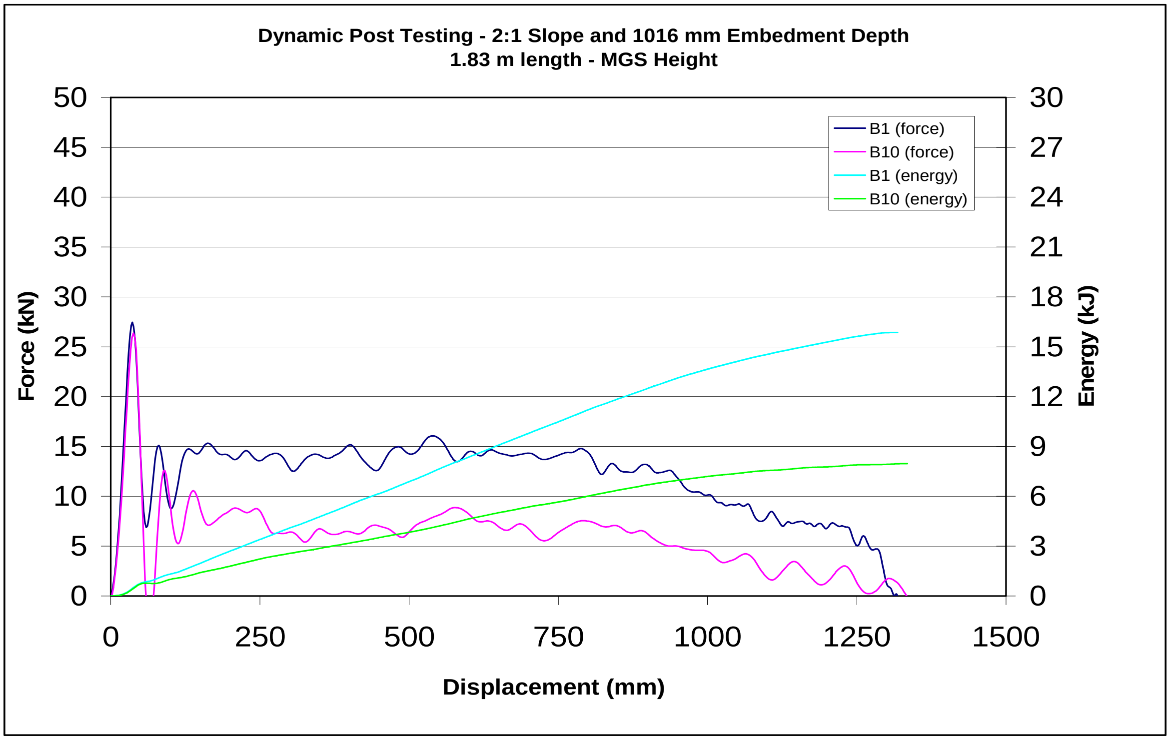
Two bogie tests were performed on 1,829-mm (6-ft) long posts at an embedment depth of 1,016 mm (40 in.). The test summaries for both of the tests are given in Table 3 and Figure 4. Force-displacement and energy-displacement curves are shown in Figure 8. The sequential photographs at regular time intervals are shown in Figure 9, while Figure 10 shows the posts in the soil after the impact test. The bogie test photographs and videos depict that soil failure was the primary mode of failure in both tests. The post rotated in the soil during the entire test period, and no post yielding took place. The force-displacement curves indicate the presence of a large inertial spike followed by a fairly uniform resisting force. The total energy dissipated in test MGS2-1B1 was almost twice the energy dissipated in test MGS2-1B10. This significant difference in energy dissipation between the two tests is believed to come from different soil compaction qualities.

Table 3. Test Results for Test Nos. MGS2-1B1 and MGS2-1B10 – (Metric)

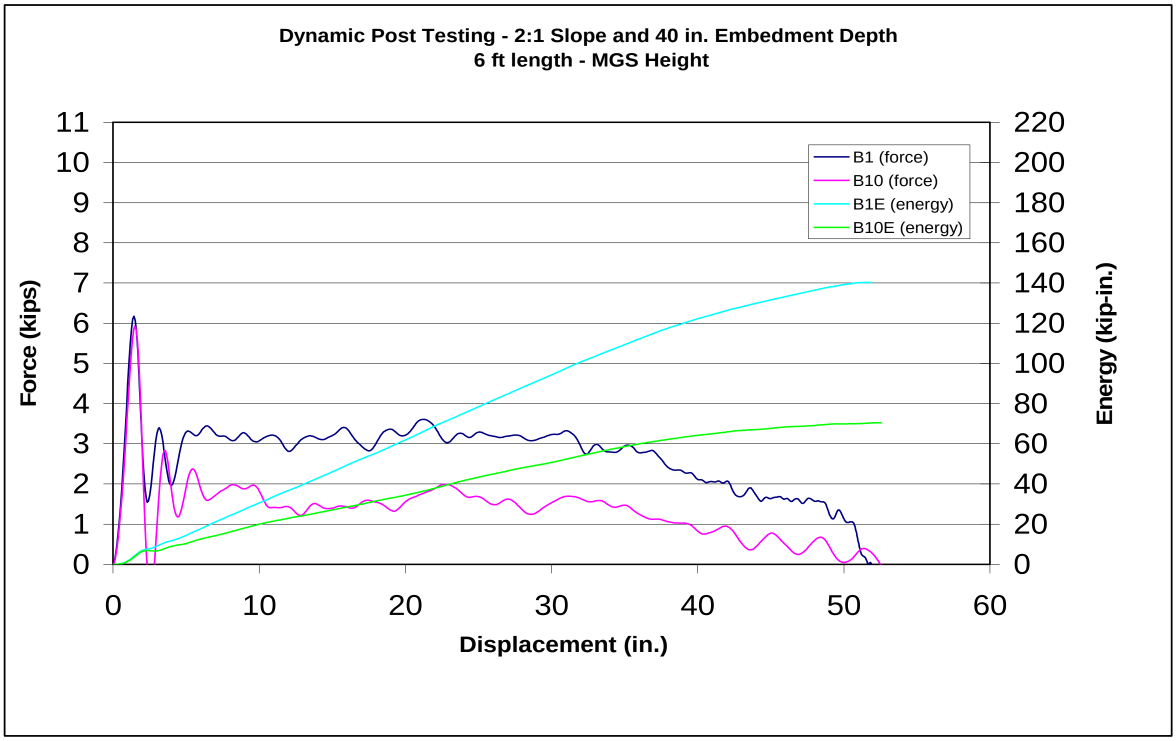
Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Force				Total Energy (kJ)	Maximum Displacement (mm)	Failure Type
			15 in. Displacement (kN)	20 in. Displacement (kN)	24 in. Displacement (kN)	30 in. Displacement (kN)			
MGS2-1B1	1016	6.88	13.66	13.80	13.94	13.99	15.86	1318	Soil
MGS2-1B10	1016	7.18	8.02	7.65	7.74	7.53	7.96	1335	Soil

Table 4. Test Results for Test Nos. MGS2-1B1 and MGS2-1B10 – (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Force				Total Energy (kip-in.)	Maximum Displacement (in.)	Failure Type
			15 in. Displacement (kips)	20 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
MGS2-1B1	40	15.40	3.07	3.10	3.13	3.15	140.33	51.90	Soil
MGS2-1B10	40	16.06	1.80	1.72	1.74	1.69	70.47	52.55	Soil

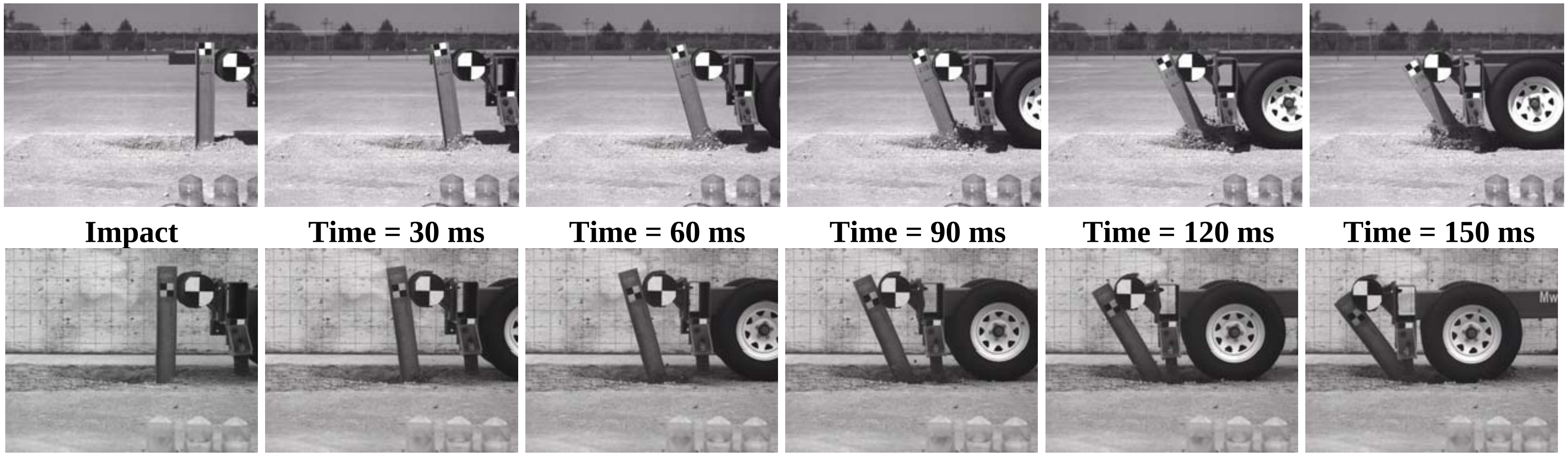


(a)



(b)

Figure 8. Force and Energy vs. Displacement Curves for MGS2-1B1 and MGS2-1B10 (a) Metric (b) English



(a)

(b)

Figure 9. Sequential Photographs (a) MGS2-1B1 and (b) MGS2-1B10

(a) (b)

Figure 10. Post-Impact Image of (a) MGS2-1B1 and (b) MGS2-1B10

4.1.2 Test Nos. MGS2-1B2 and MGS2-1B9

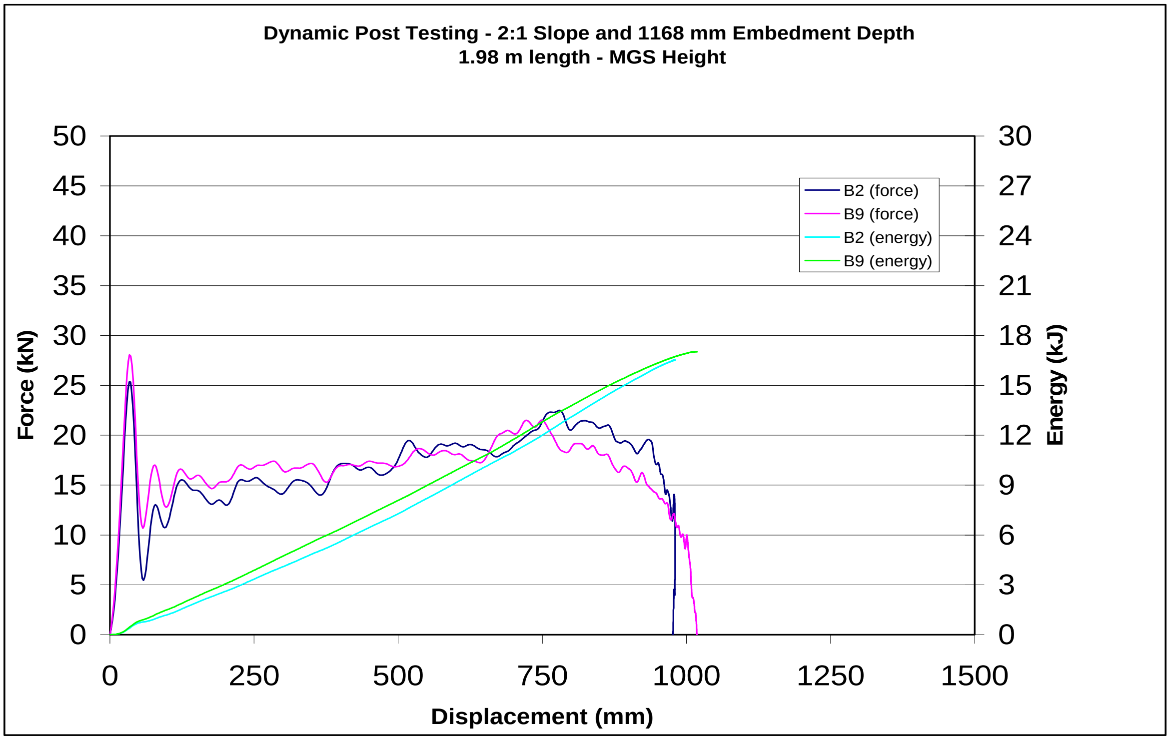
Two bogie tests were performed on 1,981-mm (6-ft 6-in.) long posts at an embedment depth of 1,168 mm (46 in.). The test summaries for both of the tests are given in Table 5 and Table 6. Force-displacement and energy-displacement curves are shown in Figure 11. The sequential photographs at regular time intervals are shown in Figure 12, while Figure 13 shows the posts in the soil after the impact test. For these tests, soil failure was the primary mode of failure. The post rotated in the soil during the entire test period, and no post yielding took place. When compared to the previous test results, the total energy dissipated in these tests were almost equal to one another, unlike that observed for MGS2-1B1 and MGS2-1B10.

Table 5. Test Results for Test Nos. MGS2-1B2 and MGS2-1B9 – (Metric)

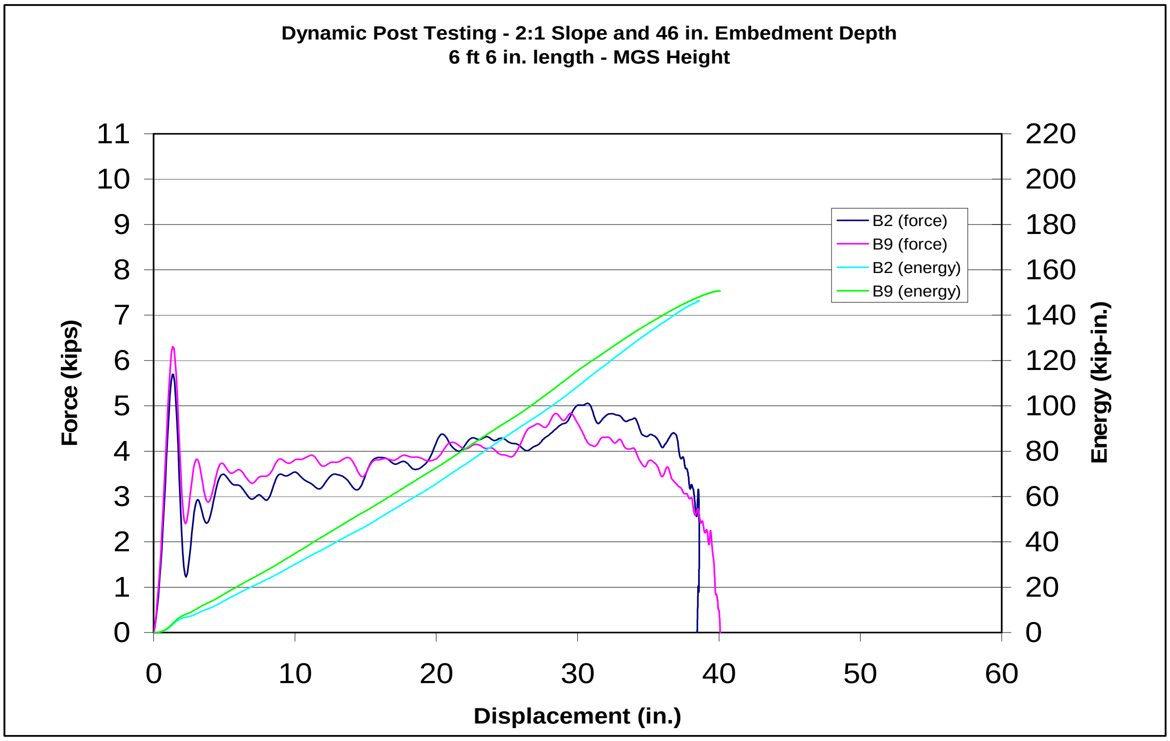
Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Force				Total Energy (kJ)	Maximum Displacement (mm)	Failure Type
			15 in. Displacement (kN)	20 in. Displacement (kN)	24 in. Displacement (kN)	30 in. Displacement (kN)			
MGS2-1B2	1168	6.74	13.92	14.63	15.29	16.11	16.53	980	Soil
MGS2-1B9	1168	6.85	15.90	16.18	16.52	17.14	17.03	1018	Soil

Table 6. Test Results for Test Nos. MGS2-1B2 and MGS2-1B9 – (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Force				Total Energy (kip-in.)	Maximum Displacement (in.)	Failure Type
			15 in. Displacement (kips)	20 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
MGS2-1B2	46	15.08	3.13	3.29	3.44	3.62	146.30	38.60	Soil
MGS2-1B9	46	15.32	3.58	3.64	3.71	3.85	150.68	40.09	Soil



(a)



(b)

Figure 11. Force and Energy vs. Displacement Curves for MGS2-1B2 and MGS2-1B9 (a) Metric (b) English

(a)


Impact | **Time = 30 ms** | **Time = 60 ms** | **Time = 90 ms** | **Time = 120 ms** | **Time = 150 ms**

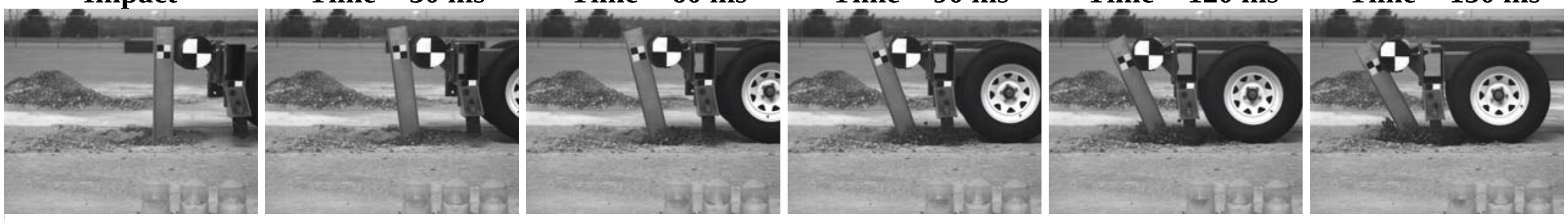
(b)


Figure 12. Sequential Photographs (a) MGS2-1B2 and (b) MGS2-1B9

(a) (b)

Figure 13. Post-Impact Image of (a) MGS2-1B2 and (b) MGS2-1B9

4.1.3 Test Nos. MGS2-1B3 and MGS2-1B8

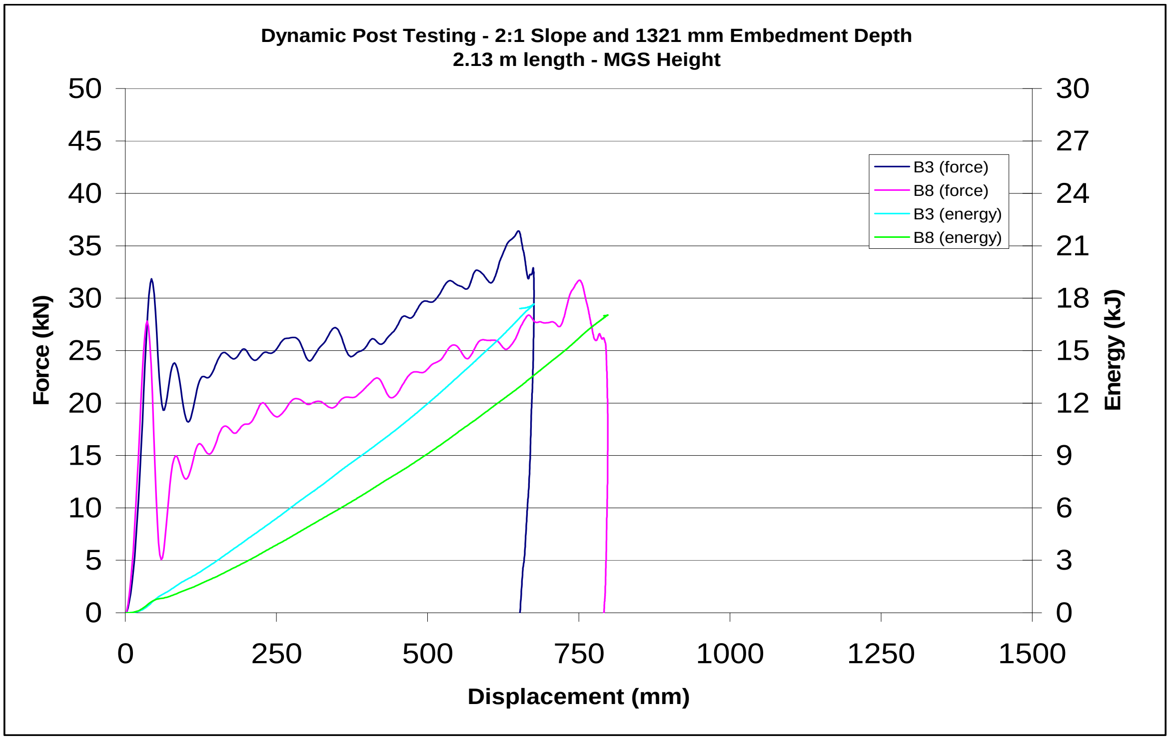
Two bogie tests were performed on 2,134-mm (7-ft) long posts at an embedment depth of 1,321 mm (52 in.). The test summaries for both of the tests are given in Table 7 and Table 8. Force-displacement and energy-displacement curves are shown in Figure 14. The sequential photographs at regular time intervals are shown in Figure 15, while Figure 16 shows the posts in the soil after the impact test. The primary mode of failure in both tests was soil failure. The post rotated in the soil during the entire test period, and no yielding of the post took place. The average force in test MGS2-1B3 was much higher than that in MGS2-1B8 but the energy values were almost equal.

Table 7. Test Results for Test Nos. MGS2-1B3 and MGS2-1B8 – (Metric)

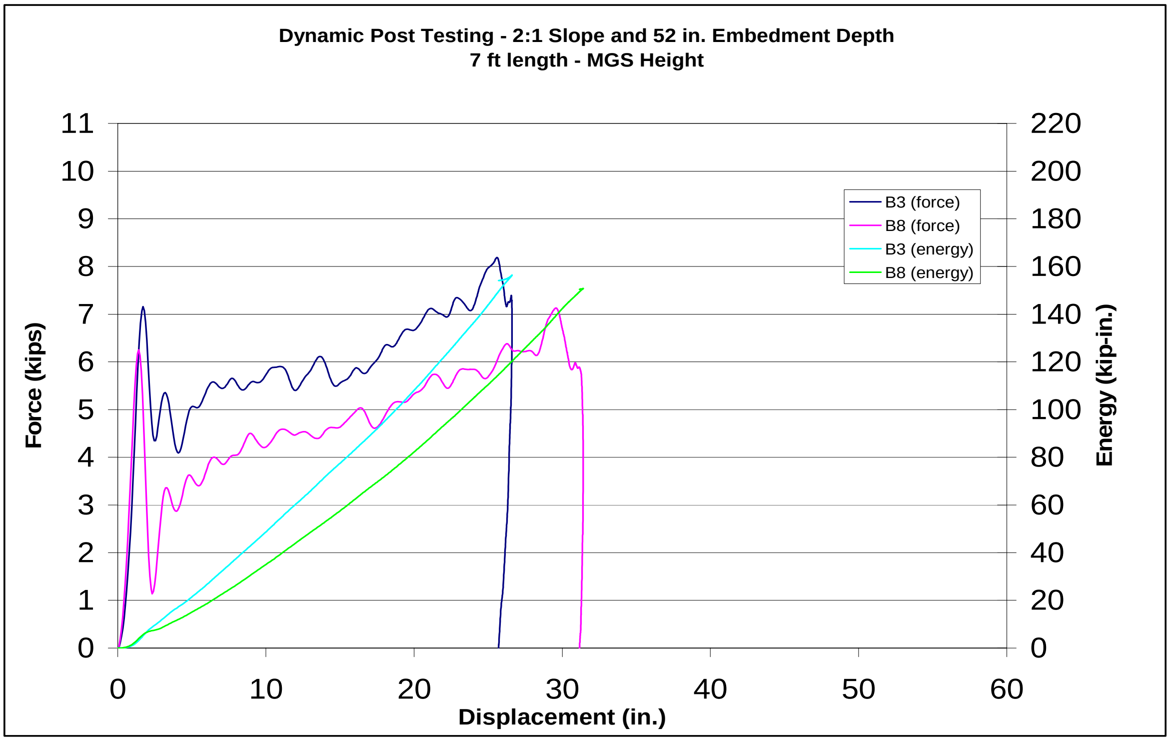
Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Force				Total Energy (kJ)	Maximum Displacement (mm)	Failure Type
			15 in. Displacement (kN)	20 in. Displacement (kN)	24 in. Displacement (kN)	30 in. Displacement (kN)			
MGS2-1B3	1321	6.97	22.96	24.03	25.27	NA	17.67	676	Soil
MGS2-1B8	1321	6.84	17.13	18.32	19.43	21.11	17.04	798	Soil

Table 8. Test Results for Test Nos. MGS2-1B3 and MGS2-1B8 – (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Force				Total Energy (kip-in.)	Maximum Displacement (in.)	Failure Type
			15 in. Displacement (kips)	20 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
MGS2-1B3	52	15.59	5.16	5.40	5.68	NA	156.36	26.61	Soil
MGS2-1B8	52	15.31	3.85	4.12	4.37	4.75	150.79	31.42	Soil



(a)



(b)

Figure 14. Force and Energy vs. Displacement Curves for MGS2-1B3 and MGS2-1B8 (a) Metric (b) English

(a)

Impact Time = 30 ms Time = 60 ms Time = 90 ms Time = 120 ms Time = 150 ms

(b)

Figure 15. Sequential Photographs (a) MGS2-1B3 and (b) MGS2-1B8

(a)

(b)

Figure 16. Post-Impact Image of (a) MGS2-1B3 and (b) MGS2-1B8

4.1.4 Test Nos. MGS2-1B4 and MGS2-1B11

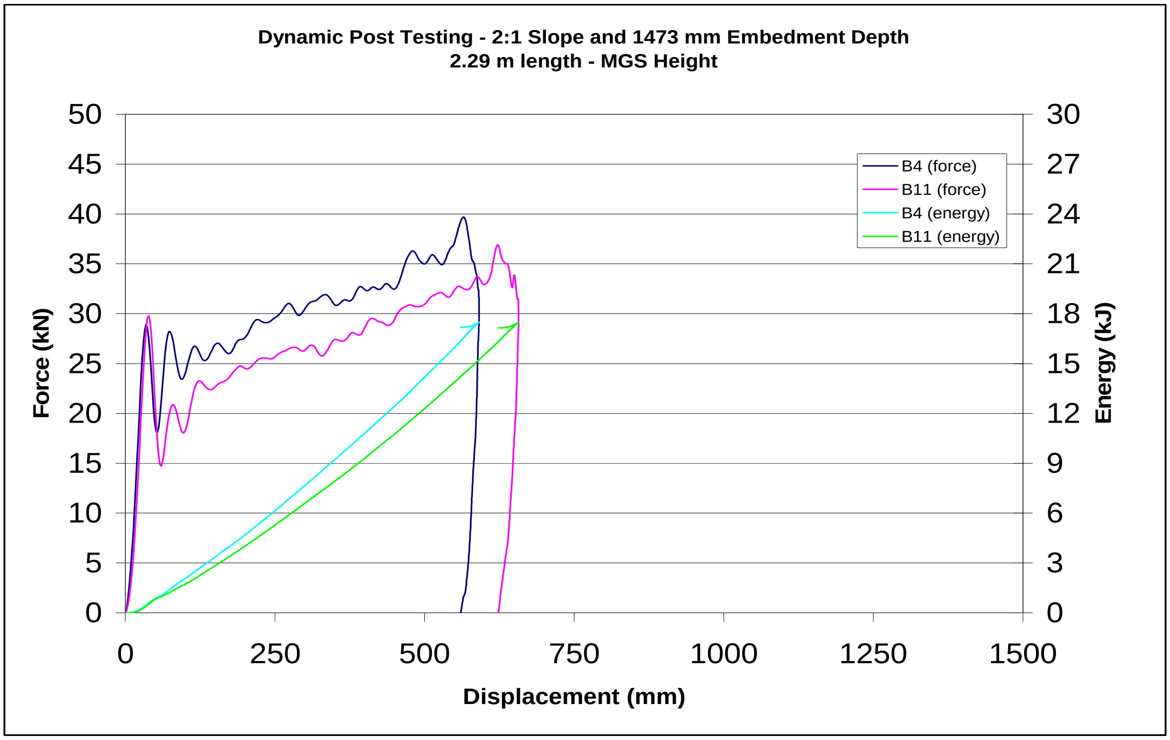
Two bogie tests were performed on 2,286-mm (7-ft 6-in.) long posts at an embedment depth of 1,473 mm (58 in.). The test summaries for both of the tests are given in Table 9 and Table 10. Force-displacement and energy-displacement curves are shown in Figure 17. The sequential photographs at regular time intervals are shown in Figure 18, while Figure 19 shows the posts in soil after the impact test. The primary mode of failure was soil failure. The post rotated in the soil and then pushed the bogie in a direction opposite to its initial motion. No visible deformation of the post was observed.

Table 9. Test Results for Test Nos. MGS2-1B4 and MGS2-1B11 – (Metric)

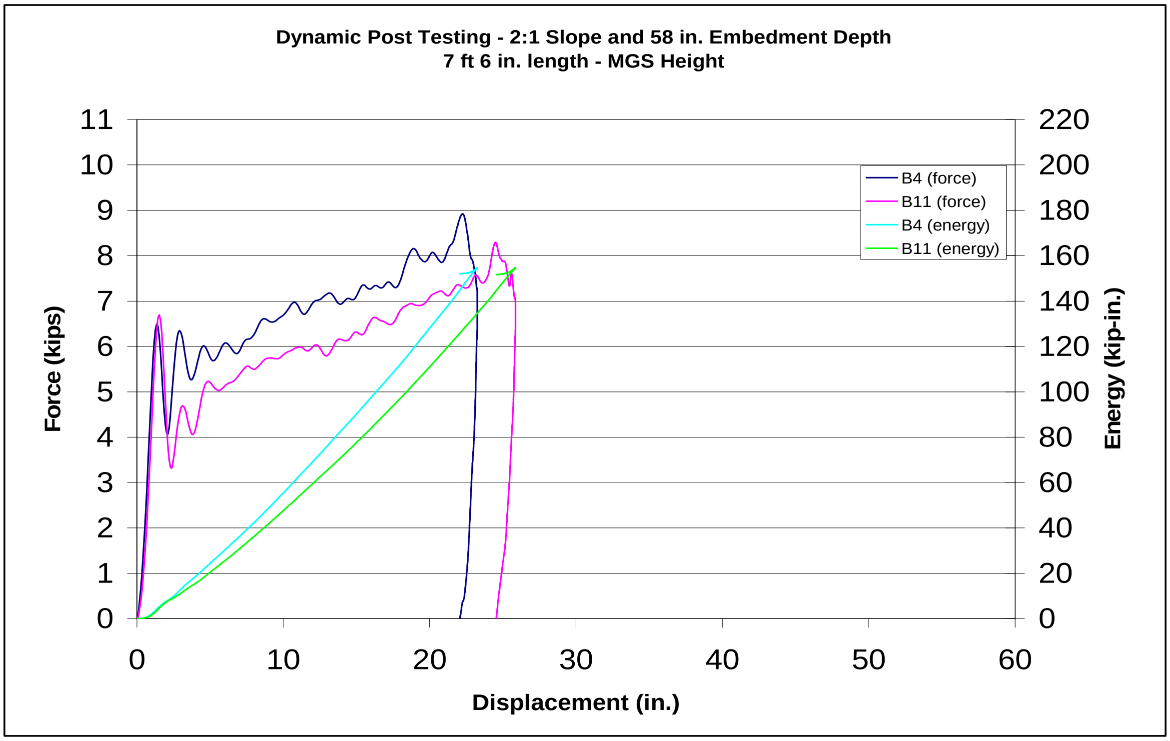
Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Force				Total Energy (kJ)	Maximum Displacement (mm)	Failure Type
			15 in. Displacement (kN)	20 in. Displacement (kN)	24 in. Displacement (kN)	30 in. Displacement (kN)			
MGS2-1B4	1473	6.93	26.77	28.49	NA	NA	17.49	591	Soil
MGS2-1B11	1473	6.93	23.02	24.72	25.99	NA	17.49	657	Soil

Table 10. Test Results for Test Nos. MGS2-1B4 and MGS2-1B11 – (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Force				Total Energy (kip-in.)	Maximum Displacement (in.)	Failure Type
			15 in. Displacement (kips)	20 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
MGS2-1B4	58	15.51	6.02	6.41	NA	NA	154.76	23.26	Soil
MGS2-1B11	58	15.51	5.17	5.56	5.84	NA	154.76	25.87	Soil



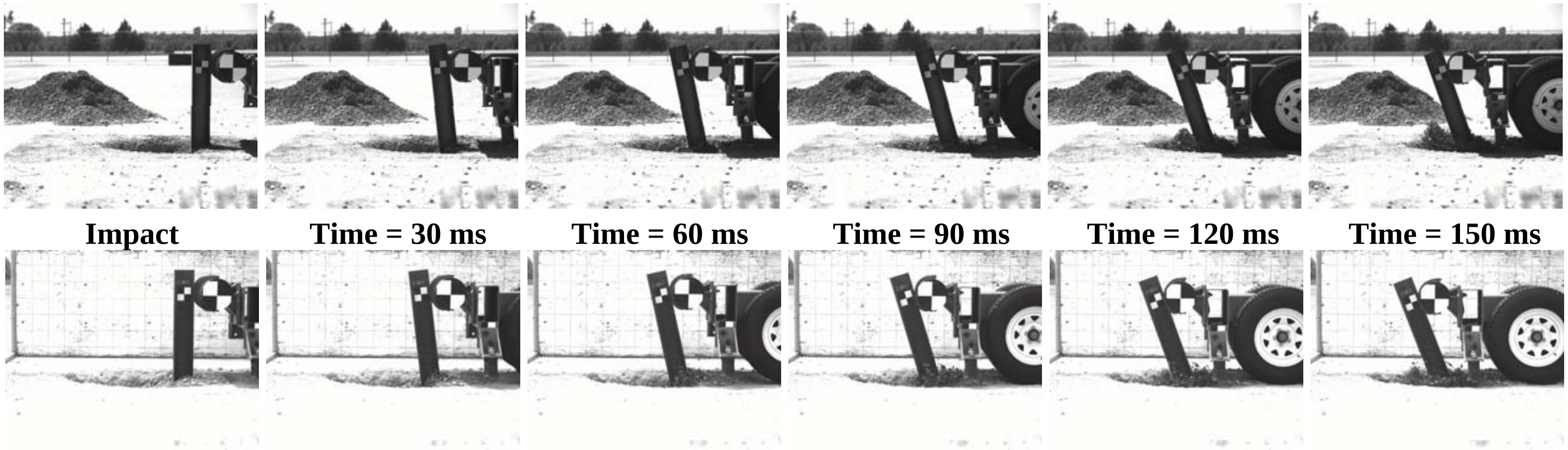
(a)



(b)

Figure 17. Force and Energy vs. Displacement Curves for MGS2-1B4 and MGS2-1B11 (a) Metric (b) English

(a)



(b)

Figure 18. Sequential Photographs (a) MGS2-1B4 and (b) MGS2-1B11

(a) (b)

Figure 19. Post-Impact Image of (a) MGS2-1B4 and (b) MGS2-1B11

4.1.5 Test Nos. MGS2-1B5 and MGS2-1B12

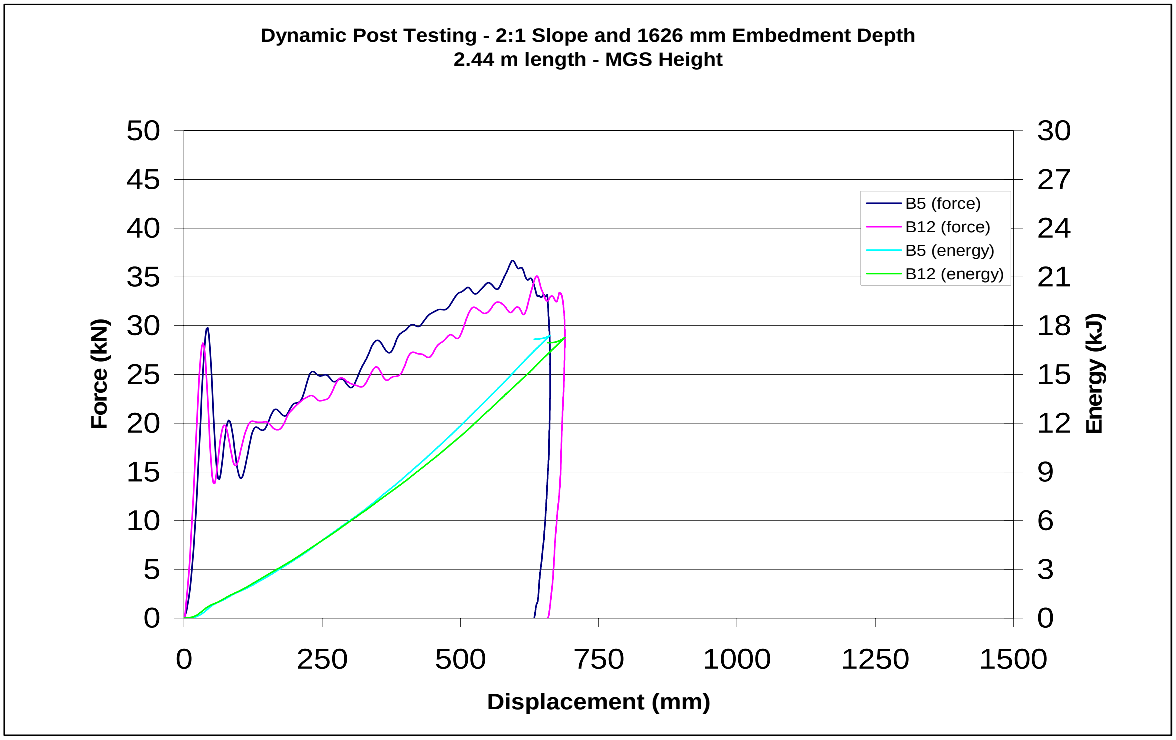
Two bogie tests were performed on 2,438-mm (8-ft) long posts at an embedment depth of 1,626 mm (64 in.). The test summaries for both the tests are given in Table 11 and Table 12. Force-displacement and energy-displacement curves are shown in Figure 20. The sequential photographs at regular time intervals are shown in Figure 21, while Figure 22 shows the posts in the soil after the impact test. The primary mode of failure was soil failure. As in the previous test series, the posts rotated in the soil and then pushed the bogie in a direction, opposite to its initial motion. No visible deformations of the posts were found. The average force and energy values for test nos. MGS2-1B5 and MGS2-1B12 were almost equal.

Table 11. Test Results for Test Nos. MGS2-1B5 and MGS2-1B12 – (Metric)

Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Force				Total Energy (kJ)	Maximum Displacement (mm)	Failure Type
			15 in. Displacement (kN)	20 in. Displacement (kN)	24 in. Displacement (kN)	30 in. Displacement (kN)			
MGS2-1B5	1626	6.92	21.50	23.83	25.64	NA	17.40	662	Soil
MGS2-1B12	1626	6.89	20.90	22.51	24.03	NA	17.26	689	Soil

Table 12. Test Results for Test Nos. MGS2-1B5 and MGS2-1B12 – (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Force				Total Energy (kip-in.)	Maximum Displacement (in.)	Failure Type
			15 in. Displacement (kips)	20 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
MGS2-1B5	64	15.47	4.83	5.36	5.76	NA	153.96	26.07	Soil
MGS2-1B12	64	15.41	4.70	5.06	5.40	NA	152.77	27.12	Soil



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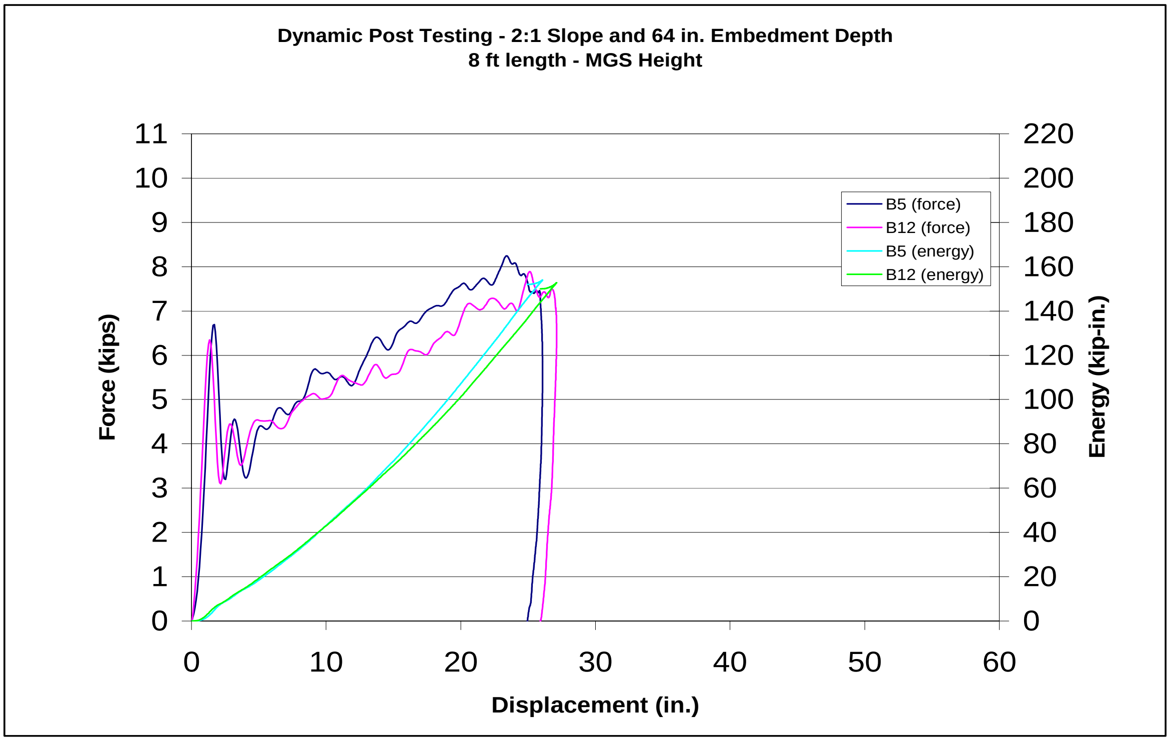


(b)

Figure 20. Force and Energy vs. Displacement Curves for MGS2-1B5 and MGS2-1B12 (a) Metric (b) English

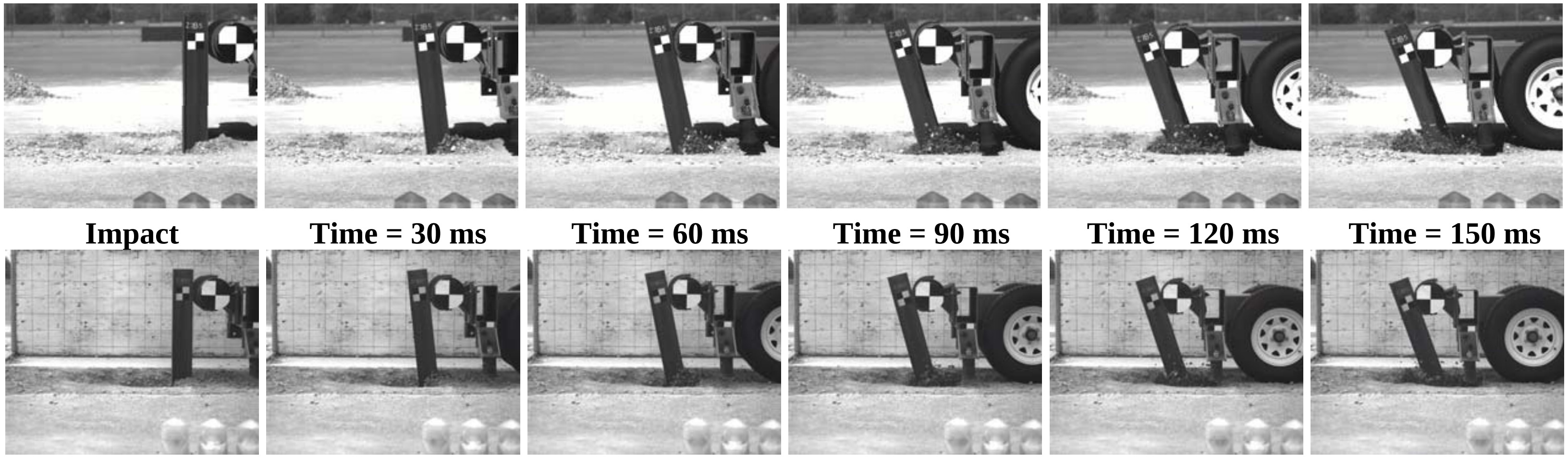


Figure 21. Sequential Photographs (a) MGS2-1B5 and (b) MGS2-1B12

(a) (b)

Figure 22. Post-Impact Image of (a) MGS2-1B5 and (b) MGS2-1B12

4.1.6 Test Nos. MGS2-1B6 and MGS2-1B13

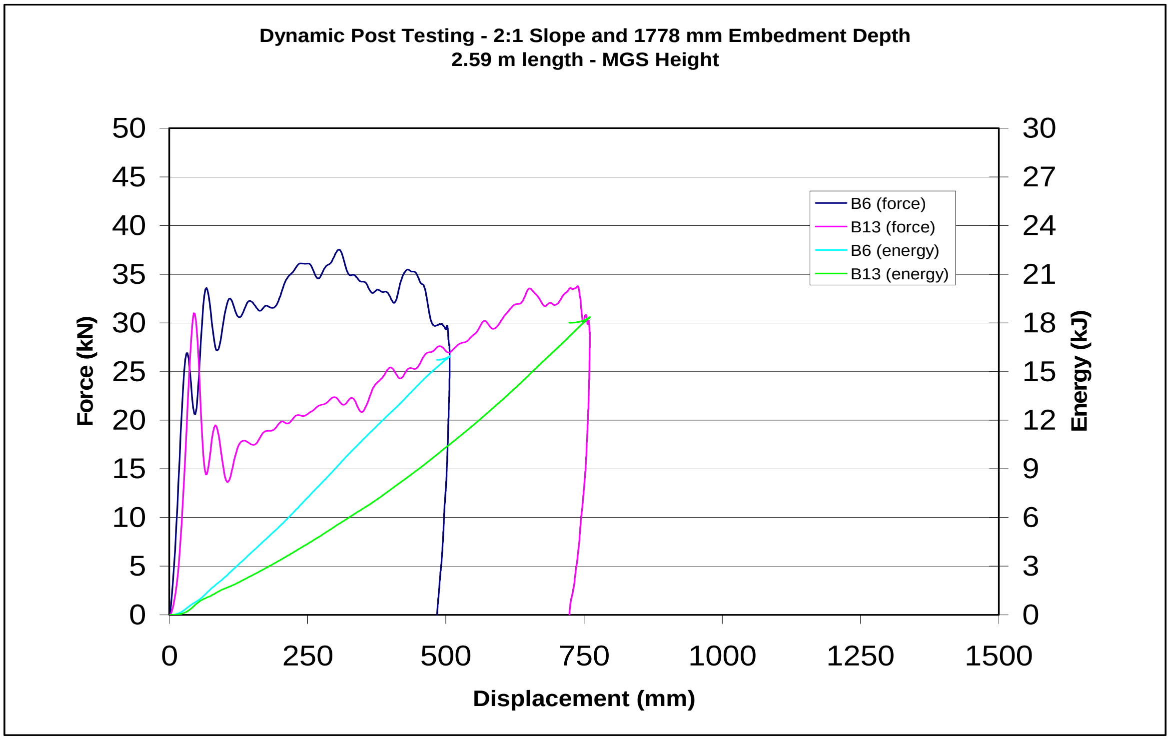
Two bogie tests were performed on 2,591-mm (8-ft 6-in.) long posts at an embedment depth of 1,778 mm (70 in.). The test summaries for both the tests are given in Table 13 and Table 14. Force-displacement and energy-displacement curves are shown in Figure 23. The sequential photographs at regular time intervals are shown in Figure 24, while Figure 25 shows the posts in soil after the impact test. Once again, the primary mode of failure was soil failure in both tests. The post rotated in the soil with slight deformation of the post in test no. MGS2-1B6 but no post deformation was observed in post test no. MGS2-1B13. The graph of the force-displacement curves revealed a significant difference in the magnitude of the average force in these two tests. The average force difference between these two tests at a displacement of 381 mm (15 in.) was approximately 12.1 kN (2.72 kips).

Table 13. Test Results for Test Nos. MGS2-1B6 and MGS2-1B13 – (Metric)

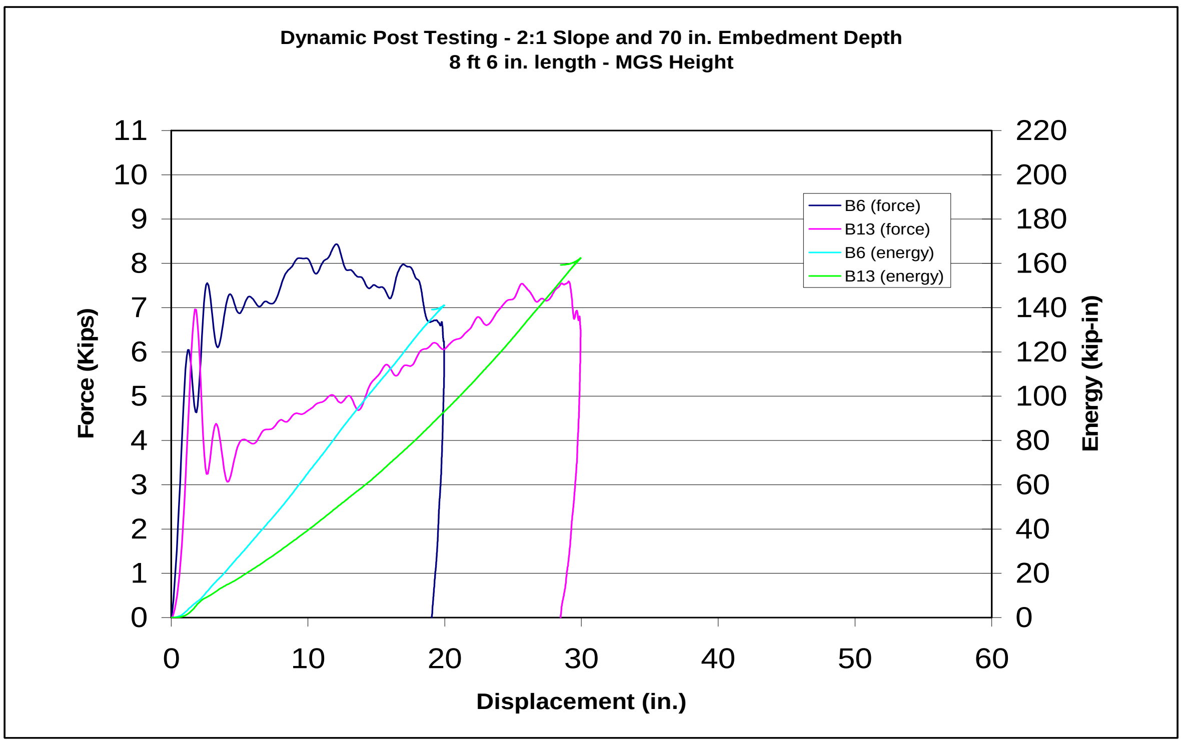
Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Force				Total Energy (kJ)	Maximum Displacement (mm)	Failure Type
			15 in. Displacement (kN)	20 in. Displacement (kN)	24 in. Displacement (kN)	30 in. Displacement (kN)			
MGS2-1B6	1778	6.62	31.10	NA	NA	NA	15.94	507	Soil
MGS2-1B13	1778	7.10	19.01	20.74	22.10	NA	18.35	761	Soil

Table 14. Test Results for Test Nos. MGS2-1B6 and MGS2-1B13 – (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Force				Total Energy (kip-in.)	Maximum Displacement (in.)	Failure Type
			15 in. Displacement (kips)	20 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
MGS2-1B6	70	14.81	6.99	NA	NA	NA	141.11	19.96	Soil
MGS2-1B13	70	15.89	4.27	4.66	4.97	NA	162.44	29.94	Soil



(a)



(b)

Figure 23. Force and Energy vs. Displacement Curves for MGS2-1B6 and MGS2-1B13 (a) Metric (b) English

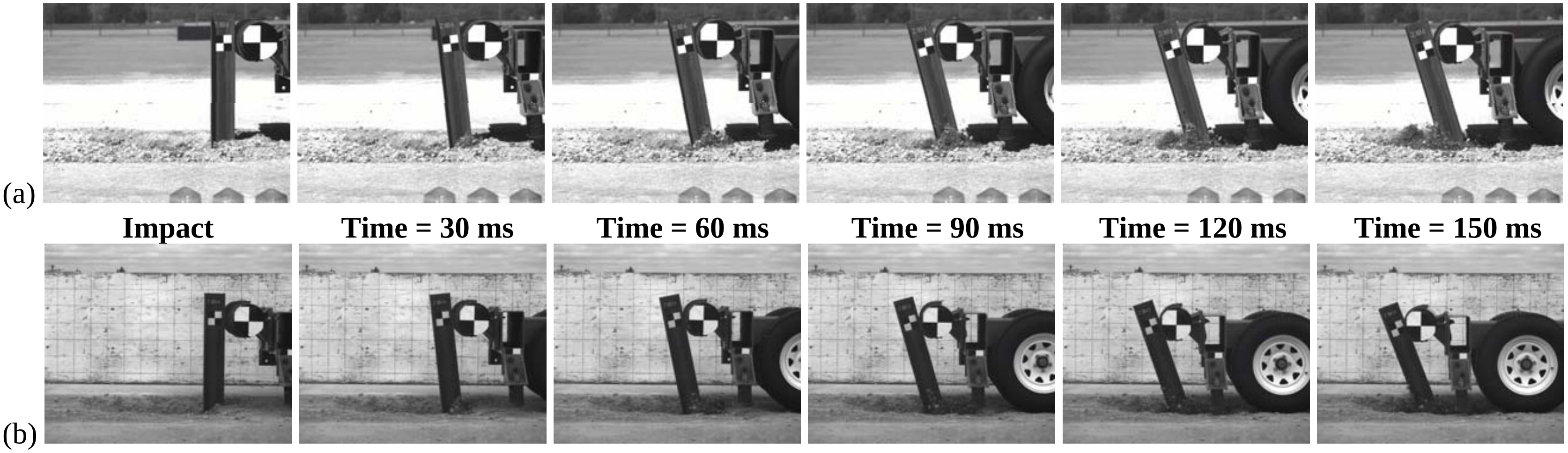


Figure 24. Sequential Photographs (a) MGS2-1B6 and (b) MGS2-1B13

(a) (b)

Figure 25. Post-Impact Image of (a) MGS2-1B6 and (b) MGS2-1B13

4.1.7 Test Nos. MGS2-1B7 and MGS2-1B14

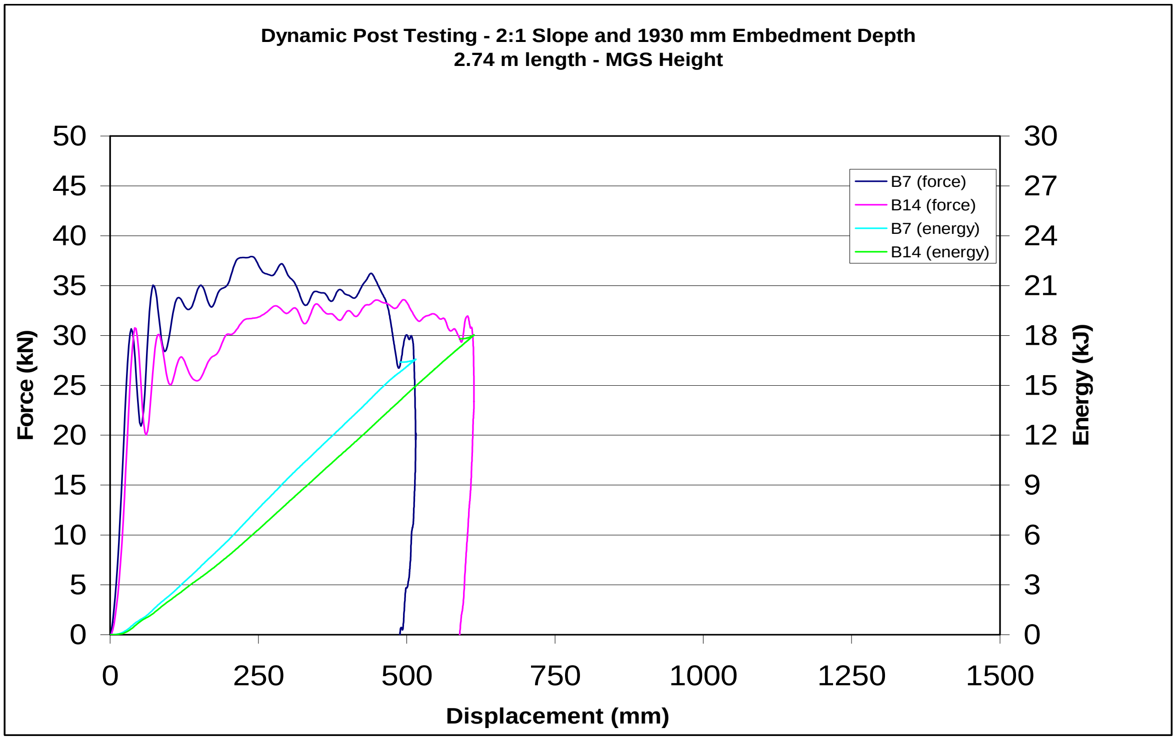
Two bogie tests were performed on 2,743-mm (9-ft) long posts at an embedment depth of 1,930 mm (76 in.). The test summaries for both the tests are given in Table 15 and Table 16. Force-displacement and energy-displacement curves are shown in Figure 26. The sequential photographs at regular time intervals are shown in Figure 27, while Figure 28 shows the posts in the soil after the impact test. The primary mode of failure was soil failure. As in the previous test series, the posts rotated in the soil with slight deformations in the web of both posts.

Table 15. Test Results for Test Nos. MGS2-1B7 and MGS2-1B14 – (Metric)

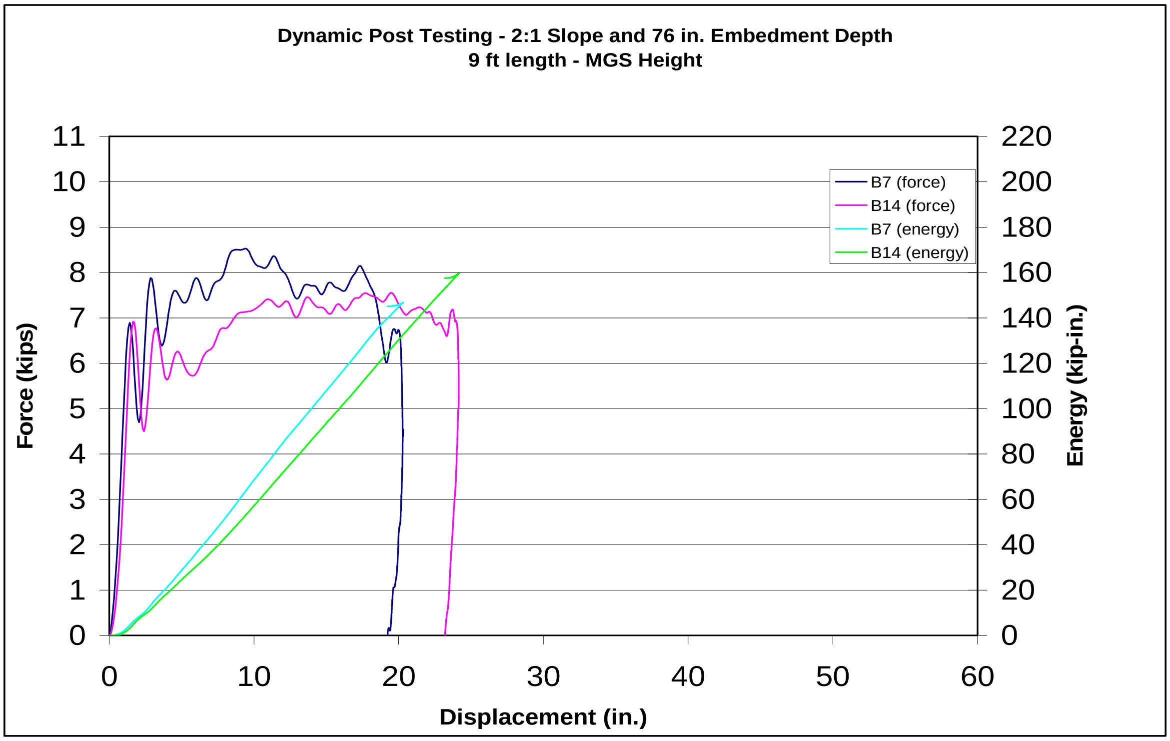
Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Force				Total Energy (kJ)	Maximum Displacement (mm)	Failure Type
			15 in. Displacement (kN)	20 in. Displacement (kN)	24 in. Displacement (kN)	30 in. Displacement (kN)			
MGS2-1B7	1930	6.75	32.00	32.23	NA	NA	16.57	516	Soil
MGS2-1B14	1930	7.04	27.80	28.99	29.39	NA	18.03	614	Soil

Table 16. Test Results for Test Nos. MGS2-1B7 and MGS2-1B14 – (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Force				Total Energy (kip-in.)	Maximum Displacement (in.)	Failure Type
			15 in. Displacement (kips)	20 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
MGS2-1B7	76	15.10	7.19	7.25	NA	NA	146.69	20.30	Soil
MGS2-1B14	76	15.75	6.25	6.52	6.61	NA	159.59	24.16	Soil



(a)



(b)

Figure 26. Force and Energy vs. Displacement Curves for MGS2-1B7 and MGS2-1B14 (a) Metric (b) English

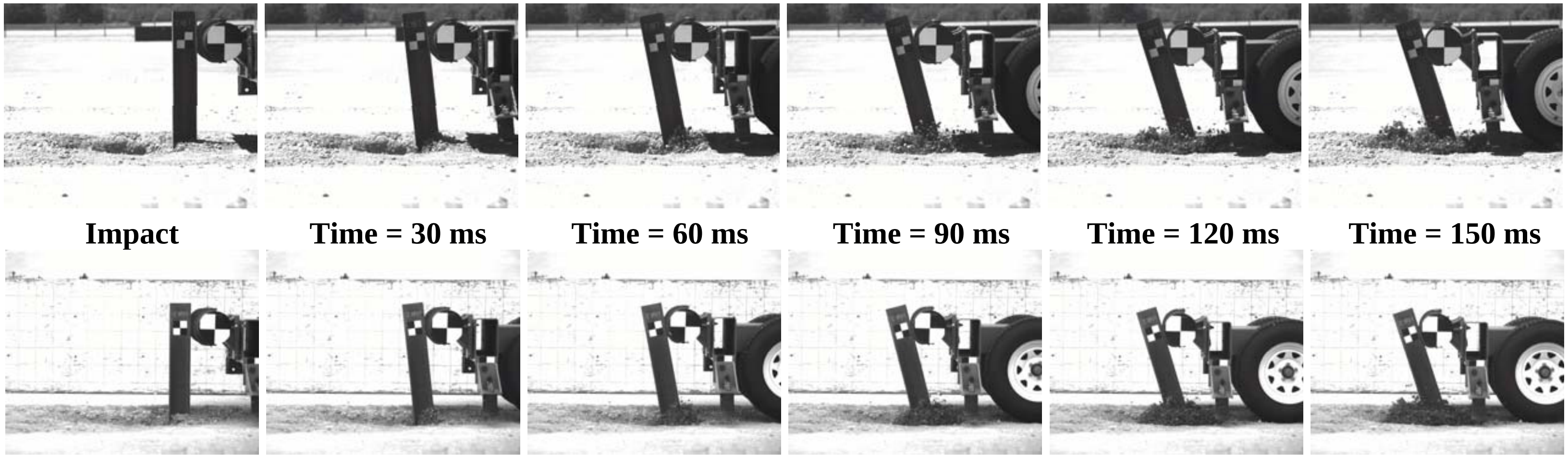
(a)
(b)


Figure 27. Sequential Photographs (a) MGS2-1B7 and (b) MGS2-1B14

(a) (b)

Figure 28. Post-Impact Image of (a) MGS2-1B7 and (b) MGS2-1B14

4.1.8 Test No. MGS2-1B15

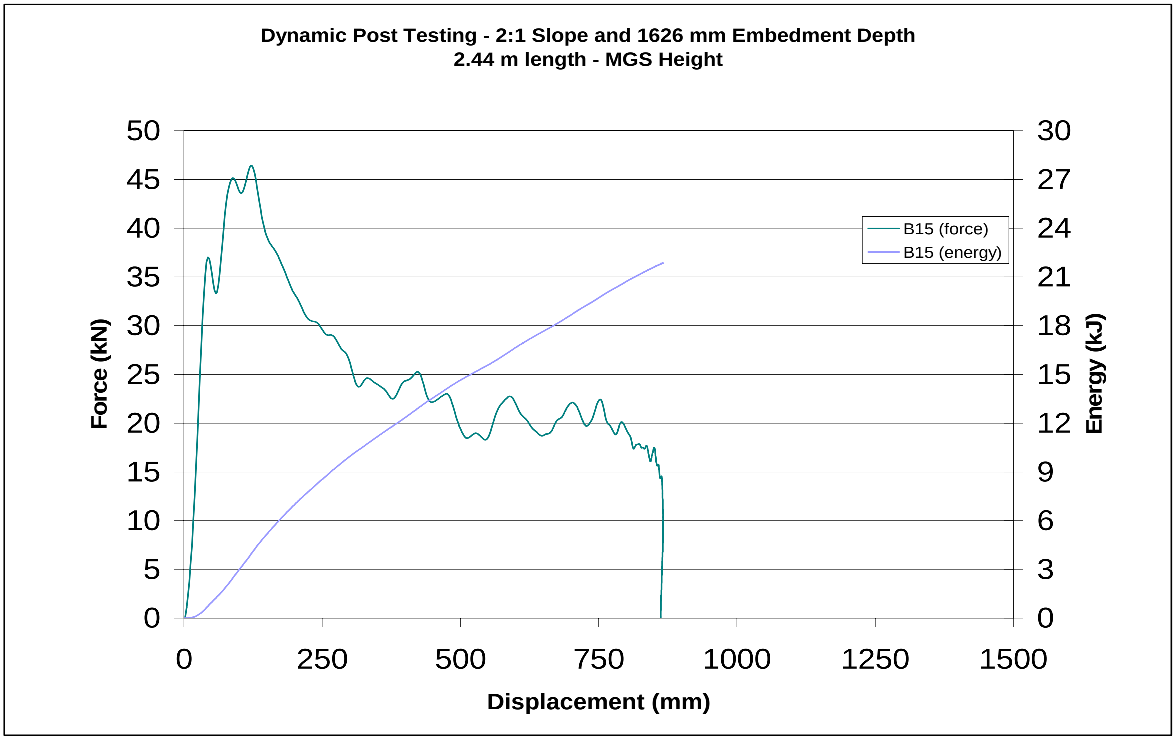
One bogie test was performed on a 2,438-mm (8-ft) long post at an embedment depth of 1,626 mm (64 in.) using the modified test setup shown in Figure 5. The test summary is given in Table 17 and Table 18. Force-displacement and energy-displacement curves are shown in Figure 29. The sequential photographs at regular time intervals are shown in Figure 30, while Figure 31 shows the post in the soil after the impact test. The primary mode of failure was soil failure. The post rotated in the soil during the entire test period, and no post deformation was observed.

Table 17. Test Results for Test No. MGS2-1B15 – (Metric)

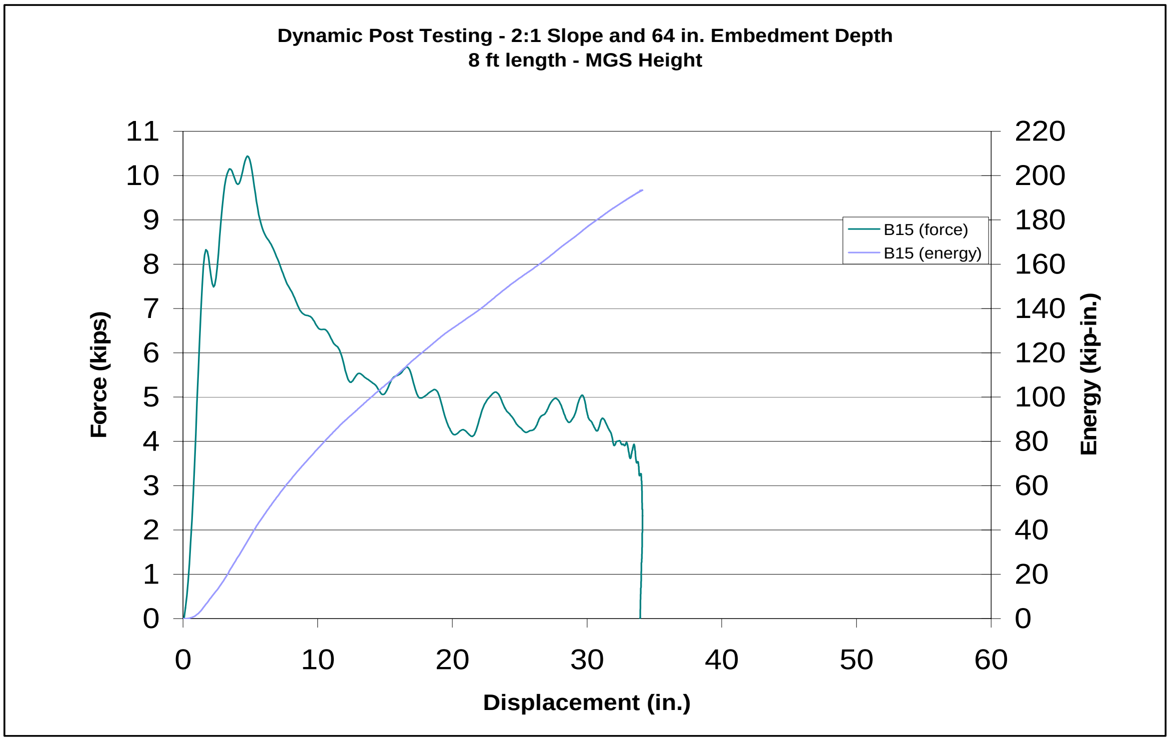
Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Force				Total Energy (kJ)	Maximum Displacement (mm)	Failure Type
			15 in. Displacement (kN)	20 in. Displacement (kN)	24 in. Displacement (kN)	30 in. Displacement (kN)			
MGS2-1B15	1626	7.75	31.23	29.16	27.68	26.22	21.86	867	Soil

Table 18. Test Results for Test No. MGS2-1B15 – (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Force				Total Energy (kip-in.)	Maximum Displacement (in.)	Failure Type
			15 in. Displacement (kips)	20 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
MGS2-1B15	64	17.34	7.02	6.56	6.22	5.89	193.43	34.12	Soil



(a)



(b)

Figure 29. Force and Energy vs. Displacement Curves for MGS2-1B15 (a) Metric (b) English

Impact | Time = 30 ms | Time = 60 ms | Time = 90 ms | Time = 120 ms | Time = 150 ms

Figure 30. Sequential Photographs MGS2-1B15

Figure 31. Post-Impact Image of MGS2-1B15

4.1.9 Test Nos. MGS2-1B16 and MGS2-1B17

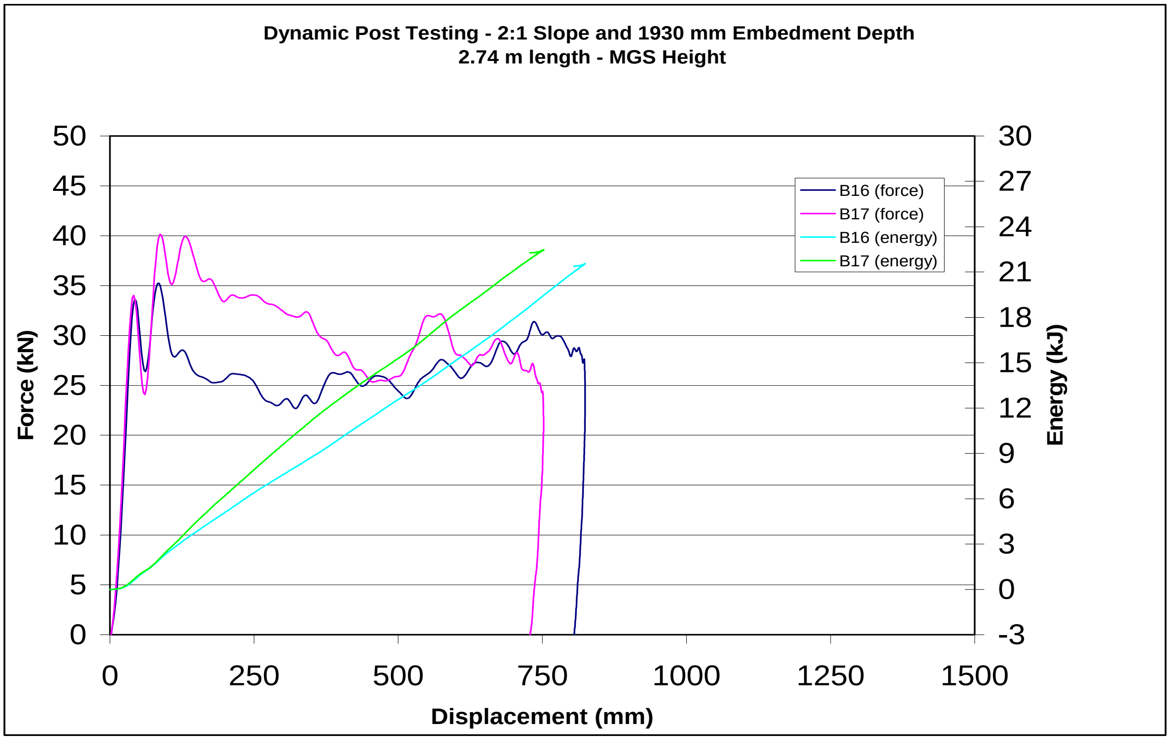
Two bogie tests were performed on 2,743-mm (9-ft) long posts at an embedment depth of 1,930 mm (76 in.) using the modified test setup shown in Figure 5. The test summaries for both the tests are given in Table 19 and Table 20. Force-displacement and energy-displacement curves are shown in Figure 32. The sequential photographs at regular time intervals are shown in Figure 33, while Figure 34 shows the posts in the soil after the impact test. Once again, the primary mode of failure was soil failure. The posts rotated in the soil during the entire test period without any post yielding.

Table 19. Test Results for Test Nos. MGS2-1B16 and MGS2-1B17 – (Metric)

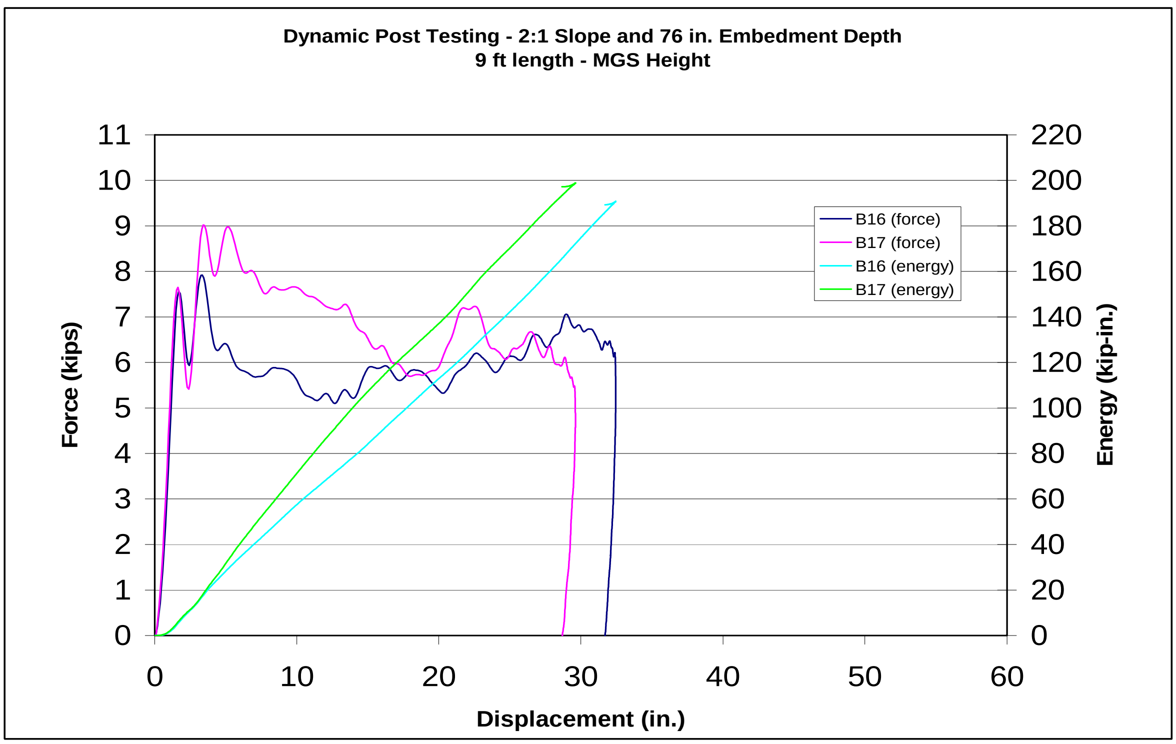
Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Force				Total Energy (kJ)	Maximum Displacement (mm)	Failure Type
			15 in. Displacement (kN)	20 in. Displacement (kN)	24 in. Displacement (kN)	30 in. Displacement (kN)			
MGS2-1B16	1930	7.70	25.04	25.15	25.29	25.92	21.55	824	Soil
MGS2-1B17	1930	7.86	31.82	30.51	30.44	NA	22.46	752	Soil

Table 20. Test Results for Test Nos. MGS2-1B16 and MGS2-1B17 – (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Force				Total Energy (kip-in.)	Maximum Displacement (in.)	Failure Type
			15 in. Displacement (kips)	20 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)			
MGS2-1B16	76	17.22	5.63	5.65	5.68	5.83	190.77	32.46	Soil
MGS2-1B17	76	17.58	7.15	6.86	6.84	NA	198.82	29.62	Soil



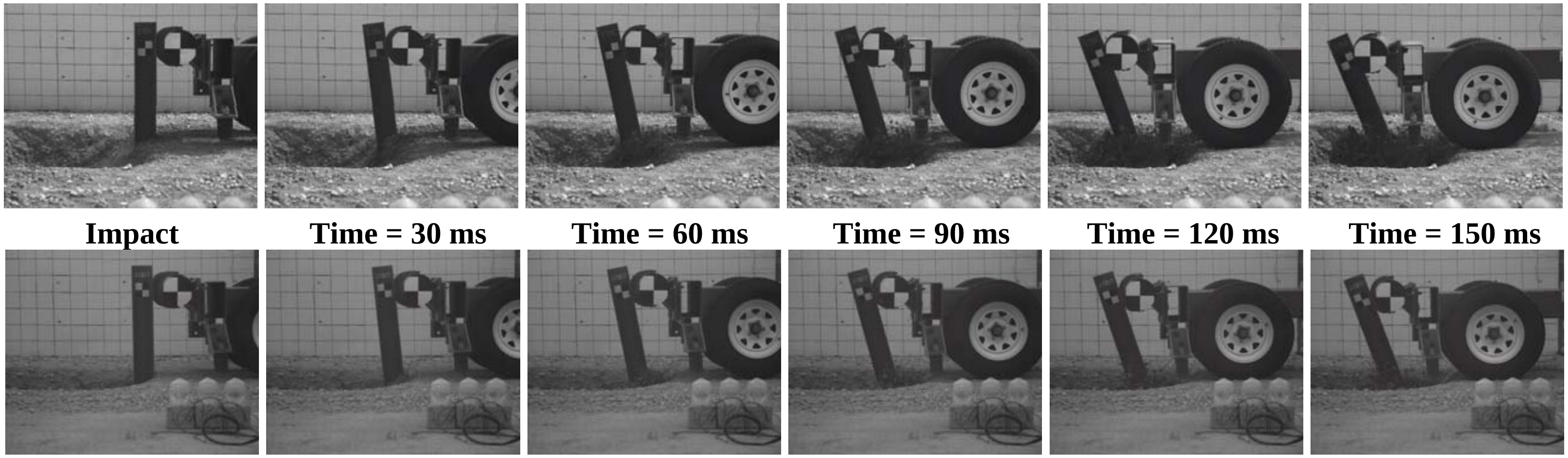
(a)



(b)

Figure 32. Force and Energy vs. Displacement Curves for MGS2-1B16 and MGS2-1B17 (a) Metric (b) English

(a)



(b)

Figure 33. Sequential Photographs (a) MGS2-1B16 and (b) MGS2-1B17

(a) (b)

Figure 34. Post-Impact Image of (a) MGS2-1B16 and (b) MGS2-1B17

4.1.10 Test Nos. MGS2-1B18 through MGS2-1B21

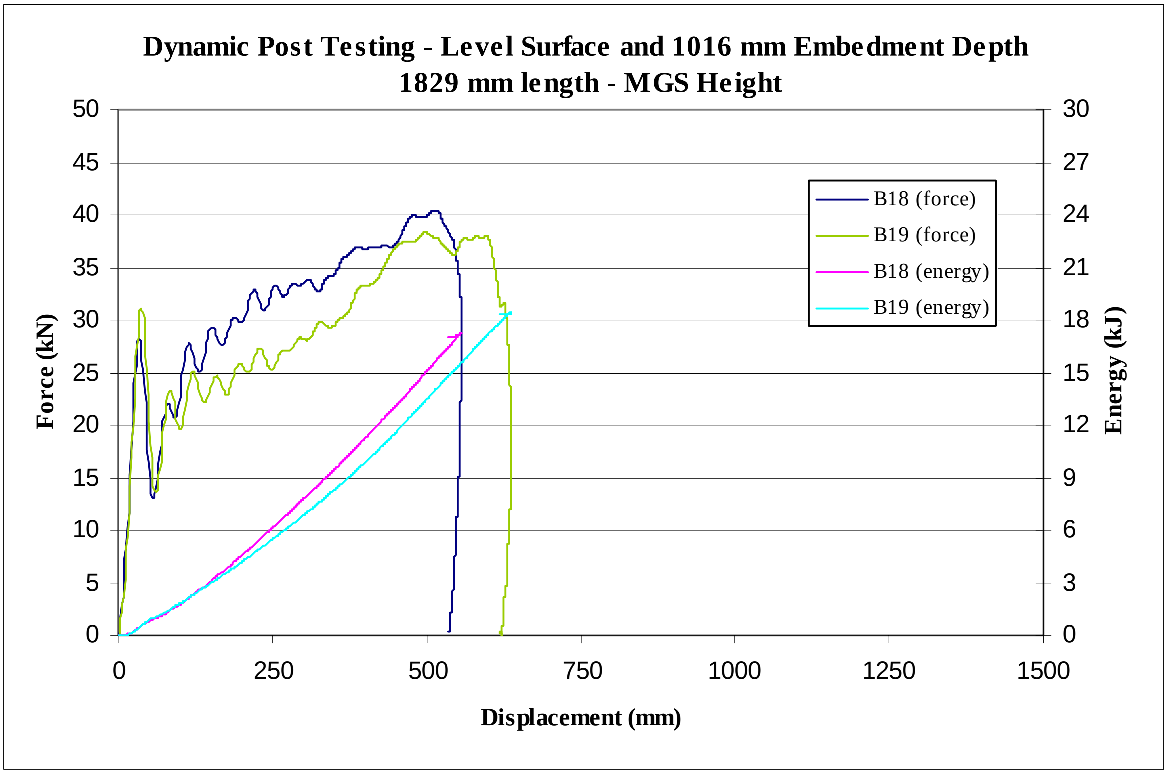
Four bogie tests were performed on 1,829-mm (6-ft) long posts at an embedment depth of 1,016-mm (40 in.) on level terrain. The test summaries for the four tests are given in Table 21 and Table 22. Force-displacement and energy-displacement curves are shown in Figure 35 and Figure 36. Test nos. MGS2-1B18 and MGS2-1B19 were plotted on the same graph, because both tests used a target impact speed of 24.14 km/h (15 mph). Test nos. MGS2-1B20 and MGS2-1B21 were plotted on a different graph, because both tests used a target impact speed of 32.19 km/h (20 mph). The sequential photographs at regular time intervals are shown in Figure 37, while Figure 38 shows the posts in soil after the impact test. The primary mode of failure in all of the tests was soil failure. The total energy was similar for MGS2-1B18 and MGS2-1B19, which had similar impact speeds and MGS2-1B20 and MGS2-1B21, which also had similar impact speeds. The average force of MGS2-1B18 was similar to MGS2-1B20, which had a different impact speed. Also, the average force of MGS2-1B19 was similar to that measured in MGS2-1B21, which also had a different impact speed. At 381-mm (15-in.) displacement, the average force for test nos. MGS2-1B18 and MGS2-1B19 was 26.04 kN (5.86 kips). At 381-mm (15-in.) displacement, the average force for test nos. MGS2-1B20 and MGS2-1B21 was 26.69 kN (6.00 kips). At 508-mm (20-in.) displacement, the average force for test nos. MGS2-1B18 and MGS2-1B19 was 28.72 kN (6.50 kips). At 508-mm (20-in.) displacement, the average force for test nos. MGS2-1B20 and MGS2-1B21 was 29.92 kN (6.72 kips).

Table 21. Test Results for Test Nos. MGS2-1B18 through MGS2-1B21 – (Metric)

Test No.	Embedment Depth (mm)	Impact Velocity (m/s)	Average Force				Average Energy		Total Energy (kJ)	Maximum Displacement (mm)	Failure Type
			15 in. Displacement (kN)	20 in. Displacement (kN)	24 in. Displacement (kN)	30 in. Displacement (kN)	15 in. Displacement (kJ)	20 in. Displacement (kJ)			
MGS2-1B18	1016	6.88	27.79	30.30	NA	NA	0.71	0.77	17.24	556.91	Soil
MGS2-1B19	1016	7.11	24.29	27.13	28.82	NA	0.62	0.69	18.40	636.50	Soil
Average			26.04	28.72							
MGS2-1B20	1016	8.64	28.68	31.73	32.97	32.67	0.73	0.81	26.59	870.74	Soil
MGS2-1B21	1016	8.86	24.70	28.11	29.30	28.20	0.63	0.71	24.04	976.29	Soil
Average			26.69	29.92							

Table 22. Test Results for Test Nos. MGS2-1B18 through MGS2-1B21 – (English)

Test No.	Embedment Depth (in.)	Impact Velocity (mph)	Average Force				Average Energy		Total Energy (kip-in.)	Maximum Displacement (in.)	Failure Type
			15 in. Displacement (kips)	20 in. Displacement (kips)	24 in. Displacement (kips)	30 in. Displacement (kips)	15 in. Displacement (kip-in)	20 in. Displacement (kip-in)			
MGS2-1B18	40	15.40	6.25	6.81	NA	NA	6.25	6.81	152.57	21.93	Soil
MGS2-1B19	40	15.91	5.46	6.10	6.48	NA	5.46	6.10	162.84	25.06	Soil
Average			5.86	6.50							
MGS2-1B20	40	19.33	6.45	7.13	7.41	7.35	6.45	7.13	235.32	34.28	Soil
MGS2-1B21	40	19.82	5.55	6.32	6.59	6.34	5.55	6.32	212.75	38.44	Soil
Average			6.00	6.72							



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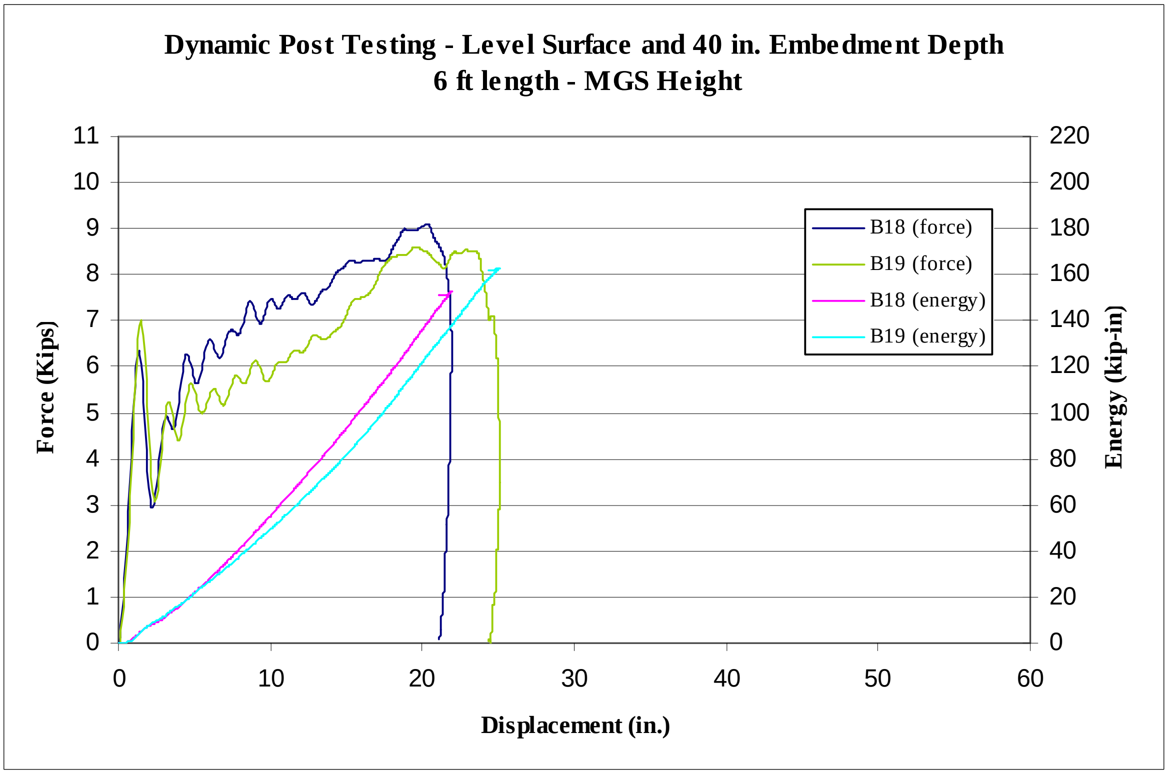
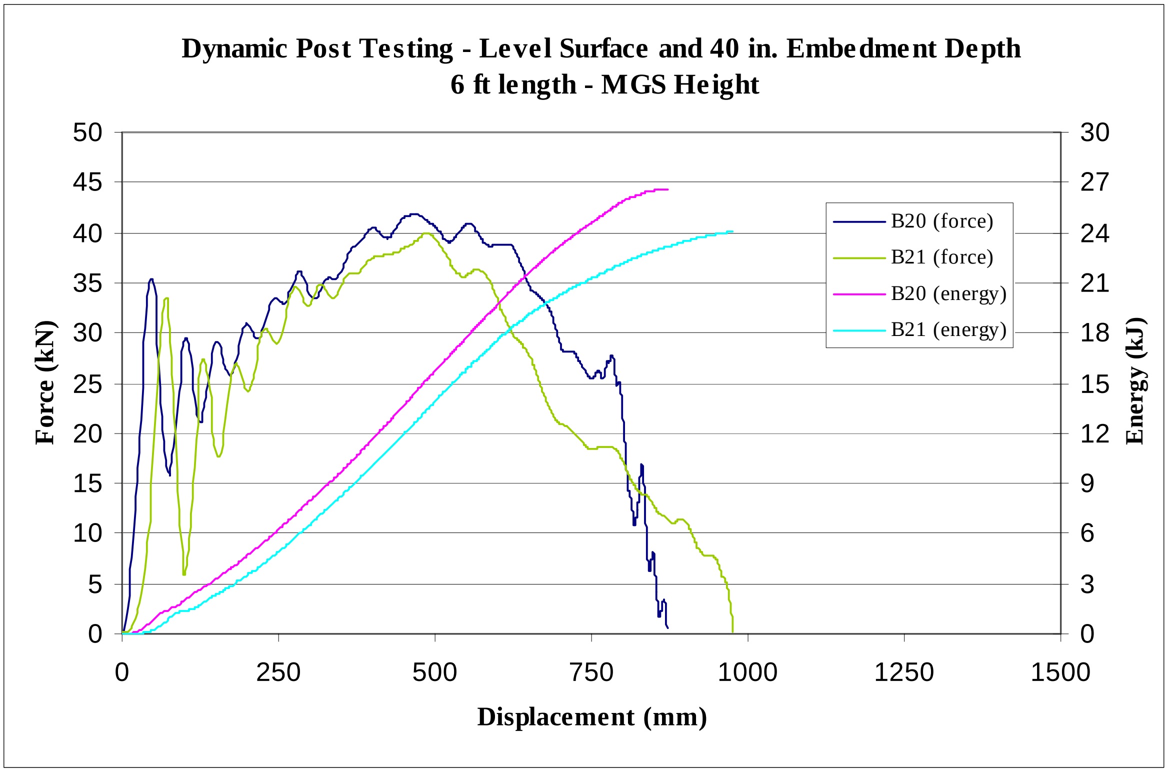
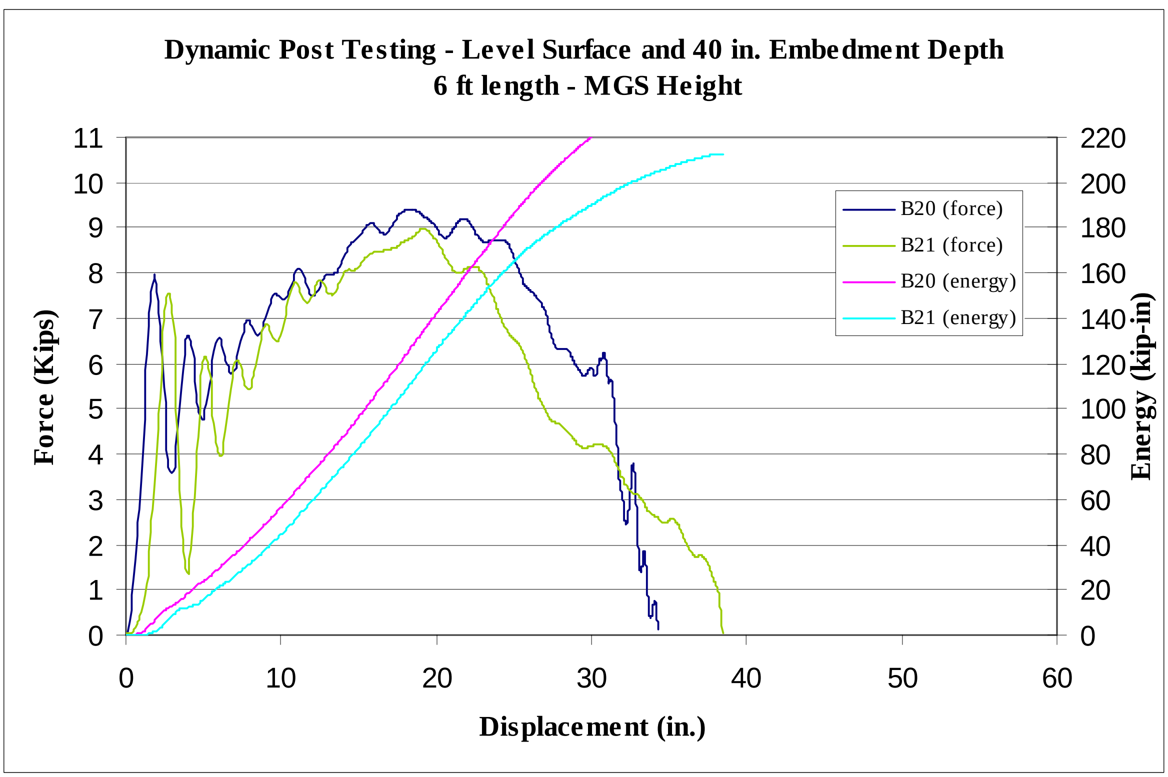


(b)

Figure 35. Force and Energy vs. Displacement Curves for MGS2-1B18 and MGS2-1B19 (a) Metric (b) English



(a)



(b)

Figure 36. Force and Energy vs. Displacement Curves for MGS2-1B20 and MGS2-1B21 (a) Metric (b) English

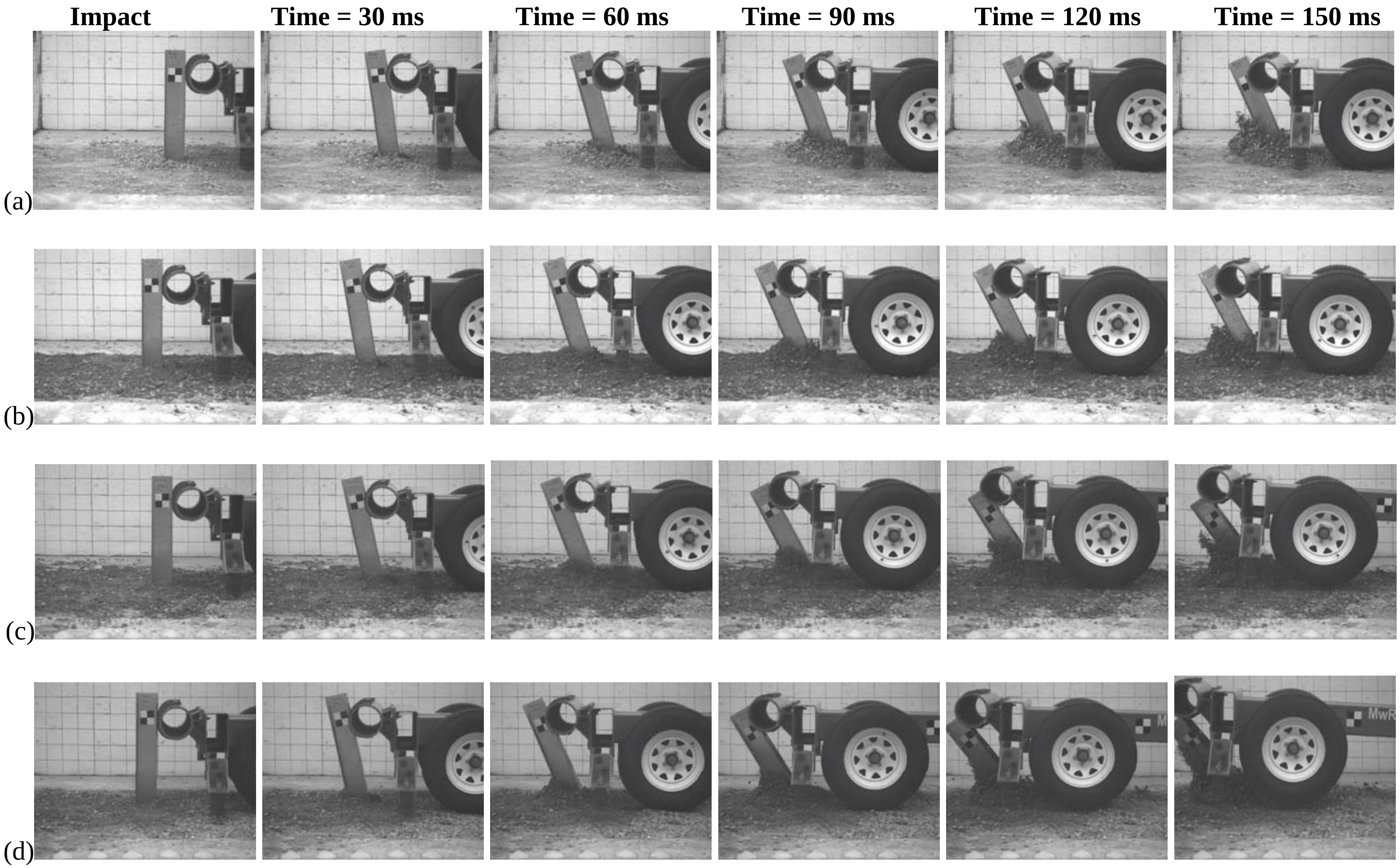


Figure 37. Sequential Photographs (a) MGS2-1B18, (b) MGS2-1B19, (c) MGS2-1B20, (d) MGS2-1B21


(a)


(b)


(c)

(d)

Figure 38. Post-Impact Image of (a) MGS2-1B18, (b) MGS2-1B19, (c) MGS2-1B20, (d) MGS2-1B

4.2 Overall Discussion, Conclusions, and Recommendations

Three rounds of bogie tests were performed at three different test setups, as shown in Figure 4, Figure 5, and Figure 6. The test results from the first round of bogie tests showed some unusual post-soil response due to the small size of the sloped test pit. It can be seen from the force-displacement graphs of test nos. MGS2-1B2 through MGS2-1B14, the force levels increased during the higher deflection regions of the post response. However, these increasing force levels would not have been observed with the use of a longer sloped test pit. Therefore, in the second round of testing, a larger test pit was used and more realistic results were found.

For the second round of testing, a 2,438-mm (8-ft) long post provided an average force of 31.23 kN (7.02 kips) for the first 381 mm (15 in.) of displacement. The average force was calculated from the energy-displacement curve using the formula:

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

where the energy was taken from the energy-displacement graph at a displacement of 381 mm (15 in.). Two more bogie tests, performed with 2,743-mm (9-ft) long posts, provided an average force of 28.43 kN (6.39 kips) for the first 381 mm (15 in.) of displacement using the above method.

Based on the round 2 bogie testing, it was determined that the 2,743-mm (9-ft) long steel posts embedded on the break line of a 2:1 fill slope should perform in a similar manner to the 1,829-mm (6-ft) long steel posts placed on level terrain [12]. From the prior research study, it has been shown that the standard length steel post installed in level terrain provided an average force of 28.46 kN (6.4 kips) at the target impact speed 31.19 km/h (20 mph) and over 381-mm (15-in.) displacement. In the round 3 bogie testing, it was demonstrated that comparable post-soil behavior was observed at both 24.14 km/h (15 mph) and 32.19 km/h (20 mph) bogie target impact speeds. For the round 3 testing contained herein, an average force of 26.04 kN (5.86 kips) and 26.69 kN (6.00 kips) was observed at a target impact speed of 24.14 km/h (15 mph) and 32.19 km/h (20 mph), respectively, for the 381-mm (15-in.) displacement. At 508-mm (20-in.) displacement, an average force of 28.72 kN (6.50 kips) and 29.92 kN (6.72 kips) was observed at a target impact speed of 24.14 km/h (15 mph) and 32.19 km/h (20 mph), respectively.

With this comparable post performance, it is anticipated that the modified Midwest Guardrail System (MGS) will be capable of safely capturing and redirecting the 1100C and 2270P vehicles contained in the Update to NCHRP Report No. 350 [7] and corresponding with the Test Level 3 impact conditions. Based on this study, it is recommended that BARRIER VII computer simulation modeling be used to further evaluate the MGS placed on a 2:1 fill slope using 2,743-mm (9-ft) long steel posts spaced on 1,905-mm (75-in.) centers as well as to determine the Critical Impact Point (CIP) for the future full-scale vehicle crash tests. Once completed, compliance testing is recommended in order to evaluate the MGS installed on a 2:1 slope.

5 REFERENCES

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6 APPENDIX A – TEST RESULTS

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

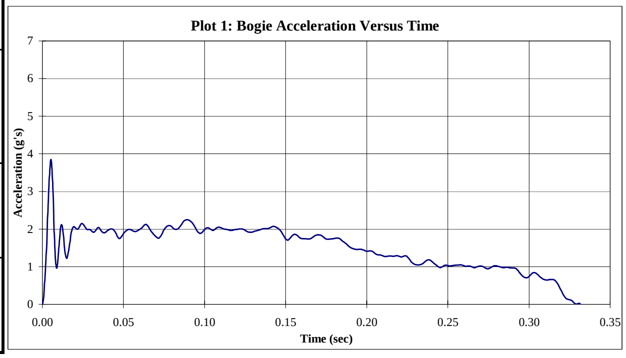
Test Parameters: MGS Bogie Test on 2:1 Slope
Test: Strong-Axis Impact at 0 degrees
Bogie Weight: 728.0 kg (1605.0 lbs)
Target Speed: 24.14 km/h (15 mph)
Bumper Height: 635 mm (25 in.)
Post Type: W152x13.4 (W6x9)
Post Length: Varying from 1,829 mm (6 ft) to 2,743 mm (9 ft)
Accelerometer: EDR-3 Data Recorder
Soil: 2,163 kg/m³ (135 lbs/ft³) NCHRP 350 (AASHTO 147-65 (1990) Grade B)

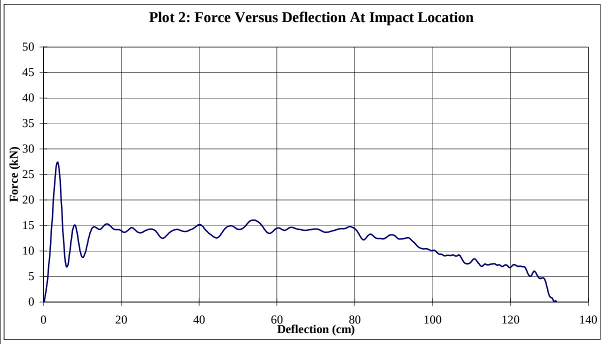
Test No.	Post Size		Embedment Depth		Speed		Bending Axis
	(ft)	(mm)	(in.)	(mm)	(mph)	(m/s)	
MGS2-1B1	6.0	1829	40.0	1016	15.40	6.88	Strong
MGS2-1B2	6.5	1981	46.0	1168	15.08	6.74	Strong
MGS2-1B3	7.0	2134	52.0	1321	15.59	6.97	Strong
MGS2-1B4	7.5	2286	58.0	1473	15.51	6.93	Strong
MGS2-1B5	8.0	2438	64.0	1626	15.47	6.92	Strong
MGS2-1B6	8.5	2591	70.0	1778	14.81	6.62	Strong
MGS2-1B7	9.0	2743	76.0	1930	15.10	6.75	Strong
MGS2-1B8	7.0	2134	52.0	1321	15.31	6.84	Strong
MGS2-1B9	6.5	1981	46.0	1168	15.32	6.85	Strong
MGS2-1B10	6.0	1829	40.0	1016	16.06	7.18	Strong
MGS2-1B11	7.5	2286	58.0	1473	15.51	6.93	Strong
MGS2-1B12	8.0	2438	64.0	1626	15.41	6.89	Strong
MGS2-1B13	8.5	2591	70.0	1778	15.89	7.10	Strong
MGS2-1B14	9.0	2743	76.0	1930	15.75	7.04	Strong
MGS2-1B15	8.0	2438	64.0	1626	17.34	7.75	Strong
MGS2-1B16	9.0	2743	76.0	1930	17.22	7.70	Strong
MGS2-1B17	9.0	2743	76.0	1930	17.58	7.86	Strong
MGS2-1B18	6.0	1829	40.0	1016	15.40	6.88	Strong
MGS2-1B19	6.0	1829	40.0	1016	15.91	7.11	Strong
MGS2-1B20	6.0	1829	40.0	1016	19.33	8.64	Strong
MGS2-1B21	6.0	1829	40.0	1016	19.82	8.86	Strong

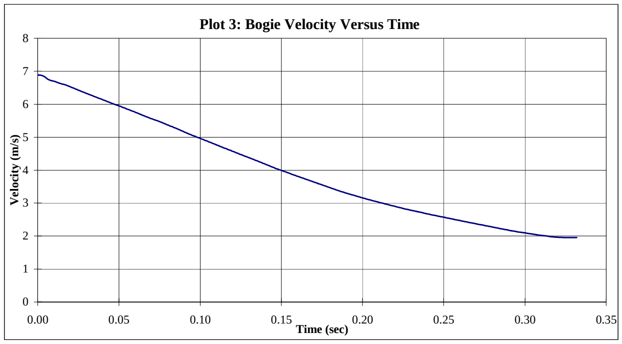
Midwest Roadside Safety Facility

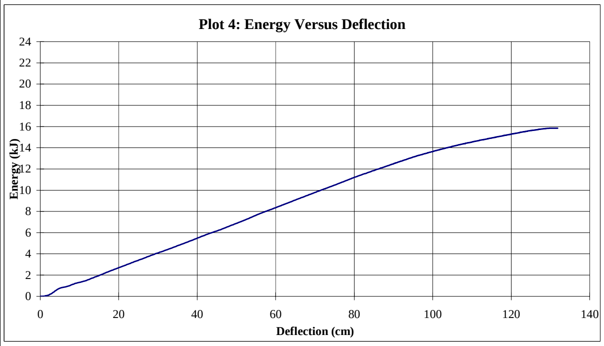
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B1		
Test Date:	11-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4 metric	W6x9	
Post Length:	182.9 cm	72 in.	
Embedment Depth:	101.6 cm	40 in.	
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	4.7%		
Compaction Method:	NA		
Soil Density, γ_d:	NA kg/m^3	NA	
Bogie Properties			
Impact Velocity:	6.9 m/s	(15.4 mph)	(22.6 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









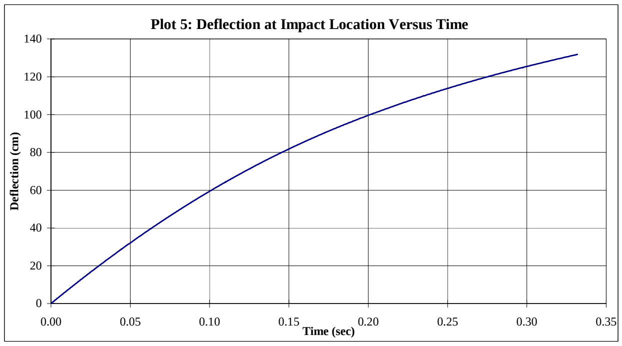


Figure 39. Test Results - MGS2-1B1

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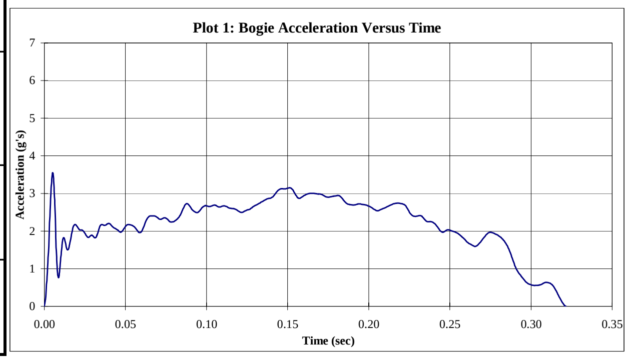
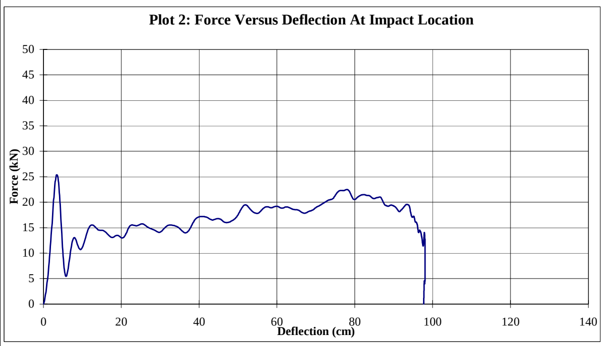
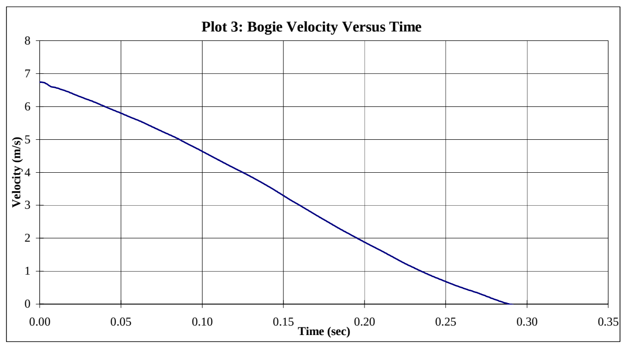
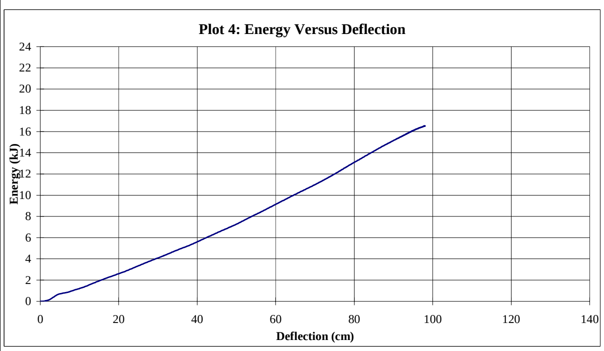
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B2		
Test Date:	11-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4 metric	W6x9	
Post Length:	198.1 cm	78 in.	
Embedment Depth:	116.8 cm	46 in.	
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	4.4%		
Compaction Method:	NA		
Soil Density, γ_d:	NA kg/m^3	NA	
Bogie Properties			
Impact Velocity:	6.7 m/s	(15.1 mph)	(22.1 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









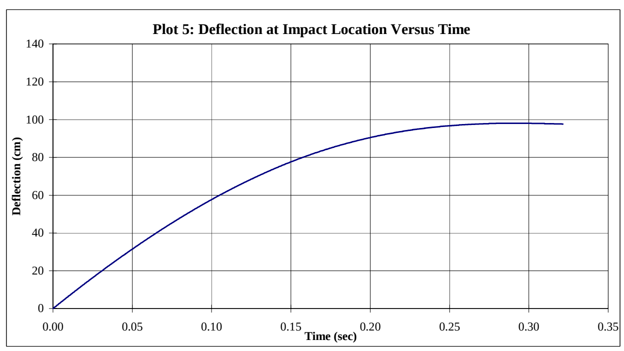


Figure 40. Test Results - MGS2-1B2

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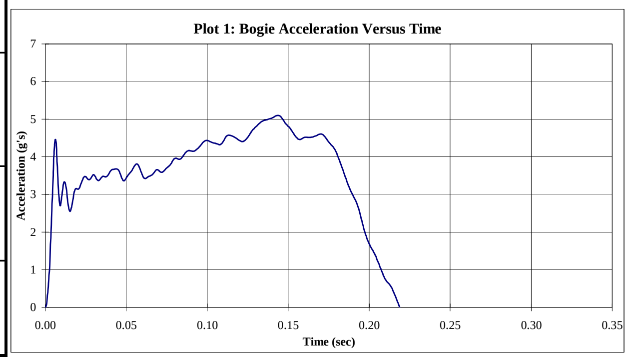
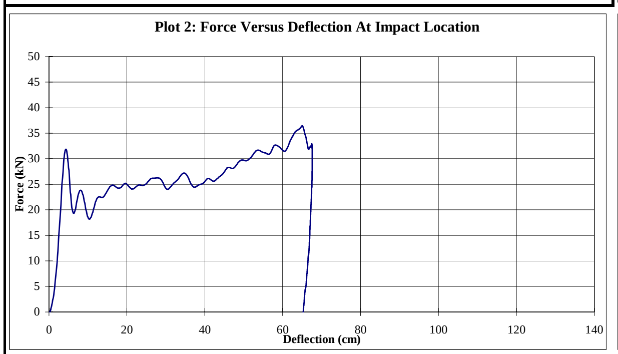
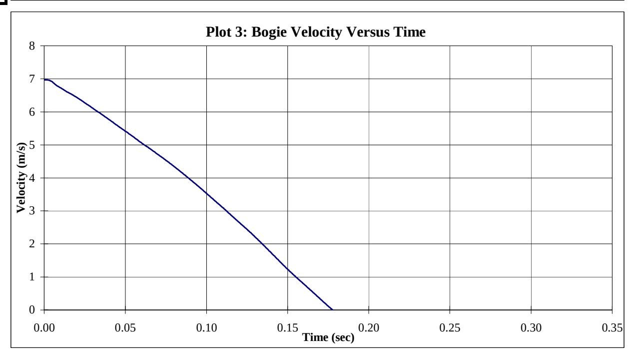
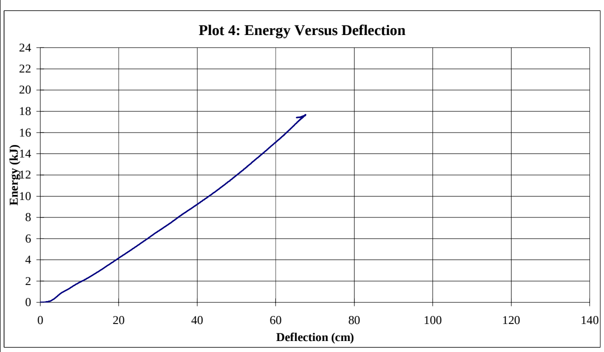
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B3		
Test Date:	11-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4	metric	W6x9
Post Length:	213.4	cm	84 in.
Embedment Depth:	132.1	cm	52 in.
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	4.4%		
Compaction Method:	NA		
Soil Density, γ_d:	NA	kg/m^3	NA
Bogie Properties			
Impact Velocity:	7.0 m/s	(15.6 mph)	(22.9 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









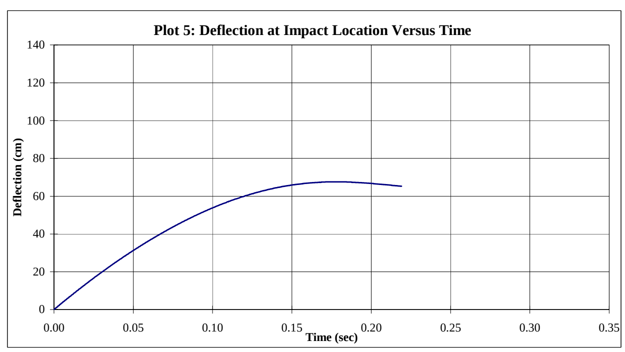
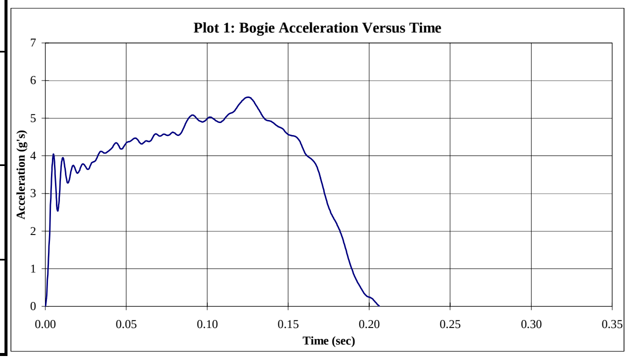


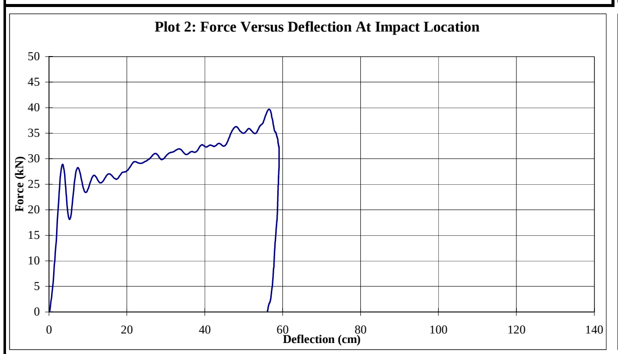
Figure 41. Test Results - MGS2-1B3

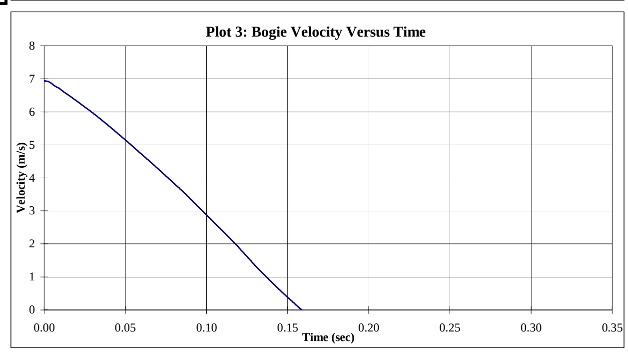
Midwest Roadside Safety Facility

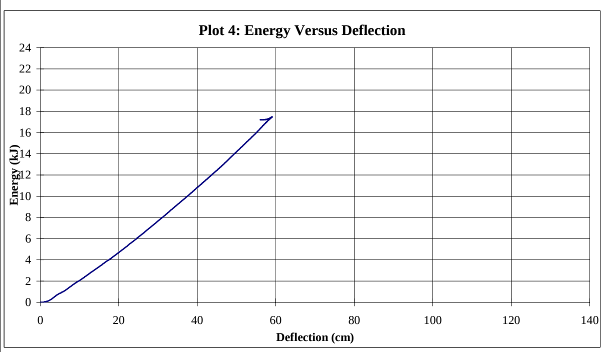
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B4		
Test Date:	11-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4 metric	W6x9	
Post Length:	228.6 cm	90 in.	
Embedment Depth:	147.3 cm	58 in.	
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	4.4%		
Compaction Method:	NA		
Soil Density, γ_d:	NA kg/m^3	NA	
Bogie Properties			
Impact Velocity:	6.9 m/s	(15.5 mph)	(22.7 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









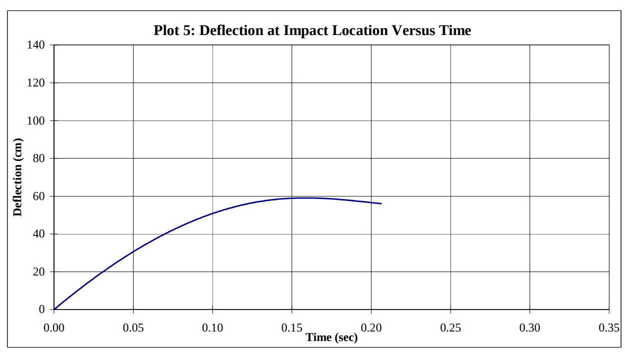
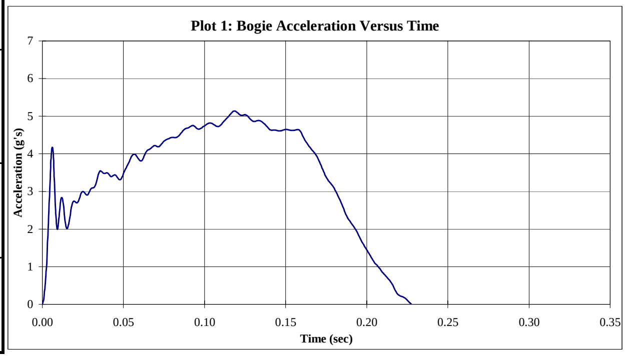


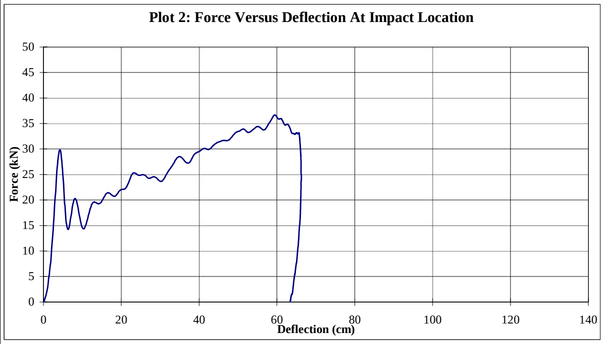
Figure 42. Test Results - MGS2-1B4

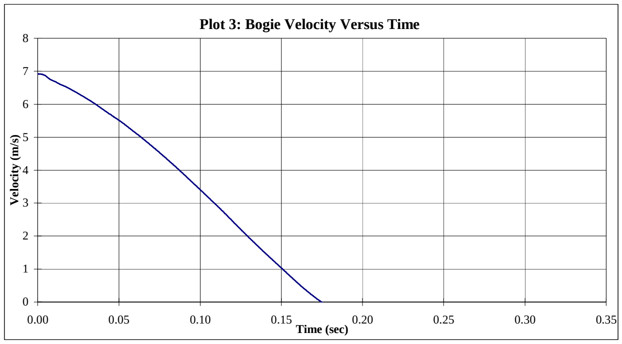
Midwest Roadside Safety Facility

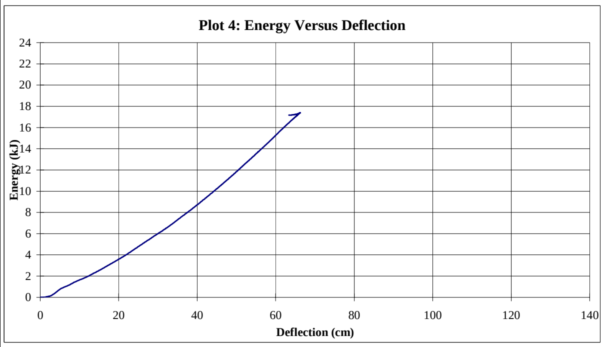
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B5		
Test Date:	12-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4 metric	W6x9	
Post Length:	243.8 cm	96 in.	
Embedment Depth:	162.6 cm	64 in.	
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	4.5%		
Compaction Method:	NA		
Soil Density, γ_d:	NA kg/m^3	NA	
Bogie Properties			
Impact Velocity:	6.9 m/s	(15.5 mph)	(22.7 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









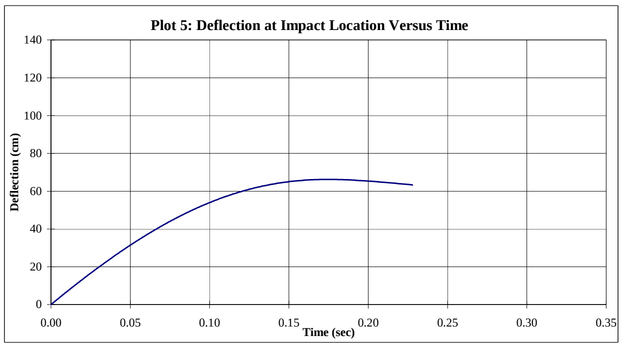
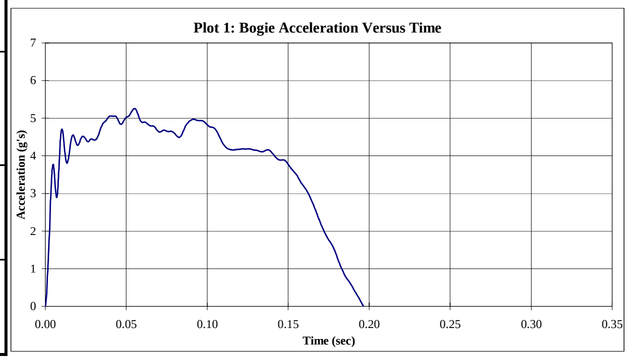


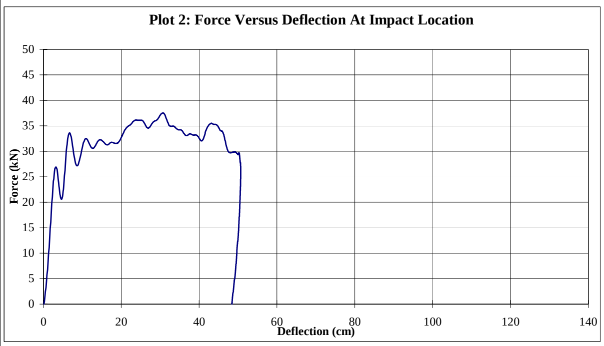
Figure 43. Test Results - MGS2-1B5

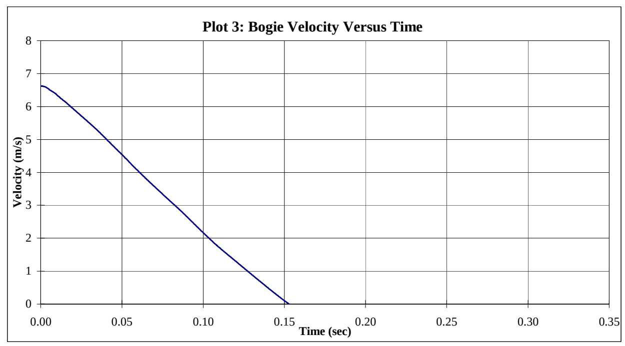
Midwest Roadside Safety Facility

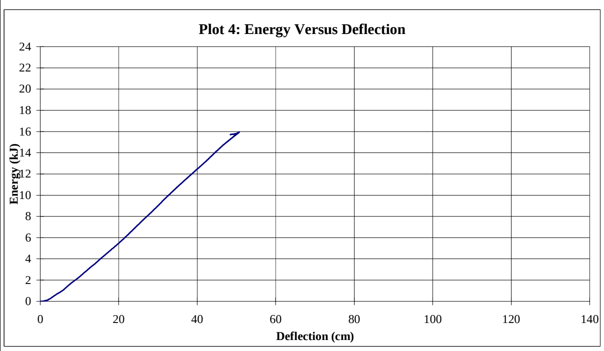
Bogie Test Summary

Test Information	CL Bogie MGS Height			
Test Number:	MGS2-1B6			
Test Date:	12-May-2006			
Failure Type:	Soil Failure			
Post Properties				
Post Type:		Steel W6x9		
Post Size:	W152x13.4 metric			0
Post Length:	259.1 cm	102 in.		
Embedment Depth:	177.8 cm	70 in.		
Category:	0			
Soil Properties				
Gradation:		NA		
Moisture Content:		4.5%		
Compaction Method:		NA		
Soil Density, γ_d:	NA kg/m^3	NA		
Bogie Properties				
Impact Velocity:	6.6 m/s	(14.8 mph)	(21.7 fps)	
Impact Location:	63.2 cm	(24.9 in)	above groundline	
Bogie Mass:	728 kg	(1605 lbf)		
Data Acquired				
Accelerometer Data:		EDR-3		
Camera Data:		AOS 2 - Side View 22' - 10"		









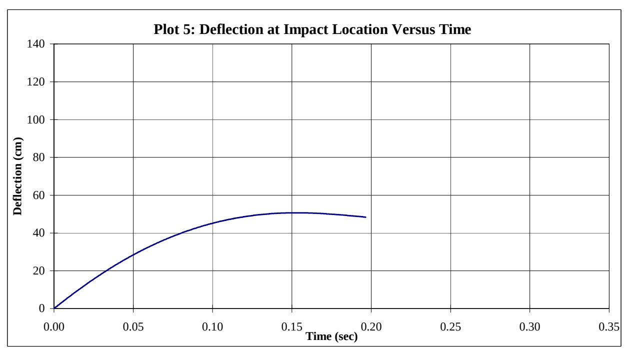
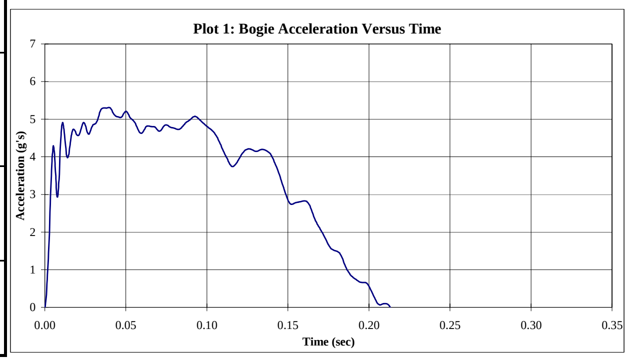


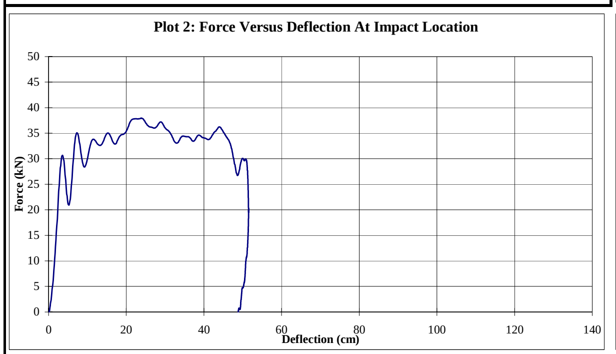
Figure 44. Test Results - MGS2-1B6

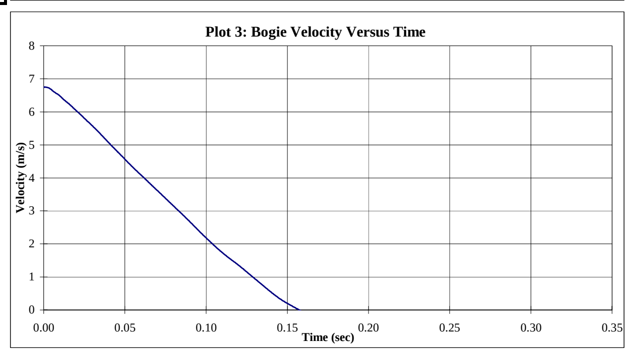
Midwest Roadside Safety Facility

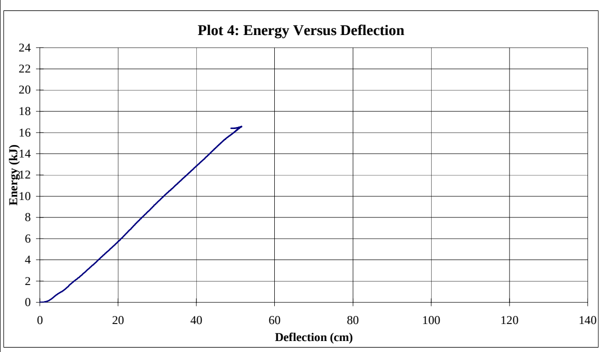
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B7		
Test Date:	12-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4 metric	W6x9	
Post Length:	274.3 cm	108 in.	
Embedment Depth:	193.0 cm	76 in.	
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	4.5%		
Compaction Method:	NA		
Soil Density, γ_d:	NA kg/m³	NA	
Bogie Properties			
Impact Velocity:	6.8 m/s	(15.1 mph)	(22.1 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









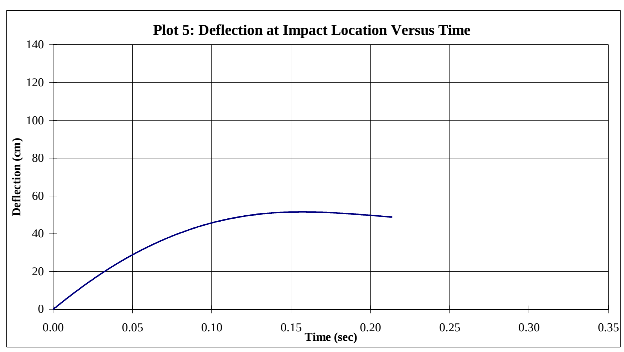
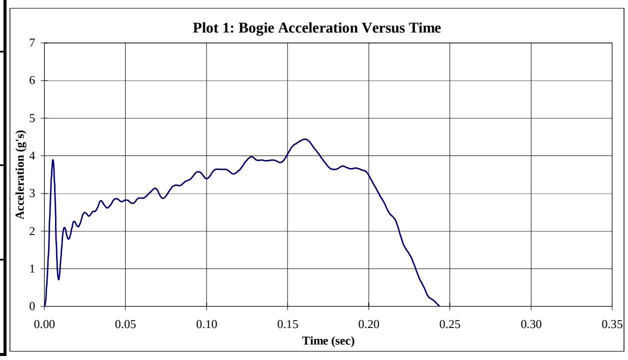


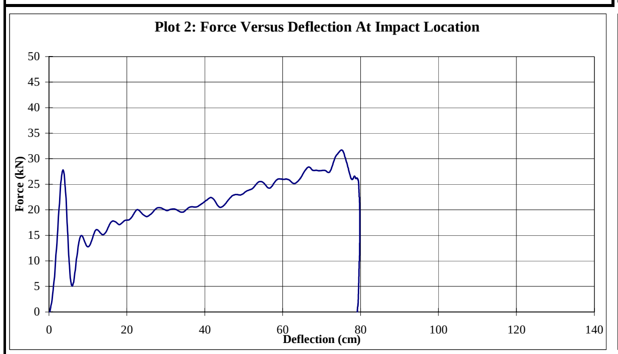
Figure 45. Test Results - MGS2-1B7

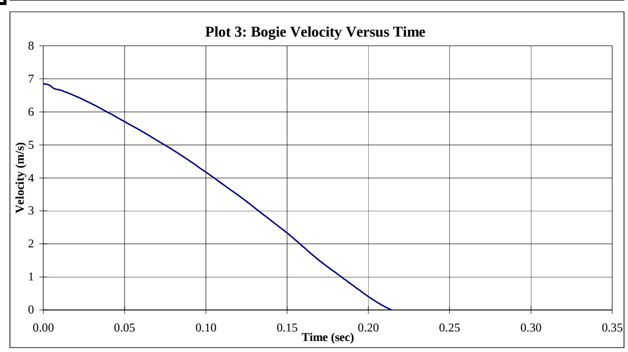
Midwest Roadside Safety Facility

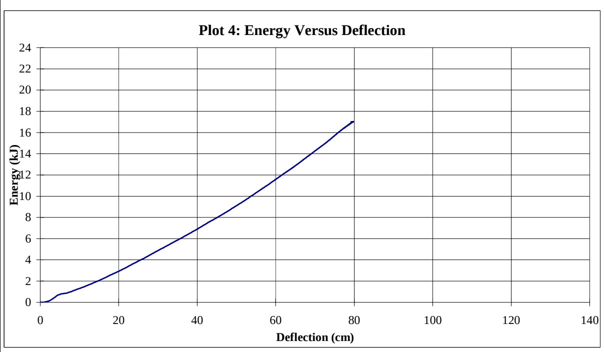
Bogie Test Summary

Test Information	CL Bogie MGS Height			
Test Number:	MGS2-1B8			
Test Date:	12-May-2006			
Failure Type:	Soil Failure			
Post Properties				
Post Type:	Steel W6x9			
Post Size:	W152x13.4	metric	W6x9	
Post Length:	213.4	cm	84	in.
Embedment Depth:	132.1	cm	52	in.
Category:	0			
Soil Properties				
Gradation:	NA			
Moisture Content:	4.5%			
Compaction Method:	NA			
Soil Density, γ_d:	NA	kg/m^3	NA	
Bogie Properties				
Impact Velocity:	6.8 m/s	(15.3 mph)	(22.5 fps)	
Impact Location:	63.2 cm	(24.9 in)	above groundline	
Bogie Mass:	728 kg	(1605 lbf)		
Data Acquired				
Accelerometer Data:	EDR-3			
Camera Data:	AOS 2 - Side View 22' - 10"			









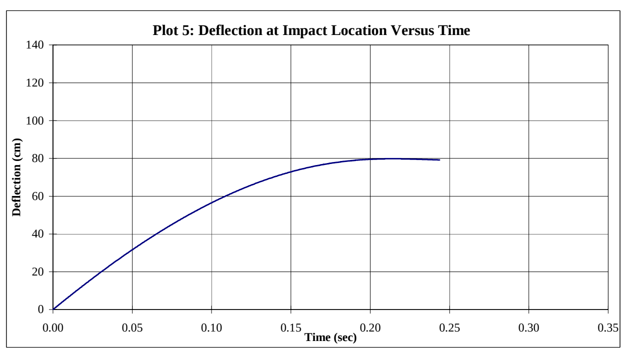
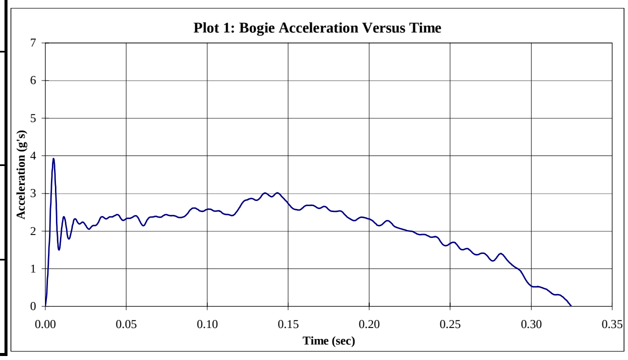


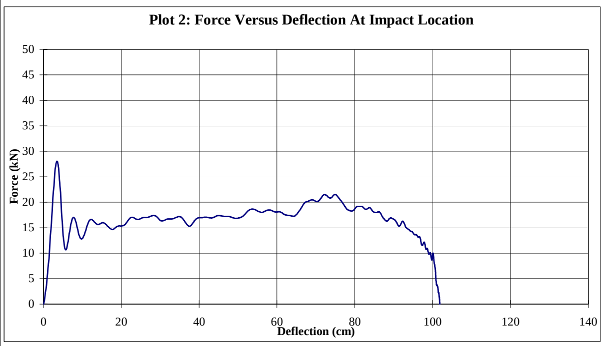
Figure 46. Test Results - MGS2-1B8

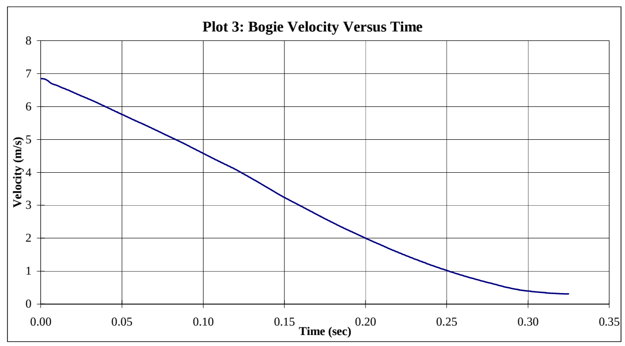
Midwest Roadside Safety Facility

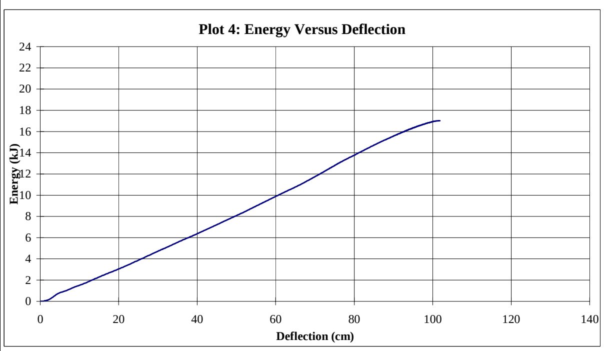
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	2-1B9		
Test Date:	15-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4	metric	W6x9
Post Length:	198.1	cm	78 in.
Embedment Depth:	116.8	cm	46 in.
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	4.5%		
Compaction Method:	NA		
Soil Density, γ_d:	NA	kg/m^3	NA
Bogie Properties			
Impact Velocity:	6.8 m/s	(15.3 mph)	(22.5 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









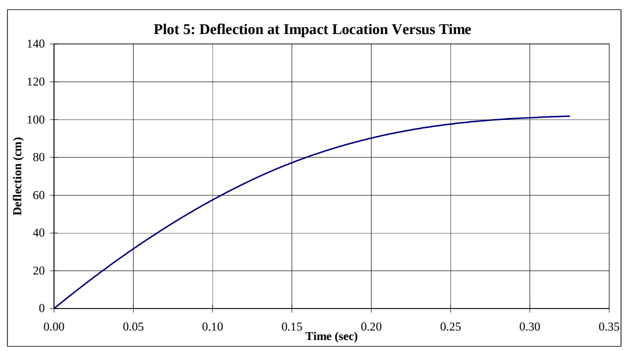


Figure 47. Test Results - MGS2-1B9

Midwest Roadside Safety Facility

Bogie Test Summary

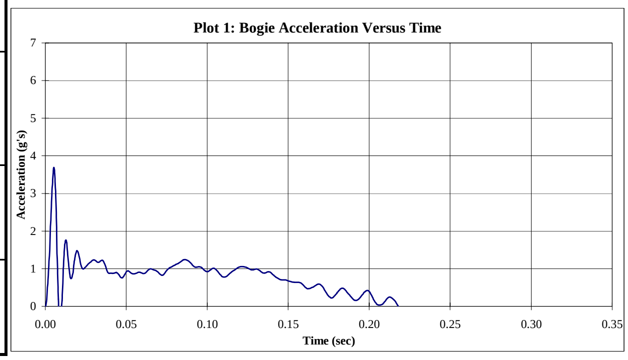
Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B10		
Test Date:	15-May-2006		
Failure Type:	Soil Failure		

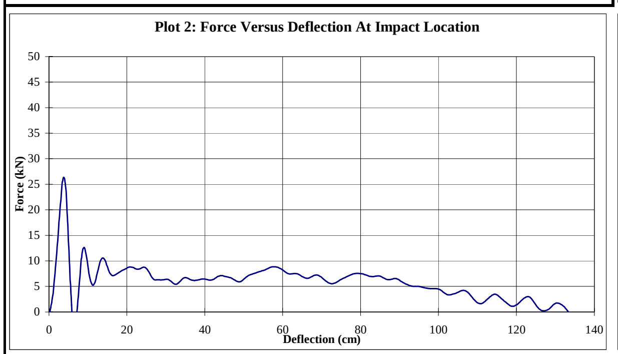
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4	metric	W6x9
Post Length:	182.9	cm	72 in.
Embedment Depth:	101.6	cm	40 in.
Category:	0		

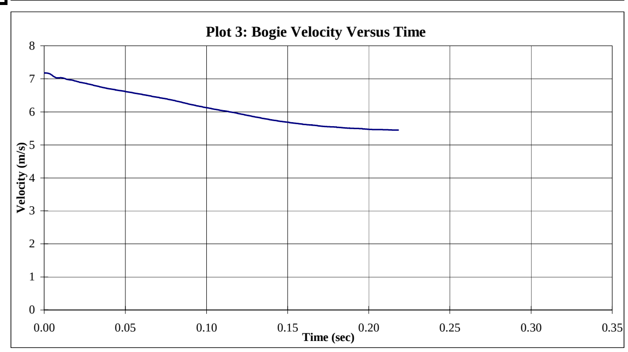
Soil Properties			
Gradation:	NA		
Moisture Content:	4.5%		
Compaction Method:	NA		
Soil Density, γ_d:	NA	kg/m^3	NA

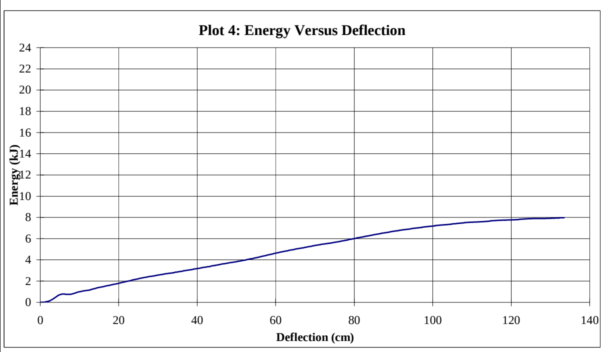
Bogie Properties			
Impact Velocity:	7.2 m/s	(16.1 mph)	(23.6 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	

Data Acquired	
Accelerometer Data:	EDR-3
Camera Data:	AOS 2 - Side View 22' - 10"









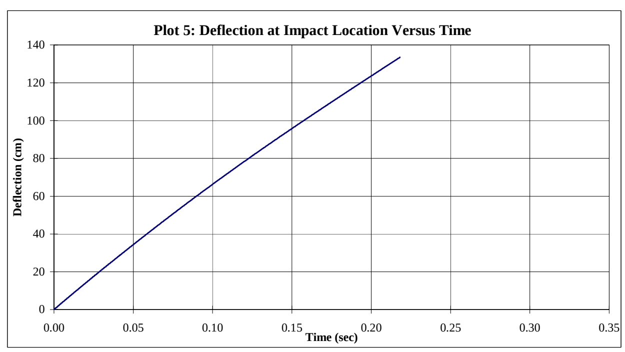
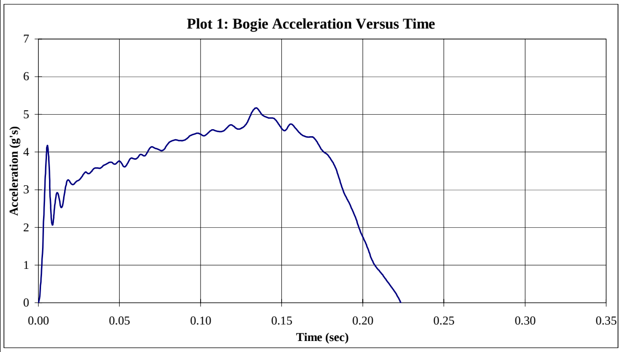


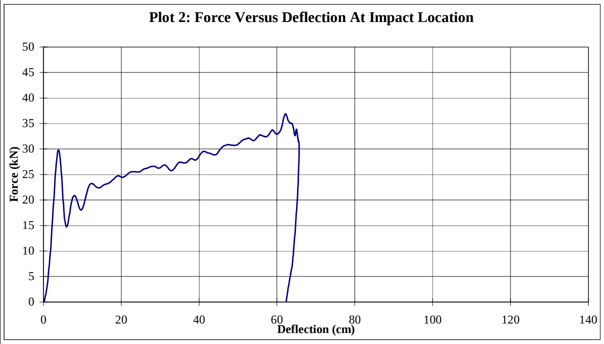
Figure 48. Test Results - MGS2-1B10

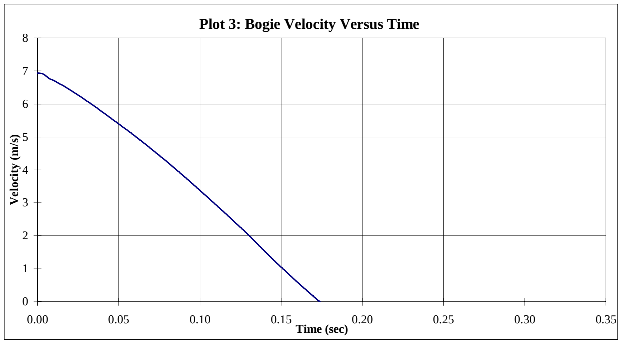
Midwest Roadside Safety Facility

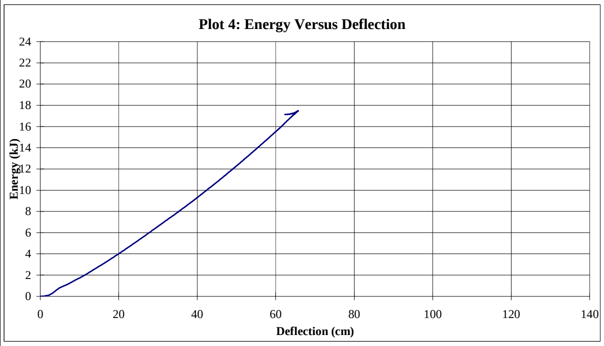
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B11		
Test Date:	15-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4 metric	W6x9	
Post Length:	228.6 cm	90 in.	
Embedment Depth:	147.3 cm	58 in.	
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	4.5%		
Compaction Method:	NA		
Soil Density, γ_d:	NA kg/m^3	NA	
Bogie Properties			
Impact Velocity:	6.9 m/s	(15.5 mph)	(22.7 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









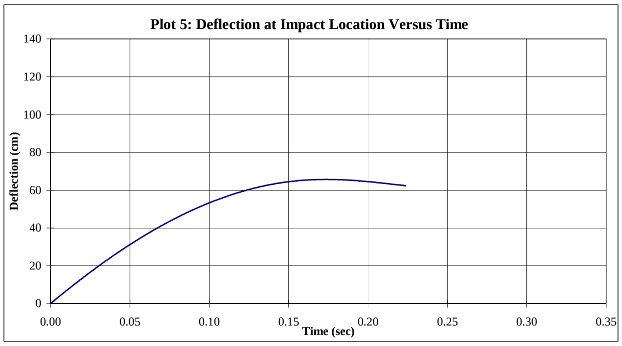
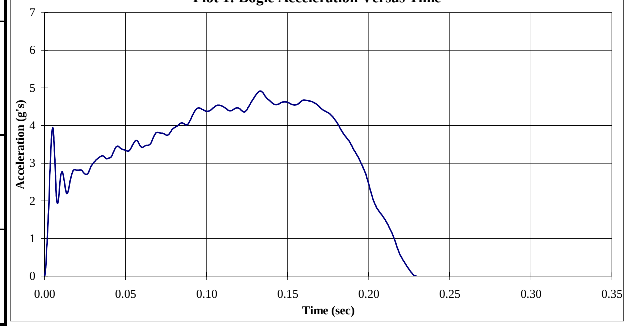


Figure 49. Test Results - MGS2-1B11

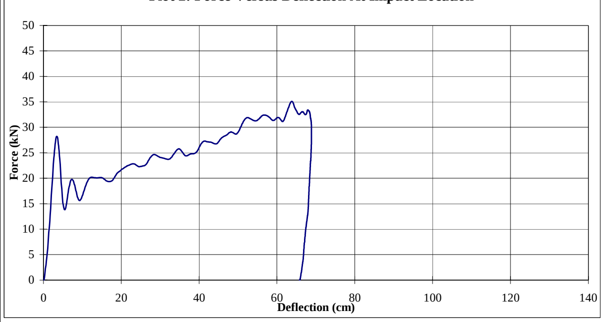
Midwest Roadside Safety Facility

Bogie Test Summary

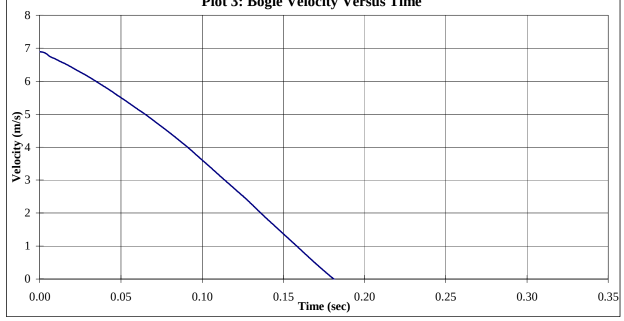
Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B12		
Test Date:	15-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4 metric	W6x9	
Post Length:	243.8 cm	96 in.	
Embedment Depth:	162.6 cm	64 in.	
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	4.5%		
Compaction Method:	NA		
Soil Density, γ_d:	NA kg/m³	NA	
Bogie Properties			
Impact Velocity:	6.9 m/s	(15.4 mph)	(22.6 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		



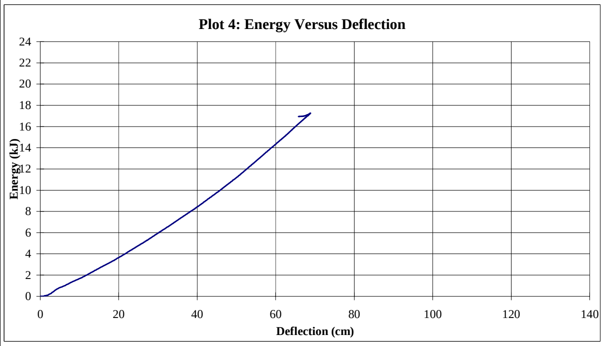
Plot 1: Bogie Acceleration Versus Time



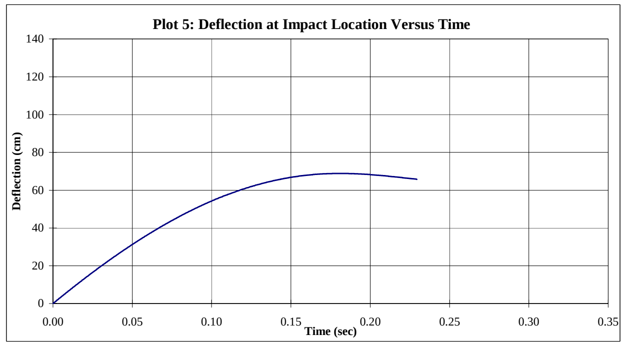
Plot 2: Force Versus Deflection At Impact Location



Plot 3: Bogie Velocity Versus Time



Plot 4: Energy Versus Deflection



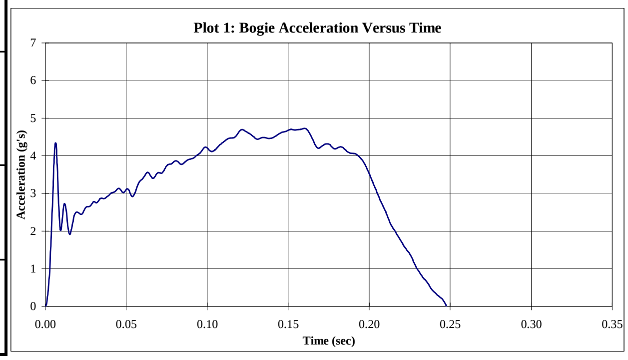
Plot 5: Deflection at Impact Location Versus Time

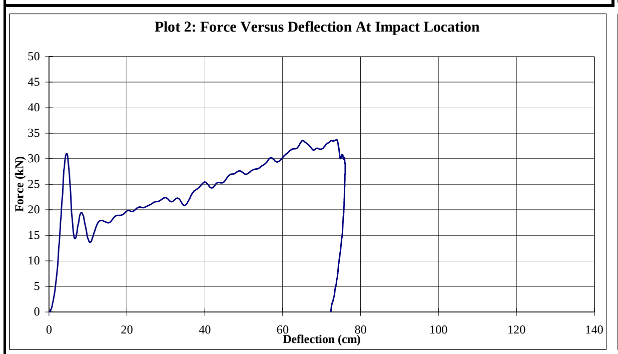
Figure 50. Test Results - MGS2-1B12

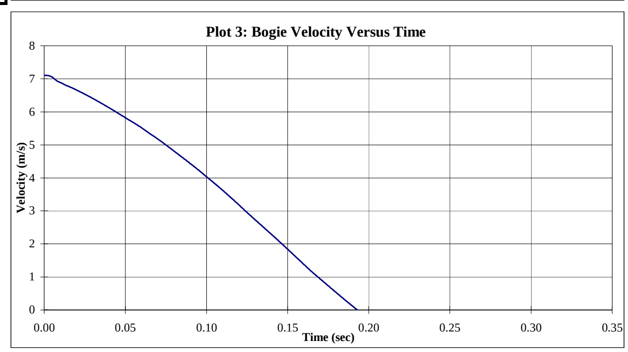
Midwest Roadside Safety Facility

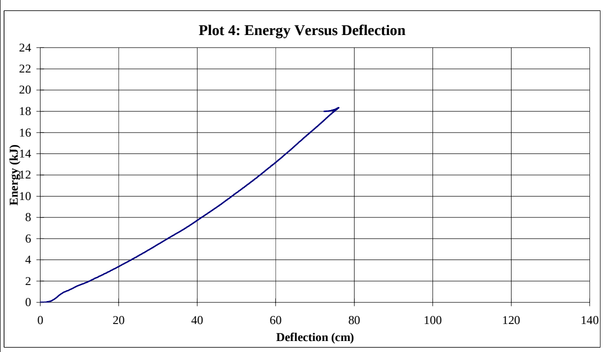
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B13		
Test Date:	16-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4 metric		W6x9
Post Length:	259.1 cm		102 in.
Embedment Depth:	177.8 cm		70 in.
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	4.5%		
Compaction Method:	NA		
Soil Density, γ_d:	NA kg/m³		NA
Bogie Properties			
Impact Velocity:	7.1 m/s	(15.9 mph)	(23.3 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









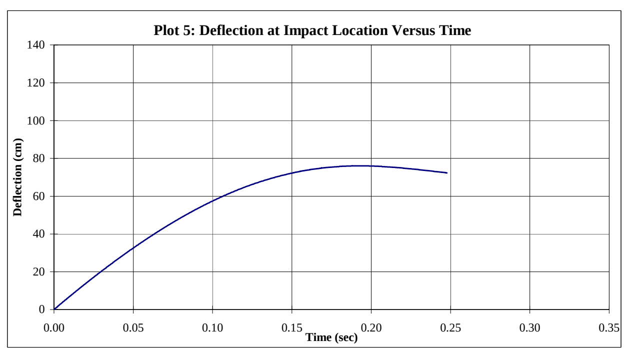
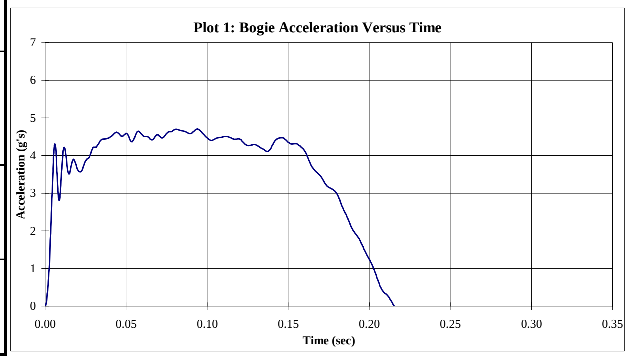


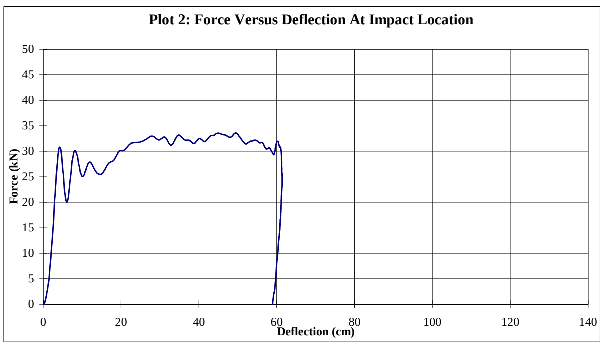
Figure 51. Test Results - MGS2-1B13

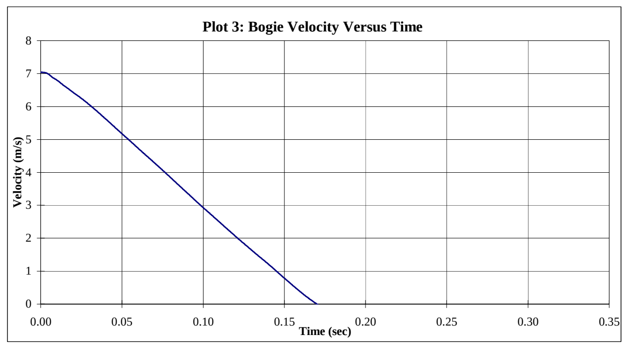
Midwest Roadside Safety Facility

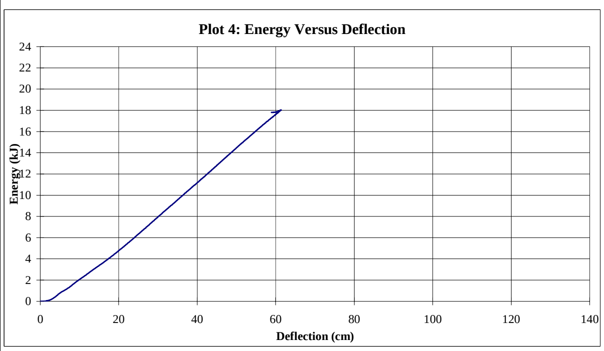
Bogie Test Summary

Test Information	CL Bogie MGS Height			
Test Number:	MGS2-1B14			
Test Date:	16-May-2006			
Failure Type:	Soil Failure			
Post Properties				
Post Type:		Steel W6x9		
Post Size:	W152x13.4	metric	W6x9	
Post Length:	274.3	cm	108 in.	
Embedment Depth:	193.0	cm	76 in.	
Category:	0			
Soil Properties				
Gradation:		NA		
Moisture Content:		4.5%		
Compaction Method:		NA		
Soil Density, γ_d:	NA	kg/m^3	NA	
Bogie Properties				
Impact Velocity:	7.0 m/s	(15.8 mph)	(23.1 fps)	
Impact Location:	63.2 cm	(24.9 in)	above groundline	
Bogie Mass:	728 kg	(1605 lbf)		
Data Acquired				
Accelerometer Data:		EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"			









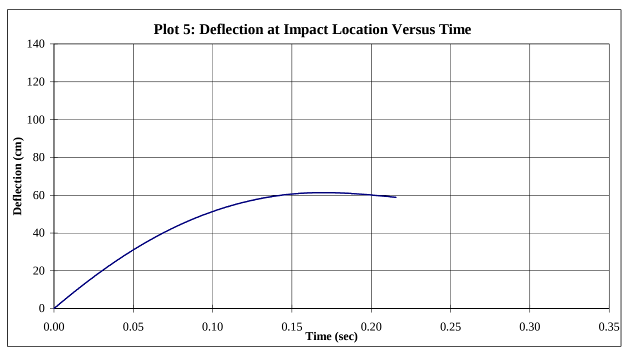
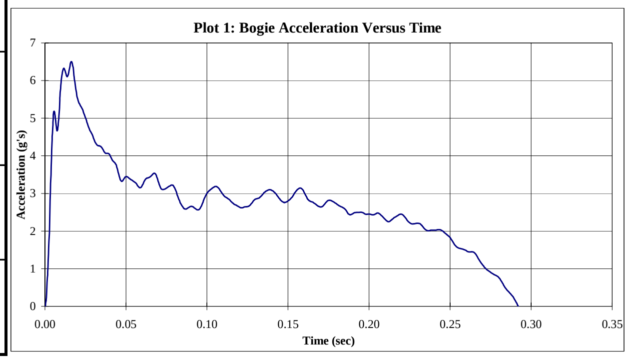


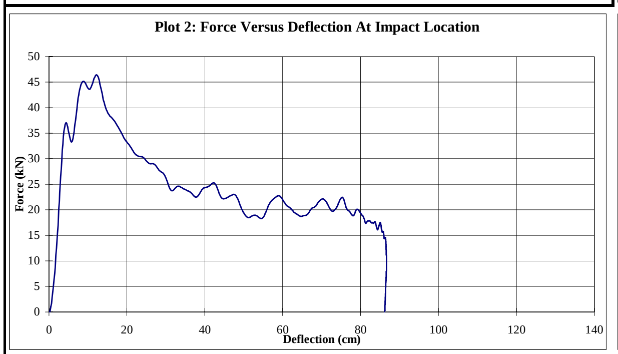
Figure 52. Test Results - MGS2-1B14

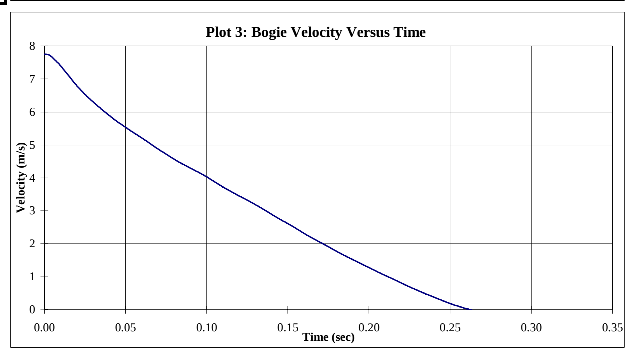
Midwest Roadside Safety Facility

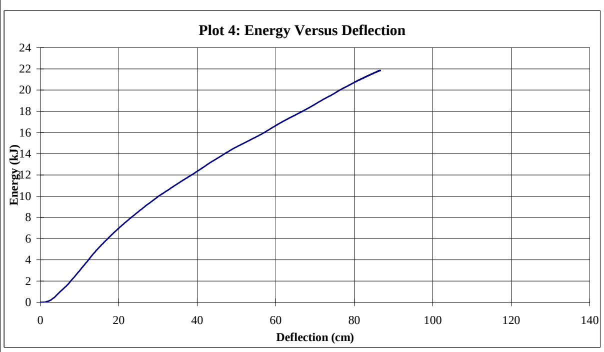
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B15		
Test Date:	23-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4	metric	W6x9
Post Length:	243.8	cm	96 in.
Embedment Depth:	162.6	cm	64 in.
Category:	0		
Soil Properties			
Gradation:			NA
Moisture Content:			NA
Compaction Method:			NA
Soil Density, γ_d:	NA	kg/m^3	NA
Bogie Properties			
Impact Velocity:	7.8 m/s	(17.3 mph)	(25.4 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









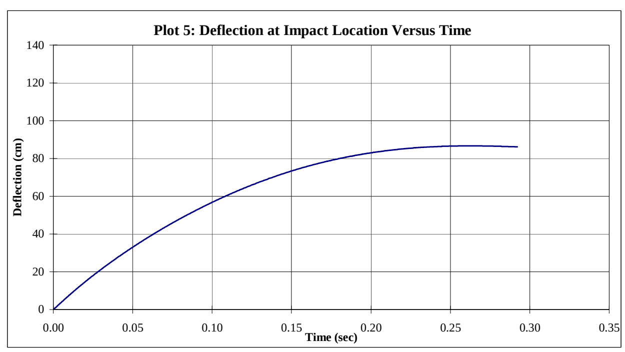
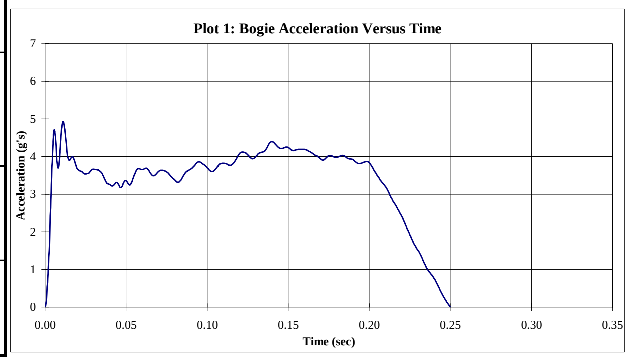


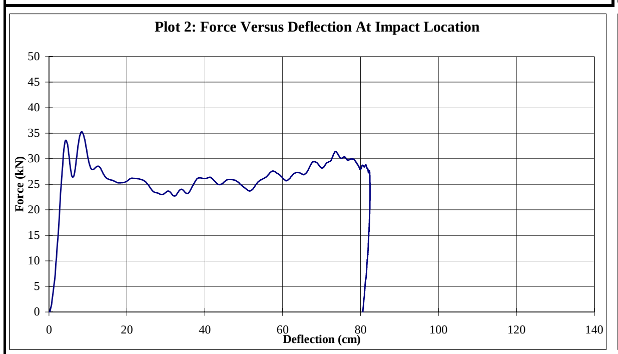
Figure 53. Test Results - MGS2-1B15

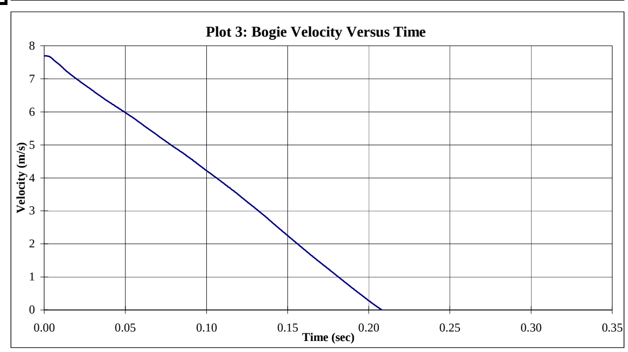
Midwest Roadside Safety Facility

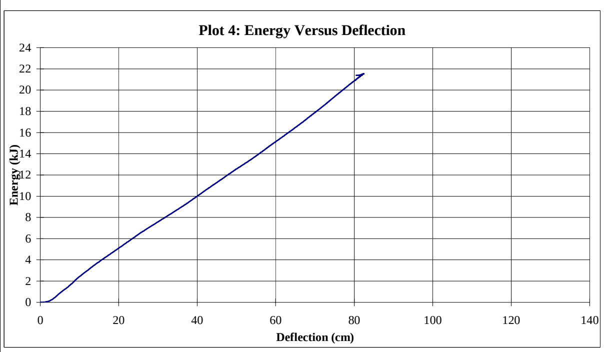
Bogie Test Summary

Test Information	CL Bogie MGS Height		
Test Number:	MGS2-1B16		
Test Date:	23-May-2006		
Failure Type:	Soil Failure		
Post Properties			
Post Type:	Steel W6x9		
Post Size:	W152x13.4	metric	W6x9
Post Length:	274.3	cm	108 in.
Embedment Depth:	193.0	cm	76 in.
Category:	0		
Soil Properties			
Gradation:	NA		
Moisture Content:	NA		
Compaction Method:	NA		
Soil Density, γ_d:	NA	kg/m³	NA
Bogie Properties			
Impact Velocity:	7.7 m/s	(17.2 mph)	(25.3 fps)
Impact Location:	63.2 cm	(24.9 in)	above groundline
Bogie Mass:	728 kg	(1605 lbf)	
Data Acquired			
Accelerometer Data:	EDR-3		
Camera Data:	AOS 2 - Side View 22' - 10"		









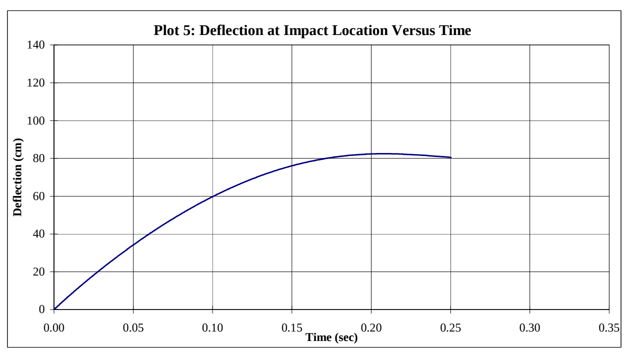


Figure 54. Test Results - MGS2-1B16

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information — CL Bogie MGS Height

Test Number:	MGS2-1B17	
Test Date:	5-Jun-2006	
Failure Type:	Soil Failure	

Post Properties

Post Type:	Steel W6x9	
Post Size:	W152x13.4metric	W6x9
Post Length:	274.3 cm	108 in.
Embedment Depth:	193.0 cm	76 in.
Category:	0	

Soil Properties

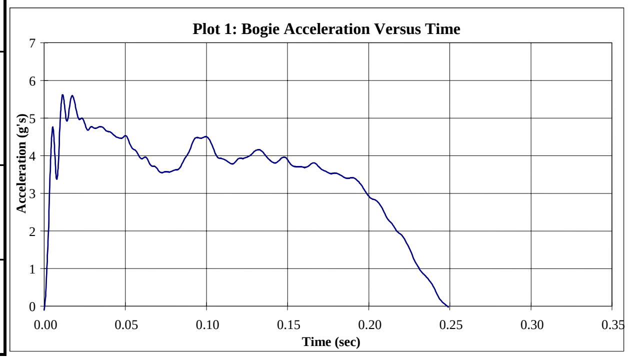
Gradation:	NA	
Moisture Content:	5.5%	
Compaction Method:	NA	
Soil Density, γ_d:	NA kg/m^3	NA

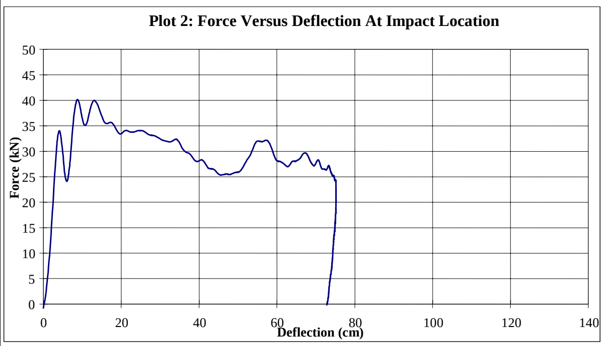
Bogie Properties

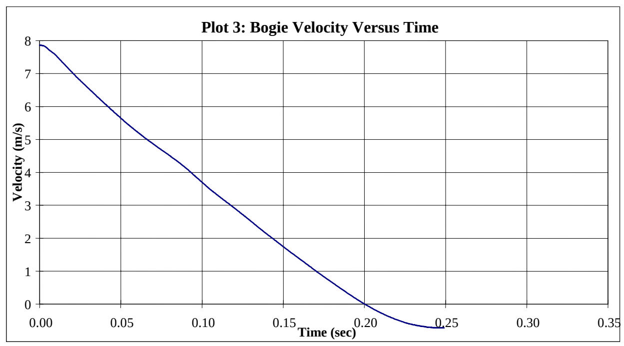
Impact Velocity:	7.9 m/s	(17.6 mph)(25.8 fps)
Impact Location:	63.2 cm	(24.9 in) above groundline
Bogie Mass:	728 kg	(1605 lbf)

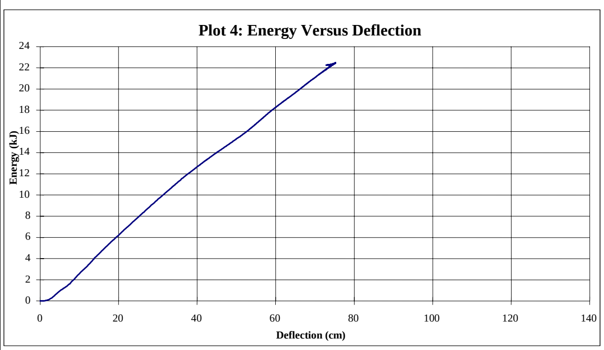
Data Acquired

Accelerometer Data:	EDR-3
Camera Data:	AOS 2 - Side View 22' - 10"









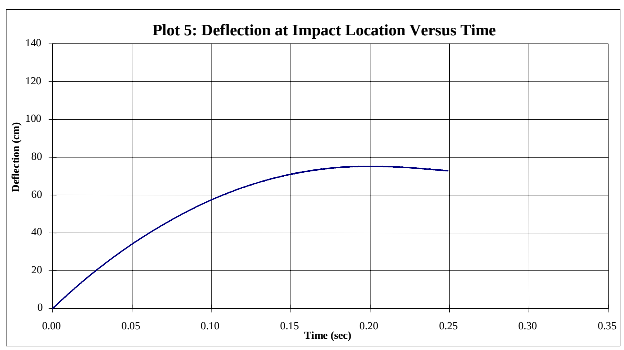


Figure 55. Test Results - MGS2-1B17

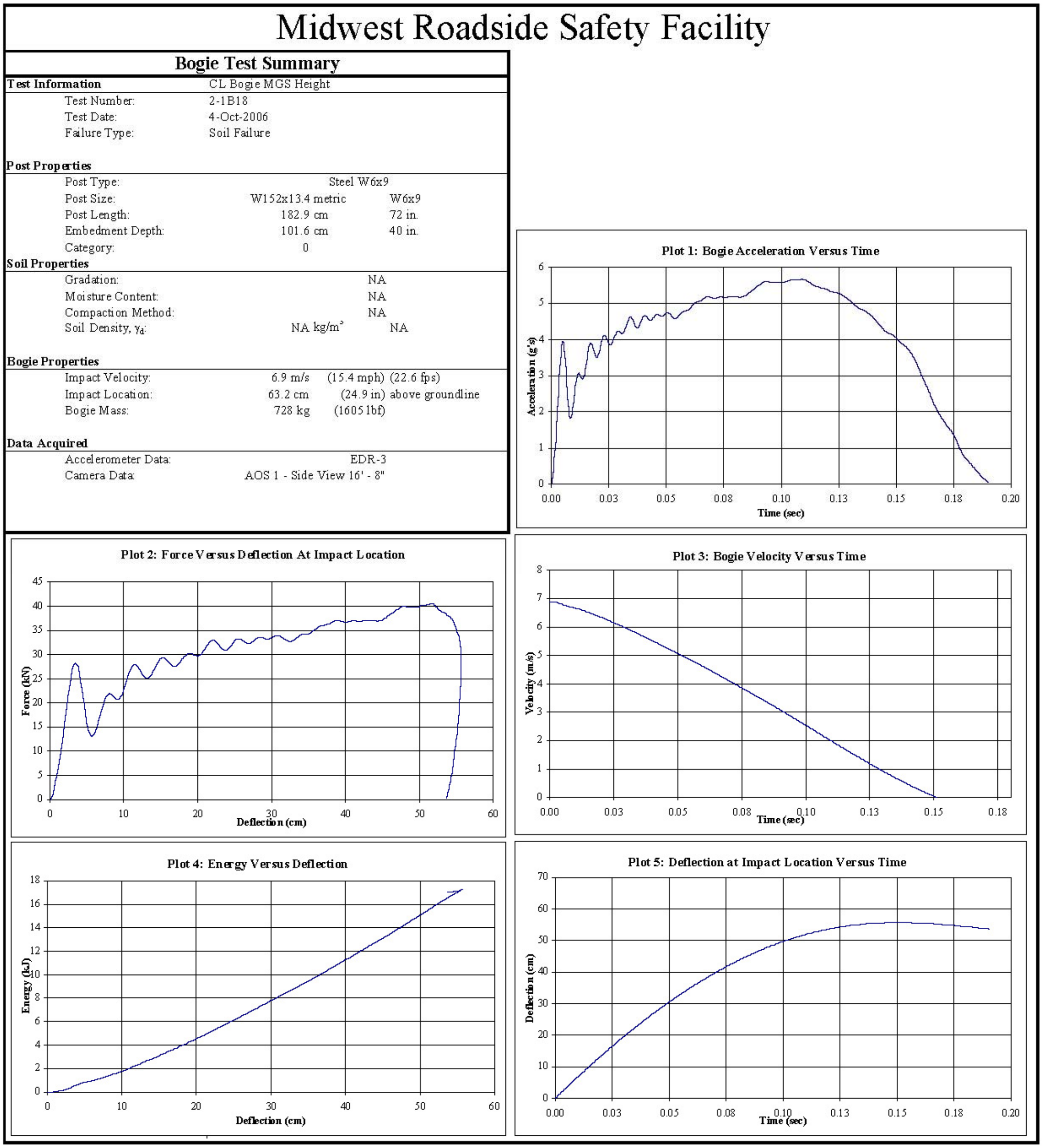
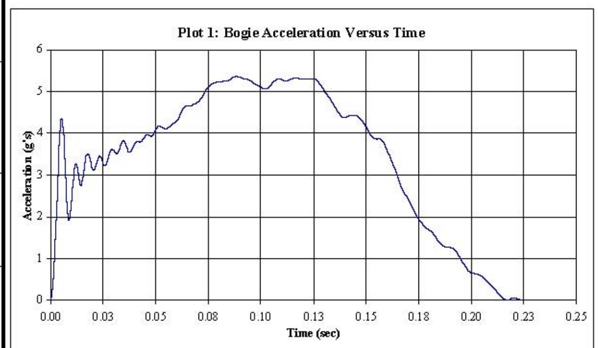


Figure 56. Test Results - MGS2-1B18

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information	CL Bogie MGS Height	
Test Number:	2-1B19	
Test Date:	4-Oct-2006	
Failure Type:	Soil Failure	
Post Properties		
Post Type:	Steel W6x9	
Post Size:	W152x13.4 metric	W6x9
Post Length:	182.9 cm	72 in.
Embedment Depth:	101.6 cm	40 in.
Category:	0	
Soil Properties		
Gradation:	NA	
Moisture Content:	NA	
Compaction Method:	NA	
Soil Density, γ_d:	NA kg/m^3	NA
Bogie Properties		
Impact Velocity:	7.1 m/s	(15.9 mph) (23.3 fps)
Impact Location:	63.2 cm	(24.9 in) above groundline
Bogie Mass:	728 kg	(1605 lbf)
Data Acquired		
Accelerometer Data:	EDR-3	
Camera Data:	AOS 1 - Side View 16' - 8"	



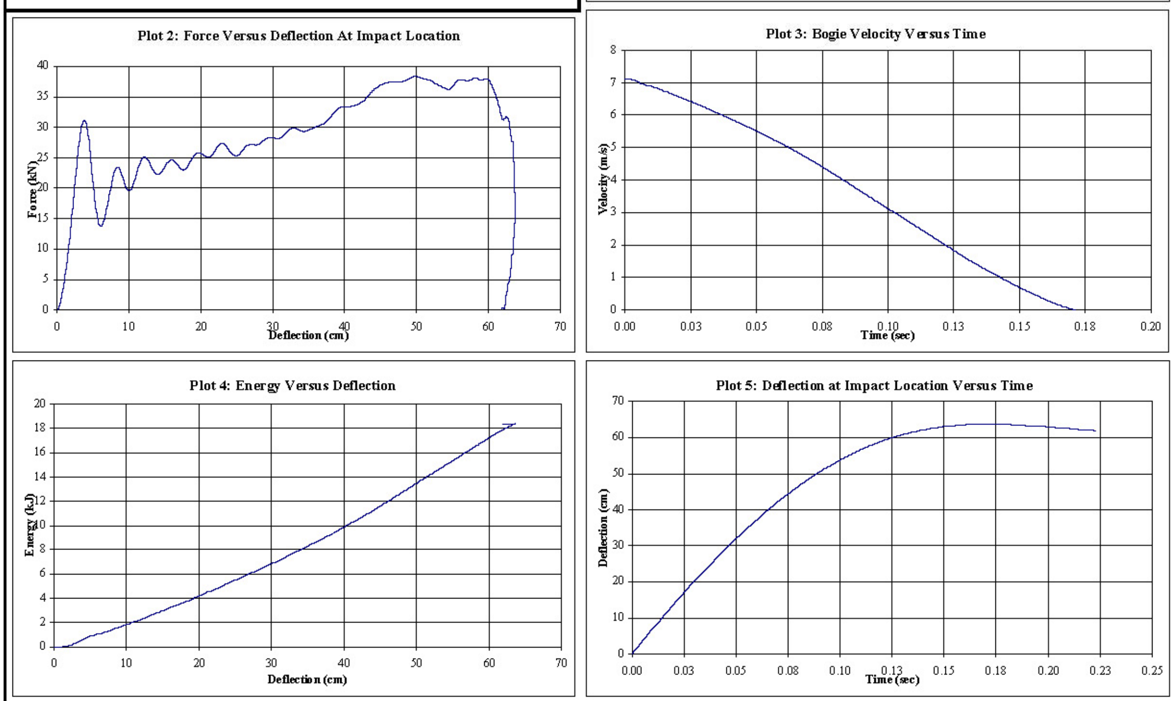
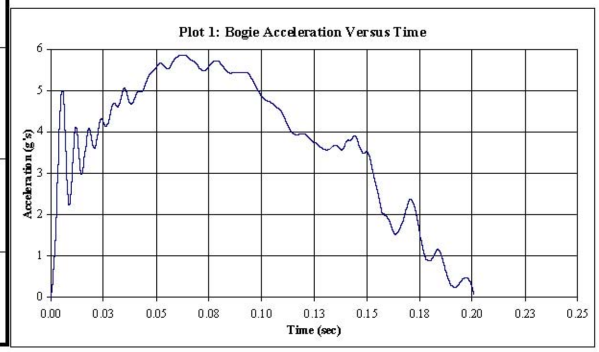


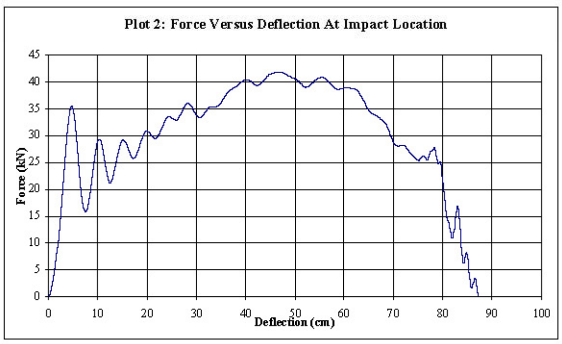
Figure 57. Test Results - MGS2-1B19

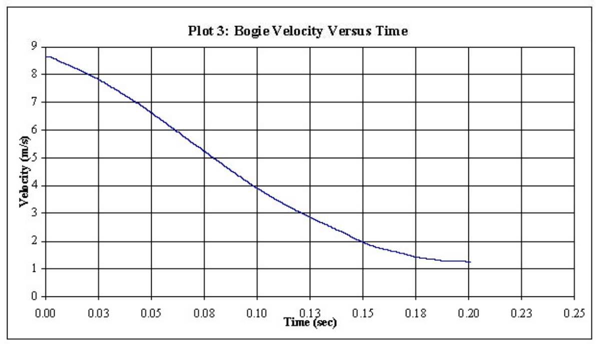
Midwest Roadside Safety Facility

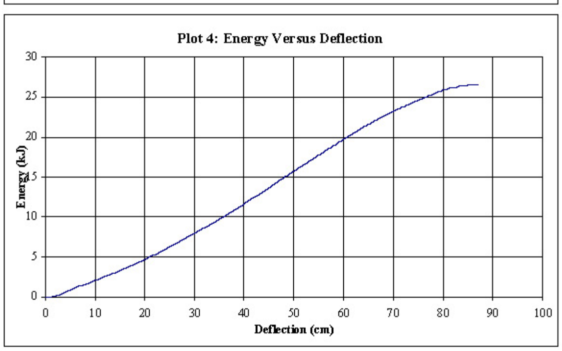
Bogie Test Summary

Test Information	CL Bogie MGS Height	
Test Number:	2-1B20	
Test Date:	4-Oct-2006	
Failure Type:	Soil Failure	
Post Properties		
Post Type:	Steel W6x9	
Post Size:	W152x13.4 metric	W6x9
Post Length:	182.9 cm	72 in.
Embedment Depth:	101.6 cm	40 in.
Category:	0	
Soil Properties		
Gradation:	NA	
Moisture Content:	NA	
Compaction Method:	NA	
Soil Density, γ_d:	NA kg/m^3	NA
Bogie Properties		
Impact Velocity:	8.6 m/s	(19.3 mph) (28.4 fps)
Impact Location:	63.2 cm	(24.9 in) above groundline
Bogie Mass:	728 kg	(1605 lbf)
Data Acquired		
Accelerometer Data:	EDR-3	
Camera Data:	AOS 1 - Side View 16' - 8"	









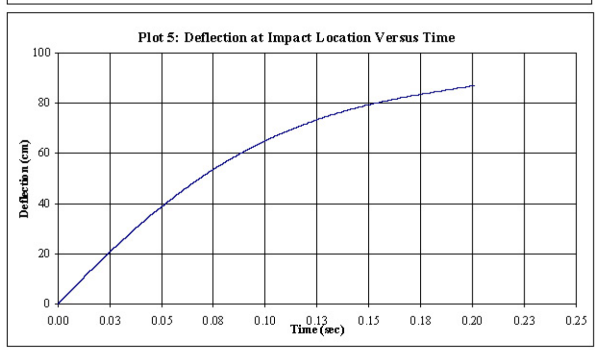
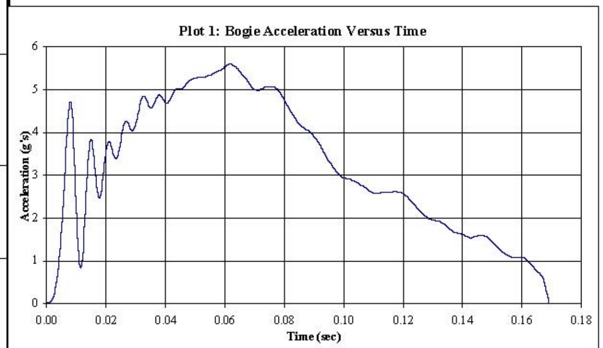


Figure 58. Test Results - MGS2-1B20

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information	CL Bogie MGS Height	
Test Number:	2-1B21	
Test Date:	4-Oct-2006	
Failure Type:	Soil Failure	
Post Properties		
Post Type:	Steel W6x9	
Post Size:	W152x13.4 metric	W6x9
Post Length:	182.9 cm	72 in.
Embedment Depth:	101.6 cm	40 in.
Category:	0	
Soil Properties		
Gradation:	NA	
Moisture Content:	NA	
Compaction Method:	NA	
Soil Density, γ_d:	NA kg/m^3	NA
Bogie Properties		
Impact Velocity:	8.9 m/s	(19.8 mph) (29.1 fps)
Impact Location:	63.2 cm	(24.9 in) above groundline
Bogie Mass:	728 kg	(1605 lbf)
Data Acquired		
Accelerometer Data:	EDR-3	
Camera Data:	AOS 1 - Side View 16' - 8"	



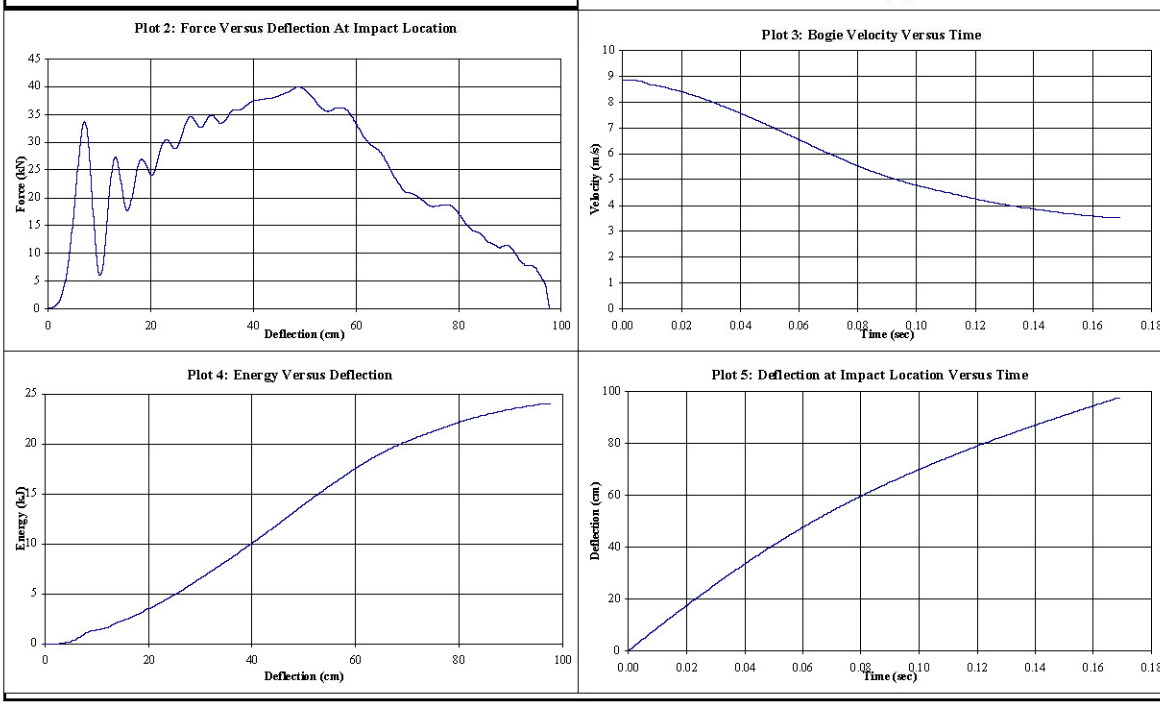


Figure 59. Test Results - MGS2-1B21