PHASE II CONTINUED INVESTIGATION AND DYNAMIC TESTING OF WOOD POSTS FOR USE ON A WIRE-FACED MSE WALL

PUBLICATION NO. FHWA-CFL/TD-12-010 **FEBRUARY 2012**

U.S. Department of Transportation
Federal Highway Administration

CTIP

Federal Lands Highway
Commitment to Excellence

CENTRAL FEDERAL LANDS HIGHWAY DIVISION
12300 WEST DAKOTA AVENUE
Lakewood, CO 80228

FOREWORD

The Federal Lands Highway Division (FLHD) designs and constructs numerous wire-faced, mechanically-stabilized earth (MSE) walls across the U.S. These MSE walls are utilized to support highways and roadways built on sloped terrain which may carry significant vehicular traffic. The FLHD designs and constructs vehicular barrier systems which are placed within the exterior region of MSE walls. This report contains Phase II research investigation and component testing results aimed at determining a wood post alternative for the steel-post, MGS barrier system placed on top of and near the exterior edge of MSE walls.

The objective of the Phase II continuation study was to further develop a non-blocked wood post version of the Midwest Guardrail System (MGS) for use on wire-faced MSE walls. The dynamic post-soil behavior for a 6-in x 8-in. (152-mm x 203 mm) wood post placed at the slope break point of a 3H:1V fill slope was investigated through dynamic component tests with a goal to select an alternative for the steel posts driven at the slope break point of a 3H:1V fill slope adjacent to and on top of an MSE wall.

The results from this study do not modify the prior recommendations that have been made to update Central Federal Lands highway Division's (CFLHD) Standard Detail C255-50, dated August 18, 2008, regarding semi-rigid barriers installed on welded, wire-face, MSE walls.

F. David Zanetell, P.E., Director of Project Delivery
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Notice

Quality Assurance Statement

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MwRSF Research Report No. TRP-03-256-12

February 2012

UNCERTAINTY OF MEASUREMENT STATEMENT

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

INDEPENDENT APPROVING AUTHORITY

The Independent Approving Authority (IAA) for the data contained herein was Mr. Bob Bielenberg, Research Associate Engineer

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16. Abstract

This study was performed to further develop a non-blocked version of the Midwest Guardrail System (MGS) for use on wire-faced, mechanically-stabilized earth (MSE) walls. The dynamic post-soil behavior for a 6-in x 8-in. (152-mm x 203 mm) wood post placed at the slope break point of a 3H:1V fill slope was investigated. A total of four dynamic component tests were performed. Dynamic testing was performed on 6-ft (1.8-m) and 6.5-ft (2.0-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood posts. The posts were embedded in strong soil. For each bogie test, force versus deflection and energy versus deflection curves were prepared. The results were compared to the dynamic post-soil behavior for the 6-ft (1.8-m) long, W6x8.5 (W152x12.6) or W6x9 (W152x13.4) steel posts recommended for use in the non-blocked version of the MGS with W-beam backup plates. This component testing program concluded that further testing would be needed to recommend a 6-ft (1.8-m) long or a 6.5-ft (2.0-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood post for a comparable alternative to the 6-ft (1.8-m) long, W6x8.5 (W152x12.6) or W6x9 (W152x13.4) steel posts driven at the slope break point of a 3H:1V fill slope adjacent to and on top of an MSE wall.

17. Key Words **ROADSIDE SAFETY, WOOD POSTS, STEEL POSTS, GUARDRAIL POSTS, BOGIE TESTING, IMPACT TESTING, MSE WALL, WIRE-FACED, FILL SLOPE, and MGS**	18. Distribution Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short ton (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela per square meter	cd/m^2
		FORCE & PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yard	yd^2
ha	hectares	2.47	acres	ac
km	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or “metric ton”)	1.103	short ton (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela per square meter	0.2919	foot-Lamberts	fl
		FORCE & PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
AOS	AOS Technologies AG
B.S.B.A.	Bachelor of Science in Business Administration
B.S.M.A.	Bachelor of Science in Management Accounting
CFL	Central Federal Lands
CFLHD	Central Federal Lands Highway Department
cm	centimeter
DM-1	DynaMax 1
DOT	Department of Transportation
DTS	Diversified Technical Systems, Incorporated
EDR	
E.I.T.	Engineer in Training
FHWA	Federal Highway Administration
FLHD	Federal Lands Highway Division
fps	feet per second
ft	foot
g's	gravitational constant
h	hour
H	Horizontal
HE8	high-energy, 8 inch lift compaction method
hr	hour
Hz	Hertz
IAA	Independent Approving Authority
in.	inch
IST	Instrumented Sensor Technology, Incorporated
J	Joule
JVC	Victor Company of Japan, Limited
kB	kilobyte
kg	kilogram
kip-in.	thousand pounds-force inches
kips	thousand pounds-force
kJ	kilojoules
kN	kilonewton
km/h	kilometer per hour
lb	pounds
m	meter
m/s	meter per second
MASH	Manual for Assessing Safety Hardware
MB	megabyte
MGS	Midwest Guardrail System
mm	millimeter
mph	miles per hour

M.S.C.E	Master of Science in Civil Engineering
MSE	Mechanically Stabilized Earth
M.S.M.E.	Master of Science in Mechanical Engineering
MwRSF	Midwest Roadside Safety Facility
NA	not applicable
No.	Number
P.E.	Professional Engineer
Ph.D.	Doctor of Philosophy
RAM	random-access memory
SAE	Society of Automotive Engineers
sec	second
SIM	Sensor Input Module
SRAM	static random-access memory
SYP	Southern Yellow Pine
TL	Test Level
U.S.	United States
V	Vertical
vs.	versus
‘	foot
“	inch
%	percent

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EXECUTIVE SUMMARY

Wire-faced, mechanically-stabilized earth (MSE) walls provide an economical method for constructing vertical structures which support roadways where local topography or high land costs preclude the use of conventional fill slopes. While an economical solution for slope stability, MSE walls create safety issues by producing deep vertical drop-offs adjacent to the roadway. For years, the Federal Lands Highway Division (FLHD) has designed and constructed a large number of MSE walls across the U.S. The accepted practice has been to install the face of conventional, wood-post W-beam guardrail nearly 10 ft (3.0 m) away from the exterior face of an MSE wall, when considering 2 ft (0.6 m) of level surface behind the posts, an adjacent 3H:1V fill slope, and a 2-ft (0.6-m) fill height. Thus, it became desirable to place the barrier systems closer to the exterior edge of the MSE wall. Unfortunately, no methods were currently available for anchoring these barriers at or near the exterior face.

The primary research objective for this study was to develop an economical barrier system for safely treating vertical drop-offs located at the outside edge of wire-faced, MSE walls. During high-speed, high-energy impacts with passenger vehicles, the new barrier system should not impart unreasonable damage to the MSE wall system. The new barrier system should be easily maintained without requiring extensive repairs to the MSE wall structure. Several design concepts were considered for a new barrier system positioned closer to the exterior edge of wire-faced, MSE walls. The standard MGS along with its design variations were also considered. The new or modified barrier system was to be evaluated according to the Test Level 3 (TL-3) safety performance criteria set forth in the American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH).

For this study, the Midwest Guardrail System (MGS) was extensively reviewed and considered for use in shielding the vertical drop-offs associated for MSE walls. From a review, the MGS was shown to provide acceptable safety performance when used for shielding wide, transverse culvert structures as well as fill slopes as steep as 2H:1V.

Muiltiple design concepts were considered for treating vertical drop-offs at the exterior face of wire-faced, MSE walls. As part of the brainstorming and selection process, several factors were considered, including: (1) control of overall project costs; (2) environmental impacts; (3) use of an economical barrier system; (4) concerns for MSE wall damage; (5) use 3H:1V fill slope at the top outer edge of MSE wall; (6) use of beam and post barriers for aesthetics; (7) constructability, maintenance, and repair of barrier system; and (8) approximate dynamic deflection and assumed vehicle trajectory for high-speed, high-energy vehicular impacts into semi-rigid guardrail. After considering concerns for constructability and repair, those barrier systems with deeply-embedded reinforced concrete foundations in combination with tension elements were eliminated from further investigation and comparison. Later, five design concepts were subjected to a basic cost analysis and system comparison. Following this effort, the project team chose to further develop a non-blocked version of the MGS with the posts placed at the slope break point of a 3H:1V fill slope.

Dynamic component testing was utilized to determine the post-soil behavior of steel and wood posts embedded in compacted, soil materials used for constructing wire-faced, MSE walls as well as to evaluate the effects of sloped terrain and different installation methods. In Phase I, twenty-six dynamic tests were performed to evaluate the propensity for MSE wall damage, select post length, and determine post material and section. Following the post testing program, a non-blocked version of the MGS was recommended for evaluation within a crash testing program using: (1) steel W-beam backup plates; (2) 6-ft (1.8-m) long posts manufactured from either W6x8.5 (W152x12.6) or W6x9 (W152x13.4) steel sections; (3) posts driven at the slope break point of a 3H:1V fill slope adjacent to and on top of a wire-faced, MSE wall; and (4) posts installed using a 40-in. (1,016-mm) embedment depth. All other MGS features were maintained, including, rail splices at mid-span locations, 31-in. (787-mm) top mounting height, and 75-in. (1,905-mm) post spacing.

A full-size, MGS and MSE wall system was constructed for testing and evaluation. The non-blocked MGS was constructed with the back side of the steel posts positioned approximately 2 ft – 9 in. (0.84 m) away from the inside edge of the wall facing fill or 5 ft – 9 in. (1.75 m) away from the outer edge of the wire-faced, MSE wall. The modified MGS system was successfully crash tested using 1100C small car and 2270P pickup truck vehicles according to the Test Level 3 (TL-3) safety performance guidelines provided in MASH. In both crash tests, no damage was observed in the MSE wall system. As a result of the extensive dynamic component testing and full-scale vehicle crash testing programs, the non-blocked MGS was recommended for use with wire-faced, MSE walls when placed at the slope break point of a 3H:1V fill slope. The modified MGS reduces the required width of the MSE wall, thus resulting in decreased construction costs.

For this research study, the test results and findings are contained in three different reports. The first report contains the design review of the MGS, design considerations, a summary of the Phase II dynamic component testing program, details for the MGS and MSE wall systems, the MASH full-scale crash testing requirements, results from the two full-scale crash tests, as well as a project summary, overall conclusions, and recommendations. This report (TRP-03-235-11) is entitled, "*Development of an Economical Guardrail System for Use on Wire-Faced, MSE Walls*." The second and report contains the procedures utilized for the Phase I dynamic bogie testing program, results from the 26 dynamic post tests, as well as post testing summaries with conclusions and recommendations specific to the component testing program. The report (TRP-03-231-11) is entitled, "*Investigation and Dynamic Component Testing of Wood and Steel Posts for MGS on a Wire-Faced, MSE Wall*."

Following the completion of the research program noted above, MwRSF researchers also determined the minimum lateral barrier offset for wire-faced MSE wall systems which utilize a 3H:1V fill slope. For non-blocked MGS systems, the back side of steel posts are recommended to be placed a minimum of 1 ft (0.30 m) away from the inside edge of the wall facing fill or 4 ft (1.22 m) away from the outer edge of the MSE wall, whichever results in the largest lateral offset between the post and exterior wall face. For this recommendation, the minimum lateral offset between the rail face and outer edge of the MSE wall would be 4 ft – 9 ¼ in. (1.45 m). For varying thickness of select wall backfill and different widths for the 3H:1V fill slope, three different configurations were prepared to demonstrate the recommended guidance regarding the minimum lateral offset for the steel posts, as shown in Figures ES-1 through ES-3. This design guidance is suitable for use under both TL-2 and TL-3 roadside applications.

Due an initial interest in using wood posts, a Phase II continuation study was performed to further investigate a non-blocked, wood post version of the MGS for use on wire-faced MSE walls. The dynamic post-soil behavior for a 6-in x 8-in. (152-mm x 203 mm) wood post placed at the slope break point of a 3H:1V fill slope was investigated through four dynamic component tests with a goal to select an alternative for the 6-ft (1.8-m) long, W6x8.5 (W152x12.6) or W6x9 (W152x13.4) steel posts driven at the slope break point of a 3H:1V fill slope adjacent to and on top of an MSE wall. This component testing program was inconclusive as to whether a 6-ft (1.8-m) long or a 6.5-ft (2.0-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood post would be a comparable alternative for the 6-ft (1.8-m) long, W6x8.5 (W152x12.6) or W6x9 (W152x13.4) steel posts. This report contains the procedures utilized for the dynamic bogie testing program, results from the 4 dynamic post tests, as well as post testing summaries with conclusions and recommendations specific to the Phase II component testing program. The report (TRP-03-256-12) is entitled, "*Phase II Continued Investigation and Dynamic Testing of Wood Posts for use on a Wire-Faced MSE Wall.*"

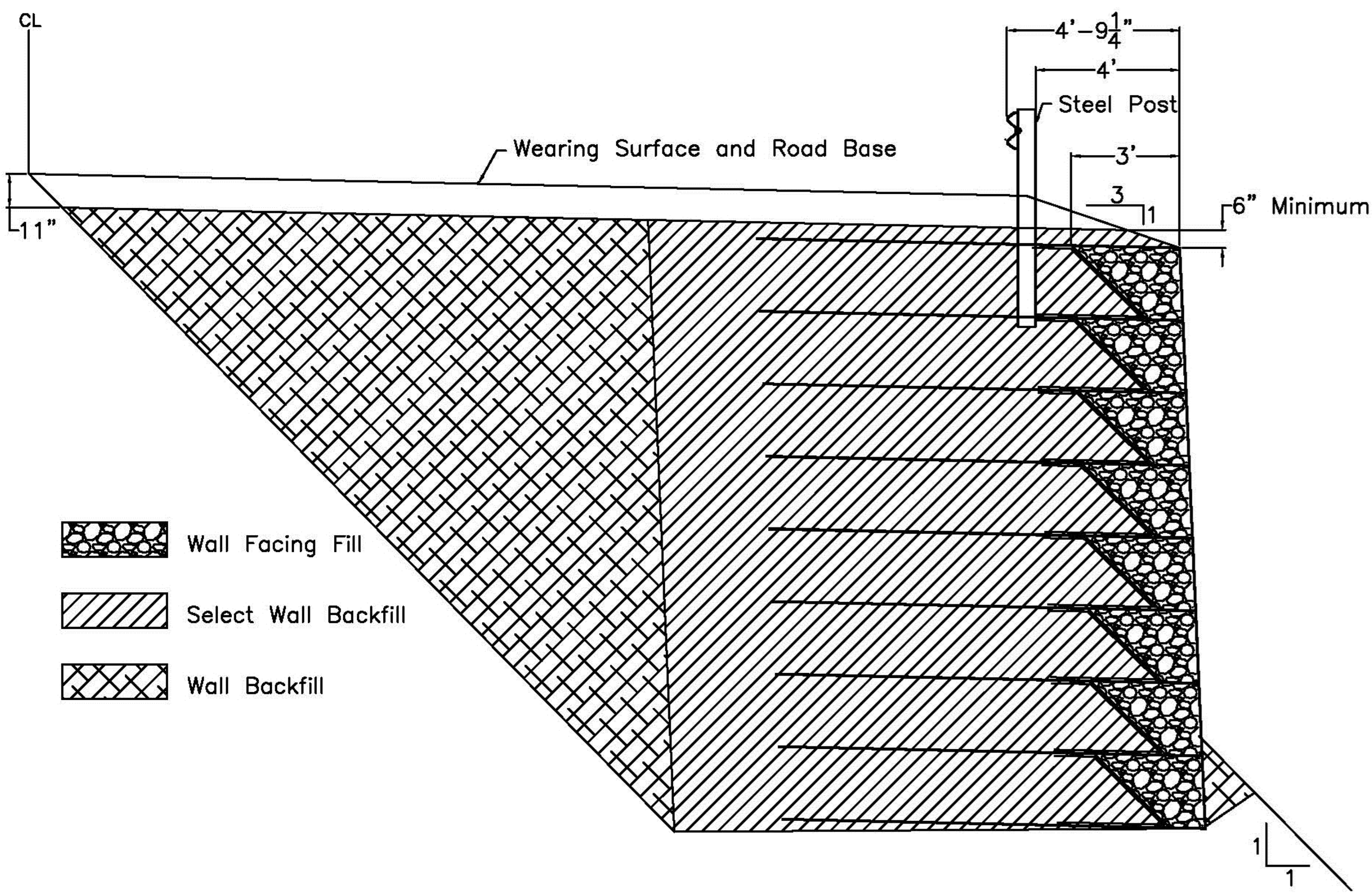


Figure ES-1. Schematic. Non-Blocked, Steel-Post MGS Centered at Slope Break Point with Minimum Lateral Offset.

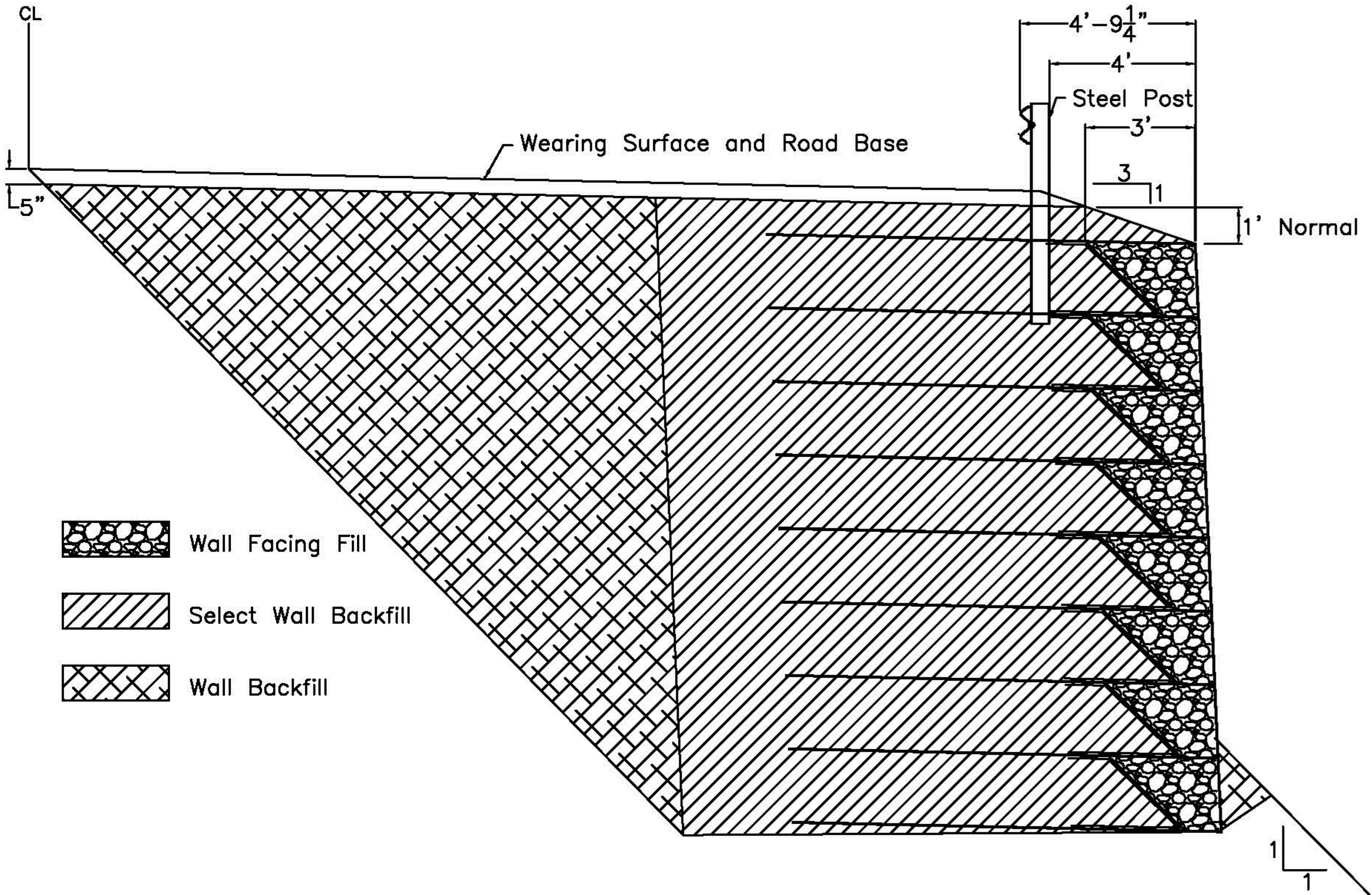


Figure ES-2. Schematic. Non-Blocked, Steel-Post MGS Centered at Slope Break Point with Minimum Lateral Offset.

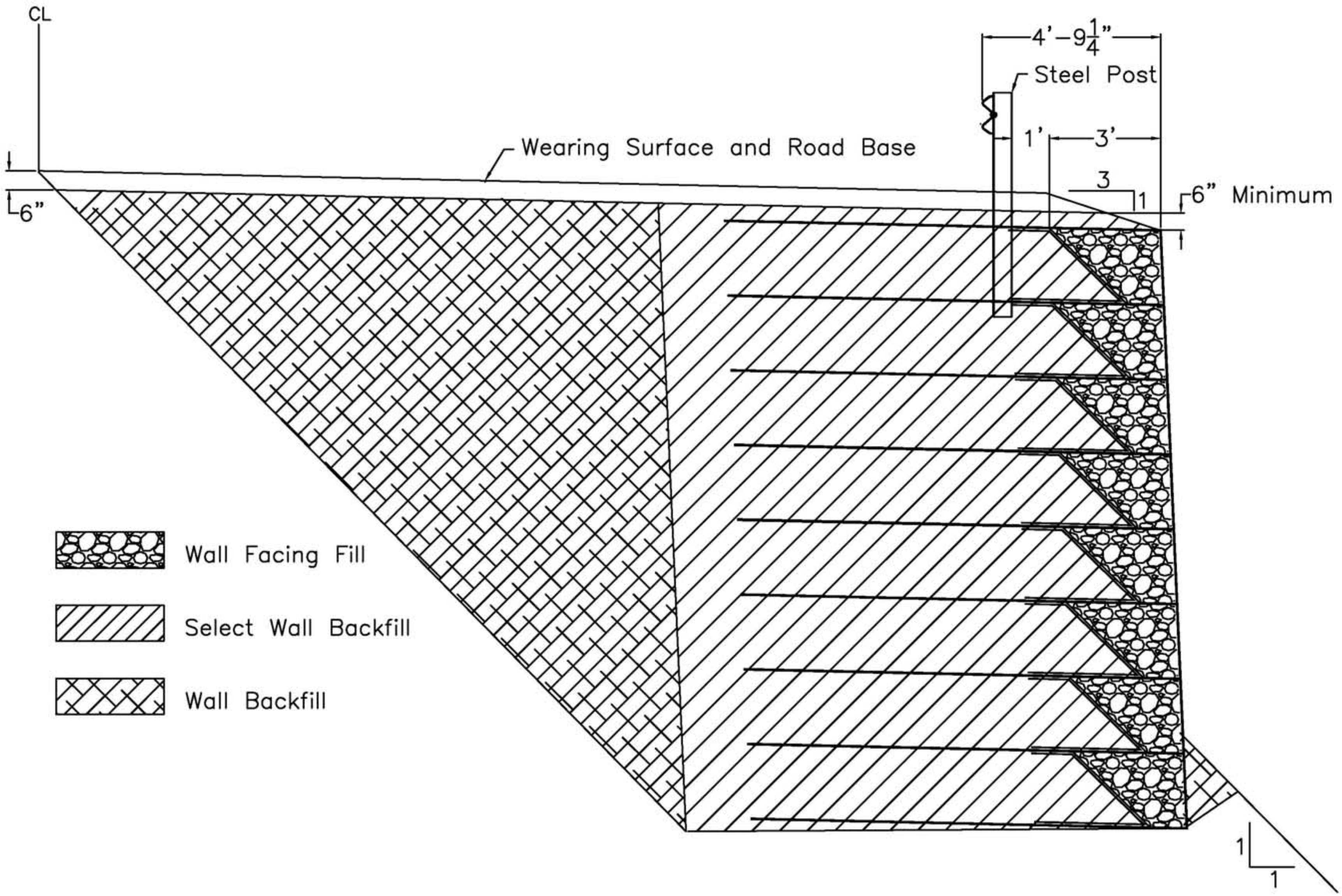


Figure ES-3. Schematic. Non-Blocked, Steel-Post MGS with Minimum Lateral Offset.

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

In 2007, the Federal Highway Administration (FHWA) and the Midwest Roadside Safety Facility (MwRSF) began an effort to develop a longitudinal barrier system for placement on a wire-faced, mechanically-stabilized earth (MSE) wall. A Phase I dynamic testing program was conducted to evaluate the effect that varying soil gradations, terrain slopes, embedment depths, installation methods, and post material types had on guardrail post performance.[1] Following the dynamic component testing effort, a non-blocked version of the Midwest Guardrail System (MGS) was developed which utilized 6-ft (1.8-m) long steel posts.[2] Following the successful crash testing according to Test Level 3 (TL-3) safety performance guidelines provided in the *Manual for Assessing Safety Hardware* (MASH), it was desired to provide a wood post equivalent for the steel post used in the MSE barrier design.[3]

1.2 OBJECTIVE

The objective of this research project was to determine an acceptable length for a 6-in. x 8-in. (152-mm x 203-mm) wood post for MSE wall applications based on dynamic post-soil behavior. The lateral strength and stiffness of the wood post should match that behavior provided by the steel posts used in the original barrier configuration.

1.3 RESEARCH APPROACH

Four dynamic tests were performed to achieve the research objective. For the first two dynamic tests, 6-ft (1.8-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood posts were embedded 40 in. (1,016 mm) into the soil and centered at the slope break point of a 3H:1V fill slope. For the last two dynamic tests, 6.5-ft (2.0-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood posts were embedded 46 in. (1,168 mm) into the soil and centered at the slope break point of a 3H:1V fill slope. This study utilized a 24⅞-in. (632-mm) impact height, which is the center height of the rail for the MGS. These results were compared to the dynamic behavior and post-soil resistance of the 6-ft (1.8-m) long, W6x8.5 (W152x12.6) or W6x9 (W152x13.4) steel sections used in the full-scale crash tested, steel-post system. Based on the results, recommendations would be provided for using 6-in x 8-in. (152-mm x 203 mm) wood posts within the MGS and installed at the slope break point of a 3H:1V fill slope on a wire-faced MSE wall.

CHAPTER 2. TEST CONDITIONS

2.1 TEST FACILITY

Physical testing of the 6-in. x 8-in. (152-mm x 203-mm) Southern Yellow Pine (SYP) posts was conducted at the MwRSF outdoor testing facility, which is located at the Lincoln Air Park on the northwest side of the Lincoln Municipal Airport. The facility is approximately 5 miles (8 kilometers) northwest from the University of Nebraska-Lincoln's city campus.

2.2 EQUIPMENT AND INSTRUMENTATION

Various types of equipment and instrumentation were utilized to conduct, collect, and record data for the dynamic post tests including a bogie vehicle, accelerometers, pressure tape switches, high-speed and standard-speed digital video cameras, and still cameras.

2.2.1 Bogie

A rigid-frame bogie vehicle was used to impact the posts. A variable-height, detachable impact head was used in the testing. The bogie head was constructed of 8-in. (203-mm) diameter, ½-in. (13-mm) thick steel pipe, with ¾-in. (19-mm) 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, creating a rigid frame with an impact height of 24⅞ in. (632 mm). The bogie with the impact head is shown in Figure 1. The weight of the bogie with the addition of the mountable impact head and accelerometers was 1,723 lb (781 kg).

The tests were conducted using a steel corrugated beam guardrail to guide the tire of the bogie vehicle. A pickup truck was used to push the bogie vehicle to the required impact velocity. After reaching the target velocity, the push vehicle braked allowing the bogie to be free rolling as it came off the track. A remote braking system was installed on the bogie, allowing it to be brought safely to rest after the test.

Figure 1. Photo. Rigid-Frame Bogie on Corrugated Beam

2.2.2 Accelerometers

Two accelerometer systems were mounted on the bogie vehicle near its center of gravity to measure the acceleration in the longitudinal, lateral, and vertical directions.

The first accelerometer, Model EDR-3, was a triaxial piezoresistive accelerometer system manufactured by IST of Okemos, Michigan. The EDR-3 was configured with 256 kB of RAM, a range of ±200 g's, a sample rate of 3,200 Hz, and a 1,120 Hz low-pass filter. The "DynaMax 1 (DM-1)" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

The second accelerometer system was a two-arm piezoresistive accelerometer system manufactured by Endevco of San Juan Capistrano, California. Three accelerometers were used to measure each of the longitudinal, lateral, and vertical accelerations independently at a sample rate of 10,000 Hz. The accelerometers were configured and controlled using a system developed and manufactured by Diversified Technical Systems, Inc. (DTS) of Seal Beach, California. More specifically, data was collected using a DTS Sensor Input Module (SIM), Model TDAS3-SIM-16M. The SIM was configured with 16 MB SRAM and 8 sensor input channels with 250 kB SRAM/channel. The SIM was mounted on a TDAS3-R4 module rack. The module rack was configured with isolated power/event/communications, 10BaseT Ethernet and RS232 communication, and an internal backup battery. Both the SIM and module rack were crashworthy. The "DTS TDAS Control" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

2.2.3 Pressure Tape Switches

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

2.2.4 Digital Cameras

One AOS X-PRI high-speed digital video camera and one JVC digital video camera were used to document each test. The AOS high-speed camera had a frame rate of 500 frames per second and the JVC digital video camera had a frame rate of 29.97 frames per second. Both cameras were placed laterally from the post, with a view perpendicular to the bogie's direction of travel. A Nikon D50 digital still camera was also used to document pre- and post-test conditions for all tests.

2.3 END OF TEST DETERMINATION

When the impact head initially contacted the test article, the force exerted by the surrogate test vehicle was directly perpendicular. However, as the post rotates, the surrogate test vehicle's orientation and path moves further from perpendicular. This behavior introduces two sources of error: (1) the contact force between the impact head and the post has a vertical component and (2) the impact head slides upward along the test article. Therefore, only the initial portion of the accelerometer trace may be used since variations in the data become significant as the system rotates and the surrogate test vehicle overrides the system. For this reason, the end of the test needed to be defined.

Guidelines were established to define the end of test time using the high-speed digital video of the crash test. The first occurrence of any one of the following three events was used to determine the end of the test: (1) the test article fractures; (2) the surrogate vehicle overrides/loses contact with the test article; or (3) a maximum post rotation of 45 degrees.

2.4 DATA PROCESSING

Initially, the electronic accelerometer data was filtered using the Society of Automotive Engineers (SAE) Class 60 Butterworth filter conforming to the SAE J211/1 specifications.[4] The pertinent acceleration signal was extracted from the bulk of the data signals. The processed acceleration data was then multiplied by the mass of the bogie to get the impact force using Newton's Second Law. Next, the acceleration trace was integrated to find the change in velocity versus time. Initial velocity of the bogie, calculated from the pressure tape switch data, was then used to determine the bogie velocity, and the calculated velocity trace was integrated to find the bogie's deflection, which is also the deflection of the post. Combining the previous results, a force vs. deflection curve was plotted for each test. Finally, integration of the force vs. deflection curve provided the energy vs. deflection curve for each test.

2.5 RESULTS

The information desired from the bogie tests was the relation between the applied force and deflection of the post at the impact location. This data was then used to find total energy (the area under the force vs. deflection curve) dissipated during each test.

Although the acceleration data was applied to the impact location, the data came from the center of gravity of the bogie. Error was added to the data since the bogie was not perfectly rigid and sustained vibrations. The bogie may have also rotated during impact, causing differences in accelerations between the bogie center of mass and the bogie impact head. While these issues may affect the data, the data was still valid. Filtering procedures were applied to the data to smooth out vibrations, and the rotations of the bogie during the tests were minor. Significant pitch angles did develop late in some tests as the bogie overrode the post; however, these occurred after the post-bogie interaction of interest. One useful aspect of using accelerometer data was that it included influences of the post inertia on reaction force. This influence was important as the mass of the post would affect barrier performance as well as test results.

The accelerometer data for each test was processed in order to obtain acceleration, velocity, and deflection curves, as well as force vs. deflection and energy vs. deflection curves. The values described herein were calculated from the EDR-3 data curves. Although the transducers used produced similar results, the EDR-3 has historically provided accurate results, and was used in all tests.

At the time of these tests, the EDR-3 was not calibrated by an ISO 17025 approved laboratory due to the lack of an ISO 17025 calibration laboratory with the capabilities of calibrating the unit. However, the EDR-3 was calibrated by IST which provided traceable documentation for the calibration. Further, MwRSF recognizes that the EDR-3 transducer does not satisfy the minimum 10,000 Hz sample frequency recommended by MASH. Following numerous test comparisons, the EDR-3 has been shown to provide equivalent results to the DTS unit which does satisfy all MASH criteria and has ISO 17025 calibration traceability. Therefore, MwRSF has continued to use the EDR-3 during physical impact testing. The equivalency of the transducers is further explained and comparisons are shown in Appendix A.

CHAPTER 3. DYNAMIC TESTING

3.1 SCOPE

A total of four bogie-tests were conducted. Each post was fabricated from Grade No. 1 or better Southern Yellow Pine (SYP) wood with a 6-in. x 8-in. (152-mm x 203-mm) nominal cross section. Two of the posts had a nominal length of 6 ft (1.8 m), while the remaining two posts were 6.5 ft (2.0 m) in length. Actual dimensions, weights, and ring densities of the posts were measured and are shown in Table 1. Due to differences in moisture contents, densities, and dimensions, each wood post had a different weight. Material specifications for the wood posts are shown in Appendix B.

As outlined in Table 2, test nos. GWPB-1 and GWPB-2 utilized the 6-ft (1.8-m) long posts installed with 40-in. (1,016-mm) embedment depths, while test nos. GWPB-3 and GWPB-4 utilized the 6.5-ft (2.0-m) long posts installed with 46-in. (1,168-mm) embedment depths. All of the posts were embedded in a well compacted strong soil. Specifics on the soil gradation can be found in Appendix C. The soil material was placed using a high-energy compaction method with 8-in. (203-mm) lifts (HE8). The posts were impacted 24$^{7}/_{8}$ in. (632 mm) above ground line at a target impact speed of 20 mph (32 km/h) for all four tests. The test matrix and installation details are shown in Figures 2 through 4.

Table 1. Wood Post Details

Test No.	Post Dimensions in. x in. (mm x mm)			Post Length in. (mm)	Weight lb (kg)	Ring Density rings/in. (rings/cm)
	Top	Ground Line	Bottom			
GWPB-1	6 x 8¼ (152 x 210)	6 x 8¼ (152 x 210)	6 x 8$^{1}/_{8}$ (152 x 206)	72½ (1,842)	97.8 (44.4)	2.5 (1.0)
GWPB-2	6 x 8 (152 x 203)	6 x 8$^{1}/_{8}$ (152 x 206)	6 x 8$^{1}/_{16}$ (152 x 205)	72$^{1}/_{16}$ (1,830)	95.0 (43.1)	2.5 (1.0)
GWPB-3	6 x 8¼ (152 x 210)	6 x 8$^{5}/_{16}$ (152 x 211)	6 x 8$^{1}/_{8}$ (152 x 206)	77¾ (1,975)	84.2 (38.2)	2.5 (1.0)
GWPB-4	6 x 8$^{3}/_{8}$ (152 x 213)	6 x 8$^{1}/_{8}$ (152 x 206)	6 x 8$^{3}/_{16}$ (152 x 208)	77⅞ (1,978)	88.2 (40.0)	3.0 (1.2)

Table 2. Dynamic Post Testing Matrix

Test No.	Post			Soil Gradation	Embedment Depth in. (mm)	Target Impact Velocity mph (km/h)	Bending Axis
	Type (Species)	Size in. x in. (mm x mm)	Length ft (m)				
GWPB-1	Wood (SYP)	6x8 (152x203)	6.0 (1.8)	AASHTO Grading B (strong soil)	40 (1,016)	20 (32)	Strong
GWPB-2	Wood (SYP)	6x8 (152x203)	6.0 (1.8)	AASHTO Grading B (strong soil)	40 (1,016)	20 (32)	Strong
GWPB-3	Wood (SYP)	6x8 (152x203)	6.5 (2.0)	AASHTO Grading B (strong soil)	46 (1,168)	20 (32)	Strong
GWPB-4	Wood (SYP)	6x8 (152x203)	6.5 (2.0)	AASHTO Grading B (strong soil)	46 (1,168)	20 (32)	Strong

MSE Wall Bogie Testing					
Post Type	Test Quantity	Load Height	Bogie No.	Estimated Bogie Weight (lb)	Bogie Speed (mph)
Southern Yellow Pine 6"x8"x6'	2	24 7/8"	3	1600	20
Southern Yellow Pine 6"x8"x6.5'	2	24 7/8"	3	1600	20

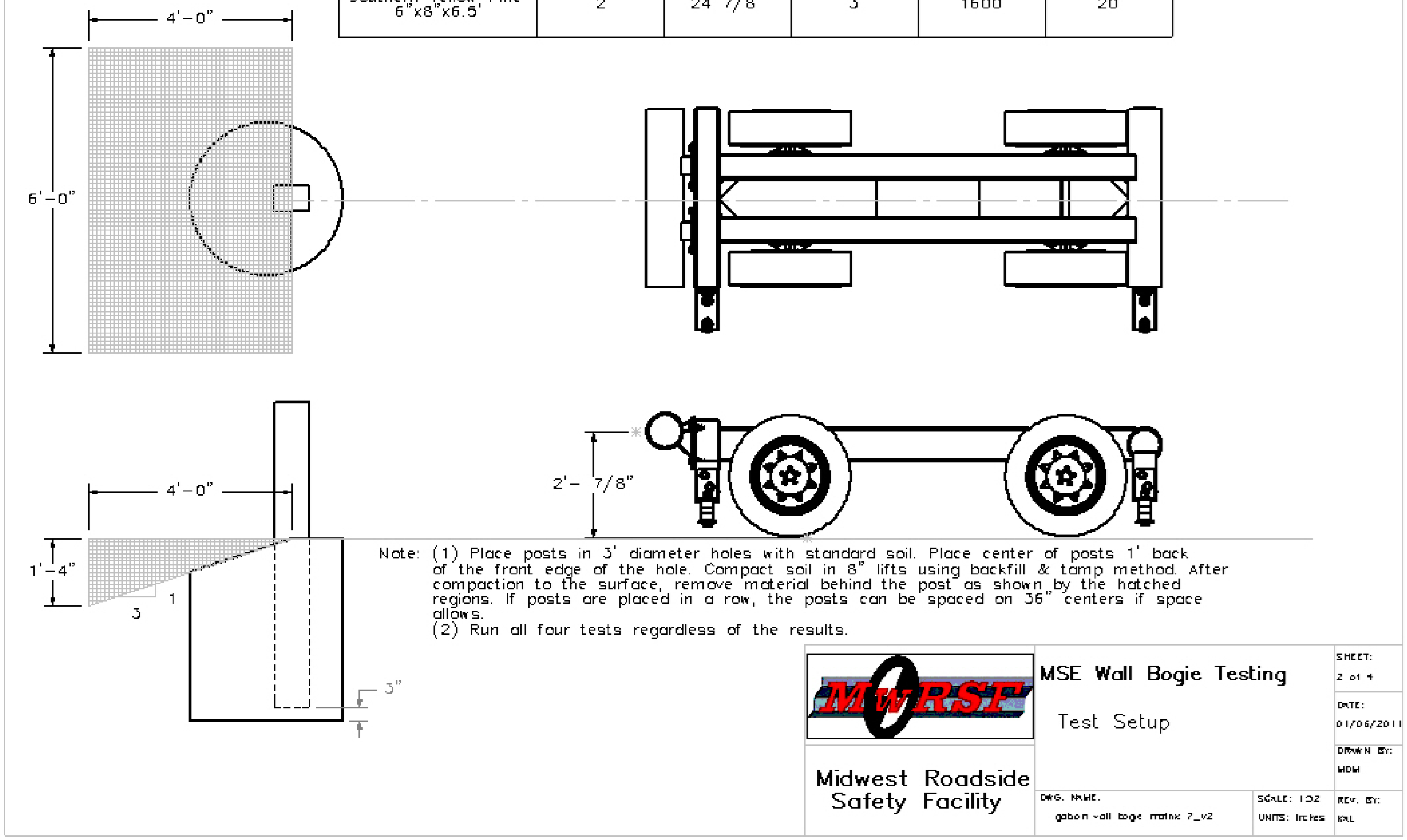


Figure 2. Schematic. Test Setup

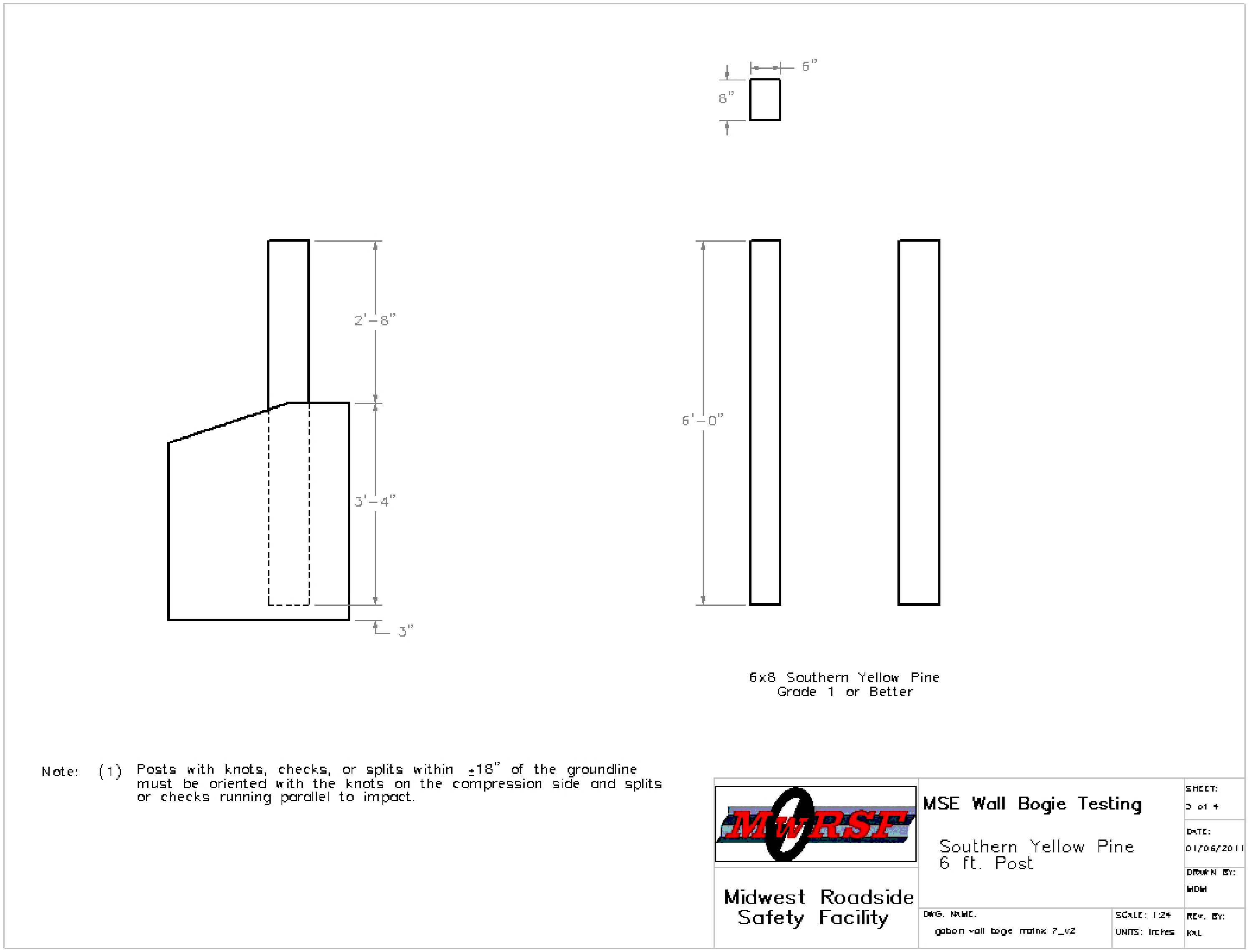


Figure 3. Schematic. Post Details, Test Nos. GWPB-1 and GWPB-2

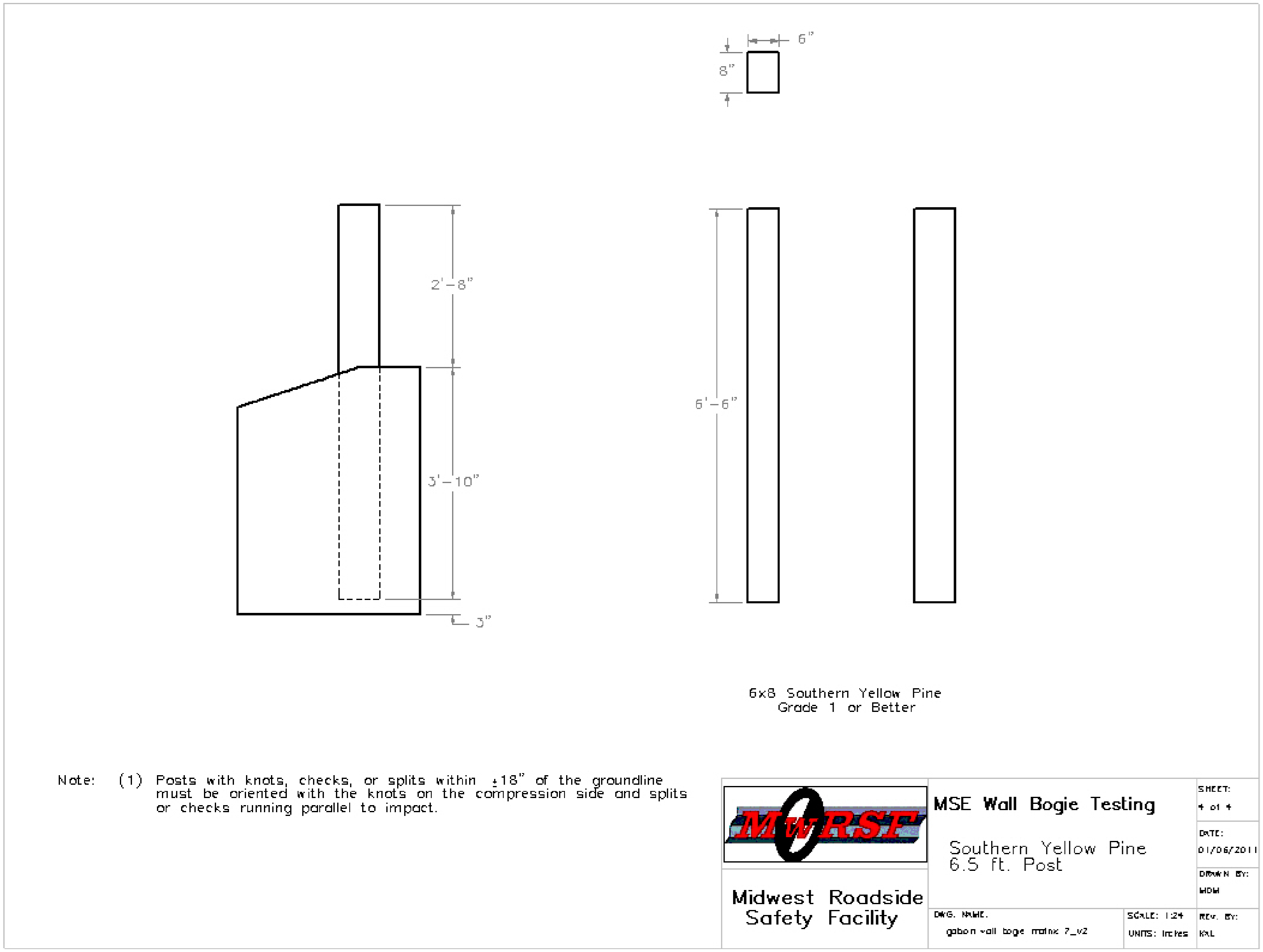


Figure 4. Schematic. Post Details, Test Nos. GWPB-3 and GWPB-4

3.2 DYNAMIC TESTING RESULTS

Results from each test are discussed in the following sections. Individual results for all accelerometers used during each test are provided in Appendix D.

3.2.1 Test No. GWPB-1

During test no. GWPB-1, the bogie impacted the 6-ft (1.8-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood post at a speed of 22.7 mph (36.5 km/h) and at an orientation causing strong-axis bending in the post. The post rotated through the soil to a maximum deflection of 40.4 in. (1,026 mm) and showed no signs of fracture. The bogie impact head lost contact with the post after 0.122 seconds, and the bogie overrode the post.

Force vs. deflection and energy vs. deflection curves were created from the accelerometer data and are shown in Figure 5. Inertial effects resulted in a peak force of 12.6 kips (56.0 kN) at approximately 2 in. (51 mm) of deflection. After the initial peak, the force remained relatively constant at approximately 7 kips (31 kN) through 12 in. (305 mm) of deflection. After this plateau, the force steadily decreased until reaching zero at a deflection of 40.4 in. (1,026 mm). The post rotating in soil absorbed a total of 158.7 kip-in. (17.9 kJ) of energy. Time-sequential and post-impact photographs are shown in Figure 6.

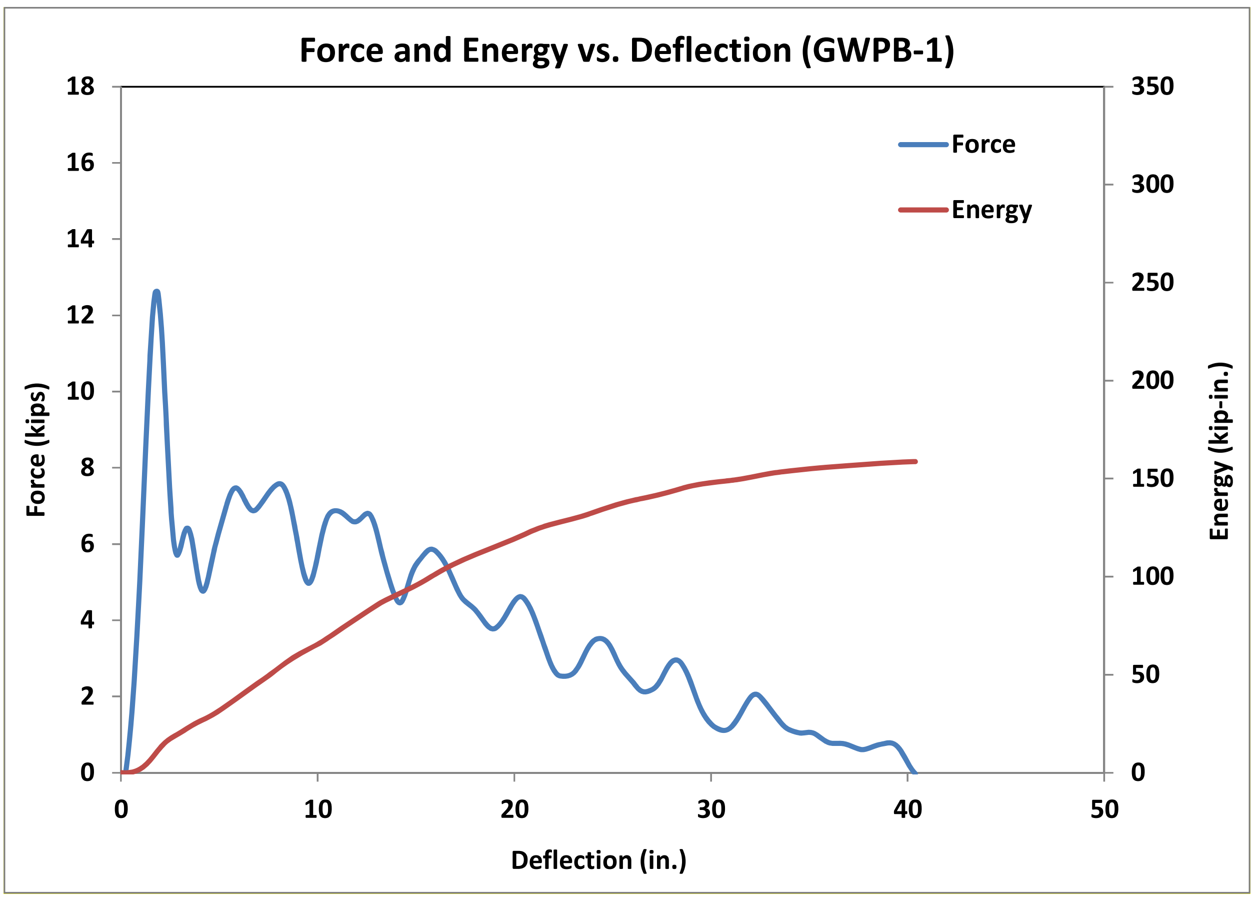
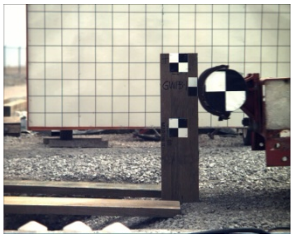
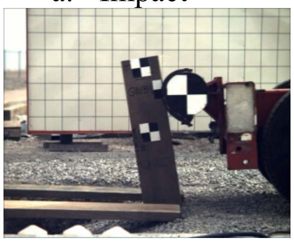


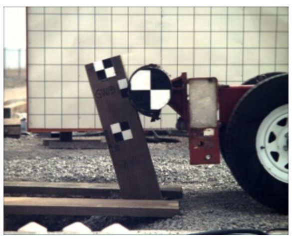
Figure 5. Graph. Force vs. Deflection and Energy vs. Deflection, Test No. GWPB-1



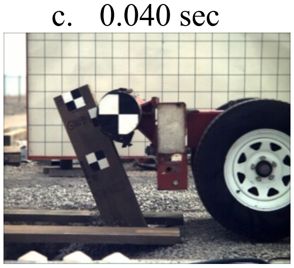
a. Impact



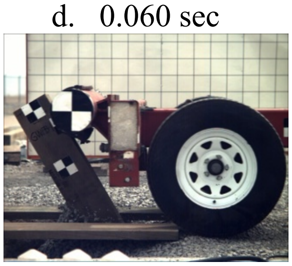
b. 0.020 sec



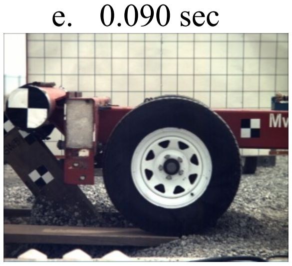
c. 0.040 sec



d. 0.060 sec



e. 0.090 sec



f. 0.120 sec

g. Post After Impact – Side View

h. Post After Impact – Front View

Figure 6. Photo. Time-Sequential and Post-Impact Photographs, Test No. GWPB-1

3.2.2 Test No. GWPB-2

During test no. GWPB-2, the bogie impacted the 6-ft (1.8-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood post at a speed of 20.5 mph (33.0 km/h) and at an orientation causing strong-axis bending in the post. The post rotated through the soil to a maximum deflection of 45.3 in. (1,151 mm) and showed no signs of fracture. The bogie impact head lost contact with the post after 0.168 seconds, and the bogie overrode the post.

Force vs. deflection and energy vs. deflection curves were created from the accelerometer data and are shown in Figure 7. Similar to GWPB-1, the inertial effects resulted in a peak force of 12.3 kips (54.7 kN) at 2 in. (51 mm) of deflection. After this, the force steadily decreased until reaching zero at a deflection of 45.3 in. (1,151 mm). The post rotating in soil absorbed a total of 174.6 kip-in. (19.7 kJ) of energy. Time-sequential and post-impact photographs are shown in Figure 8.

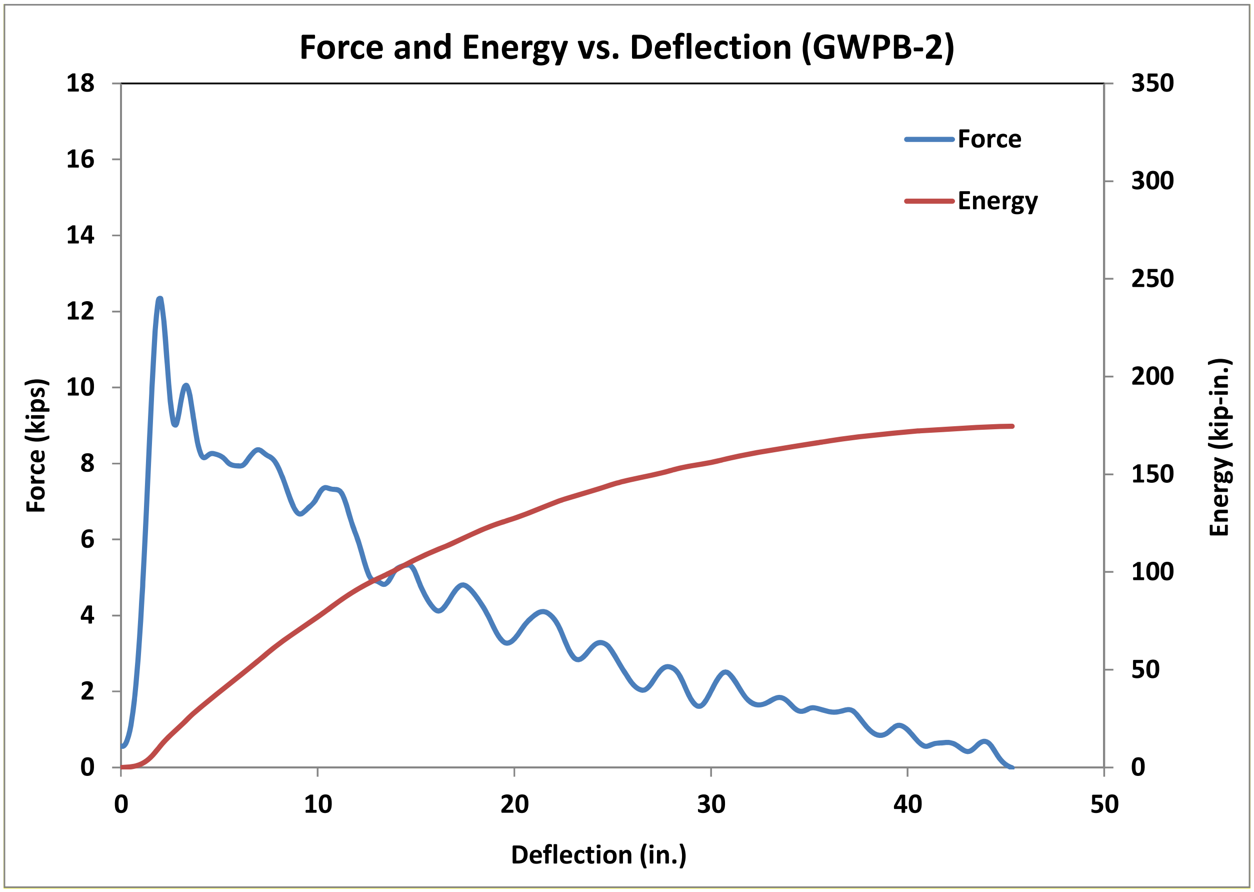
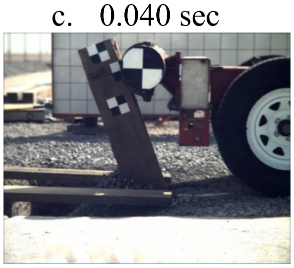


Figure 7. Graph. Force vs. Deflection and Energy vs. Deflection, Test No. GWPB-2

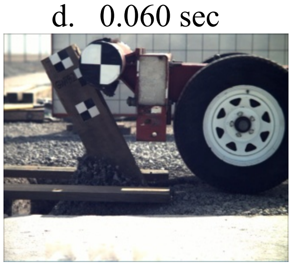
a. Impact

b. 0.020 sec

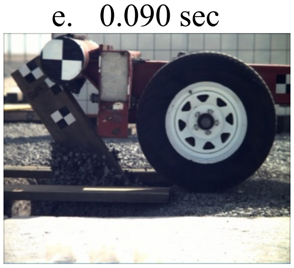
c. 0.040 sec



d. 0.060 sec



e. 0.090 sec



f. 0.120 sec

g. Post After Impact – Side View

h. Post After Impact – Soil Displacement

Figure 8. Photo. Time-Sequential and Post-Impact Photographs, Test No. GWPB-2

3.2.3 Test No. GWPB-3

During test no. GWPB-3, the bogie impacted the 6.5-ft (2.0-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood post at a speed of 21.5 mph (34.6 km/h) and at an orientation causing strong-axis bending in the post. The post deflected 4.8 in. (122 mm) before fracture was initiated approximately 0.013 seconds after impact. Fracture occurred approximately 12 in. (305 mm) below ground level with no apparent post defects. The maximum deflection was 7.2 in. (183 mm) at the time of complete fracture.

Force vs. deflection and energy vs. deflection curves were created from the accelerometer data and are shown in Figure 9. The peak resistive force was 10.8 kips (48.0 kN) at 3.3 in. (84 mm) of deflection. As the post rotated through the soil and fractured, it absorbed a total energy of 53.6 kip-in. (6.1 kJ) at a deflection of 7.2 in. (183 mm). Time-sequential and post-impact photographs are shown in Figure 10.

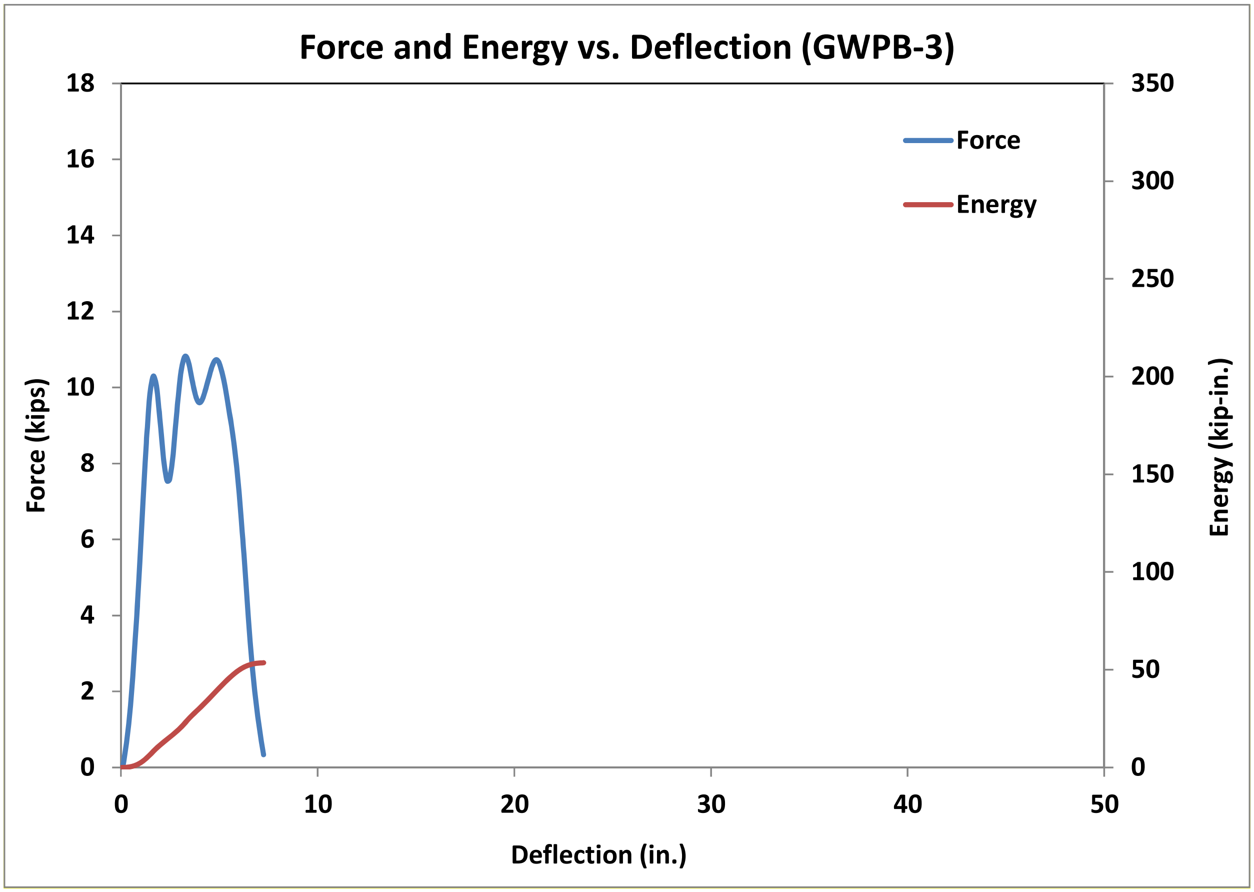
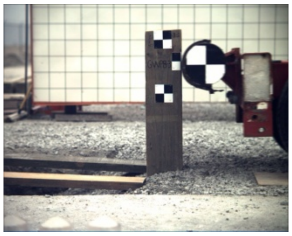


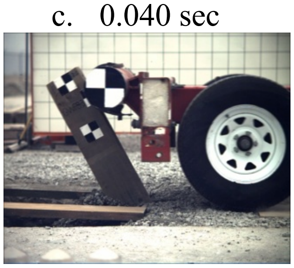
Figure 9. Graph. Force vs. Deflection and Energy vs. Deflection, Test No. GWPB-3



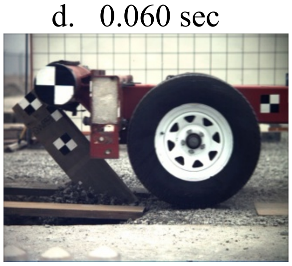
a. Impact

b. 0.020 sec

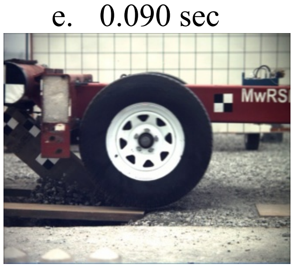
c. 0.040 sec



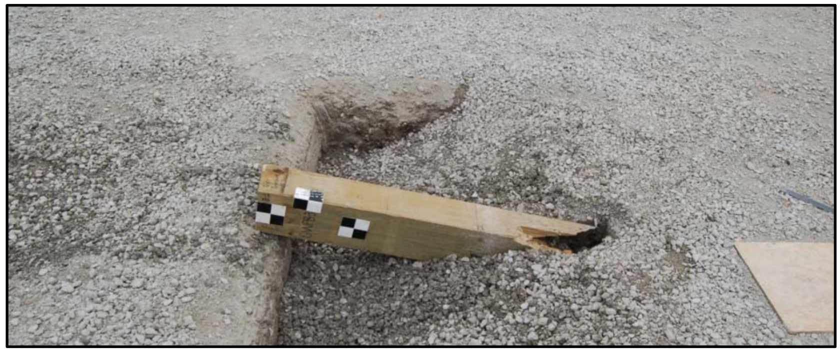
d. 0.060 sec



e. 0.090 sec



f. 0.120 sec



g. Post After Impact – Side View

h. Post After Impact – Front Quarter View

i. Close-up of Post Fracture

Figure 10. Photo. Time-Sequential and Post-Impact Photographs, Test No. GWPB-3

3.2.4 Test No. GWPB-4

During test no. GWPB-4, the bogie impacted the 6.5-ft (2.0-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood post at a speed of 20.1 mph (32.3 km/h) and at an orientation causing strong-axis bending in the post. The post rotated through the soil and showed no signs of fracturing. The bogie impact head lost contact with the post after 0.22 seconds, and the bogie overrode the post.

Force vs. deflection and energy vs. deflection curves were created from the accelerometer data and are shown in Figure 11. The resistive force quickly increased to approximately 9.6 kips (42.7 kN) at 2 in. (51 mm) of deflection and remained relatively constant through a deflection of 15 in. (381 mm). The force then steadily decreased until reaching zero at a deflection of 42.2 in. (1,072 mm). The post rotating in soil reached a peak force of 10.1 (44.9 kN) at 5.4 in. (137 mm) of deflection and absorbed a total of 254.6 kip-in. (28.8 kJ) of energy. Time-sequential and post-impact photographs are shown in Figure 12.

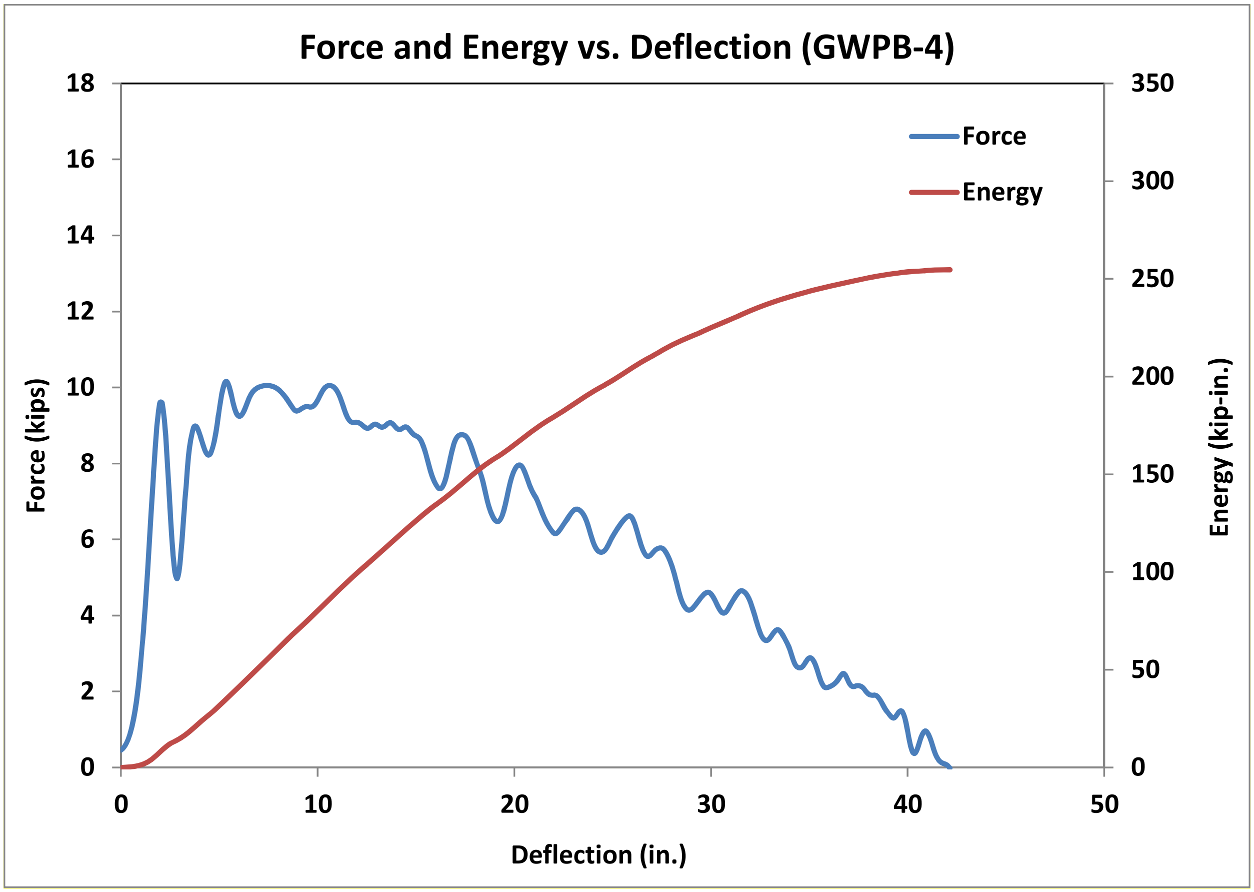
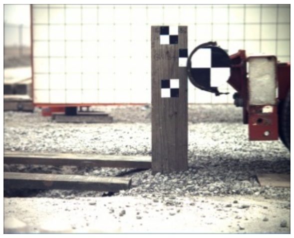


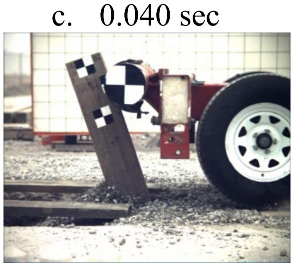
Figure 11. Graph. Force vs. Deflection and Energy vs. Deflection, Test No. GWPB-4



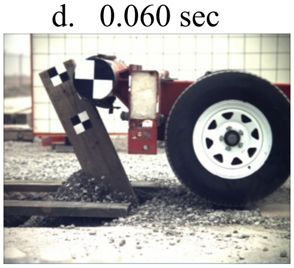
a. Impact

b. 0.020 sec

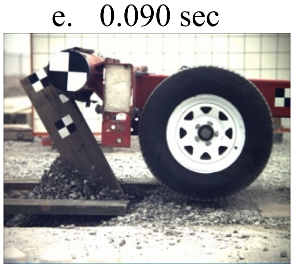
c. 0.040 sec



d. 0.060 sec



e. 0.090 sec



f. 0.120 sec

g. Post After Impact – Side View

h. Post After Impact – Front View

Figure 12. Photo. Time-Sequential and Post-Impact Photographs, Test No. GWPB-4

3.3 SUMMARY OF DYNAMIC TESTING

The bogie testing program consisted of four tests to evaluate the force-deflection characteristics of 6-in. x 8-in. (152-mm x 203-mm) wood posts. The posts were installed in a strong soil using a high-energy compaction method at the slope break point of a 3H:1V fill slope. Test nos. GWPB-1 and GWPB-2 were performed on 6-ft (1.8-m) long, SYP wood posts with 40-in. (1,016-mm) embedment depths, while test nos. GWPB-3 and GWPB-4 were performed on 6.5-ft (2.0-m) long, SYP wood posts with 46-in. (1,168-mm) embedment depths. A summary of the bogie testing is shown in Table 3, and force vs. deflection and energy vs. deflection curves are shown in Figure 13.

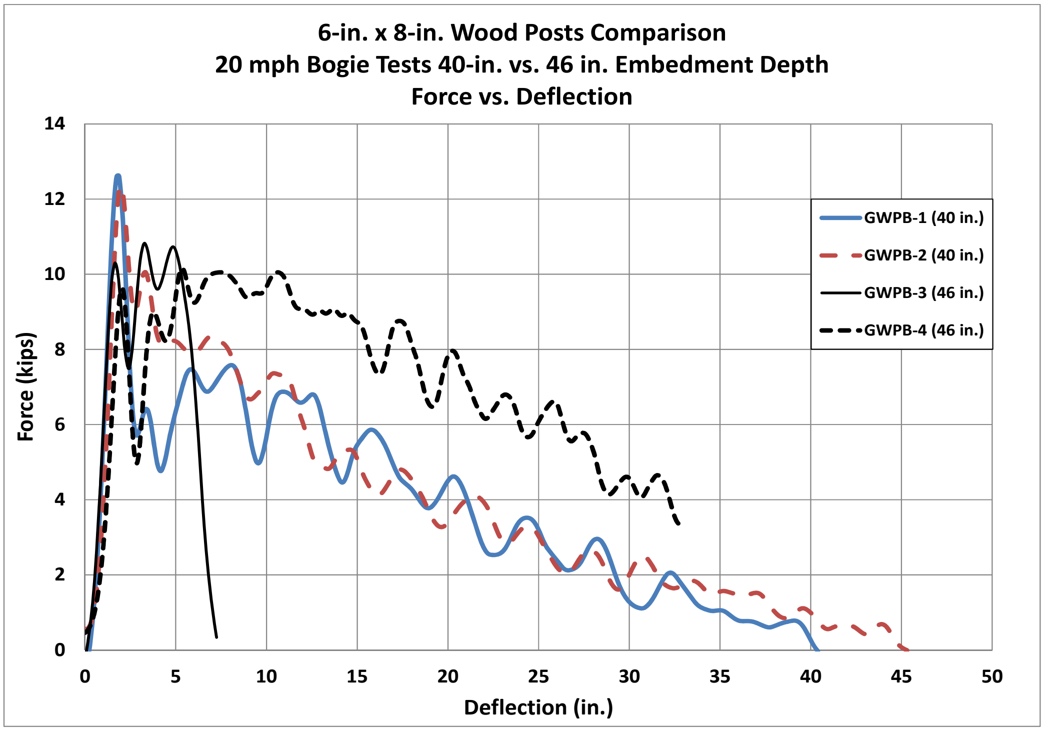
The force vs. deflection and energy vs. deflection curves for test nos. GWPB-1 and GWPB-2 were similar in shape and magnitude with both tests causing the post to rotate through the soil. The 40-in. (1,016-mm) embedment depth provided average forces of 6.8 kips (30.0 kN) and 6.2 kips (27.5 kN) through deflections of 15 in. (381 mm) and 20 in. (508 mm), respectively. The average total energy absorbed was 166.7 kip-in. (18.8 kJ).

The force vs. deflection and energy vs. deflection curves for GWPB-3 and GWPB-4 were similar in shape and magnitude through 5 in. (127 mm) of deflection. Test no. GWPB-3 resulted in post fracture, while test no. GWPB-4 resulted in post rotation through the soil. The total energy absorbed was 53.6 kip-in. (6.1 kJ) for test no. GWPB-3. Test no. GWPB-4 provided average forces of 8.4 kip (37.4 kN) and 8.3 kip (36.7 kN) at deflections of 15 in. (381 mm) and 20 in. (508 mm), respectively. The total energy absorbed during test no. GWPB-4 was 254.6 kip-in. (28.8 kJ).

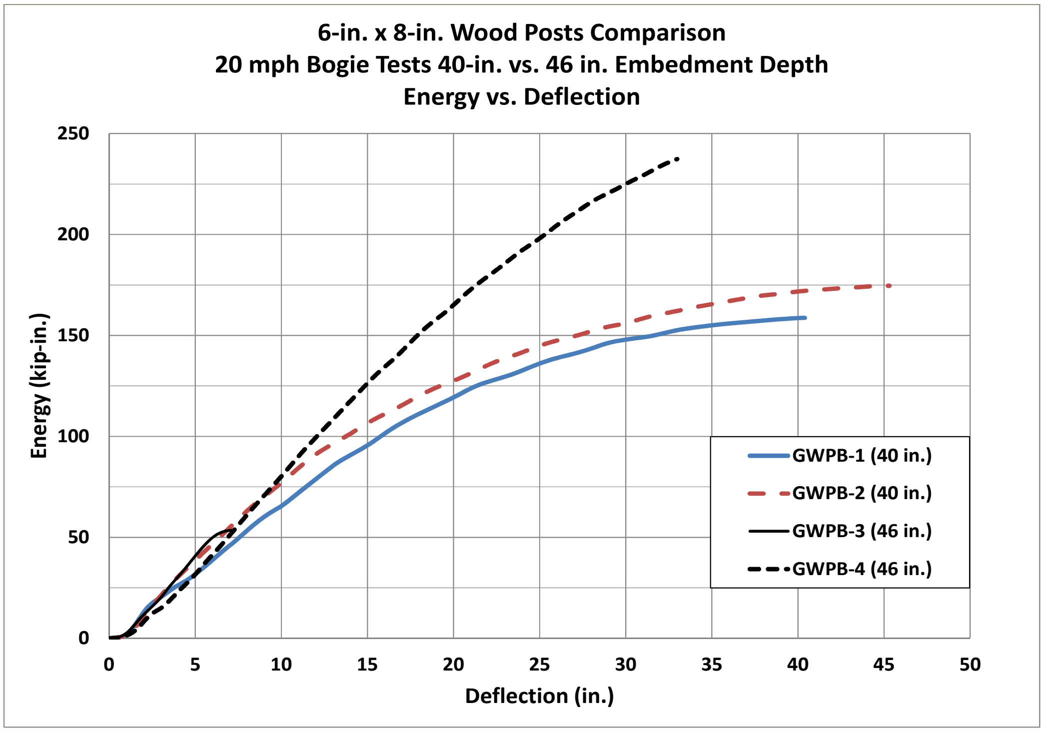
Test nos. GWPB-1, GWPB-2, and GWPB-4 resulted in force vs. deflection curves of similar shape but slightly different magnitudes. More specifically, the average resistive force through 20 in. (508 mm) in test no. GWPB-4 was approximately 2.1 kips (9.3 kN) larger than observed in test nos. GWPB-1 and GWPB-2. The energy vs. deflection curves for both post lengths were similar during the first 7.5 in. (190 mm) of deflection. After this deflection, the energy absorbed by GWPB-4 increased at a faster rate than for GWPB-1 and GWPB-2. The total absorbed energy for GWPB-4 was 60.4 and 45.8 percent higher than test nos. GWPB-1 and GWPB-2, respectively.

Table 3. Testing Results – 6-in. x 8-in. (152-mm x 203-mm) Wood Posts with 40-in. (1,016-mm) vs. 46-in. (1,168-mm) Embedment Depths at 20 mph (32.2 km/h) and at Slope Break Point of 3H:1V Fill Slope

Test No.	Impact Velocity	Peak Force		Average Force		Total Energy	Maximum Deflection	Failure Type
		Force	Deflection	@ 15 in.	@ 20 in.			
	mph (km/h)	kips (kN)	in. (mm)	kips (kN)	kips (kN)	kip-in. (kJ)	in. (mm)	
6-ft (1.8-m) long, 6-in. x 8-in. (152-mm x 203-mm) SYP Wood Posts, 40-in. (1,016-mm) Embedment Depth								
GWPB-1	22.7 (36.5)	12.6 (56.1)	1.9 (47)	6.4 (28.4)	6.0 (26.6)	158.7 (17.9)	40.4 (1,026)	Rotation in Soil
GWPB-2	20.5 (33.0)	12.3 (54.9)	2.0 (51)	7.1 (31.6)	6.4 (28.4)	174.6 (19.7)	45.3 (1,151)	Rotation in Soil
Average	21.6 (34.8)	12.5 (55.5)	2.0 (49)	6.8 (30.0)	6.2 (27.5)	166.6 (18.8)	42.9 (1,089)	
6.5-ft (2.0-m) long, 6-in. x 8-in. (152-mm x 203-mm) SYP Wood Posts, 46-in. (1,168-mm) Embedment Depth								
GWPB-3	21.5 (34.6)	10.8 (48.1)	3.3 (83)	NA	NA	53.6 (6.1)	7.2 (183)	Fracture
GWPB-4	20.1 (32.3)	10.1 (45.1)	5.4 (137)	8.4 (37.4)	8.3 (36.7)	254.6 (28.8)	42.2 (1,072)	Rotation in Soil
Average	20.8 (33.5)	10.5 (46.6)	4.4 (110)	NA	NA	154.1 (17.5)	24.7 (628)	



a. Force vs. Deflection



b. Energy vs. Deflection

Figure 13. Graph. Force vs. Deflection and Energy vs. Deflection of Wood Posts on 3H:1V Slope Break Point

CHAPTER 4. COMPARISON TO STEEL POST TESTING ON MSE WALL

4.1 DIRECT COMPARISON OF TESTS

At the conclusion of the dynamic testing program, the results of the 6-in. x 8-in. (152-mm x 203-mm) wood post tests were compared to three dynamic tests previously conducted on the steel-post configuration that was full-scale crash tested. Test nos. GWR5-4, GWBR5-3, and GWBR5-6 consisted of 6-ft (1.8-m) long, W6x8.5 (W152x12.6) steel posts embedded 40 in. (1,016 mm) in strong soil and placed at the slope break point of a 3H:1V fill slope.[1] Test no. GWR5-4 was installed using an auger and backfill method and embedded in a soil foundation which did not include the wire mesh used in the MSE wall. Test nos. GWBR5-3 and GWBR5-6 were tested with wire mesh interaction as the posts were driven into the soil at the slope break point of the MSE wall. The tests are summarized in Table 4, and the force vs. deflection and energy vs. deflection curves are shown in Figure 14.

Comparisons were made between the test results for the steel and wood posts using the categories of peak force, average force at prescribed displacements, and total energy at prescribed displacements. Peak force shows the highest resistive force from the soil and the corresponding deflection. Average force depicts the average resistive force applied to the post through the first 15 in. (381 mm) and 20 in. (508 mm) of deflection. Total energy shows the total energy absorbed at 15 in. (381 mm) and 20 in. (508 mm) of deflection.

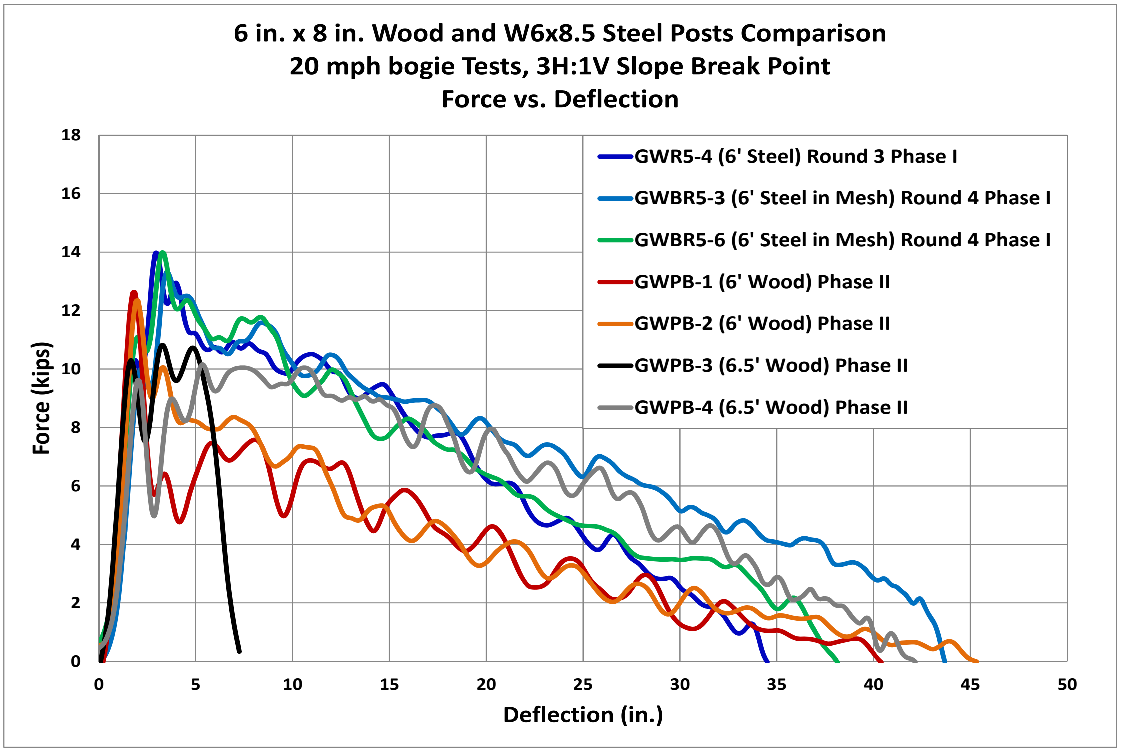
The steel posts provided higher peak and average resistive forces than observed for the wood posts at either embedment depth, as shown in Table 4. The wood posts with a 40-in. (1,016-mm) embedment depth resulted in 31 and 33 percent lower average resistance forces at 15 in. (381 mm) and 20 in. (508 mm) of deflection, respectively. The wood post with a 46-in. (1,168-mm) embedment depth resulted in 14 and 11 percent lower average resistance forces at 15 in. (381 mm) and 20 in (508 mm) of deflection, respectively. The shape and magnitude of the force vs. deflection curves were similar between the 6-ft (1.8-m) long, W6x8.5 (W152x12.6) steel posts and the 6.5-ft (2.0-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood post in test no. GWPB-4. However, the W6x8.5 (W152x12.6) steel posts provided higher resistive forces through the first 10 in. (254 mm) of deflection.

The steel posts also provided more energy absorption than the wood posts at either embedment depth. As shown in Table 4, the total energy absorbed through 15 in. (381 mm) and 20 in. (508 mm) of deflection is provided for both wood and steel posts. The wood posts with a 40-in. (1,016-mm) embedment depth resulted in 31 and 34 percent lower total energy at 15 in. (381 mm) and 20 in. (508 mm) of deflection, respectively. The wood post with a 46-in. (1,168-mm) embedment depth resulted in 14 and 12 percent lower total energy at 15 in. (381 mm) and 20 in. (508 mm) of deflection, respectively.

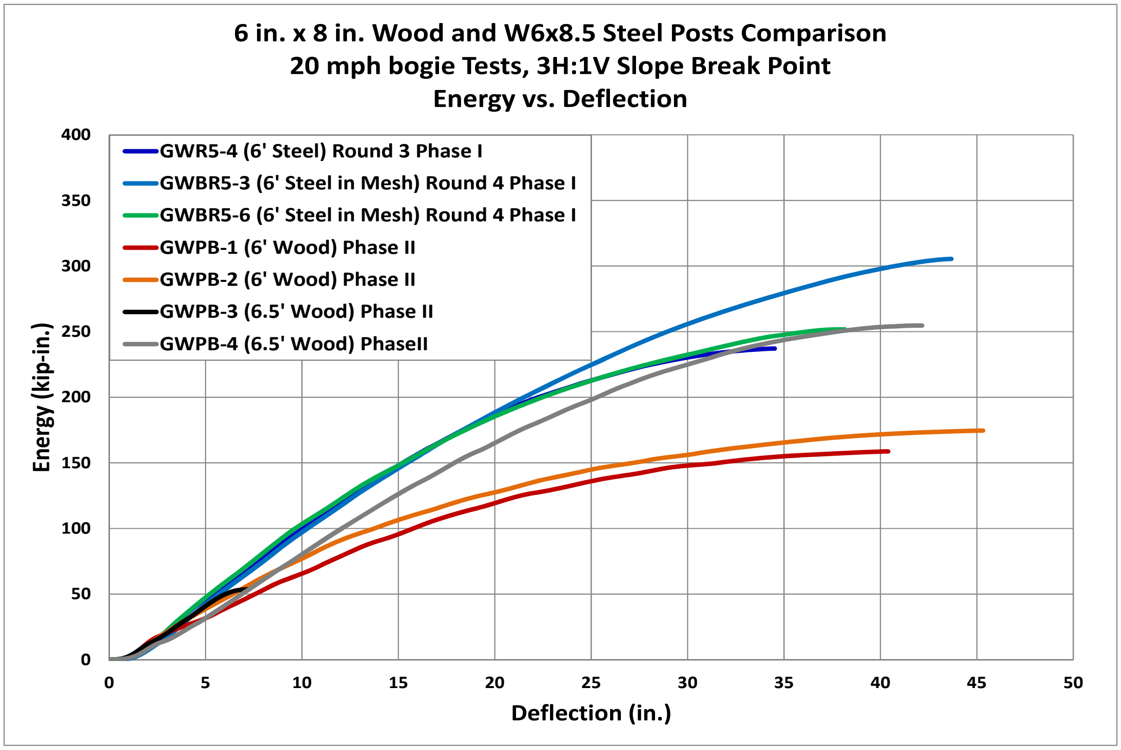
Table 4. Comparison of Steel and Wood Posts on 3H:1V Slope Break Point

Test No.	Impact Velocity mph (km/h)	Peak Force		Average Force		Total Energy		Failure Type
		Force kips (kN)	Deflection in. (mm)	@ 15 in. kips (kN)	@ 20 in. kips (kN)	@ 15 in. kip-in. (kJ)	@ 20 in. kip-in. (kJ)	
6-ft (1.8-m) long, 6-in. x 8-in. (152-mm x 203-mm) SYP Wood Posts, 40-in. (1,016-mm) Embedment Depth								
GWPB-1[1]	22.7 (36.5)	12.6 (56.1)	1.9 (47)	6.4 (28.4)	6.0 (26.6)	95.2 (10.8)	119.5 (13.5)	Rotation in Soil
GWPB-2[1]	20.5 (33.0)	12.3 (54.9)	2.0 (51)	7.1 (31.6)	6.4 (28.4)	106.6 (12.0)	127.4 (14.4)	Rotation in Soil
Average	21.6 (34.8)	12.5 (55.5)	2.0 (49)	6.8 (30.0)	6.2 (27.5)	100.9 (11.4)	123.5 (14.0)	
6.5-ft (2.0-m) long, 6-in. x 8-in. (152-mm x 203-mm) SYP Wood Posts, 46-in. (1,168-mm) Embedment Depth*								
GWPB-3[1]	21.5 (34.6)	10.8 (48.1)	3.3 (83)	NA	NA	NA	NA	Fracture
GWPB-4[1]	20.1 (32.3)	10.1 (45.1)	5.4 (137)	8.4 (37.4)	8.3 (36.7)	126.5 (14.3)	165.0 (18.6)	Rotation in Soil
***Averages were not included for the 6.5-ft (2.0-m) long wood posts due to the fracturing during test no. GWPB-3.**								
6-ft (1.8-m) long, W6x8.5 (W152x12.6) Steel Posts, 40-in. (1,016-mm) Embedment Depth								
GWR5-4[1]	20.6 (33.2)	14.0 (65.6)	2.9 (74)	9.9 (44.2)	9.3 (40.0)	148.0 (16.7)	186.5 (21.1)	Rotation in Soil and Yielding
GWBR5-3[2]	22.1 (35.6)	13.3 (59.2)	3.5 (89)	9.7 (43.3)	9.4 (41.9)	145.7 (16.5)	188.7 (21.3)	Rotation in Soil and Yielding
GWBR5-6[2]	22.9 (36.8)	14.0 (62.2)	3.2 (82)	9.9 (43.9)	9.3 (41.2)	147.7 (16.7)	185.2 (20.9)	Rotation in Soil and Yielding
Average	21.9 (35.2)	13.8 (62.3)	3.2 (82)	9.8 (43.8)	9.3 (41.0)	147.1 (25.0)	186.8 (21.1)	

[1] Posts set in augered and backfilled holes.
[2] Posts driven on 3H:1V slope through mesh.



a. Force vs. Deflection



b. Energy vs. Deflection

Figure 14. Graph. Force vs. Deflection and Energy vs. Deflection, Wood and Steel Post Comparison at 20 mph and 3H:1V Slope Break Point

CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 SUMMARY

Test nos. GWPB-1 through GWPB-4 were performed on 6-in. x 8-in. (152-mm x 203-mm) wood posts placed at the slope break point of a 3H:1V fill slope with various embedment depths. For test nos. GWPB-1 and GWPB-2, the 6-ft (1.8-m) long wood posts rotated through the soil when installed with a 40-in. (1,016-mm) embedment depth. For test nos. GWPB-3 and GWPB-4, the 6.5-ft (2.0-m) wood posts provided inconclusive results when installed with a 46-in. (1,168-mm) embedment depth. In test no. GWPB-3, the wood post fractured. However, the wood post rotated through the soil in test no. GWPB-4.

For test no. GWPB-4, the average soil resistance was 23.5 percent and 33.9 percent higher at 15 in. (381 mm) and 20 in. (508 mm) of displacement, respectively, as compared to the results obtained for the wood posts with a 40-in. (1,016-mm) embedment depth. In addition and for test no. GWPB-4, the total energy was 25.4 percent and 33.6 percent higher at 15 in. (381 mm) and 20 in. (508 mm) of displacement, respectively, as compared to the results obtained for the wood posts with a 40-in. (1,016-mm) embedment depth.

Subsequently, the test results for the wood posts were compared to those results previously obtained for 6-ft (1.8-m) long, W6x8.5 (W152x12.6) steel posts with embedment depths of 40 in. (1,016 mm) and placed at the slope break point of a 3H:1V fill slope. The 6-ft (1.8-m) long, wood posts with a 40-in. (1,016-mm) embedment depth provided 30.6 percent and 33.3 percent lower average resistance force at 15 in. (381 mm) and 20 in. (508 mm) of deflection as compared to the 6-ft (1.8-m) long, steel posts. In addition, the 6-ft (1.8-m) long, wood posts with a 40-in. (1,016-mm) embedment depth provided 31.4 percent and 33.9 percent lower total energy at 15 in. (381 mm) and 20 in. (508 mm) of deflection as compared to the 6-ft (1.8-m) long, steel posts.

In test no. GWPB-4, the 6.5-ft (2.0-m) long, wood post provided 14.2 percent and 10.8 percent lower average resistance force at 15 in. (381 mm) and 20 in. (508 mm) of deflection as compared to the 6-ft (1.8-m) long, steel posts. In addition, the 6.5-ft (2.0-m) long, wood post with a 46-in. (1,168-mm) embedment depth provided 14.0 percent and 11.7 percent lower total energy at 15 in. (381 mm) and 20 in. (508 mm) of deflection as compared to the 6-ft (1.8-m) long, steel posts. Due to wood fracture, test no. GWPB-3 could not be compared after 5 in. (127 mm) of deflection.

5.2 CONCLUSIONS

From the prior comparisons of test results noted above, it is evident that the 6-ft (1.8-m) and 6.5-ft (2.0-m) long wood posts provide lower average resistance force and energy dissipation as compared to the 6-ft (1.8-m) long steel posts. For the 6-ft (1.8-m) long wood posts, the average resistive force and energy dissipation were more than 30 percent lower than observed for the 6-ft (1.8-m) long steel posts. For the 6.5-ft (2.0-m) long wood posts, varied post-soil performance resulted in either wood fracture or post rotation in soil. Although one 6.5-ft (2.0-m) long wood post did rotate in the soil, its average resistive force and energy dissipation was more than 10 percent lower than observed for the 6-ft (1.8-m) long steel posts.

As noted above, fracture occurred in one out of two tests on 6.5-ft (2.0-m) long wood posts. As a result, it was believed that the risk for wood fracture would be increased for 6.5-ft (2.0-m) long wood posts installed in actual MSE wall structures containing layers of wire mesh reinforcement.

Based on the wood post testing reported herein, the 6-ft (1.8-m) and 6.5-ft (2.0-m) long, 6-in. x 8-in. (152-mm x 203-mm) wood posts showed limited promise for serving as an acceptable alternative to the 6-ft (1.8-m) long steel posts used in the MGS when installed at the slope break point of a 3H:1V fill slope on a wire-faced, MSE wall. If wood posts are to be eventually considered for use in the MGS barrier system when installed on wire-faced, MSE walls, then it may be necessary to component test and evaluate larger cross sections of wood posts.

5.3 RECOMMENDATIONS

Wood posts have a much larger cross-sectional area as compared to standard steel guardrail posts. Thus, it may be difficult to drive wood posts into the top of a MSE wall structure due to presence of the steel, wire-mesh reinforcement found below grade. If wood posts are to be considered in the future, research would be necessary to: (1) investigate whether wood posts can be driven into a wire-faced, MSE wall; (2) evaluate the propensity for a wire-faced, MSE wall to be damaged during wood post placement, rotation in soil, or during post removal and barrier repair; and (3) determine whether fractured posts can be easily and efficiently removed from the compacted, soil foundation. Further dynamic component testing would be necessary to investigate whether alternative sizes of wood posts can be safely and practically used within the MGS installed at the 3H:1V fill slope on top of wire-faced, MSE walls.

CHAPTER 6. REFERENCES

1. Homan, D.M., Thiele, J.C., Faller, R.K., Rosenbaugh, S.K., Rhode, J.R., Arens, S.W., Lechtenberg, K.A., Sicking, D.L., Reid, J.D., *Investigation and Dynamic Testing of Wood and Steel Posts for MGS on a Wire-Faced, MSE Wall*, Final Report to Federal Highway Administration (FHWA), Central Federal Lands Highway Division, FHWA Report No. FHWA-CFL/TD-12-008, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, February 2012.

2. McGhee, M.D., Faller, R.K., Rohde, J.R., Lechtenberg, K.A., Sicking, D.L., and Reid, J.D., *Development of an Economical Guardrail System for use on Wire Faced, MSE Walls*, Final Report to Federal Highway Administration (FHWA), Central Federal Lands Highway Division, FHWA Report No. FHWA-CFL/TD-12-009, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, February 2012.

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

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

Appendix A. EDR-3 Equivalency to Approved Transducer

At the time of testing, only the manufacturer, IST, had the capabilities to calibrate the EDR-3 unit because it is a self contained transducer utilizing IST software. Since IST is not an ISO 17025 accredited laboratory, the EDR-3 was not viewed as a transducer calibrated to ISO 17025. Additionally, both MASH and SAE J211-1 recommend a minimum sampling rate of at least 10 times the Channel Frequency Class (CFC). With the recommended CFC 1000 pre-sampling filter to prevent aliasing errors in the sampling process, the minimum sampling rate was recommended to be 10,000 Hz. The EDR-3 does not satisfy this limit as it records data at 3,200 Hz. It should also be noted that the Nyquist theory states that data must be sampled at a minimum of two times the highest frequency to be examined. Since CRC 180 data examines data up to 3000 Hz (a stopband edge of FS = 3000 Hz), the minimum sampling frequency is 6000 Hz.

Although the EDR-3 has a lower than recommended sampling frequency and was not ISO 17025 calibrated, it has historically provided accurate and precise data when compared to MASH compliant transducers that have been ISO 17025 calibrated and high-speed video analysis results of physical testing. Thus, MwRSF has viewed the EDR-3 as an equivalent transducer and has continued using it during physical impact testing as a backup acceleration transducer. Appendix B of SAE J211-1 entitled "Transducer Equivalency" states that to establish equivalency, tests must be performed to ensure that the transducer under consideration yields similar results for the application of interest. Further, transducers may be placed side-by-side in actual test conditions as the basis of comparison. Consequently, MwRSF has compared the EDR-3 to the ISO 17025 calibrated and MASH compliant DTS unit to establish equivalency.

The DTS was calibrated on July 10, 2010 by a laboratory in the process of becoming ISO 17025 accredited and was able to provide reverse traceability. The EDR-3 was directly compared to the DTS unit utilizing impact testing at the MwRSF test site that occurred before and after the calibration. Comparisons with the results from two full scale crash tests, test nos. MGSWP-1 and DB-1, are shown in this appendix. During these tests, the EDR-3 and DTS transducers were placed next to each other on the impacting vehicle, allowing for a direct comparison.

According to MwRSF procedure, the accelerometers would be considered equivalent if the following criteria were met. These criteria were meant to ensure that the data provided by the EDR-3 would yield accurate occupant risk values.

(1) The acceleration traces were similar in shape and magnitude, e.g., major peaks and valleys correlate throughout the impact event on a CFC 180 10 msec average acceleration vs. time plot.

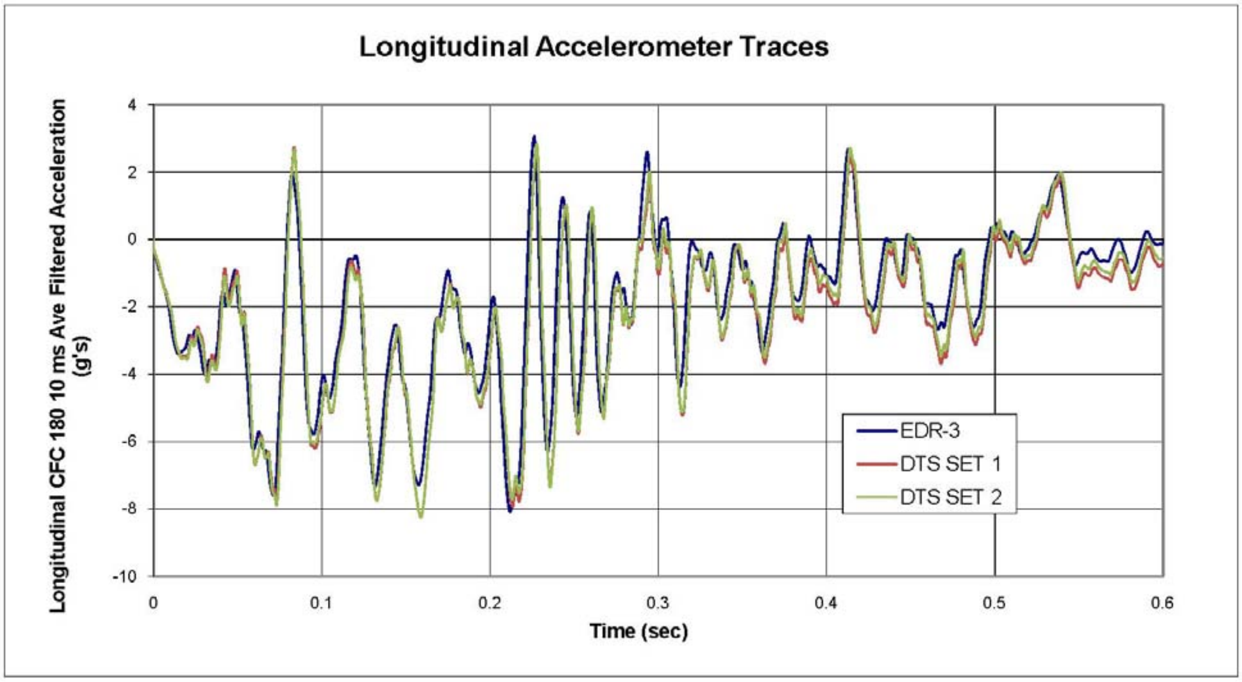
(2) The total change in velocity (area under the acceleration vs. time curves) should differ by less than 15 percent over the initial 250 msec of the impact event.

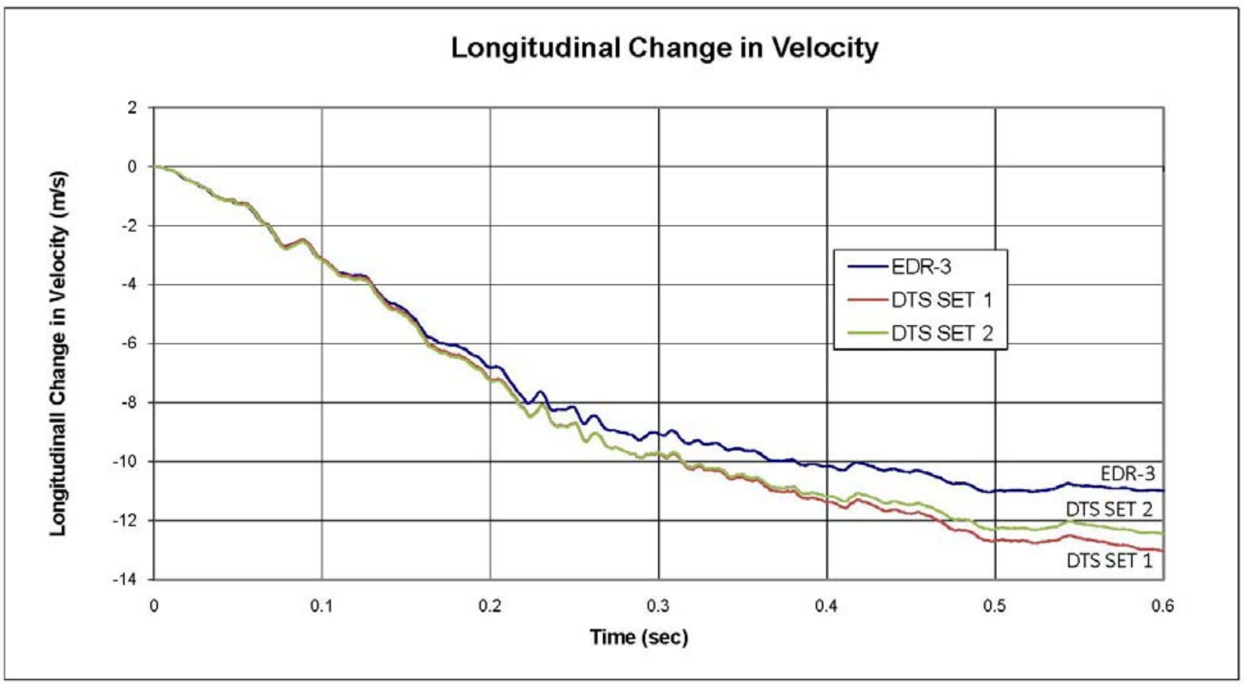
Comparison of acceleration data taken from the EDR-3 and DTS transducers is complex given the differences in mounting location, transducer type, sample rate, and other factors. In general, MwRSF is seeking to compare the performance of the acceleration transducers for an event length of approximately 500 msec. For impact event time durations less than 500 msec, acceleration measurements from different transducers tend to compare relatively well. However, as the comparison time approaches and/or exceeds the 500-msec range, the integrated change in velocity curves generated by the two units can become different in magnitude even when they may have compared very well early in the impact event. This divergence of the integrated change in velocity values can occur without a significant error in the transducer and is due to differences in the two transducers. The sample rate for the DTS is 10 kHz as compared to the EDR-3 unit's lower sample rate of 3.2 kHz. This lower sample rate means that the DTS system will tend to record higher peak acceleration values than the EDR-3. This leads to higher integrated change in velocity values when using the DTS system. The difference in the integrated change in velocity curves becomes more pronounced over extended times as the lower peak acceleration values recorded by the EDR-3 are summed together during integration and cause the calculated velocity from the EDR-3 to diverge from that calculated with the DTS system. In addition to the effects of sample rate, differences in mounting and the location of the transducers in the vehicle may cause differences in the measured acceleration values.

While inherent differences in the two transducer systems could pose an issue for events with long time durations, the impact events studied by MwRSF are typically around 500 msec or less in length. In addition, MwRSF is mainly concerned with determination of accurate occupant risk values which are calculated based on the contact of the theoretical occupant with the vehicle interior using the Flail Space Model. In most impact events, occupant impact time and determination of the OIV values occur in the first 100 msec to 250 msec of the impact when the integrated displacements and velocities from both transducers are very similar. Thus, any difference in the occupant impact time and the OIV value would be minimal. As noted above, the lower sample rate of the EDR-3 will tend to record lower peak accelerations and thus could be expected to produce slightly lower magnitude ORA values. However, the difference in magnitude of any single peak acceleration value due to the difference in sample rate is generally very small. Thus, while there would be some concern that the ORA values obtained from the EDR-3 were lower than DTS if the measured ORA was near the limiting values in MASH, general ORA values calculated with the EDR-3 are expected to be very similar to those produced from the DTS system. This has been born out in past occupant risk value comparisons using the two transducer units, as shown in the following figures.

The two criteria above were satisfied in the noted impact tests, as shown in the following figures. Therefore, the EDR-3 was deemed equivalent to the DTS and approved for use.

Test: MGSWP-1 Date: 4/2/2010 Test Type: Full-Scale Crash Test



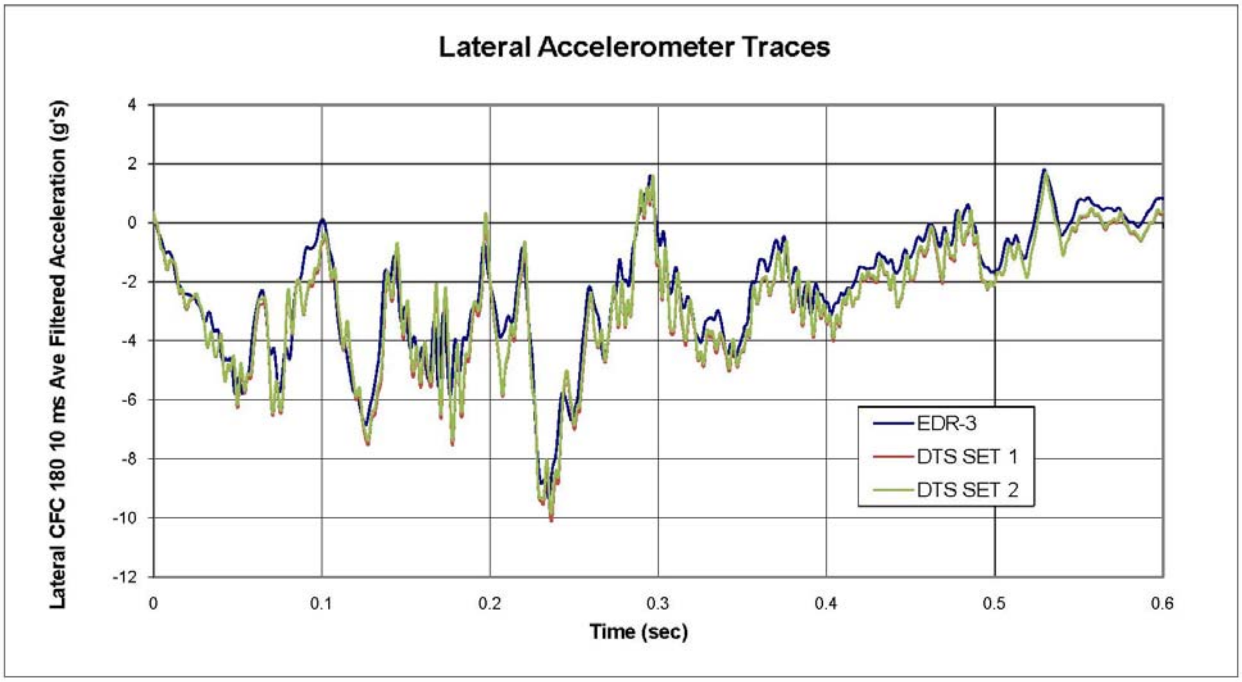


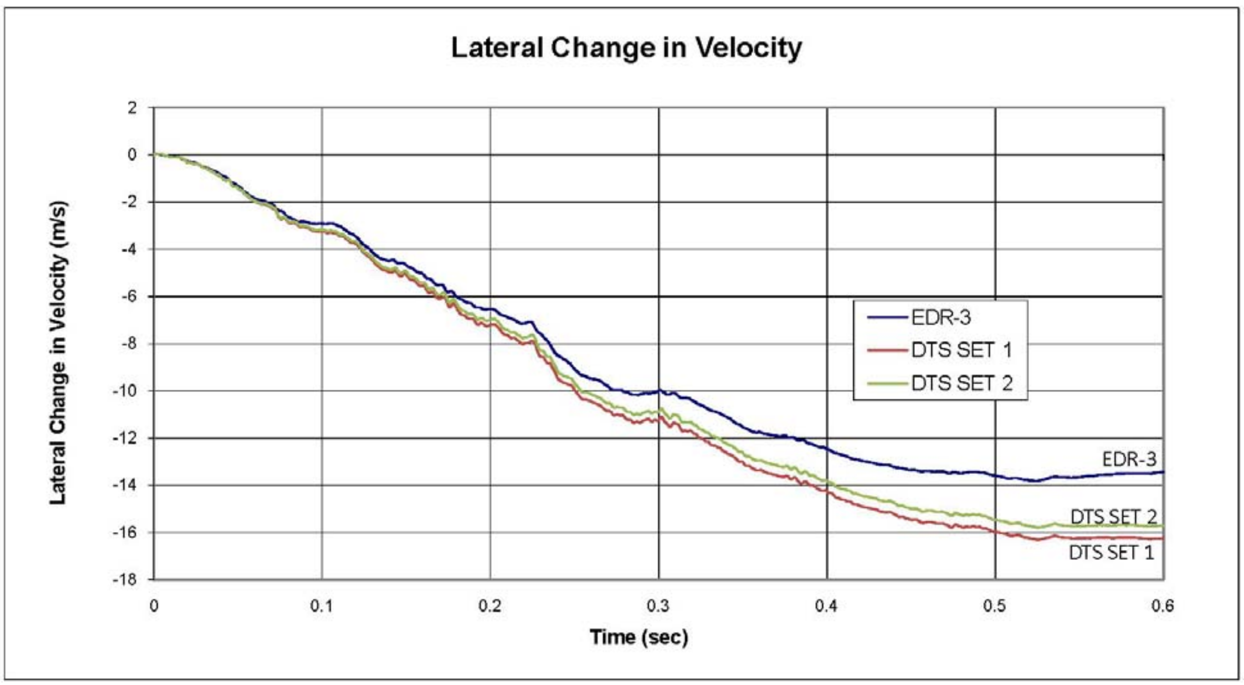
	DTS SET 1	EDR-3	% Difference
ΔV at 0.25 sec:	-8.69	-8.16	6.15%

	DTS SET 2	EDR-3	% Difference
ΔV at 0.25 sec:	-8.71	-8.16	6.33%

Figure 15. Graph. Longitudinal EDR-3 and DTS Equivalency Comparisons, Test No. MGSWP-1

Test: MGSWP-1 Date: 4/2/2010 Test Type: Full-Scale Crash Test



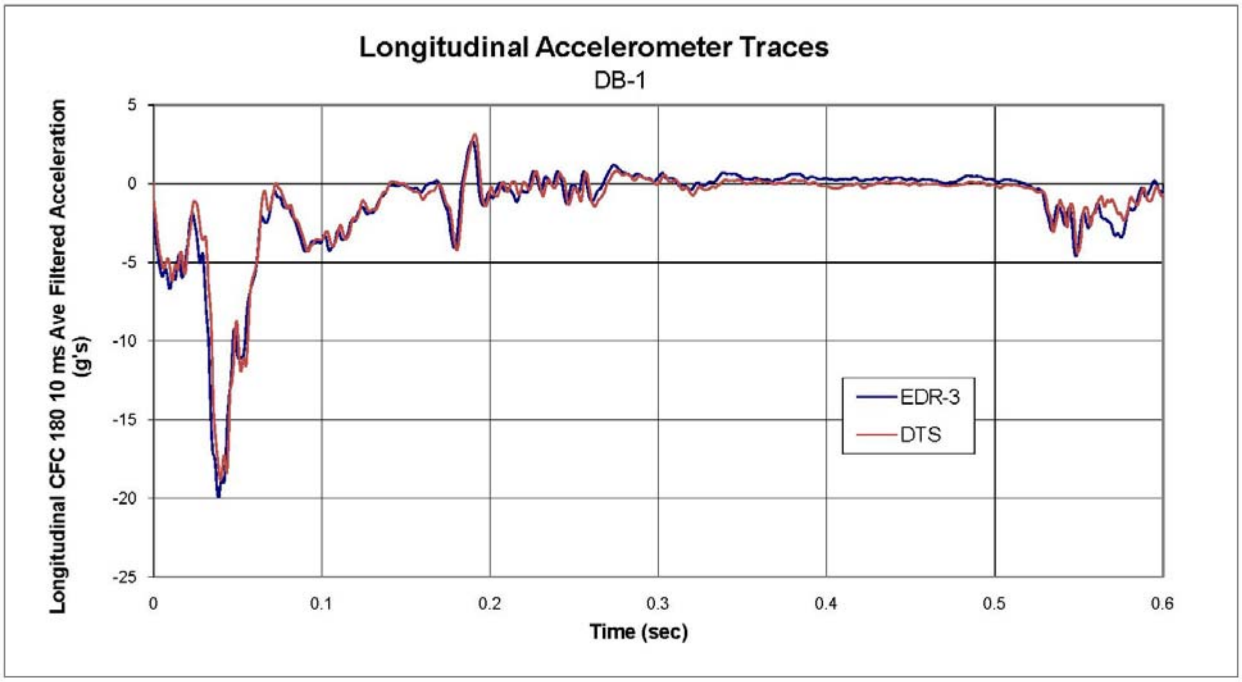


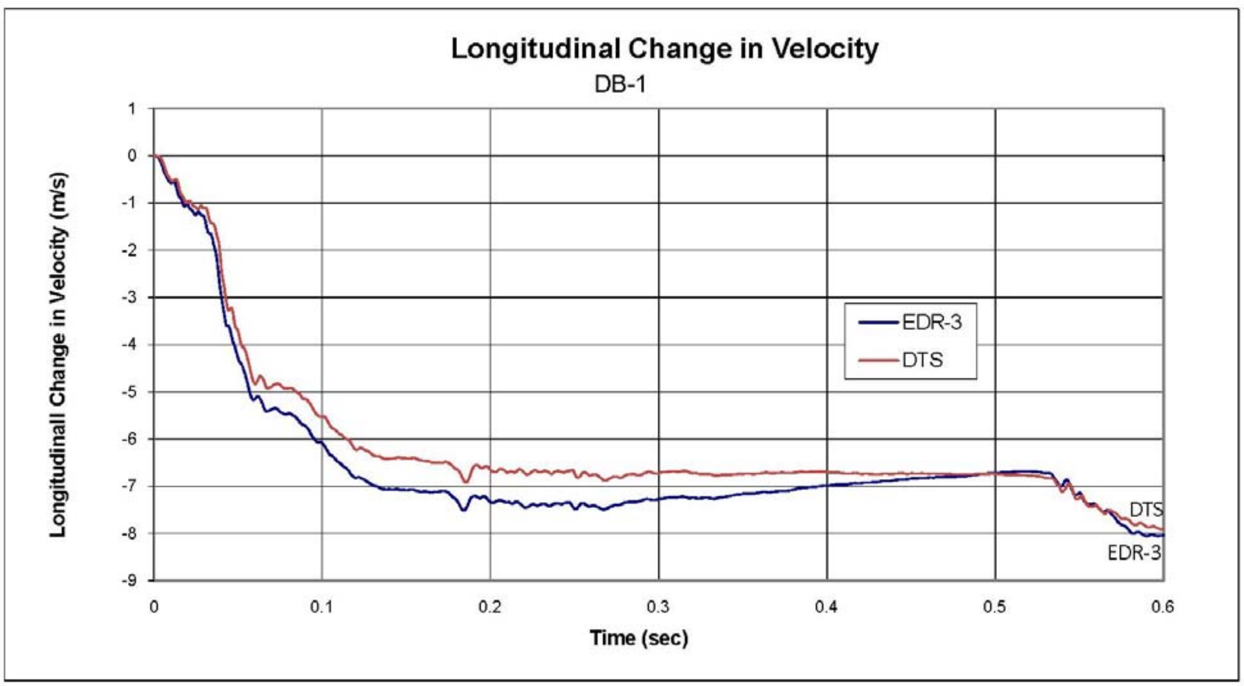
	DTS SET 1	EDR-3	% Difference
ΔV at 0.25 sec:	-9.95	-9.07	8.86%

	DTS SET 2	EDR-3	% Difference
ΔV at 0.25 sec:	-9.67	-9.07	6.15%

Figure 16. Graph. Lateral EDR-3 and DTS Equivalency Comparisons, Test No. MGSWP-1

Test: DB-1 Date: 8/3/2010 Test Type: Full-Scale Crash Test

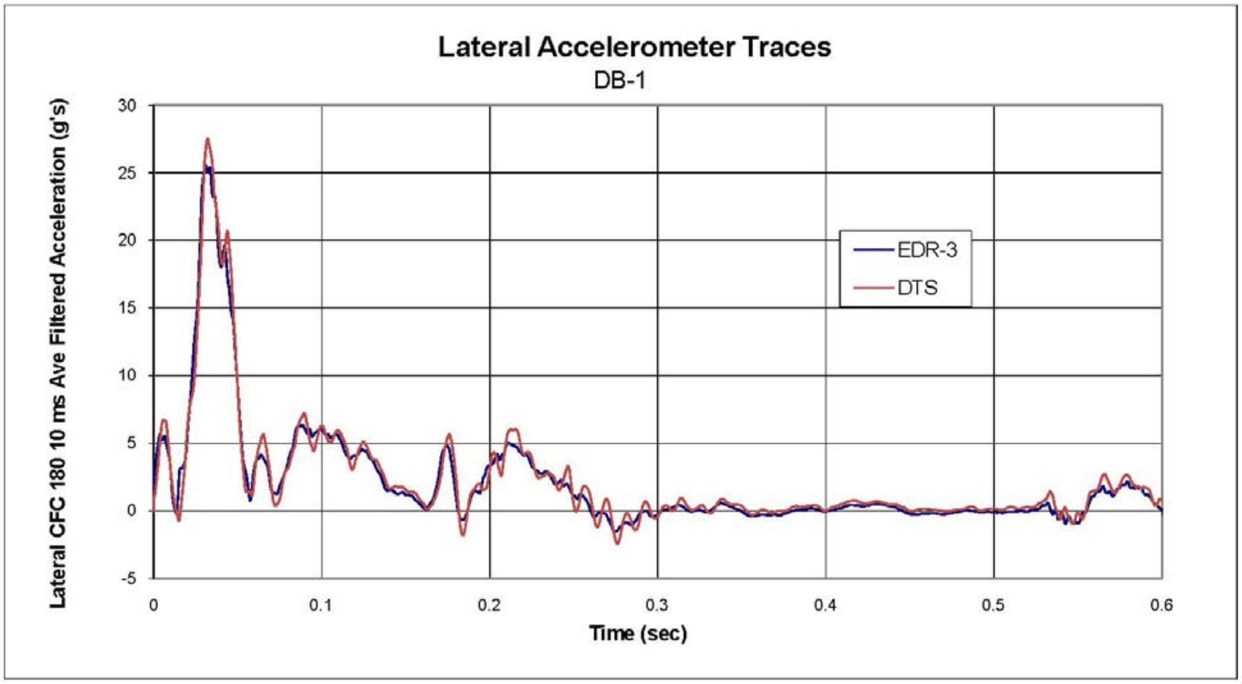


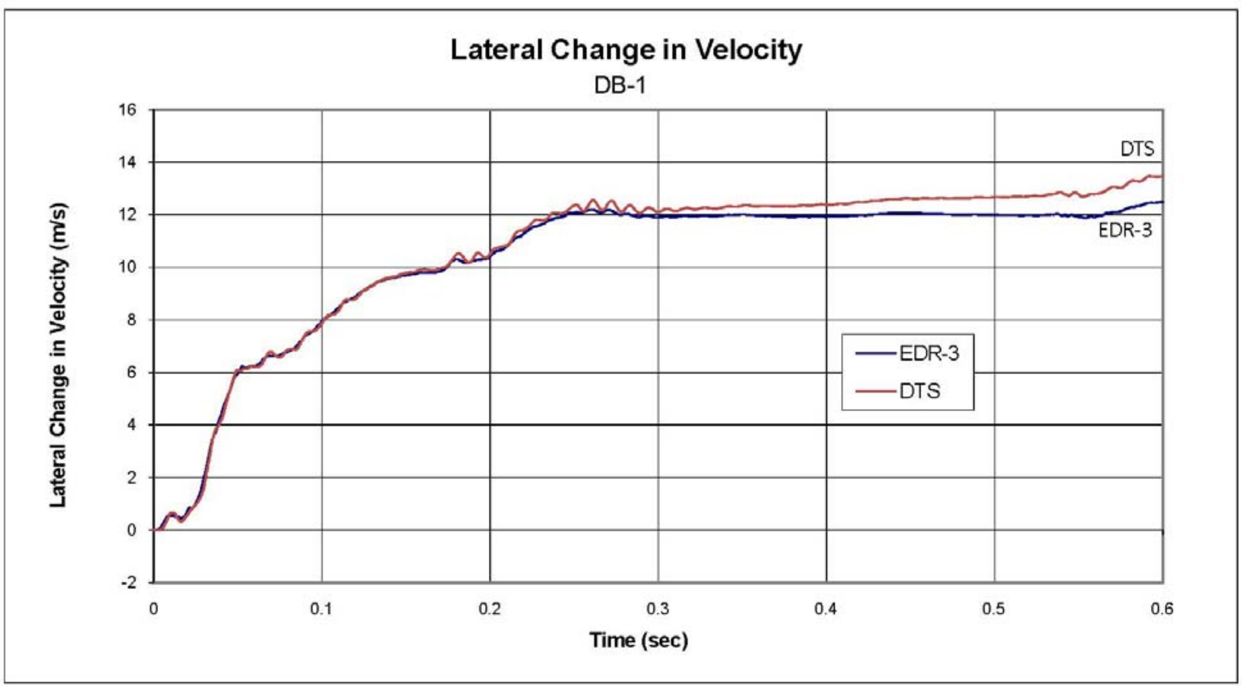


	DTS	EDR-3	% Difference
ΔV at 0.25 sec:	-6.71	-7.47	11.32%

Figure 17. Graph. Figure A-1. Longitudinal EDR-3 and DTS Equivalency Comparisons, Test No. DB-1

Test: DB-1 Date: 8/3/2010 Test Type: Full-Scale Crash Test

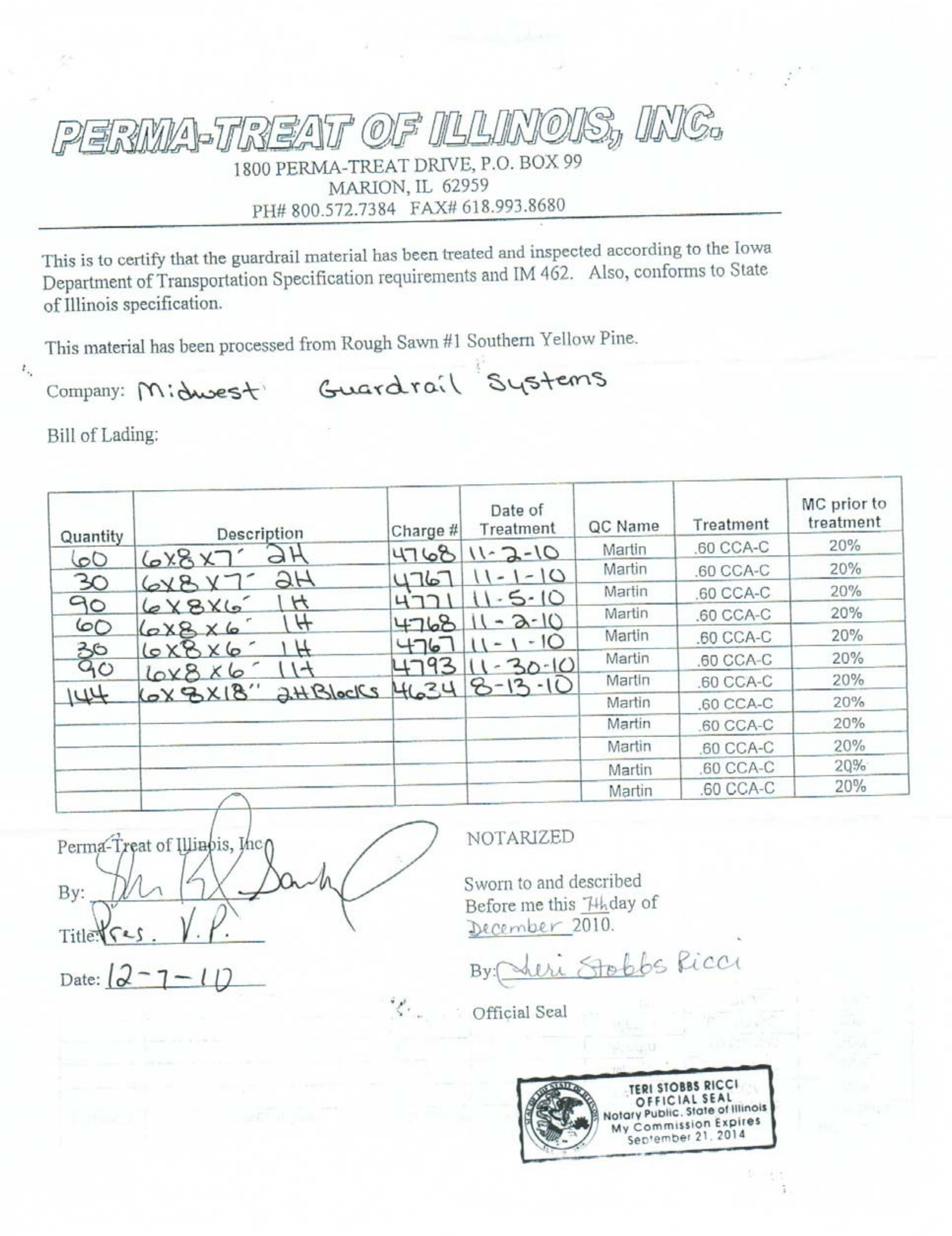




	DTS	EDR-3	% Difference
ΔV at 0.25 sec:	12.35	12.08	2.21%

Figure 18. Graph. Lateral EDR-3 and DTS Equivalency Comparisons, Test No. DB-1

Appendix B. Material Specifications



PERMA-TREAT OF ILLINOIS, INC.
1800 PERMA-TREAT DRIVE, P.O. BOX 99
MARION, IL 62959
PH# 800.572.7384 FAX# 618.993.8680

This is to certify that the guardrail material has been treated and inspected according to the Iowa Department of Transportation Specification requirements and IM 462. Also, conforms to State of Illinois specification.

This material has been processed from Rough Sawn #1 Southern Yellow Pine.

Company: Midwest Guardrail Systems

Bill of Lading:

Quantity	Description	Charge #	Date of Treatment	QC Name	Treatment	MC prior to treatment
60	6x8x7' 2H	4768	11-2-10	Martin	.60 CCA-C	20%
30	6x8x7' 2H	4767	11-1-10	Martin	.60 CCA-C	20%
90	6x8x6' 1H	4771	11-5-10	Martin	.60 CCA-C	20%
60	6x8x6' 1H	4768	11-2-10	Martin	.60 CCA-C	20%
30	6x8x6' 1H	4767	11-1-10	Martin	.60 CCA-C	20%
90	6x8x6' 1H	4793	11-30-10	Martin	.60 CCA-C	20%
144	6x8x18" 2H Blocks	4634	8-13-10	Martin	.60 CCA-C	20%
				Martin	.60 CCA-C	20%
				Martin	.60 CCA-C	20%
				Martin	.60 CCA-C	20%
				Martin	.60 CCA-C	20%
				Martin	.60 CCA-C	20%

Perma-Treat of Illinois, Inc.
By: [signature]
Title: Pres. V.P.
Date: 12-7-10

NOTARIZED

Sworn to and described
Before me this 7th day of
December 2010.

By: Teri Stobbs Ricci

Official Seal

TERI STOBBS RICCI
OFFICIAL SEAL
Notary Public, State of Illinois
My Commission Expires
September 21, 2014

Figure 19. Photo. W6x8 Wood Post Material Specification

Appendix C. Soil Sieve Data

The result of the washed soil sieve from the batch of soil used for this round of dynamic bogie tests is provided in Figure 20. The graph shows the passing percentages for the soil.

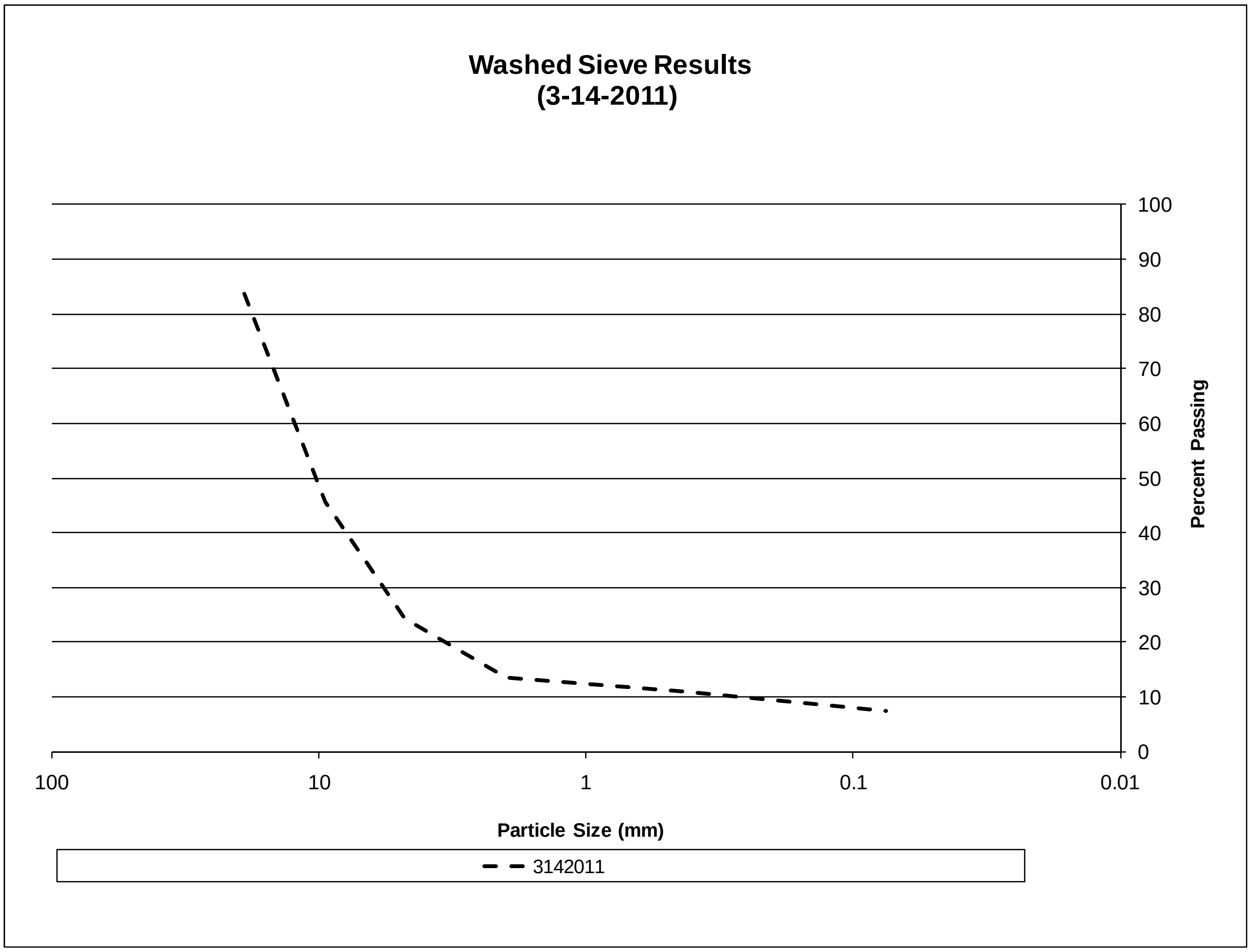


Figure 20. Graph. Soil Gradation for Test Nos. GWPB-1 through GWPB-4

Appendix D. Dynamic Test Results

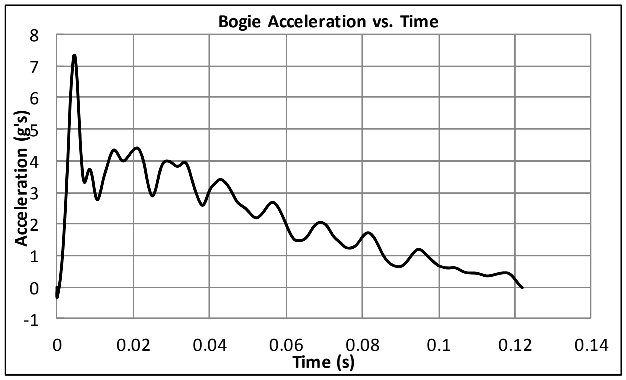
The results of the recorded data from each accelerometer for every dynamic bogie test are provided in the summary sheets in Figures 21 through 28. Summary sheets include acceleration, velocity, and deflection vs. time plots as well as force and energy vs. deflection plots.

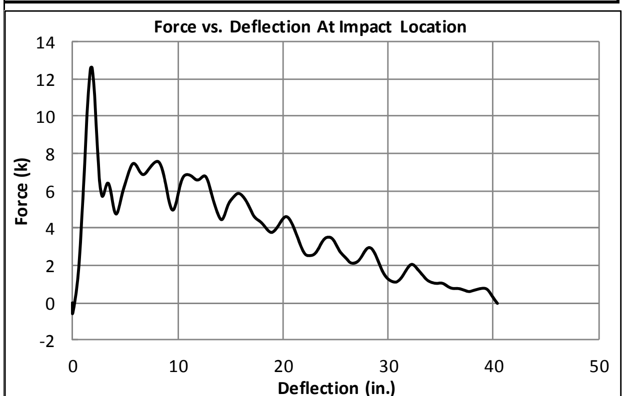
MIDWEST ROADSIDE SAFETY FACILITY

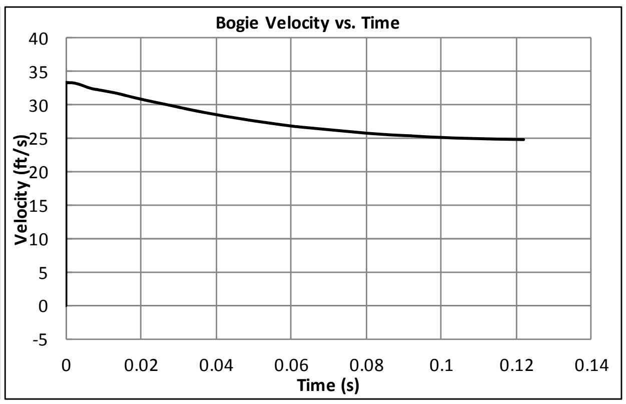
Bogie Test Summary

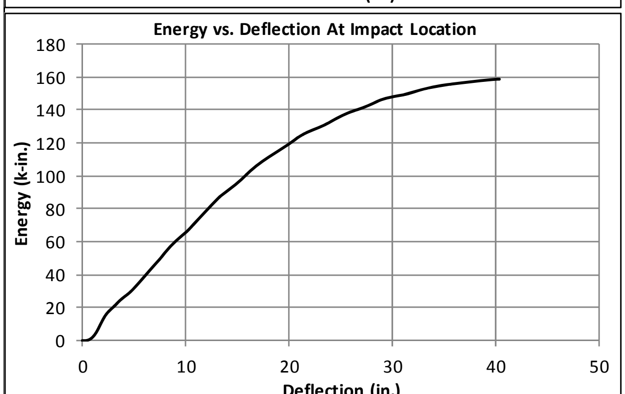
Test Information	SYP post on 3:1 slope	
Test Number:	GWPB-1	
Test Date:	17-Mar-2011	
Failure Type:	Rotated in soil	
Post Properties		
Post Type:	SYP - Gr 1 or Better	
Post Size:	6x8	152.4x203.8
Post Length:	72 in.	182.9 cm
Embedment Depth:	40 in.	101.6 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	31411 - MM 1" crusher run	
Moisture Content:	2.6 %	
Compaction Method:	HE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	22.7 mph (33.3 fps)	10.15 m/s
Impact Height:	24.875 in.	63.2 cm
Bogie Mass:	1722.6 lb	781.4 kg
Data Acquired		
Acceleration Data:	EDR-3	
Camera Data:	AOS-5	

Test Results Summary		
Max. Deflection:	40.4	in.
Peak Force:	12.6	k
Initial Linear Stiffness:	6.8	k/in.
Total Energy:	158.7	k-in.









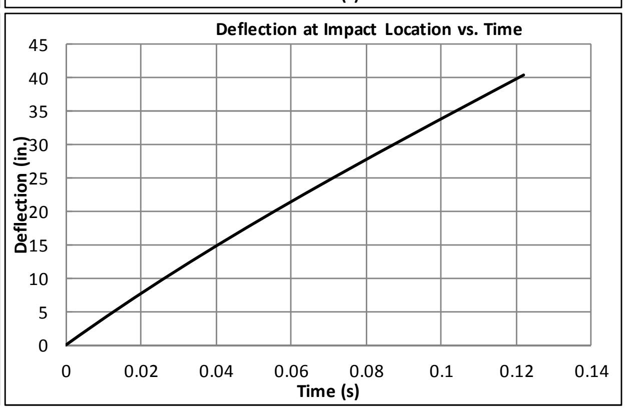


Figure 21. Graph. Test No. GWPB-1 Results (EDR-3)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information SYP post on 3:1 slope

Test Number:	GWPB-1	
Test Date:	17-Mar-2011	
Failure Type:	Rotated in soil	

Post Properties

Post Type:	SYP - Gr 1 or Better	
Post Size:	6x8	152.4x203.8
Post Length:	72 in.	182.9 cm
Embedment Depth:	40 in.	101.6 cm
Orientation:	Strong Axis	

Soil Properties

Gradation:	31411 - MM 1" crusher run
Moisture Content:	2.6 %
Compaction Method:	HE8
Soil Density, γd:	NA

Bogie Properties

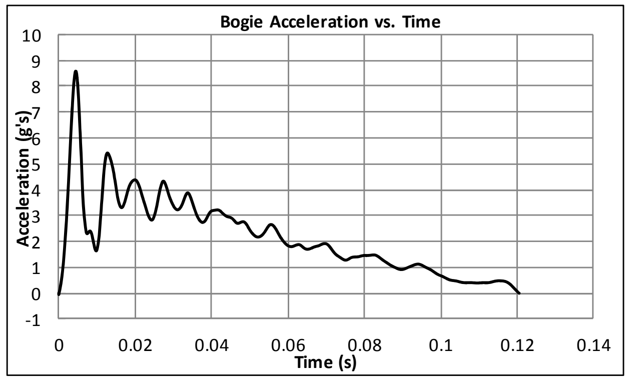
Impact Velocity:	22.7 mph (33.3 fps)	10.15 m/s
Impact Height:	24.875 in.	63.2 cm
Bogie Mass:	1722.6 lb	781.4 kg

Data Acquired

Acceleration Data:	DTS
Camera Data:	AOS-5

Test Results Summary

Max. Deflection:	40.0	in.
Peak Force:	14.8	k
Initial Linear Stiffness:	8.4	k/in.
Total Energy:	157.9	k-in.



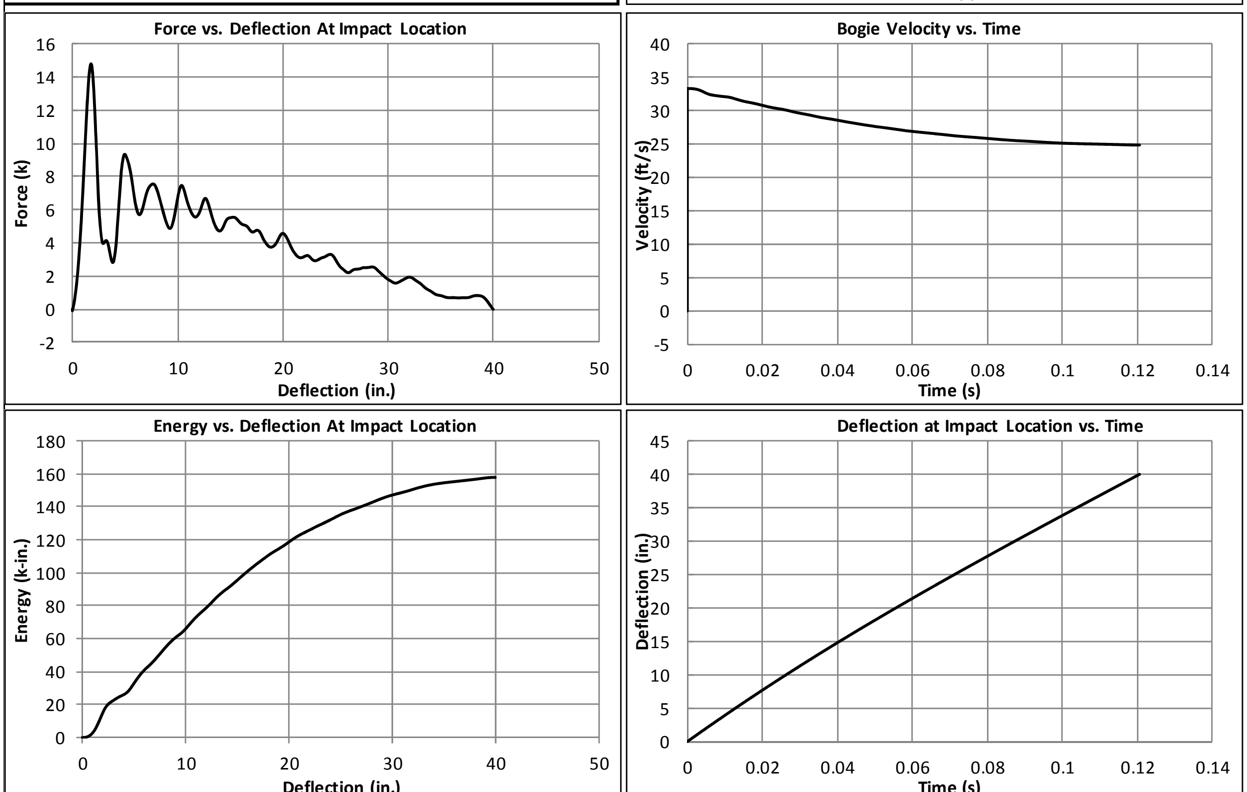


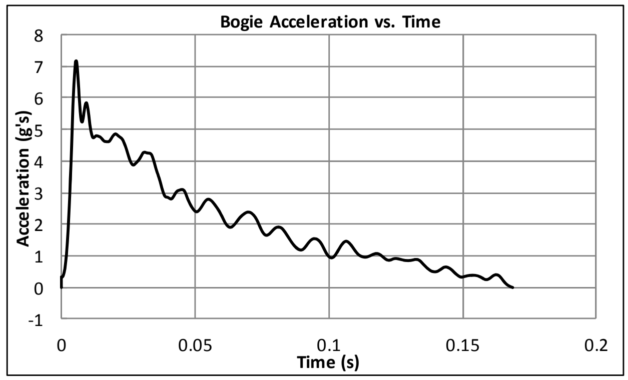
Figure 22. Graph. Test No. GWPB-1 Results (DTS)

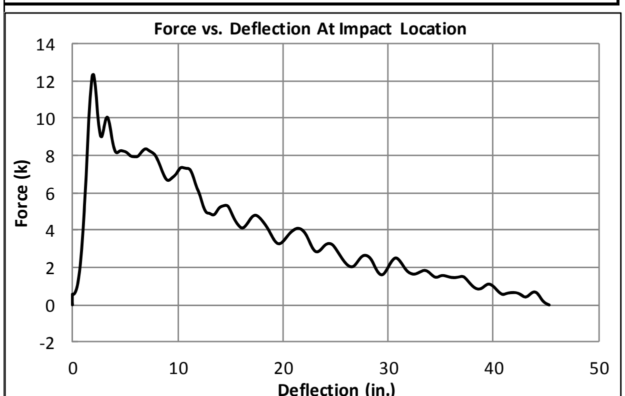
MIDWEST ROADSIDE SAFETY FACILITY

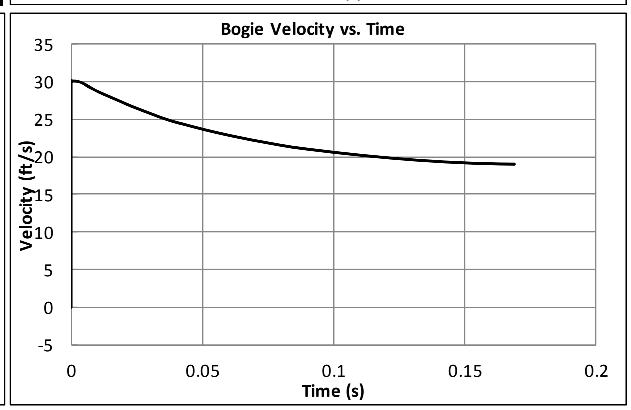
Bogie Test Summary

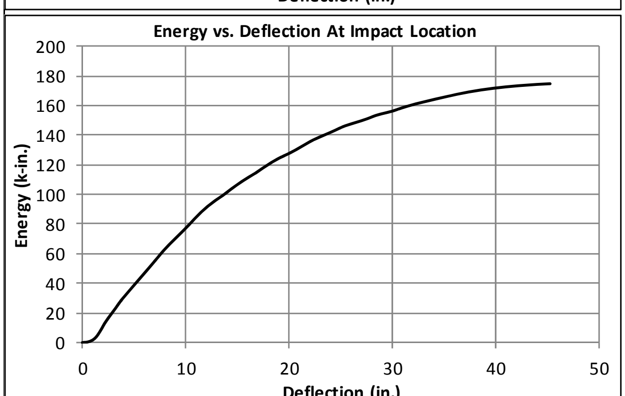
Test Information	SYP post on 3:1 slope	
Test Number:	GWPB-2	
Test Date:	18-Mar-2011	
Failure Type:	Rotated in soil	
Post Properties		
Post Type:	SYP - Gr 1 or Better	
Post Size:	6x8	152.4x203.8
Post Length:	72 in.	182.9 cm
Embedment Depth:	40 in.	101.6 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	31411 - MM 1" crusher run	
Moisture Content:	2.0 %	
Compaction Method:	HE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	20.51 mph (30.1 fps)	9.17 m/s
Impact Height:	24.875 in.	63.2 cm
Bogie Mass:	1722.6 lb	781.4 kg
Data Acquired		
Acceleration Data:	EDR-3	
Camera Data:	AOS-5	

Test Results Summary		
Max. Deflection:	45.3	in.
Peak Force:	12.3	k
Initial Linear Stiffness:	6.1	k/in.
Total Energy:	174.6	k-in.









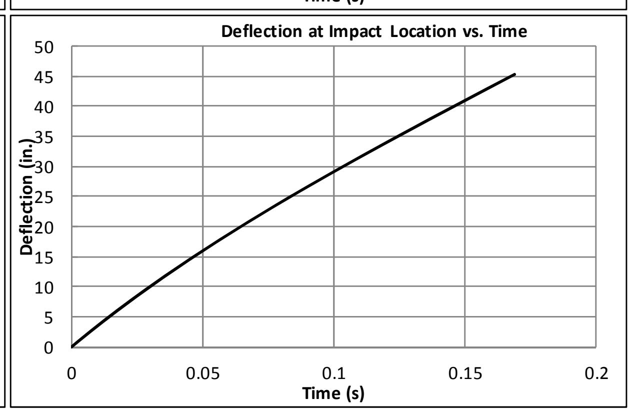


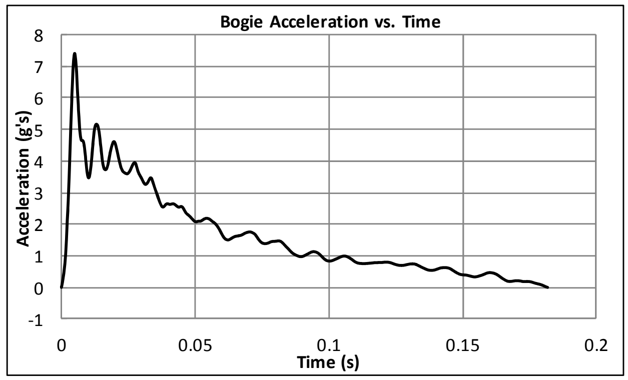
Figure 23. Graph. Test No. GWPB-2 Results (EDR-3)

MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information	SYP post on 3:1 slope	
Test Number:	GWPB-2	
Test Date:	18-Mar-2011	
Failure Type:	Rotated in soil	
Post Properties		
Post Type:	SYP - Gr 1 or Better	
Post Size:	6x8	152.4x203.8
Post Length:	72 in.	182.9 cm
Embedment Depth:	40 in.	101.6 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	31411 - MM 1" crusher run	
Moisture Content:	2.0 %	
Compaction Method:	HE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	20.51 mph (30.1 fps)	9.17 m/s
Impact Height:	24.875 in.	63.2 cm
Bogie Mass:	1722.6 lb	781.4 kg
Data Acquired		
Acceleration Data:	DTS	
Camera Data:	AOS-5	

Test Results Summary		
Max. Deflection:	50.7	in.
Peak Force:	12.7	k
Initial Linear Stiffness:	7.1	k/in.
Total Energy:	155.0	k-in.



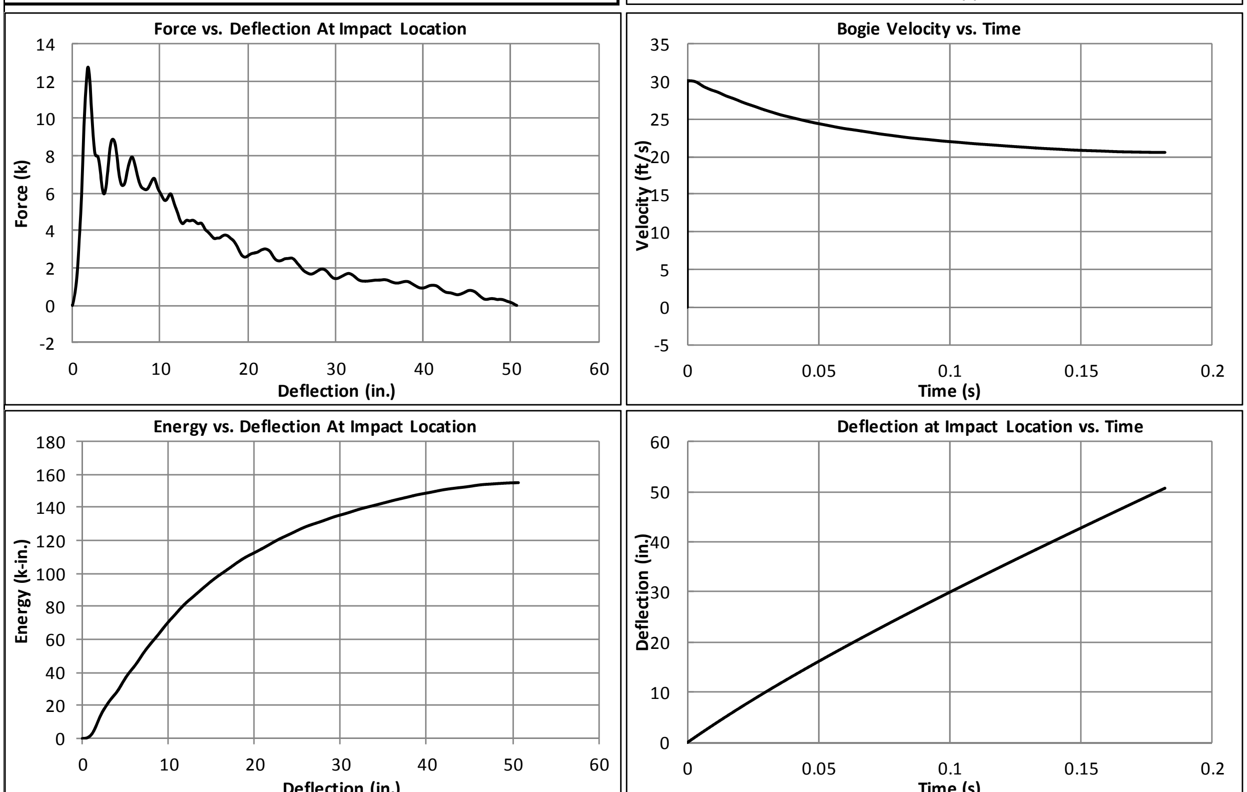


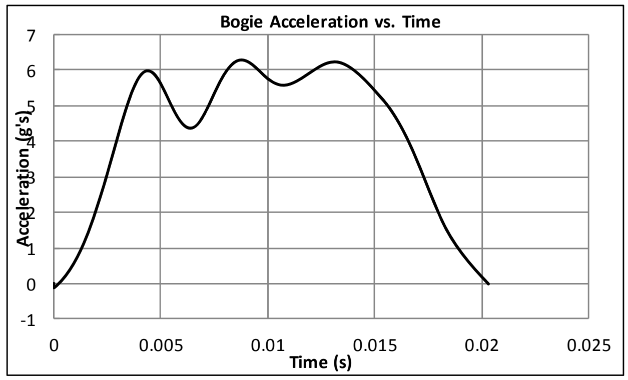
Figure 24. Graph. Test No. GWPB-2 Results (DTS)

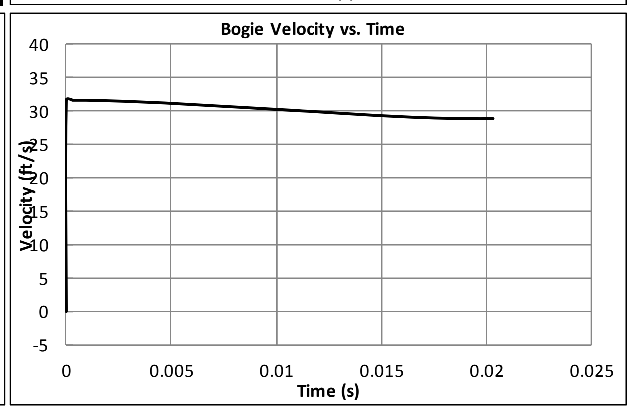
MIDWEST ROADSIDE SAFETY FACILITY

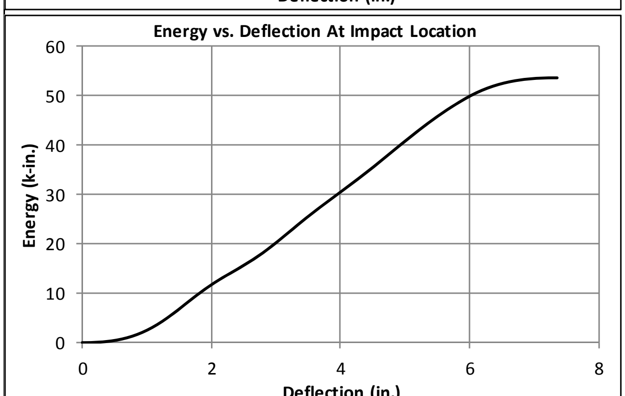
Bogie Test Summary

Test Information	SYP post on 3:1 slope	
Test Number:	GWPB-3	
Test Date:	21-Mar-2011	
Failure Type:	Post fractured	
Post Properties		
Post Type:	SYP - Gr 1 or Better	
Post Size:	6x8	152.4x203.8
Post Length:	78 in.	198.1 cm
Embedment Depth:	46 in.	116.8 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	3142011 - MM 1" crusher run	
Moisture Content:	2.1 %	
Compaction Method:	HE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	21.54 mph (31.6 fps)	9.63 m/s
Impact Height:	24.875 in.	63.2 cm
Bogie Mass:	1722.6 lb	781.4 kg
Data Acquired		
Acceleration Data:	EDR-3	
Camera Data:	AOS-5	

Test Results Summary		
Max. Deflection:	7.4	in.
Peak Force:	10.8	k
Initial Linear Stiffness:	3.3	k/in.
Total Energy:	53.6	k-in.







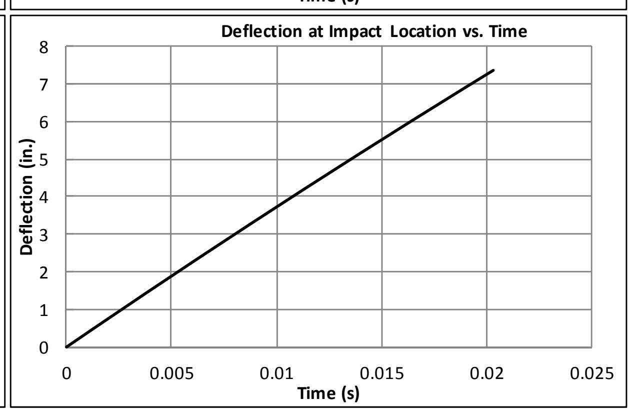


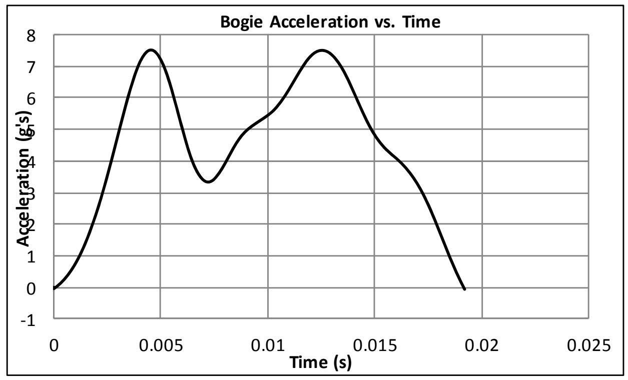
Figure 25. Graph. Test No. GWPB-3 Results (EDR-3)

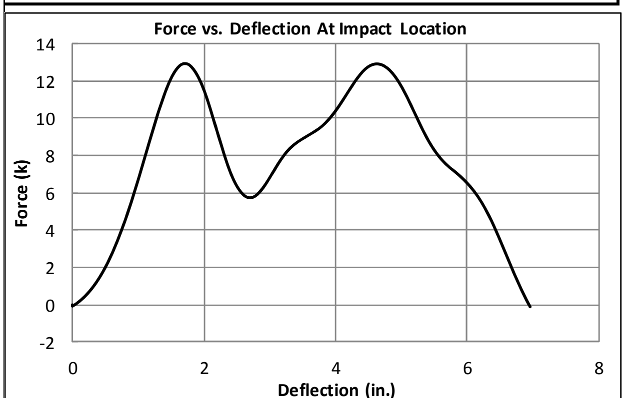
MIDWEST ROADSIDE SAFETY FACILITY

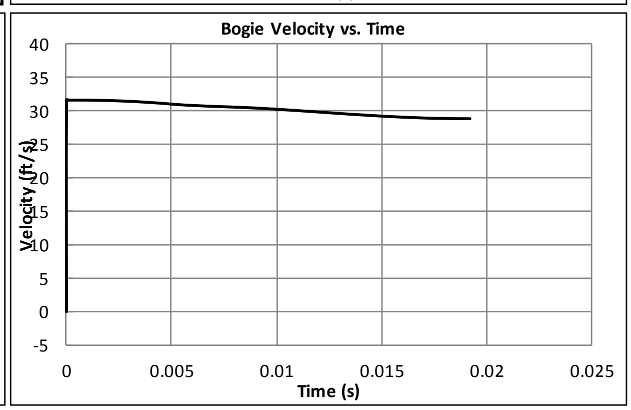
Bogie Test Summary

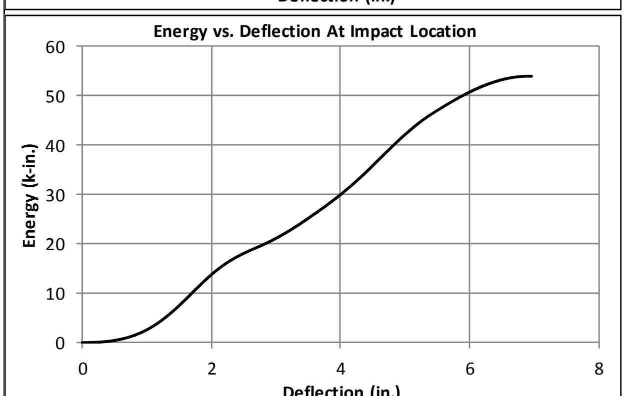
Test Information	SYP post on 3:1 slope	
Test Number:	GWPB-3	
Test Date:	21-Mar-2011	
Failure Type:	Post fractured	
Post Properties		
Post Type:	SYP - Gr 1 or Better	
Post Size:	6x8	152.4x203.8
Post Length:	78 in.	198.1 cm
Embedment Depth:	46 in.	116.8 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	3142011 - MM 1" crusher run	
Moisture Content:	2.1 %	
Compaction Method:	HE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	21.54 mph (31.6 fps)	9.63 m/s
Impact Height:	24.875 in.	63.2 cm
Bogie Mass:	1722.6 lb	781.4 kg
Data Acquired		
Acceleration Data:	DTS	
Camera Data:	AOS-5	

Test Results Summary		
Max. Deflection:	7.0	in.
Peak Force:	12.9	k
Initial Linear Stiffness:	7.6	k/in.
Total Energy:	53.9	k-in.









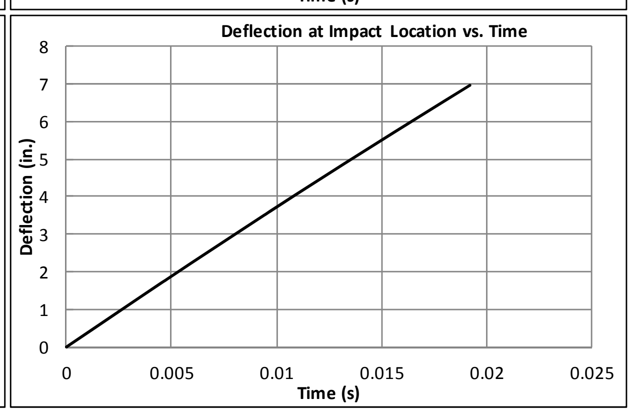


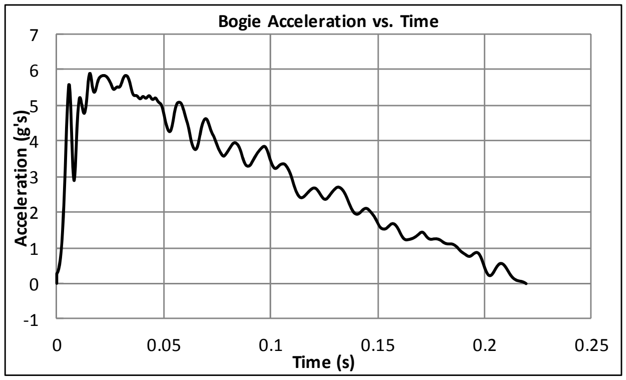
Figure 26. Graph. Test No. GWPB-3 Results (DTS)

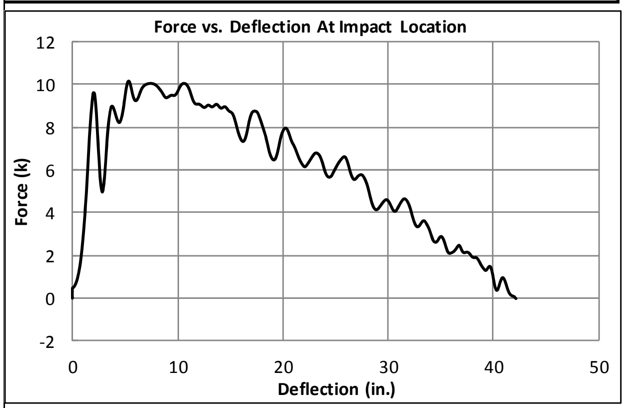
MIDWEST ROADSIDE SAFETY FACILITY

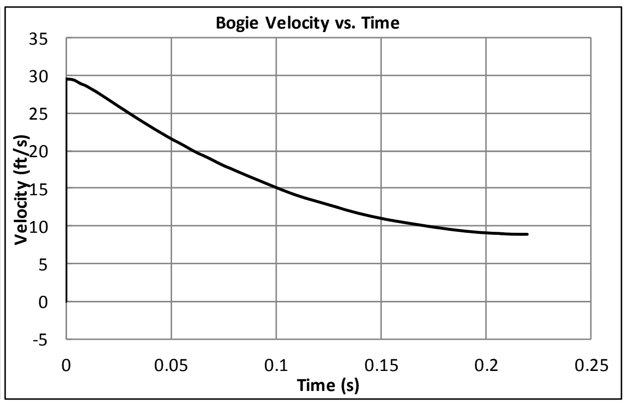
Bogie Test Summary

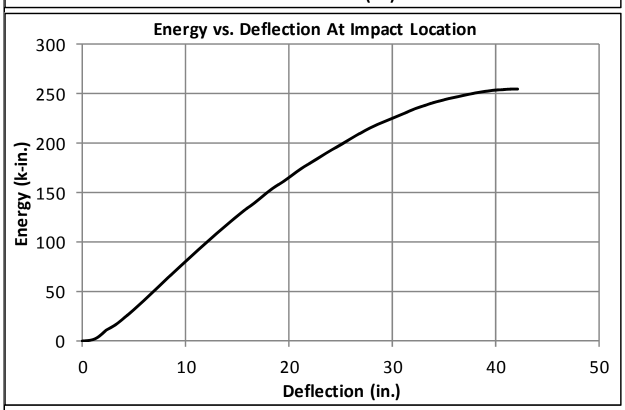
Test Information	SYP post on 3:1 slope	
Test Number:	GWPB-4	
Test Date:	21-Mar-2011	
Failure Type:	Post rotated in soil	
	Post may have been installed 2" too high based on film.	
Post Properties		
Post Type:	SYP - Gr 1 or Better	
Post Size:	6x8	152.4x203.8
Post Length:	78 in.	198.1 cm
Embedment Depth:	46 in.	116.8 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	3142011 - MM 1" crusher run	
Moisture Content:	4.2 %	
Compaction Method:	HE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	20.13 mph (29.5 fps)	9 m/s
Impact Height:	24.875 in.	63.2 cm
Bogie Mass:	1722.6 lb	781.4 kg
Data Acquired		
Acceleration Data:	EDR-3	
Camera Data:	AOS-5	

Test Results Summary		
Max. Deflection:	42.2	in.
Peak Force:	10.1	k
Initial Linear Stiffness:	4.8	k/in.
Total Energy:	254.6	k-in.









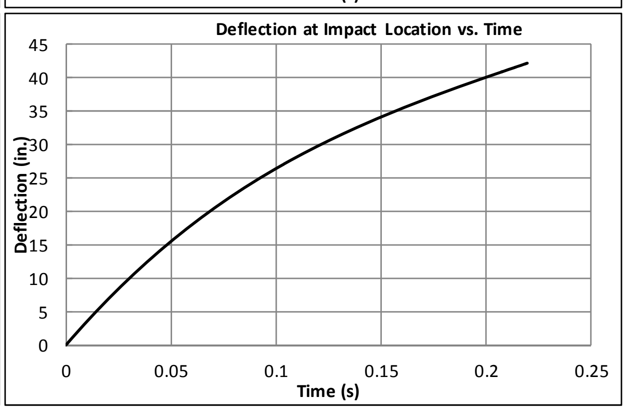


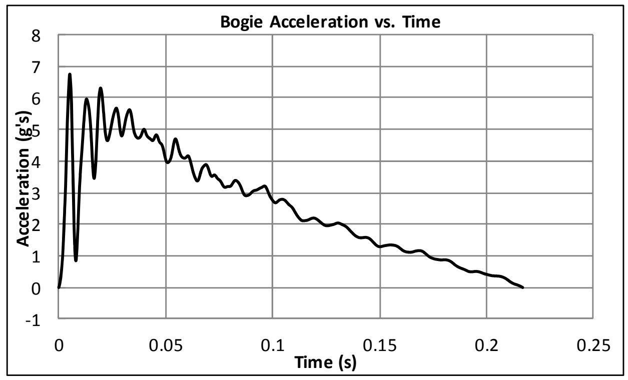
Figure 27. Graph. Test No. GWPB-4 Results (EDR-3)

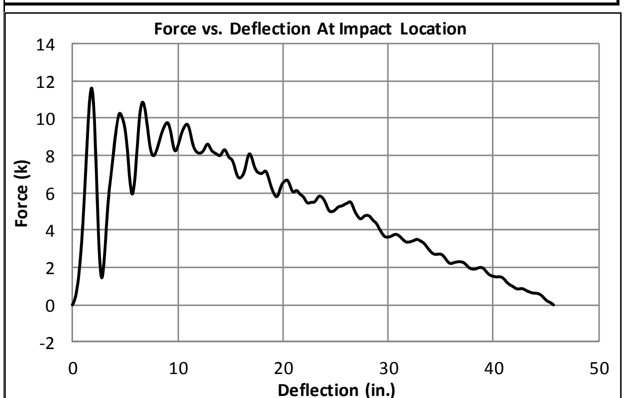
MIDWEST ROADSIDE SAFETY FACILITY

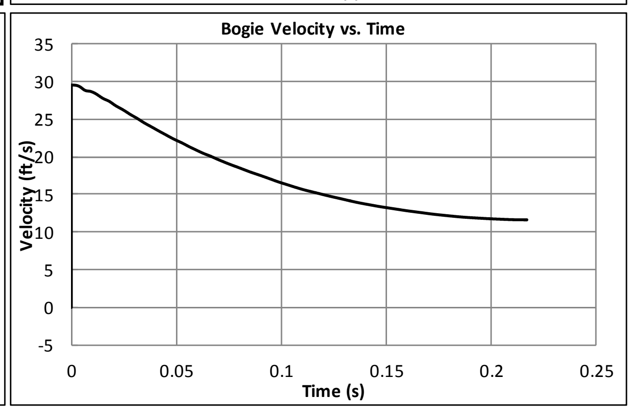
Bogie Test Summary

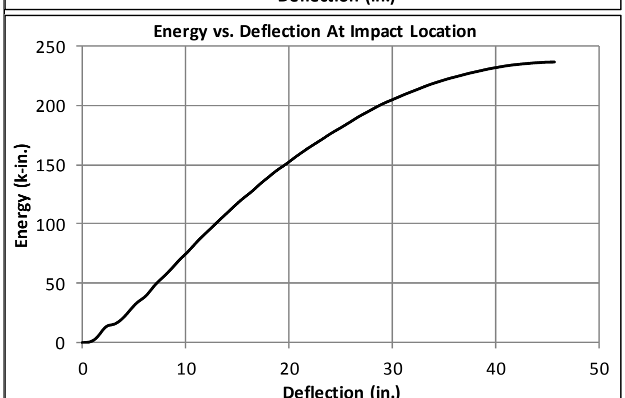
Test Information	SYP post on 3:1 slope	
Test Number:	GWPB-4	
Test Date:	21-Mar-2011	
Failure Type:	Post rotated in soil	
Post may have been installed 2" too high based on film.		
Post Properties		
Post Type:	SYP - Gr 1 or Better	
Post Size:	6x8	152.4x203.8
Post Length:	78 in.	198.1 cm
Embedment Depth:	46 in.	116.8 cm
Orientation:	Strong Axis	
Soil Properties		
Gradation:	3142011 - MM 1" crusher run	
Moisture Content:	4.2 %	
Compaction Method:	HE8	
Soil Density, γd:	NA	
Bogie Properties		
Impact Velocity:	20.13 mph (29.5 fps)	9 m/s
Impact Height:	24.875 in.	63.2 cm
Bogie Mass:	1722.6 lb	781.4 kg
Data Acquired		
Acceleration Data:	DTS	
Camera Data:	AOS-5	

Test Results Summary		
Max. Deflection:	45.7	in.
Peak Force:	11.6	k
Initial Linear Stiffness:	6.3	k/in.
Total Energy:	236.5	k-in.









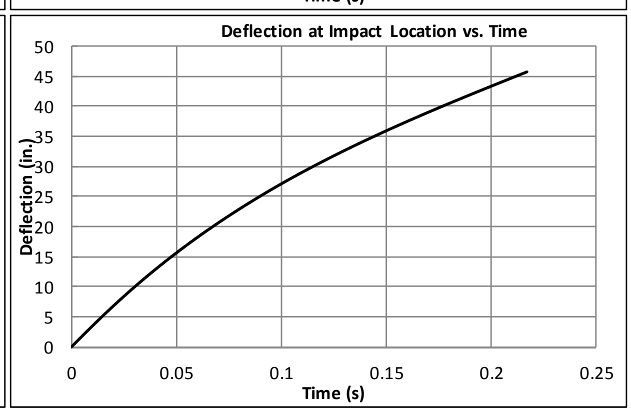


Figure 28. Graph. Test No. GWPB-4 Results (DTS)

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