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GUIDANCE FOR INSTALLATION OF MIDWEST GUARDRAIL SYSTEM ADJACENT TO SLOPES

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16. Abstract

The report provides general guidance for the installation of the Midwest Guardrail System (MGS) adjacent to slopes. Previous full-scale crash testing of W-beam guardrail adjacent to or on slopes and relevant dynamic bogie testing of posts on or adjacent to slopes was reviewed. Based on that review, general guidance for the use of the MGS with slopes was developed. This guidance included recommended barrier configurations adjacent to slope, discussion of dynamic deflection and working width, and recommendations regarding the use of MGS special applications with slopes.

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UNCERTAINTY OF MEASUREMENT STATEMENT

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

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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^2
		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^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliter	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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1 INTRODUCTION

The Midwest Guardrail System (MGS) [1-2] has proven to be a high performance, adaptable system that can be installed on or near slopes. Variations of the MGS have been tested and evaluated adjacent to various slopes with varying post lengths, post embedment depths, blockout depths, and barrier offsets relative to the slope. Some guidance for the MGS placed adjacent to slopes has been previously documented in various research reports as well as on the Midwest Pooled Fund Q/A website. However, no consolidated guidance for the MGS placed adjacent to slopes has been provided for the complete range of slopes and barrier offsets potentially required by state departments of transportation (DOTs) and other end users.

As such, a need existed to develop general guidance for installation of the MGS near fill slopes. A survey of the Midwest Pooled Fund Program member states indicated that the DOTs require guidance for the MGS placed adjacent to fill slopes ranging from 1V:10H to 1V:2H and for post offsets ranging between 2 ft in front of the slope break-point to at or beyond the slope break-point under *Manual for Assessing Safety Hardware* (MASH) Test Level 3 (TL-3) impact conditions [3-4]. It was desired that a single document be provided that has clear, concise guidance on all options available to designers when installing MGS near slopes.

1.1 Background

Guardrail placed adjacent to slopes has been a common barrier application for state DOTs. In the past, several states have requested guidance regarding safe guardrail offsets or information on the necessary system modifications to guardrail post spacing and/or post embedment depth when the barrier is placed directly adjacent to steep fill slopes. Guidance provided in the American Association of State Highway and Transportation Officials' (AASHTO) *Roadside Design Guide, 4th Edition 2011* [5] has recommended that guardrail systems can generally be installed on slopes as steep as 1V:10H and that systems installed adjacent to steeper slopes should be installed a minimum of 2 ft in front of the slope break point to provide for proper vehicle stability and development of adequate post-soil resistive forces. With respect to MGS, the Midwest Roadside Safety Facility (MwRSF) has made conservative recommendations based on engineering judgment, bogie testing, and full-scale crash testing regarding the placement of the MGS adjacent to slopes. While these recommendations were based on the best available information at the time regarding the use of beam guardrail adjacent to slopes, they have not been updated to reflect more recent research nor do they cover the entire range of slope and barrier placement scenarios.

Over the past several years, variations of the MGS installed adjacent to steep slopes have been developed and full-scale crash tested. The results from these full-scale crash tests and dynamic component testing of posts adjacent to slopes provide a great deal of insight that can be used to develop generalized guidance for the placement of the MGS adjacent to steep fill slopes.

1.2 Objective

The objective of this research was to develop general guidance and recommendations for MGS installed adjacent to fill slopes ranging from level terrain to 1V:2H and barrier offsets ranging between 2 ft in front of the slope breakpoint to beyond the slope breakpoint. The goal was to consolidate current knowledge of the MGS performance adjacent to slopes into concise guidance for placement of the MGS near fill slopes under MASH TL-3 criteria.

1.3 Scope

The research effort began with a literature search to compile the existing full-scale and component test data related to the MGS installed adjacent to slopes as well as previous guidance that has been provided to the states for installing MGS in combination with slopes. This information was reviewed and utilized to provide generalized guidance for the MGS adjacent to fill slopes based on post spacing, post embedment depth, blockout depth, and barrier offset.

2 LITERATURE REVIEW

A literature search was conducted to review full-scale testing and evaluation of W-beam barriers on or adjacent to slopes under various test criteria. A review of research related to dynamic bogie testing performed after the adoption of MASH and the development of the MGS with respect to W-beam guardrail posts on or adjacent to slopes was also collected. Dynamic bogie testing of posts performed prior to MASH and the development of the MGS was not reviewed due to changes in guardrail height and soil conditions brought about by the advent of 31-in. guardrail and the adoption of MASH, respectively.

2.1 Full-Scale Crash Testing

2.1.1 NCHRP Report 230 Crash Testing

The earliest research and full-scale crash testing regarding guardrail placement and performance on slopes collected for this study was conducted by the Texas A&M Transportation Institute (TTI) in 1983 [6]. The TTI study determined the typical conditions for which longitudinal barriers are placed on nonlevel terrain, evaluated the impact behavior of common barrier systems placed on non-level terrain, and developed guidelines for the selection and placement of barriers on non-level terrain. The report covered seven tests conducted under NCHRP Report 230 safety performance criteria [7], four of which were conducted on G4(1S) W-beam guardrail with a top mounting height of 27 in. and a post embedment of 41 in. The crash-tested G4(1S) system consisted of 12-gauge W-beam mounted on W6x8.5 posts, a post spacing of 75 in., and 1-ft long W-beam backup plates placed at non-splice posts. Blockouts consisted of W6x8.5 by 14-in. long steel sections. The impact conditions and test results are shown in Table 1. A schematic of the system for these for tests is shown in Figure 1.

Table 1. NCHRP Report 230 Full-Scale Crash Testing of W-beam Guardrail Adjacent to Slope

Test Parameters	Test No.							
	3659-1 [6]	3659-2 [6]	3659-3 [6]	3659-4 [6]	1717-1-88 [8]	1717-2-88 [8]	1717-3-88 [8]	1717-4-88 [8]
Slope	1V:6H	1V:6H	1V:6H	1V:6H	1V:2H	1V:2H	1V:2H	1V:2H
System Length (ft)	200	200	200	200	112½	125	125	125
System Height (in.)	28	27	28	27	27	27	27	27
Barrier Offset1 (in.)	-80¾	-80¾	-152¾	-152¾	2 15/16	2 15/16	2 15/16	2 15/16
Vehicle Weight (lb)	4,500	4,500	4,500	2,300	4,506	4,350	4,343	4,361
Post Type	W6x8.5	W6x8.5	W6x8.5	W6x8.5	W6x8.5	W6x8.5	W6x8.5	W6x8.5
Post Length (in.)	69	69	69	69	84	84	84	72
Post Embedment (in.)	42	42	42	42	56	56	56	45
Post Spacing (in.)	75	75	75	75	75	75	75	75
Blockout Type	W6x8.5	W6x8.5	W6x8.5	W6x8.5	W6x8.5	W6x8.5	W6x8.5	W6x8.5
Blockout Depth (in.)	5⅞	5⅞	5⅞	5⅞	5⅞	5⅞	5⅞	5⅞
Impact Speed (mph)	62.8	63.6	62.9	58.2	61.0	61.2	60.8	61.2
Impact Angle (degrees)	25	14.75	26.25	14.75	26	27	25	26
Exit Speed (mph)	44.4	55.3	31.1	49.0	N/A	N/A	35.8	37.8
Exit Angle (degrees)	N/A	9.5	N/A	6	N/A	N/A	9	13
Dynamic Deflection (in.)	15.6	18	49.2	10.2	Unreported	Unreported	Unreported	Unreported
Permanent Set Deflection (in.)	11.5	15.6	Unreported	6.8	Unreported	Unreported	Unreported	Unreported
Pass/Fail	Fail	Pass	Fail	Pass	Fail	Fail	Fail	Pass
Failure Mechanism	Barrier Override	None	Barrier Penetration	None	Barrier Penetration/ Anchorage Failure	Vehicle Rollover/Barrier Override	Excessive velocity change	None

[1] Distance from the center of post to the slope break point, where negative values are downslope.

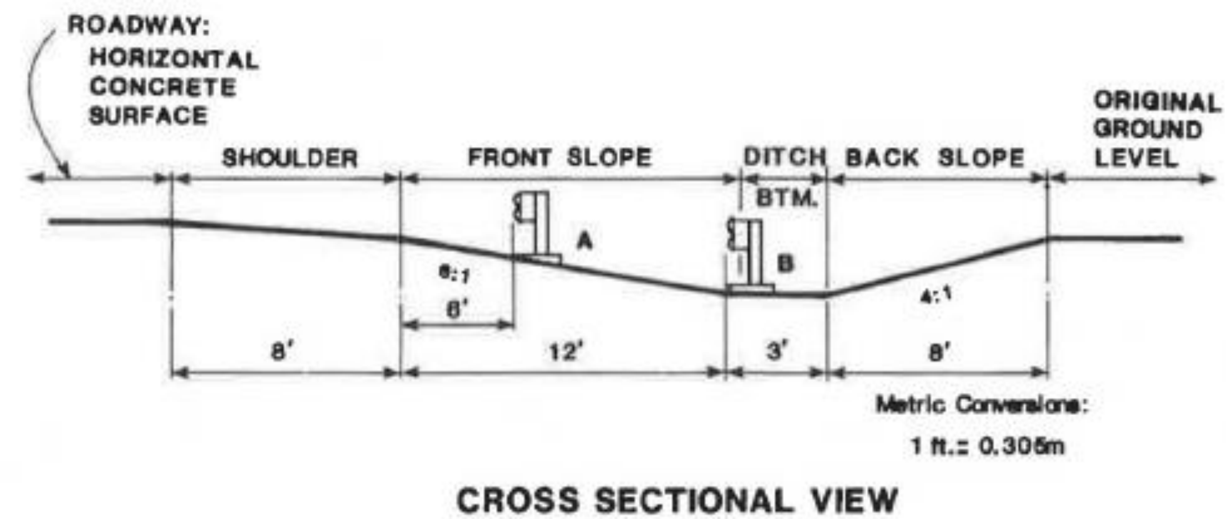


Figure 1. G4(1S) Installation on Slopes for Test Nos. 3659-1 through 3659-4 [6]

The study found that the G4(1S) system, placed at a lateral offset of 12 ft down from the slope break point on a 6:1 slope, did not satisfy the structural adequacy requirements when impacted with a 4,500-lb vehicle at a speed of 62.9 mph and an angle of 26.25 degrees, as the rail ruptured and the vehicle penetrated the system. The G4(1S) system, placed at a lateral offset of 6 ft down from the slope break point on a 6:1 slope, did not satisfy the structural adequacy requirements due to the vehicle vaulting over the system when the system was impacted with a 4,500-lb vehicle at a speed of 62.8 mph and an angle of 25.0 degrees. The G4(1S) system, placed at a lateral offset of 6 ft down from the slope break point on a 6:1 slope, adequately contained and redirected a 4,500-lb vehicle impacting the system at a speed of 63.6 mph and an angle of 14.75 degrees. The G4(1S) system, placed at a lateral offset of 12 ft down from the slope break point on a 6:1 slope, also contained and redirected a 2,300-lb vehicle impacting at 58.2 mph and an angle of 14.75 degrees. Thus, the barrier systems redirected the vehicles with impact angles that were 10 degrees lower than the angle specified in the safety performance criteria and had trajectories that could pose a hazard to traffic in adjacent lanes.

Additional investigation into guardrail placed on slope was conducted in 1988 by ENSCO, Inc. [8]. The research consisted of 57 pendulum tests, six static tests, and four full-scale crash tests with 4,500-lb sedan vehicles. The full-scale crash tests utilized G4(1S) guardrail with a top of rail height of 27 in., 6-ft and 7-ft long W6x8.5 steel posts at 75-in. post spacing, and the back of the posts installed at the slope break point of a 1V:2H fill slope. Blockouts consisted of W6x8.5, 14-in. long steel sections bolted to the steel post. Test details and results are shown in Table 1. Schematic diagrams of the G4(1S) systems with 6-ft and 7-ft long W6x8.5 steel posts are shown in Figures 2 and 3, respectively. The three tests conducted with 7-ft long posts did not meet NCHRP Report 230 safety requirements due to vehicle vaulting, vehicle penetration of the barrier, and an excess change in velocity. One test conducted with 6-ft long posts did meet the NCHRP Report 230 criteria.

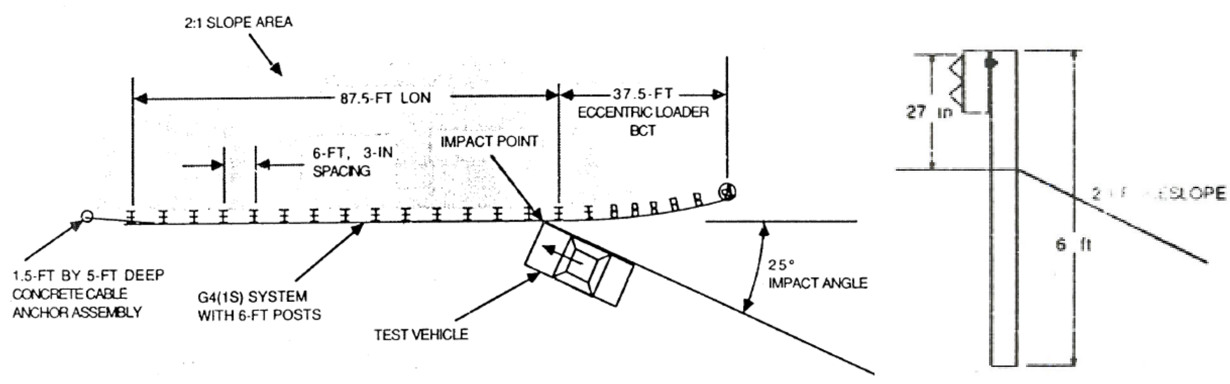


Figure 2. G4(1S) Installation Adjacent to 1V:2H Slope with 6-ft Long Steel Posts for Test No. 1717-4-88 [8]

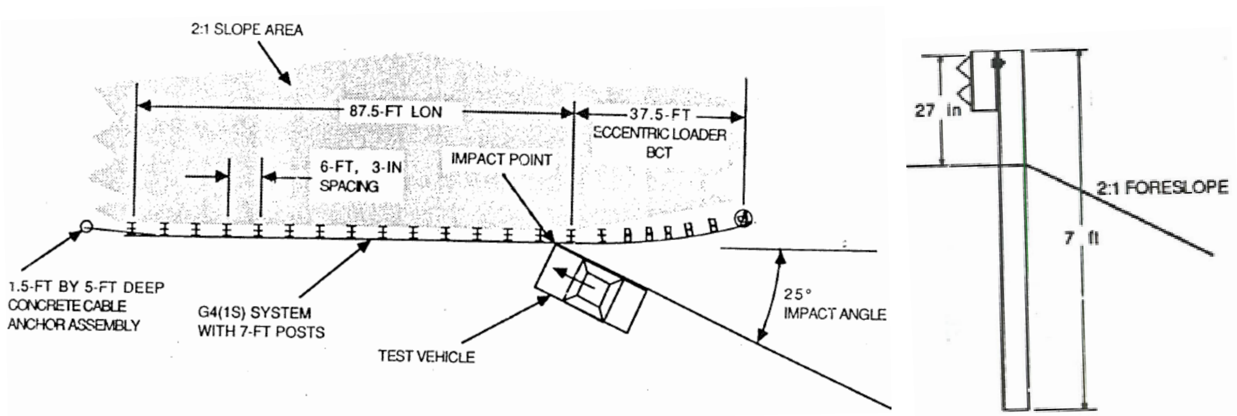


Figure 3. G4(1S) Installation Adjacent to 1V:2H Slope with 7-ft Long Steel Posts for Test Nos. 1717-1-88 through 1717-3-88 [8]

2.1.2 AASHTO PL-2 Crash Testing

Further full-scale testing was performed by ENSCO, Inc. in 1993 [9] under AASHTO *1989 Guide Specifications for Bridge Railings* Performance Level 2 (PL-2) [10] to investigate the performance of barriers installed on super-elevated curves. A series of seventeen crash tests were run, three of which involved testing W-beam guardrail systems adjacent to fill slopes. A summary of these tests is provided in Table 2.

Test no. 1862-6-89 was run on a standard G4(1S) W-beam rail installed on a 1,192-ft radius curve with super elevation, as shown in Figure 4. The system consisted of 150 ft of W-beam in the curved section, 75 ft of straight rail prior to the curve, and a 37.5-ft standard Breakaway Cable Terminal (BCT) on the upstream end, for a total system length of 262.5 ft. The super elevation consisted of 20 ft of a 10% upslope and 10 ft of a 2% rising shoulder. The front face of the guardrail was 9 in. past the edge of the shoulder. The terrain fell away in a 1V:2H downslope 4 ft past the edge of the shoulder, which resulted in the back of the guardrail posts being 2 ft from the slope break point of the 1V:2H slope. For 4 ft on either side of the 2%/1V:2H slope break point, the slopes were rounded such that a smooth merge existed between the two slopes. During test no.

1862-6-89, a 5,399-lb pickup truck impacted the barrier at 60.9 mph and an angle of 20 degrees. The vehicle was captured and redirected by the barrier, but the deflection of the guardrail allowed the vehicle to extend out over the 1V:2H slope, which induced increased vehicle roll that eventually led to rollover of the impacting vehicle.

Table 2. AASHTO PL-2 Full-Scale Crash Testing of W-beam Guardrail Adjacent to Slope

Test Parameters	Test No.			
	1862-6-89 [9]	1862-9-90 [9]	1862-16-91 [9]	1862-15-92 [9]
Slope	1V:2H	1V:2H	1V:2H	1V:6H to 1V:2H
System Length (ft)	262.5	262.5	218.75	125
System Height (in.)	27	27	27	27
Barrier Offset[1] (in.)	27	27	150	-189, 1V:6H SBP 27, 1V:2H SBP
Vehicle Weight (lb)	5,399	5,410	5,422	5,393
Post Type	W6x9	W6x9	W6x9	W6x9
Post Length (in.)	72	84	72	72
Post Embedment (in.)	45	57	45	45
Post Spacing (in.)	75	75	75	75
Blockout Type	Wood	Wood	Wood	Wood
Blockout Depth (in.)	8	8	8	8
Impact Speed (mph)	60.9	60.6	61.6	59.7
Impact Angle (degrees)	20	20	20	20
Exit Speed (mph)	Unreported	Unreported	Unreported	24.0
Exit Angle (degrees)	Unreported	Unreported	Unreported	16
Dynamic Deflection (in.)	30		Unreported	Unreported
Permanent Set Deflection (in.)	43		24	46
Pass/Fail	Fail	Fail	Fail	Pass
Failure Mechanism	Vehicle Rollover	Vehicle Rollover	Vehicle Rollover	None

[1] Distance from the center of post to the slope break point, where negative values are downslope.

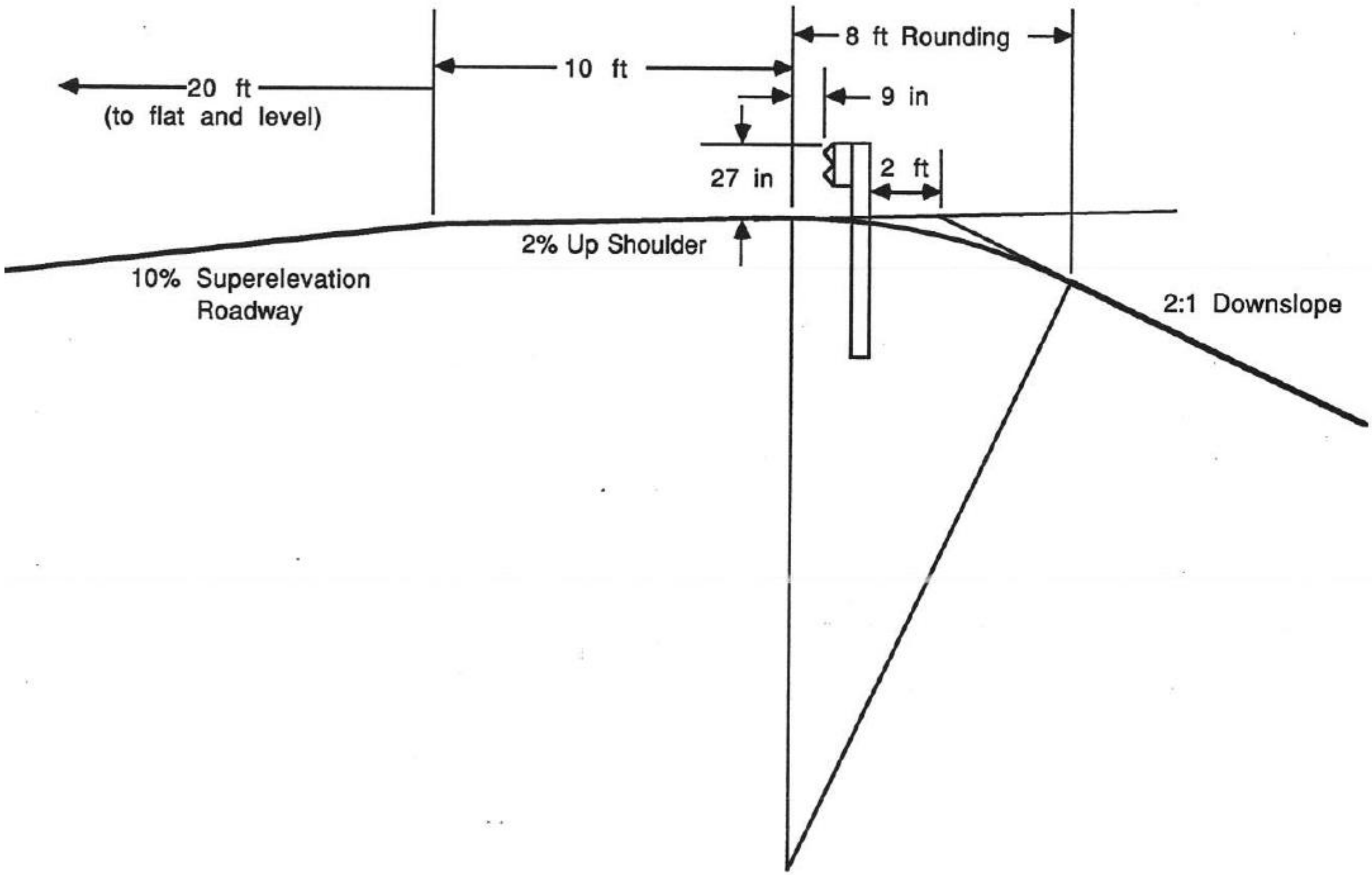


Figure 4. Barrier Installation, Test No. 1862-6-89 [9]

Test no. 1862-16-91 maintained the same elevation features as test no. 1862-6-89 while shifting the barrier system 10.25 ft down the slope of the 2% rising shoulder and closer to the 10% super elevation, as shown in Figure 5. This configuration placed the front of the system 6 in. past the edge of the 10% upslope and generated a larger offset between the barrier system and the 1V:2H slope. During test no. 1862-16-91, a 5,422-lb pickup truck impacted the barrier at 61.6 mph and an angle of 20 degrees. The vehicle was partially redirected by the rail but was launched airborne and rolled and yawed 180 degrees prior to coming down on top of the barrier system.

Test no. 1862-15-92 consisted of 125 ft of straight G4(1S) guardrail installed on sloped terrain, as shown in Figure 6. The downslope consisted of 12 ft of a 2% sloped shoulder, 18 ft of a 1V:6H downslope, followed by 12 ft of a 1V:2H downslope. For 2 ft on either side of the 2%/1V:6H slope break point, the slopes were rounded such that a smooth merge existed between the two slopes. The system was placed such that the back of the posts in the system were 2 ft in front of the slope break point between the 1V:6H and 1V:2H slopes. During test no. 1862-15-92, a 5,393-lb pickup truck impacted the barrier at 59.7 mph and an angle of 20 degrees. The vehicle was safely redirected by the barrier system in this test.

Test no. 1862-9-90 maintained the same elevation features and W-beam guardrail system as test no. 1862-6-89, but the G4(1S) guardrail system was modified to use 7-ft long, W6x9 posts, as shown in Figure 7. During test no. 1862-9-90, a 5,410-lb pickup truck impacted the barrier at 60.6 mph and an angle of 20 degrees. The vehicle was initially captured and redirected by the barrier, but the vehicle overrode the barrier and rollover during redirection.

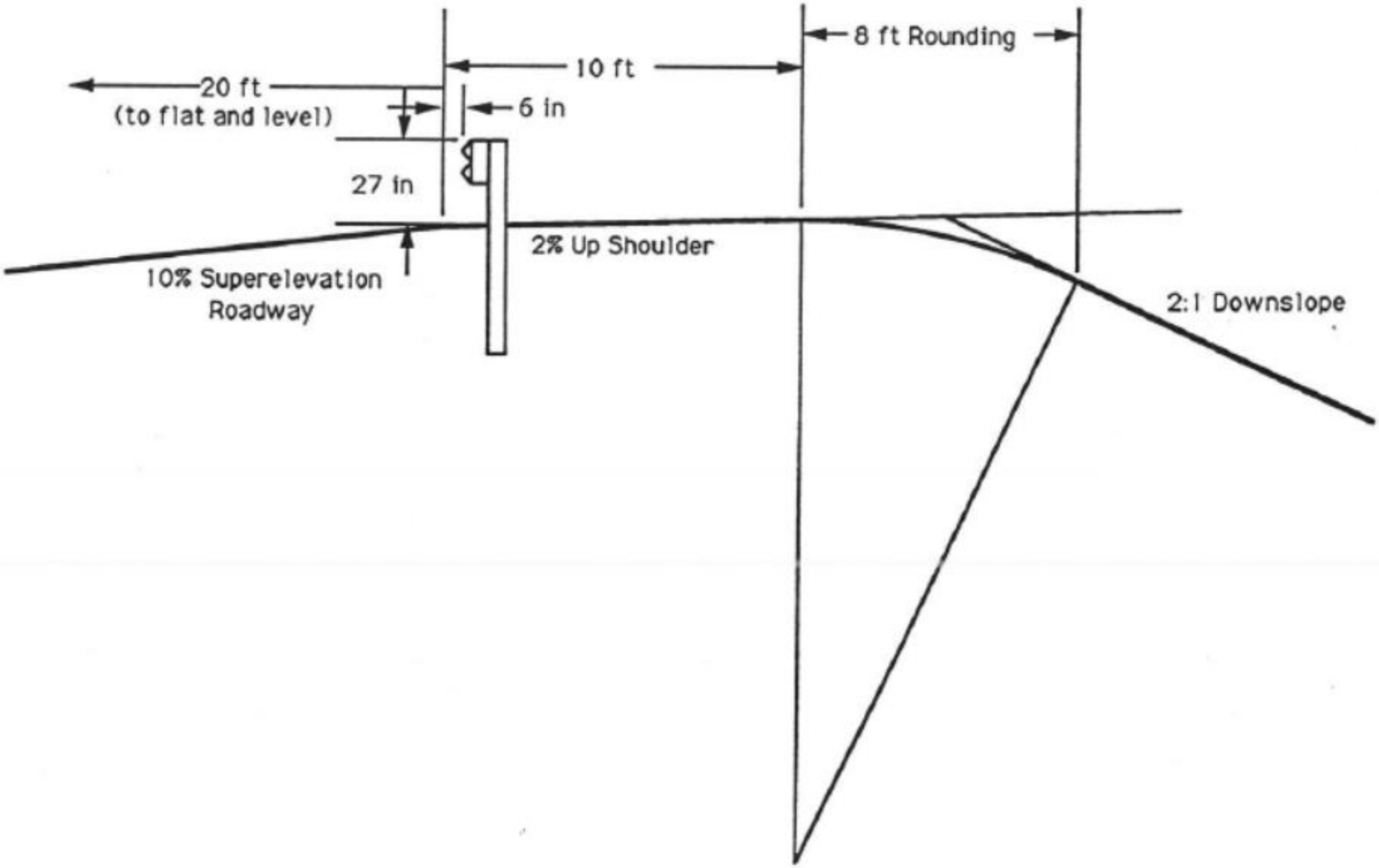


Figure 5. Barrier Installation, Test No. 1862-16-91 [9]

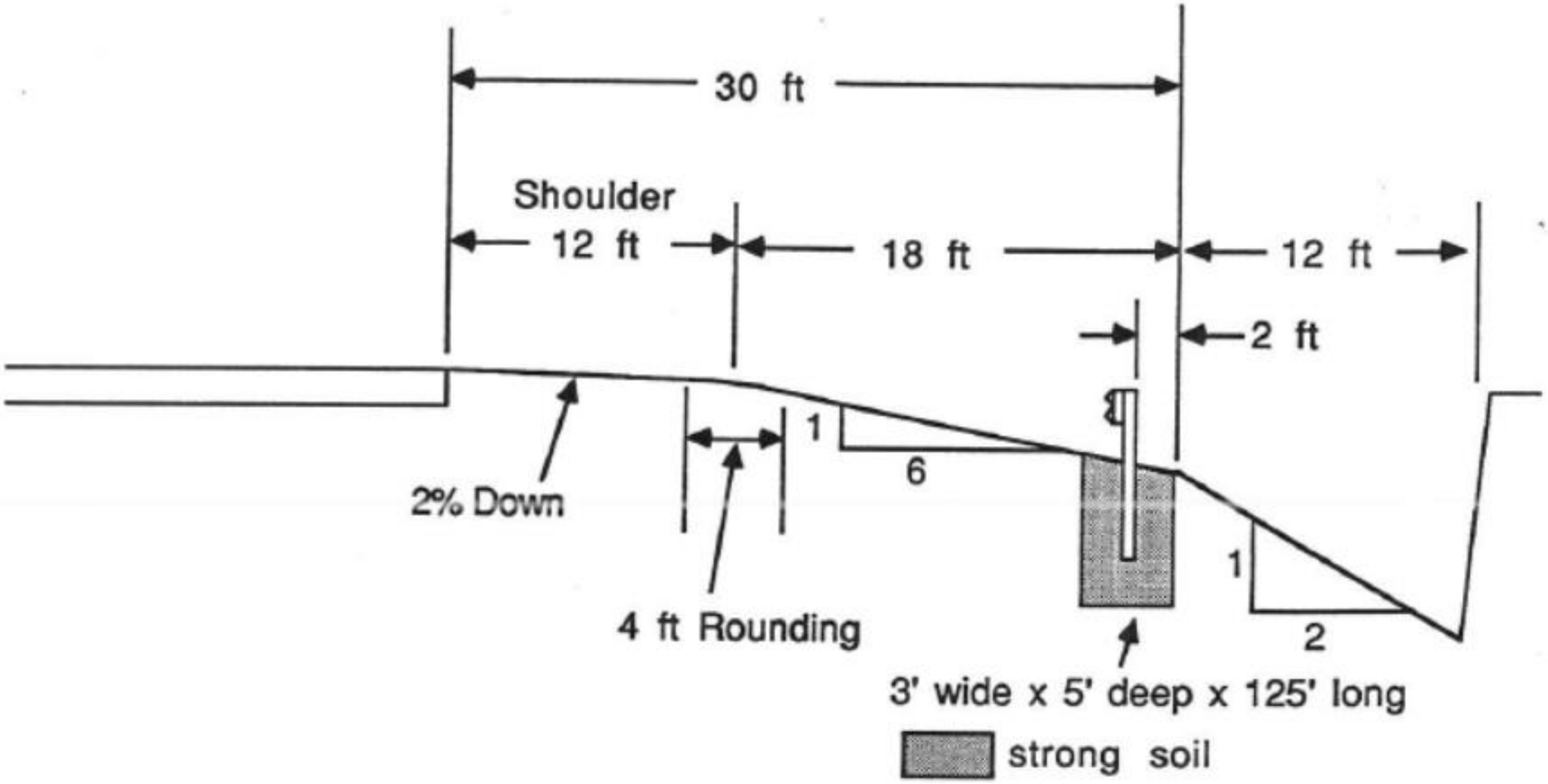


Figure 6. Barrier Installation, Test No. 1862-15-92 [9]

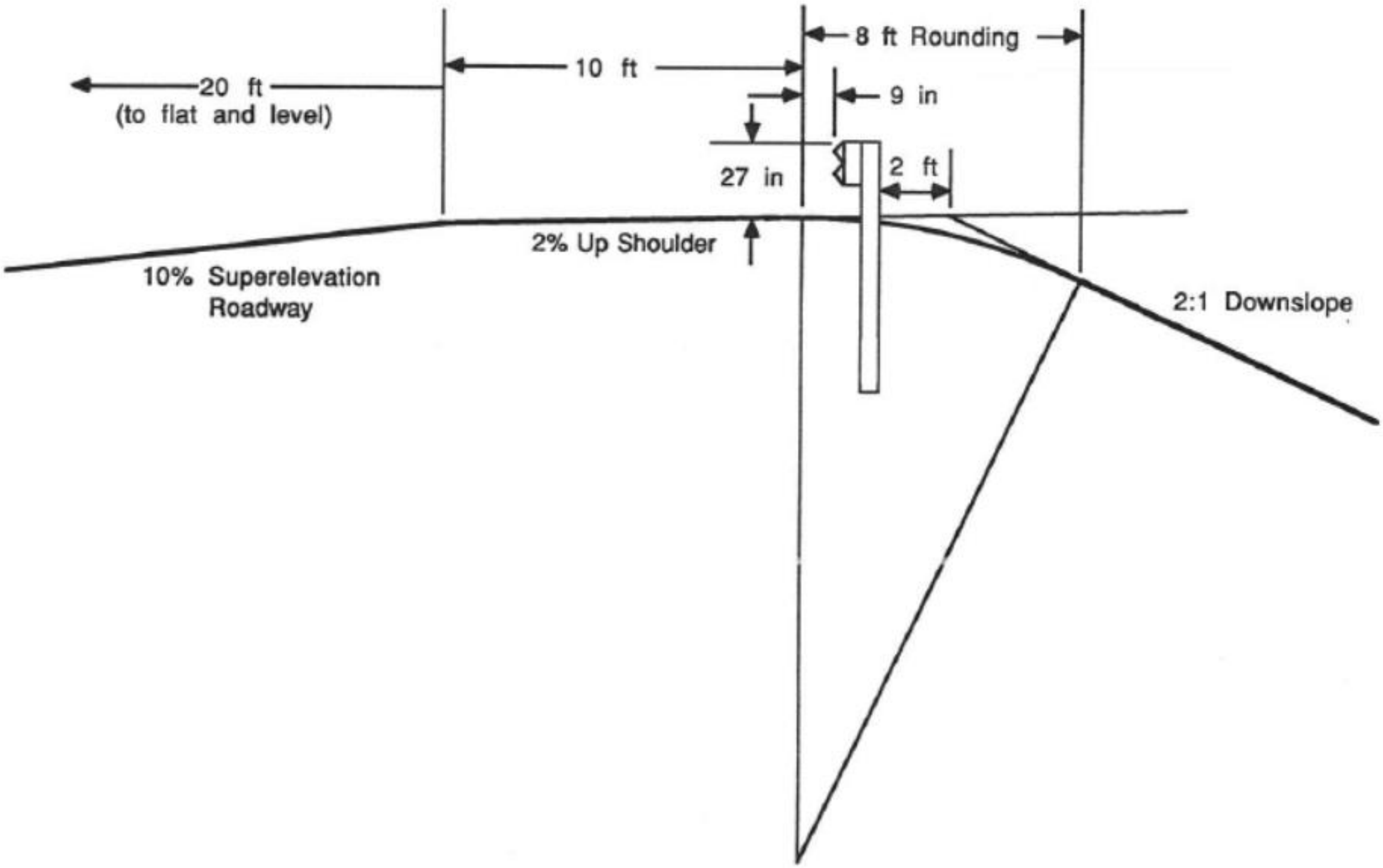


Figure 7. Barrier Installation, Test No. 1862-9-90 [9]

The results of the ENSCO study provided only limited insight into the performance of W-beam guardrail on slopes. The two failed crash tests were conducted on systems with significant curvature and relatively large offsets from the 1V:2H slope. As such, it was difficult to determine if the performance of the W-beam guardrail in those tests was more adversely affected by the rail curvature than the presence of the 1V:2H slope offset behind the barrier. It was clear that the combination of super-elevated curves and slopes affected barrier performance. Test no. 1862-15-92 did indicate the potential for acceptable barrier performance on approach slopes with a large barrier offset. However, small car testing and evaluation of more critical offsets would likely be needed in order to evaluate such a barrier installation.

2.1.3 NCHRP Report 350 Crash Testing

Evaluation of W-beam guardrail adjacent to slope continued under NCHRP Report 350 [11]. A summary of these tests is provided in Table 3. MwRSF conducted full-scale crash testing on a W-beam guardrail system installed at the slope break point between level terrain and a 1V:2H slope with half-post spacing [12]. One full-scale crash test, test no. MOSW-1, was conducted according to test designation no. 3-11 on a 175-ft long W-beam guardrail system supported by W6x9 posts. Posts in the critical region were 84 in. long with a post spacing of 37.5 in., while posts outside the impact region were 72 in. long with a post spacing of 75 in. The barrier system used 8-in. deep timber blockouts, and the top mounting height of the W-beam guardrail was 27.75 in. Details of the barrier system are shown in Figure 8. During test no. MOSW-1, the impacting pickup truck was safely contained and redirected. The researchers noted that it was unclear as to the magnitude of the factor of safety provided by the as-tested barrier system, and that it may be possible to obtain acceptable safety performance from a guardrail design which incorporated longer posts, a wider post spacing, or combinations thereof.

Table 3. NCHRP Report 350 Full-Scale Crash Testing of W-beam Guardrail Adjacent to Slope

Test Parameters	Test No.			
	MOSW-1 [12]	405160-4 [13]	MGSAS-1 [14]	MGSAS-2 [14]
Slope	1V:2H	1V:2H	1V:8H	1V:8H
System Length (ft)	175	175	175	175
System Height (in.)	27¾	27	31	31
Barrier Offset[1] (in.)	0	-14 15/16	-62 15/16	-62 15/16
Vehicle Weight (lb)	4,462	4,610	4,489	1,845
Post Type	W6x9	W6x8.5	W6x9	W6x9
Post Length (in.)	84	96	72	72
Post Embedment (in.)	55¼	62	40	40
Post Spacing (in.)	37½	37½	75	75
Blockout Type	Wood	Wood	Wood	Wood
Blockout Depth (in.)	8	8	12	12
Impact Speed (mph)	62.6	62.3	62.4	61.9
Impact Angle (degrees)	28.5	25.1	25.9	21.9
Exit Speed (mph)	31.3	Unreported	Unreported	49.2
Exit Angle (degrees)	25.8	Unreported	Unreported	8.2
Dynamic Deflection (in.)	32.3	68.8	57⅝	25
Permanent Set Deflection (in.)	23.1	22.8	34¼	14⅝
Pass/Fail	Pass	Fail	Pass	Pass
Failure Mechanism	None	Vehicle Rollover	None	None

[1] Distance from the center of post to the slope break point, where negative values are downslope.

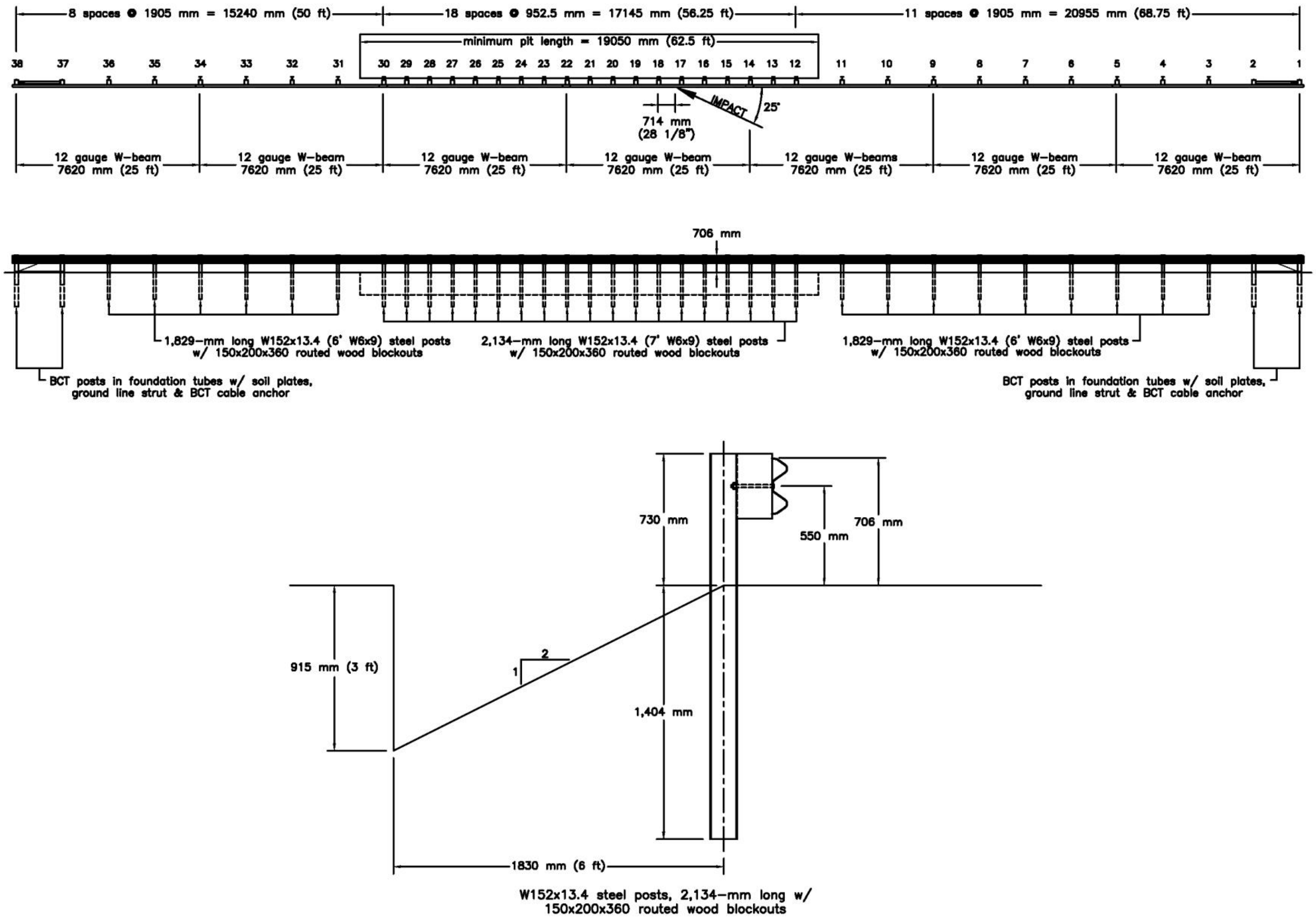


Figure 8. Barrier Installation, Test No. MOSW-1 [12]

TTI conducted full-scale crash testing and evaluation of a more aggressive W-beam guardrail system placed on a slope in 2008 [13]. The barrier system consisted of 175 ft of 12-gauge W-beam guardrail mounted on 8-ft long, W6x8.5 steel posts spaced at 37½ in. The barrier system was placed on a 1V:2H slope with the face of the barrier at the slope break point. Routed wood blockouts measuring 6 in. x 8 in. x 14 in. were utilized between the posts and rail. The barrier was evaluated through test designation no. 3-11. Test details and results are located in Table 3 and details of the barrier system are shown in Figure 9. In test no. 405160-4-1, the pickup truck was contained and redirected. However, after exiting the installation, the vehicle rolled onto its left side. Thus, the system failed to meet NCHRP Report 350 safety criteria.

Finally, MwRSF conducted full-scale crash testing and evaluation of the MGS installed on 1V:8H approach slopes under test designation nos. 3-10 and 3-11 [14]. The researchers simulated various offsets for the standard MGS installed on an 1V:8H approach slope and selected a 5-ft lateral offset down the slope as the most critical location. Tests were then conducted on an MGS barrier consisting of 175 ft of 12-gauge W-beam guardrail supported by 6-ft long, W6x9 steel posts at 75-in. spacing with a top rail height of 31 in. The barrier system used 6-in. x 12-in. x 14-in. wood blockouts and was installed with the front of the post at a 5-ft lateral offset down an 1V:8H approach slope. The test details and results are shown in Table 3. The first crash test, test no. MGSAS-1, was performed with a ¾-ton pickup truck according to test designation no. 3-11. The truck was safely contained and redirected, and test no. MGSAS-1 was determined to be acceptable according to NCHRP Report 350 safety performance criteria. The second crash test, test no. MGSAS-2, was performed with a small car according to test designation no. 3-10. The vehicle was safely contained and redirected, and test no. MGSAS-2 was determined to be acceptable according to NCHRP Report 350 safety performance criteria. It was noted that the safety performance of the MGS installed on an 1V:8H approach slope appeared to be near its limits when evaluated under NCHRP Report 350 TL-3 criteria.

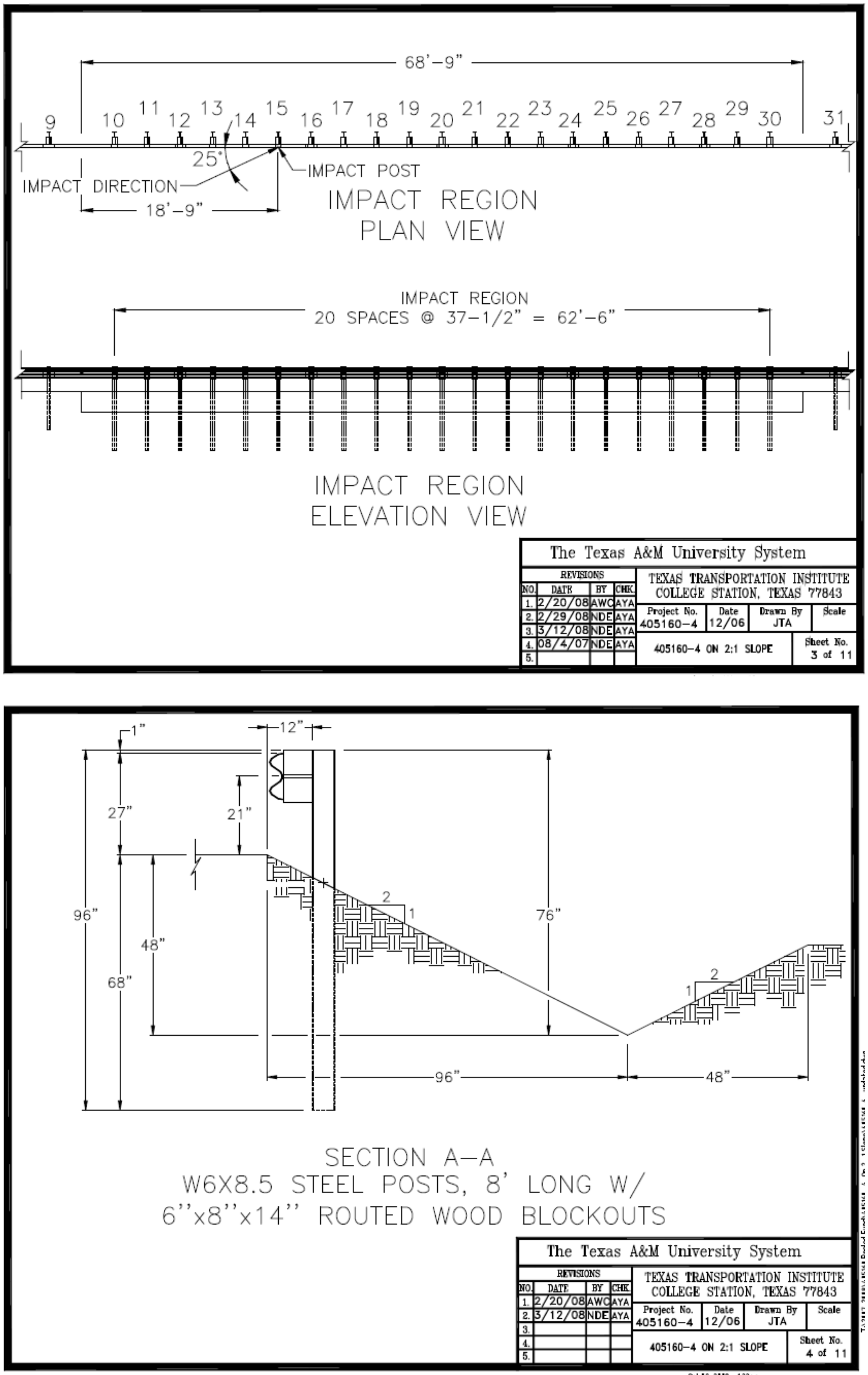


Figure 9. Barrier Installation, Test No. 405160-4-1 [13]

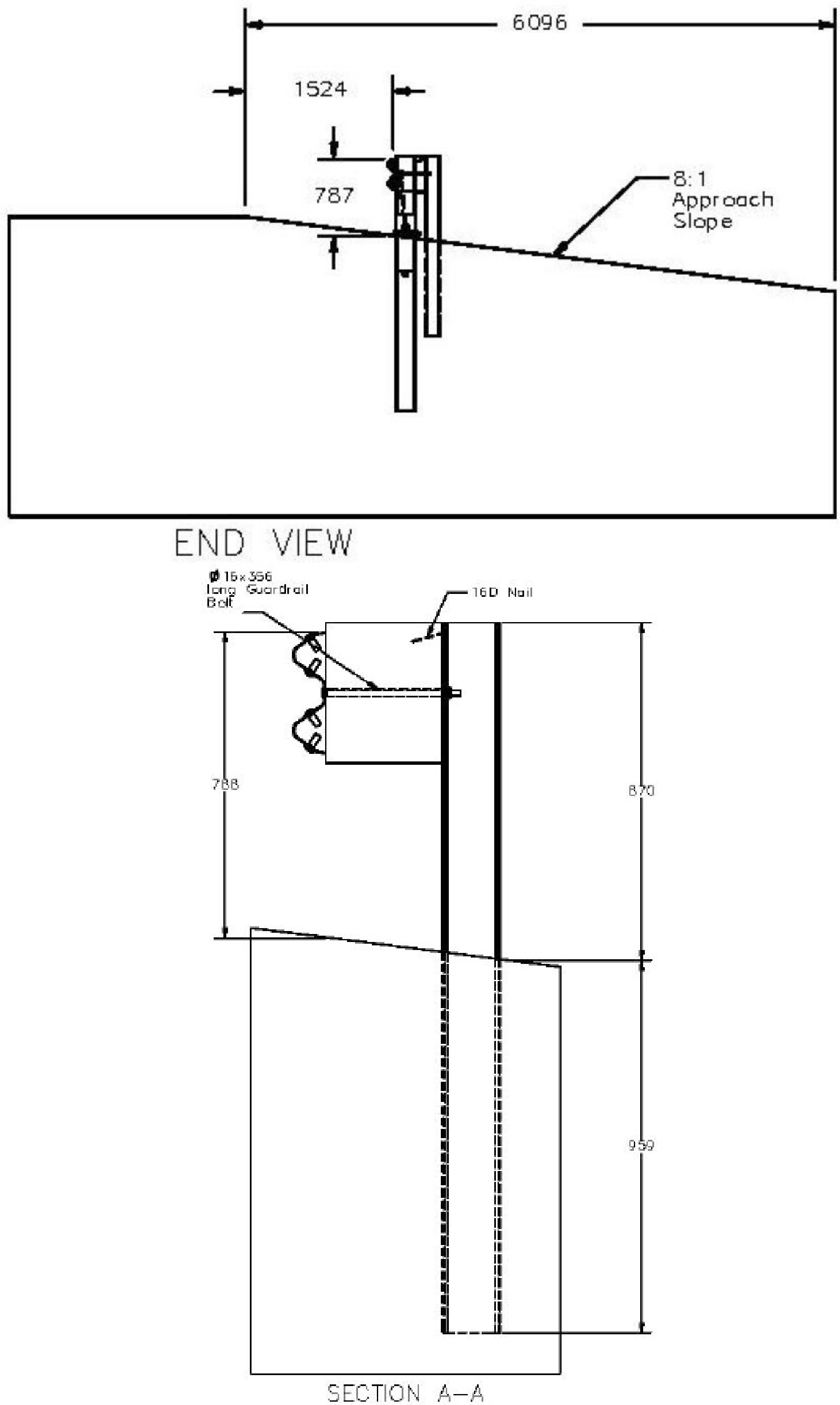


Figure 10. Barrier Installation, Test Nos. MGSAS-1 and MGSAS-2 [14]

2.1.4 MASH Crash Testing

Multiple versions of the MGS and 31-in. W-beam guardrail adjacent to slopes have been full-scale crash tested to MASH TL-3. A summary of these tests is provided in Table 4. The first MASH TL-3 evaluation of guardrail adjacent to slopes was conducted by MwRSF on a modified version of the MGS [15]. The barrier system incorporated 9-ft long, W6x9 steel posts spaced 75-in. on center and installed at the slope breakpoint of a 1V:2H slope. Two full-scale crash tests were conducted on this system. The first full-scale crash test, test no. MGS221-1, was performed on the MGS with a 27¾-in. top mounting height according to test designation no. 3-11 of MASH, as shown in Figure 11. The test consisted of a 5,000-lb pickup truck impacting the modified MGS at a speed of 63.1 mph and at an angle of 27.1 degrees. During the test, the barrier did not adequately contain nor redirect the 2270P vehicle as the vehicle overrode the top of the system and subsequently landed behind the system. The test results were determined to be unacceptable according to MASH safety requirements. The second full-scale crash test, test no. MGS221-2, was performed on the same MGS system adjacent to a 2:1 fill slope, with a 31-in. top mounting height, according to test designation no. 3-11 of MASH, as shown in Figure 12. The test consisted of a 5,013-lb pickup truck impacting the barrier at a speed of 63.1 mph and at an angle of 25.5 degrees. The test results were determined to be acceptable according to MASH safety requirements as the pickup truck was contained, redirected, and safely brought to a controlled stop.

Table 4. MASH Full-Scale Crash Testing of W-beam Guardrail Adjacent to Slope

Test Parameters	Test No.						
	MGS221-1 [15]	MGS221-2 [15]	MGSGW-1 [16-18]	MGSGW-2 [16-18]	405160-20-1 [19]	405160-20-2 [19]	MGSS-1 [20]
Slope	1V:2H	1V:2H	1V:3H	1V:3H	1V:2H	1V:2H	1V:2H
System Length (ft)	175	175	175	175	181¼	181¼	175
System Height (in.)	27¾	31	31	31	31	31	31
Barrier Offset[1] (in.)	0	0	0	0	-14 15/16	-14 15/16	0
Vehicle Weight (lb)	5,000	5,013	2,427	4,999	5,044	2,429	4,992
Post Type	W6x9	W6x9	W6x8.5	W6x8.5	W6x8.5	W6x8.5	W6x8.5
Post Length (in.)	108	108	72	72	96	96	72
Post Embedment (in.)	79¼	76	40	40	58	58	40
Post Spacing (in.)	75	75	75	75	75	75	75
Blockout Type	Wood	Wood	None	None	Wood	Wood	Wood
Blockout Depth (in.)	12	12	N/A	N/A	8	8	12
Impact Speed (mph)	63.1	60.7	61.0	65.3	63.9	60.3	61.6
Impact Angle (degrees)	27.1	25.5	25.3	25.1	25.0	25.9	26.3
Exit Speed (mph)	N/A	38.6	10.2	43.8	N/A	31.3	40.5
Exit Angle (degrees)	N/A	17.4	58.3	20.4	10.0	32.3	16
Dynamic Deflection (in.)	44¼	57⅝	27.4	35.7	51.6	32.4	72.9
Permanent Set Deflection (in.)	42¾	42	20⅛	26¼	37.2	22.8	56
Pass/Fail	Fail	Pass	Pass	Pass	Pass	Pass	Pass
Failure Mechanism	Override of Rail	None	None	None	None	None	None

[1] Distance from the center of post to the slope break point, where negative values are downslope.

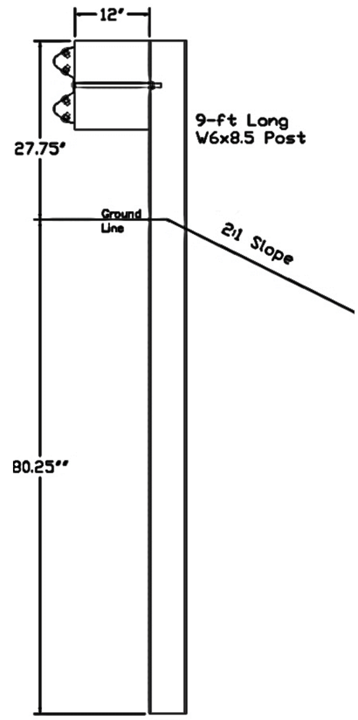


Figure 11. Barrier Installation, Test No. MGS221-1 [15]

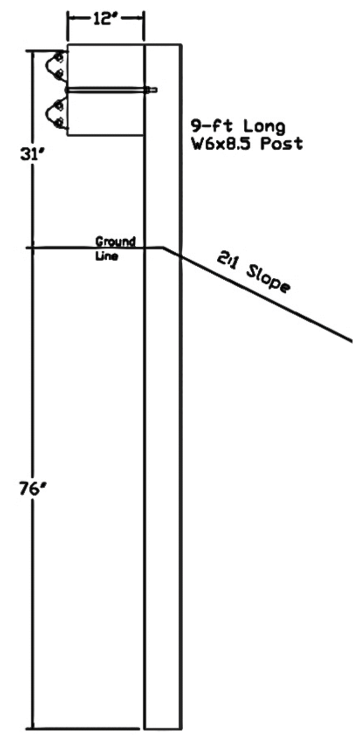


Figure 12. Barrier Installation, Test No. MGS221-2 [15]

The MGS without blockouts was also evaluated with 6-ft long W6x9 steel posts at standard 75-in. spacing installed on a wire-faced, mechanically stabilized earth (MSE) wall at the slope breakpoint of a 1V:3H fill slope [16-18], as shown in Figure 13. This system was successfully tested with both the 1100C and 2270P vehicles under the MASH safety requirements in test nos. MGSGW-1 and MGSGW-2, respectively. Test details and results are shown in Table 4. While this system did perform acceptably using standard post lengths and spacing adjacent to a slope, it should be noted that the slope was not as severe as the 1V:2H slope tested previously, the system used a high quality and very strong fill material, and the base of the posts were actually embedded in the rock layer of the wire-faced, MSE wall. Thus, the installation method used for these posts produced higher soil resistive forces and limited post rotation as compared to a more typical MGS installation adjacent to a steep fill slope.

TTI crash tested a 31-in. tall, W-beam with posts spaced at 75 in. on a 1V:2H slope [19], as shown in Figure 14. This system used 8-ft long, W6x9 posts with 8-in. deep blockouts and placed the face of the rail at the slope breakpoint. TTI conducted successful full-scale crash tests on this system according to the TL-3 requirements for MASH test designation nos. 3-10 and 3-11. Test details and results are summarized in Table 4. Because this system used shorter posts that were installed farther down the slope, it seems reasonable to assume that 8-ft long posts at standard post spacing would work at the slope breakpoint as well. In addition, there was potential for the use of even shorter posts at the post breakpoint.

In order to investigate the potential for the use of shorter posts with the MGS adjacent to steep slopes, MwRSF full-scale crash tested a MGS with standard post spacing and 6-ft long W6x8.5 posts installed at the slope break point of a 1V:2H slope according to MASH TL-3 test designation no. 3-11 [20], as shown in Figure 15. Existing guidance at the time recommended minimum lateral offsets between 1 ft and 2 ft from the back of the post to the slope break point for the standard MGS with 6-ft long posts, depending on the slope grade. These recommended lateral offsets maintained the safety performance of the system but created a great deal of additional expense in terms of earthwork. Test no. MGSS-1 consisted of a 4,992-lb pickup truck impacting the MGS at a speed of 61.6 mph and an angle of 26.3 degrees. The vehicle was contained and smoothly redirected. Thus, the standard MGS placed at the slope break point of a 1V:2H slope was acceptable according to the safety performance criteria presented in MASH. Test details and results are summarized in Table 4. It was noted that the reduced post embedment utilized by this type of installation significantly increased the dynamic deflection and working width of the barrier system.

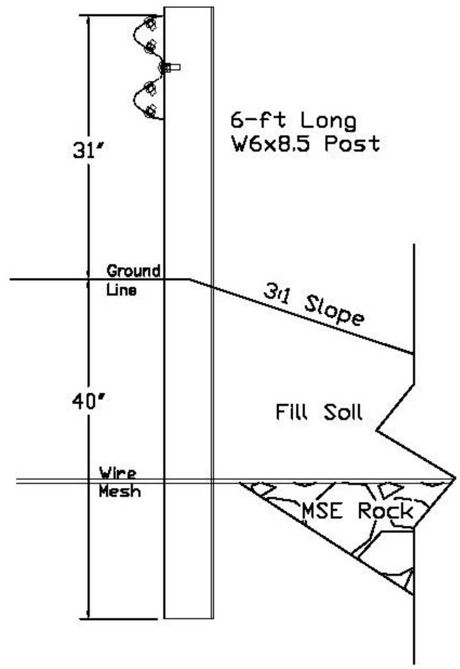


Figure 13. Barrier Installation, Test Nos. MGSGW-1 and MGSGW-2 [16]

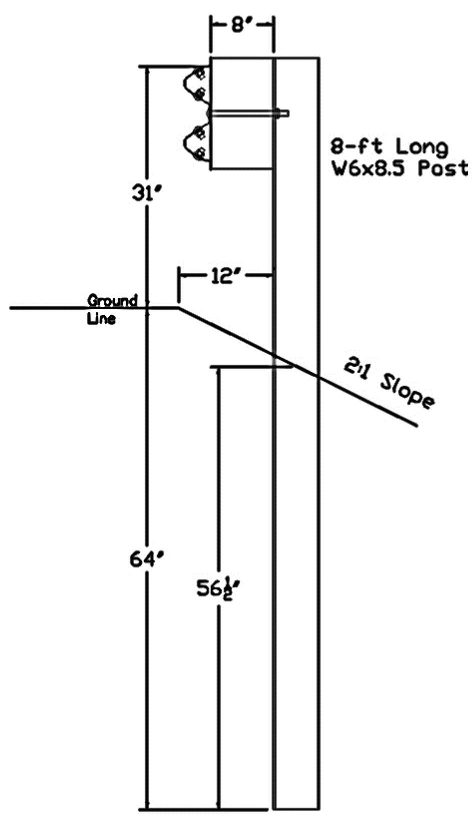


Figure 14. Barrier Installation, Test Nos. 405160-20-1 and 405160-20-2 [19]

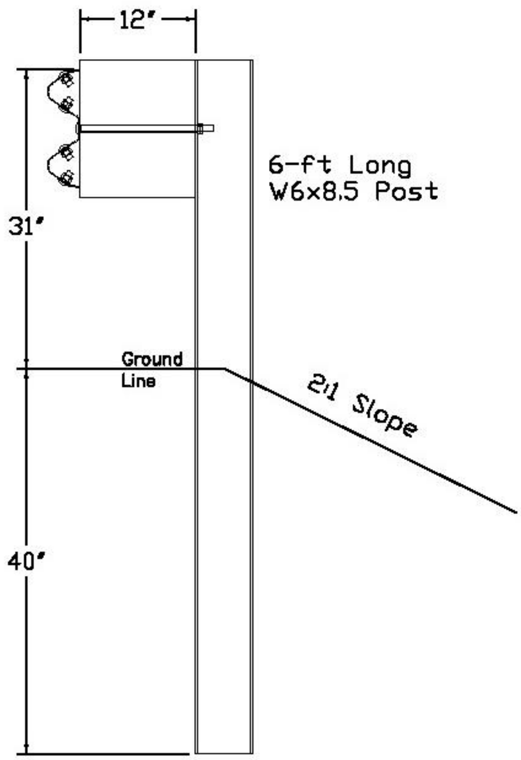


Figure 15. Barrier Installation, Test Nos. MGSS-1 [20]

It should be noted that an ongoing MwRSF study involves investigation of the MGS installed at the slope break point of a 1V:2H fill slope with 7-ft long posts and ½ post spacing, while a second TTI research effort involves investigation of guardrail installed adjacent to slopes steeper than 1V:2H . However, those two research efforts are not yet completed and could not inform this research effort.

2.2 Full-Scale Crash Testing Conclusions

The review of previous full-scale crash testing of W-beam guardrail systems adjacent to slopes provided valuable insight into barrier performance. Four factors were observed to be critical to the successful performance of W-beam guardrail systems adjacent to slopes.

1. Slope rate – Steeper slopes were observed to have a greater effect on post-soil resistance and resulting barrier deflections, which tended to degrade overall barrier performance. Steeper slopes also tended to reduce the effectiveness of vehicle capture and decreased vehicle stability.

2. Slope offset – Increased lateral barrier offset in front of the slope break point tended to improve barrier performance by providing higher post-soil resistive forces, lower barrier deflections, and improved vehicle capture and stability. However, select W-beam guardrail systems have shown the ability to be installed at or beyond the slope break point.

3. Post embedment and spacing – Increased post embedment length and reduced post spacing tended to increase post-soil resistive forces and the corresponding lateral barrier stiffness and strength. This can improve the performance of guardrail systems placed adjacent to steep slopes by compensating for the reduction in post-soil resistive forces induced by placement of the barrier adjacent to slopes.

4. Rail height – W-beam guardrail systems with increased guardrail height, such as the MGS, appeared to provide improved vehicle capture and containment as well as better barrier performance adjacent to sloped terrain.

The review of the data from previous full-scale crash tests also found that several configurations of the MGS or 31-in. tall guardrail were capable of safely containing and redirecting vehicles when installed adjacent to slopes as steep as 1V:2H under MASH TL-3 impact conditions. The full-scale crash testing indicated that MGS installed at the slope break point of a 1V:2H fill slope with standard 75-in. post spacing and post lengths ranging from 6 ft to 9 ft can meet MASH TL-3. However, it was noted that full-scale testing and evaluation of the MGS with a 6-ft post length installed at the slope break point of a 1V:2H fill slope displayed increased dynamic deflection and working width. These results would also suggest that installation of the MGS with standard 6-ft long posts and standard 75-in. post spacing would perform acceptably when installed at the slope break point of slopes shallower than 1V:2H . Blockout depths ranging from 12 in. down to non-blocked guardrail were also observed to meet MASH TL-3 criteria.

There were some limitations and/or gaps observed in the available full-scale crash test data. No full-scale crash testing was found that examined barrier performance on slopes steeper than 1V:2H . Additionally, no full-scale crash testing of W-beam guardrail was conducted with timber posts, but dynamic component testing of timber posts on slopes had been conducted and will be discussed in a subsequent section. Full-scale crash testing of W-beam guardrail adjacent to slopes with increased post length and reduced spacing was previously evaluated under NCHRP Report 350, but it has yet to be evaluated to the MASH criteria.

Only limited full-scale crash testing was found regarding W-beam guardrail systems installed down the fill slope or on approach slopes. The only examples of these types of systems evaluated to recent hardware evaluation criteria were: (1) a MASH TL-3 compliant 31-in. tall W-beam guardrail system that utilized 8-ft long posts at standard posts spacing and was installed with the face of the guardrail installed flush with the slope break point of a 1V:2H fill slope tested at TTI; and (2) the MGS installed on an 1V:8H approach slope that was evaluated under NCHRP Report 350. Performance of the MGS on 1V:8H approach slopes under NCHRP Report 350 conditions appeared to be near the limits of vehicle capture for the offset evaluated. Additionally, the performance of MGS installed on 1V:8H approach slopes may be reduced under the MASH TL-3 criteria due to increased vehicle masses, the increased center of gravity (CG) height of the 2270P vehicle, and the increased impact angle for the 1100C vehicle. Thus, recommendations for use of guardrail on approach slopes may be more limited than those installation guidelines suggested for the barriers installed at or in front of the slope break point.

2.3 Dynamic Bogie Testing

Dynamic bogie testing of posts embedded in soil is a relatively common practice to determine post-soil resistance for individual posts with variations in post section, soil embedment, and slope conditions. As such, a wide variety of research exists in the literature on dynamic bogie testing of posts. For the purposes of this study, review of dynamic bogie testing of posts was limited to post research corresponding to the development, testing, and evaluation of MASH W-beam guardrail systems on fill slopes.

During the development of the modified MGS adjacent to 1V:2H fill slopes [15], a series of bogie tests were conducted on W6x9 posts with various embedment depths installed at the slope break point of a 1V:2H fill slope [21]. This bogie testing was performed to evaluate the post-soil behavior for various embedment depths, which led to the selection of a proposed post length for the MGS installed at the slope break point of a 1V:2H fill slope that provided similar performance to a 6-ft long post installed on level terrain. A total of seventeen bogie crash tests were performed with post lengths varying from 6 ft to 9 ft and with embedment depths ranging between 40 in. and 76 in. For each test, acceleration data was processed to create force-displacement and energy-displacement plots. Additionally, average post-soil forces were calculated for the initial 15 in. of post displacement. Average post-soil forces were then compared to the baseline average post capacity of 6 kips, which was representative of 6-ft long steel posts found in the MGS placed on a level terrain. From these comparisons, a recommended post length was selected for the 75-in. standard post spacing. A 9-ft long post with a 76-in. embedment depth was found to best meet the post requirements while providing an average force of 6.39 kips. As such, this post configuration was recommended for use in the MGS with standard post spacing installed at the slope break point of a 1V:2H fill slope. The study also noted that 8-ft long W6x9 posts installed at the slope break point of a 1V:2H fill slope provided nearly identical resistive forces as the 9-ft long posts. This finding would suggest that the 8-ft long posts had the potential to perform adequately in the MGS when installed at the slope break point of a 1V:2H fill slope. The previously-noted, full-scale crash testing of a W-beam guardrail with 8-ft long, W6x9 posts and 8-in. deep blockouts placed with face of the rail at the slope breakpoint further validated that conclusion [19].

A follow-on study was conducted by MwRSF to evaluate the potential use of wood posts with the MGS adjacent to 1V:2H fill slopes [22]. Dynamic impact testing was performed on 6-in. x 8-in. southern yellow pine (SYP) wood posts with 7.5 and 8 ft lengths and 9-ft long, W6x9 steel posts placed at the break point of a 1V:2H fill slope. This testing program was used to evaluate the post-soil behavior and to select a wood post alternative for the 9-ft long, W6x9 steel post utilized in the MGS placed adjacent to a steep fill slope.

The review of the data from all seven impact tests found that the 7.5-ft long, 6-in. x 8-in. SYP wood posts provided the best alternative to the 9-ft long, W6x9 steel posts. Three tests of 8-ft long, 6-in. x 8-in. SYP wood posts resulted in post fracture due to the post-soil forces exceeding the capacity of the wood post. The wood fracture prevented effective rotation of the post in the soil as well as resulted in insufficient energy absorption during the impact. Thus, the 8-ft long wood posts were deemed unsuitable for the MGS when installed adjacent to a 1V:2H fill slope.

In contrast, the 7.5-ft long, 6-in. x 8-in. SYP wood posts correlated reasonably well with the data obtained from the 9-ft long, W6x9 steel post tests. The 7.5-ft long posts did not fracture during impact but rather rotated through the soil. The average peak force for the two 7.5-ft long, wood post tests was only 5.7 percent greater than the average peak force of the two W6x9 steel post tests. Similarly, the average total energy of the two 7.5-ft long, wood post tests was only 6.5 percent greater than the average total energy of the two W6x9 steel post tests. The average forces for the 7.5-ft long, wood post tests were 23 percent greater through 15 in. of deflection than the values obtained from the steel post testing program. Thus, the two 7.5-ft (2.29-m) long wood posts compared very well with the steel posts in terms of peak force and total energy absorbed, while being slightly higher in terms of average force. It was not believed that the reasonably small differences observed between the 7.5-ft long wood post and the 9-ft long steel post would have any adverse effects on the performance of the MGS. Based on this comparison, the researchers determined that the 7.5-ft long, 6-in. x 8-in. SYP wood post provided a suitable alternative to the 9-ft long, W6x9 steel post in the MGS when installed adjacent to a 1V:2H fill slope.

3 GUIDANCE FOR MGS INSTALLED ADJACENT TO SLOPES

3.1 Introduction

The 2011 AASHTO *Roadside Design Guide* has recommended that guardrail systems can generally be installed on slopes as steep as 1V:10H . Further, systems installed adjacent to steeper slopes should be installed a minimum of 2 ft in front of the slope break point of a fill slope to provide for proper vehicle stability as well as adequate post-soil resistive forces. Following the review of existing full-scale crash tests on W-beam guardrail systems adjacent to slopes and related dynamic bogie testing of posts on slopes, guidance was developed for the placement of the MGS adjacent to slopes. Generalized placement guidance for MASH TL-3-compliant MGS configurations adjacent to slopes is summarized in Table 5. Further explanation of this guidance is outlined in the subsequent sections along with additional implementation recommendations for special applications.

The guidance within this document was developed based on the current knowledge base with respect to full-scale crash testing and research of the MGS adjacent to slopes and other MGS systems. MwRSF did not have access to in-service performance data or crash data related to MGS installed adjacent to slopes, nor was collection of this data intended as part of this study. As such, these recommendations are intentionally conservative to account for potential limits of the barrier system's performance that have not been fully defined in full-scale crash testing and research and cannot adequately be resolved without further research. This guidance is intended as recommendations for the installation of MASH TL-3 compliant MGS adjacent to fill slopes, and it does not constitute a standard or specification with which any user agency must comply. User agencies may apply installations outside of the recommendations herein based on their own installation scenarios, internal data, and decision-making processes.

3.2 General Guidance for MGS Offset 0 ft to 2 ft from Slope Break Point

The MASH TL-3, standard MGS with 6-ft long, W6x8.5 or W6x9 posts spaced at 75 in. on centers may be installed at any offset ranging from 0 ft to 2 ft in front of the slope breakpoint of fill slopes, which can range from level terrain to 1V:2H . Previous full-scale crash testing of the MGS at the slope break point of a 1V:2H fill slope with standard post spacing and post lengths ranging from 6 ft to 9 ft was proven satisfactory according to the MASH TL-3 safety performance criteria. Additionally, the standard MGS was full-scale crash tested on level terrain under MASH TL-3 conditions. Thus, it is reasonable to conclude that the standard MGS would perform safely when placed adjacent to less severe fill slopes and at intermediate lateral offsets between 0 ft and 2 ft.

There are some limitations to this recommendation based on existing research. This recommendation is only applicable to the MGS due to the performance benefits derived from its design features, such as midspan splices and a 31-in. top mounting height. Full-scale crash testing under MASH test designation no. 3-11 on the modified MGS with a 27¾-in. top mounting height and posts at the sloped break point was unsuccessful as the 2270P pickup overrode this lower-height guardrail [15]. Subsequently, it is recommended that all MGS adjacent to slopes to be installed with a minimum rail height of 31 in. until further research is completed. Additionally, the

Table 5. Recommended MASH TL-3 MGS Configurations Adjacent to Slope

Fill Slope	Post Offset from Slope [1,2] (ft)	Post Type	Post Length, L (ft)	Blockout Depth (in.)	Working Width (in.)	Post Spacing (in.)	Rail Height (in.)
1V:2H	0 (at SBP[3])	W6x8.5 or W6x9	6 ≤ L ≤ 9	0 - 12	See Figure 17	75	31
		6-in. x 8-in. Southern Yellow Pine (SYP)	6 ≤ L ≤ 7.5	8 - 12	See Figure 17	75	
		6-in. x 8-in. White Pine (WP)	6.5	8 - 12	NA	37.5	
		6-in. x 8-in. White Pine (WP)	6	8 - 12	See Figure 17	75	
≤ 1V:2H	0 (at SBP[3])	W6x8.5 or W6x9	6	0 - 12	See Figure 16	75	31
		6-in. x 8-in. Southern Yellow Pine (SYP)	6	8 - 12	See Figure 16	75	
		6-in. x 8-in. White Pine (WP)	6	8 - 12	See Figure 16	37.5	
≤ 1V:2H	0 < Offset < 2	W6x8.5 or W6x9	6	0 - 12	See Figure 16 and Figure 18	75	31
		6-in. x 8-in. Southern Yellow Pine (SYP)	6	8 - 12	See Figure 16 and Figure 18	75	
		6-in. x 8-in. White Pine (WP)	6	8 - 12	See Figure 16 and Figure 18	37.5	
1V:2H	-1.25 (down slope)	W6x8.5 or W6x9	8	8 - 12	55.2	6.25	31

[1] – Slope offset is measured from slope break point to center of post
[2] – Slope offset is positive (+) in front of the slope break point and negative (-) down the slope
[3] – SBP = Slope Break Point

MGS has only been evaluated and full-scale crash tested adjacent to fill slopes as steep as 1V:2H. Thus, these guardrail systems should be limited to slopes of 1V:2H or flatter until further evaluation is performed.

The soil foundation of the posts affects post-soil resistive forces. Thus, the strength of the soil is critical for the MGS placed adjacent to a 1V:2H fill slope. For typical longitudinal barriers, it has generally been assumed that the use of strong soils is more critical for full-scale crash testing and evaluation as strong soils tend to produce higher post-soil resistive forces, which tend to create higher rail forces, increased snag on barrier support posts, and result in higher occupant risk values. However, in the case of the standard MGS installed at the slope break point of a 1V:2H fill slope with 6-ft long steel posts, the soil resistive forces are being reduced due to reduced soil fill behind the posts. This decreased post-soil resistance can lead to increased guardrail post rotation and greater lateral barrier deflection during vehicle collision, potentially resulting in barrier override or a lower capacity to contain and redirect errant vehicles. Thus, while the MGS has been full-scale crash tested with posts embedded in strong soil conditions in compliance with MASH, there are unknowns with respect to the installation of the standard MGS on or adjacent to slopes configured with weaker soils.

The unknowns pertain to MGS behavior with reduced barrier post-soil resistive forces and increased barrier deflections in these real-world, weaker soil applications. For an MGS installed at the slope break point of a 1V:2H fill slope with standard, 6-ft long, steel posts embedded in weaker soils may increase barrier deflections. Excessive barrier deflections could lead to inadequate vehicle capture or override of the barrier system. As such, it is recommended that the MGS be installed at the slope break point of a 1V:2H fill slope with standard, 6-ft long, steel posts when similar soil strength to the as-tested system is provided. Further it is recommended that end users compensate for the presence of weaker soils by using the increased post length options in Table 5 with the MGS placed at the sloped break point of 1V:2H fill slopes.

3.2.1 MGS MSE Wall Installation Adjacent to Slope

The MGS without or without blockouts is MASH TL-3 compliant with 6-ft long W6x9 steel posts at standard 75-in. spacing installed on a wire-faced, mechanically stabilized earth (MSE) wall at the slope breakpoint of a 1V:3H fill slope [16-18]. This system was successfully tested with both the 1100C and 2270P vehicles under the MASH safety requirements. It should be noted that the slope was not as severe as the 1V:2H slope tested previously, the system used a high quality and very strong fill material, and the base of the posts were actually embedded in the rock layer of the wire-faced, MSE wall. Thus, the installation method used for these posts produced higher soil resistive forces and limited post rotation as compared to a more typical MGS installation adjacent to a steep fill slope, and it was not included in the generalized MASH TL-3 guidance for the MGS installed adjacent to slopes in Table 5. Full details of the MGS installed on a wire faced, MSE wall can be found in the corresponding research reports [16-18]. User agencies should refer to those documents for specific guidance for the use of MGS with the wire faced, MSE wall.

3.2.2 Blockout Depth for MGS Adjacent to Slope

As noted previously, the 31-in. tall MGS with 6-ft and 9-ft long steel posts was successfully crash tested under the MASH TL-3 criteria when installed at the slope break point of a 1V:2H fill slope using standard post spacing and blockouts. Additionally, full-scale crash testing was successful on a non-blocked MGS when installed both on level terrain and adjacent to slopes. A non-blocked MGS installed at the slope break point of a 1V:3H fill slope positioned on top of an MSE wall was tested under the MASH TL-3 safety criteria for both the 1100C and 2270P vehicles. Subsequent MASH testing was also successfully performed on a non-blocked MGS installed on level terrain with both the 1100C and 2270P vehicles [23-24]. A comparison of the non-blocked and blocked versions of the MGS revealed that the safety performance of the standard MGS with 12-in. deep blockouts improved as compared to the non-blocked system, and the safety performance of the non-blocked system was acceptable under the MASH criteria.

Using the results from these successful crash testing programs, it is believed that satisfactory performance would also be provided by an 8-in. deep blockout or non-blocked versions of the MGS with standard, 6-ft long steel posts when installed at the slope break point of slopes ranging from 1V:2H to level terrain. It is also believed that modified versions of the MGS with longer posts (up to 9 ft) installed at the slope break point of a 1V:2H fill slope may utilize blockout depths from 0 in. to 12 in. The use of longer posts on shallower slopes will be discussed later in the report.

3.2.3 Wood Posts with MGS Adjacent to Slope

Over the years, MwRSF has crash tested several wood-post MGS systems, including rectangular, southern yellow pine (SYP) wood posts and alternative wood species round and rectangular posts. A comparison of MASH crash testing with both steel and rectangular wood posts found that the performance of the MGS with steel and rectangular SYP wood posts correlated very well [25-26]. Dynamic deflections, working widths, occupant risk values, and vehicle stability measures were generally unaffected by the change in the post type. Only minor differences in the system behavior were found, and no concerns were identified that suggested that one system had a safety performance advantage over the other. Thus, it was concluded that the 6-in. wide x 8-in. deep x 72-in. long wood-post and W6x8.5 x 72-in. long steel-post MGS provide equivalent impact safety performance. Based on the similar performance observed for the wood- and steel-post MGS, there may be a desire for end users to install a wood-post MGS adjacent to slopes.

As noted previously, 31-in. tall MGS with both 6-ft and 9-ft long W6x8.5 steel posts was successfully crash tested under the MASH TL-3 safety performance criteria when installed at the slope break point of a 1V:2H fill slope using standard post spacing and blockouts. Later and based on dynamic component testing, a wood post version of the MGS was configured with 7.5-ft long, SYP posts and for use in shielding a 1V:2H fill slope. For the SYP wood-post variation, the embedment depth was 58 in. However, comparison of the performance of the MGS with 6-ft long steel and SYP posts on level terrain found nearly identical performance between the two systems [27]. This would suggest that the MGS with 6-ft long, SYP posts would perform similarly to the MGS with 6-ft long, steel posts when installed adjacent to slopes. Thus, it is recommended that the MGS with 6-in. wide x 8-in. deep x 72-in. long SYP posts may be installed at the slope break point of a 1V:2H fill slope. As noted previously, end users with lower strength soil foundations may wish to consider the use of the 7.5-ft long, SYP posts adjacent to 1V:2H slopes to compensate for lower post-soil resistive forces. Similarly, it is believed that the MGS with 6-in. wide x 8-in. deep x 72-in. long SYP posts at 75-in. spacing may be installed at the slope break point of 1V:2H or shallower slopes and at larger lateral offsets from the slope break point.

Similarly, the MGS was successfully evaluated under the MASH criteria when installed with 6-in. wide x 8-in. deep x 72-in. long, white pine posts on level terrain [28]. At the time of that research, MwRSF recommended that a white pine MGS located adjacent to a 1V:2H fill slope utilize 6.5-ft long, 6-in. x 8-in. wood posts at half-post spacing, or on 37½-in. centers. Dynamic deflection and working width for the this proposed alternative were not determined. This post length was shorter when compared to the SYP posts adjacent to slope in order to prevent post fracture of the lower strength white pine, while still providing adequate post-soil resistive forces. Reduced post spacing was also recommended to maintain adequate post-soil resistive forces. The full-scale crash testing of the MGS installed at the slope break point of a 1V:2H fill slope with standard, 6-ft long steel posts detailed herein suggests that further reduction in post embedment is acceptable. Additionally, comparison of the performance of full-scale crash tests of the MGS on level terrain with both 6-ft long white pine posts and 6-ft long W6x8.5 steel posts found similar barrier performance between the two post alternatives [27]. This would suggest that the use of half-post spacing would not be required for the use of the MGS with 6-ft long, white pine posts adjacent to slope. Thus, it is believed that the MGS with 6-in. wide x 8-in. deep x 72-in. long white pine posts may be installed at the slope break point of a 1V:2H or shallower fill slope as well. As noted previously, end users with lower strength soil foundations may wish to consider the use of the 6.5-ft long white pine posts at half-post spacing adjacent to 1V:2H slopes to compensate for lower post-soil resistive forces.

As noted above, other testing and evaluation of wood posts has been conducted with the MGS. Several alternative species of round, wood posts have been evaluated with the MGS based on NCHRP Report 350 testing. Note that these posts have different strengths, embedment depths, and geometry as compared to the a 6-in. wide x 8-in. deep x 72-in. long SYP post. Furthermore, they have not been evaluated with the MGS under the MASH criteria, Therefore, the use the standard length, alternative species, round wood posts adjacent to a 1V:2H or shallower slope may not be MASH TL-3 compliant and may require further analysis to verify its safety performance.

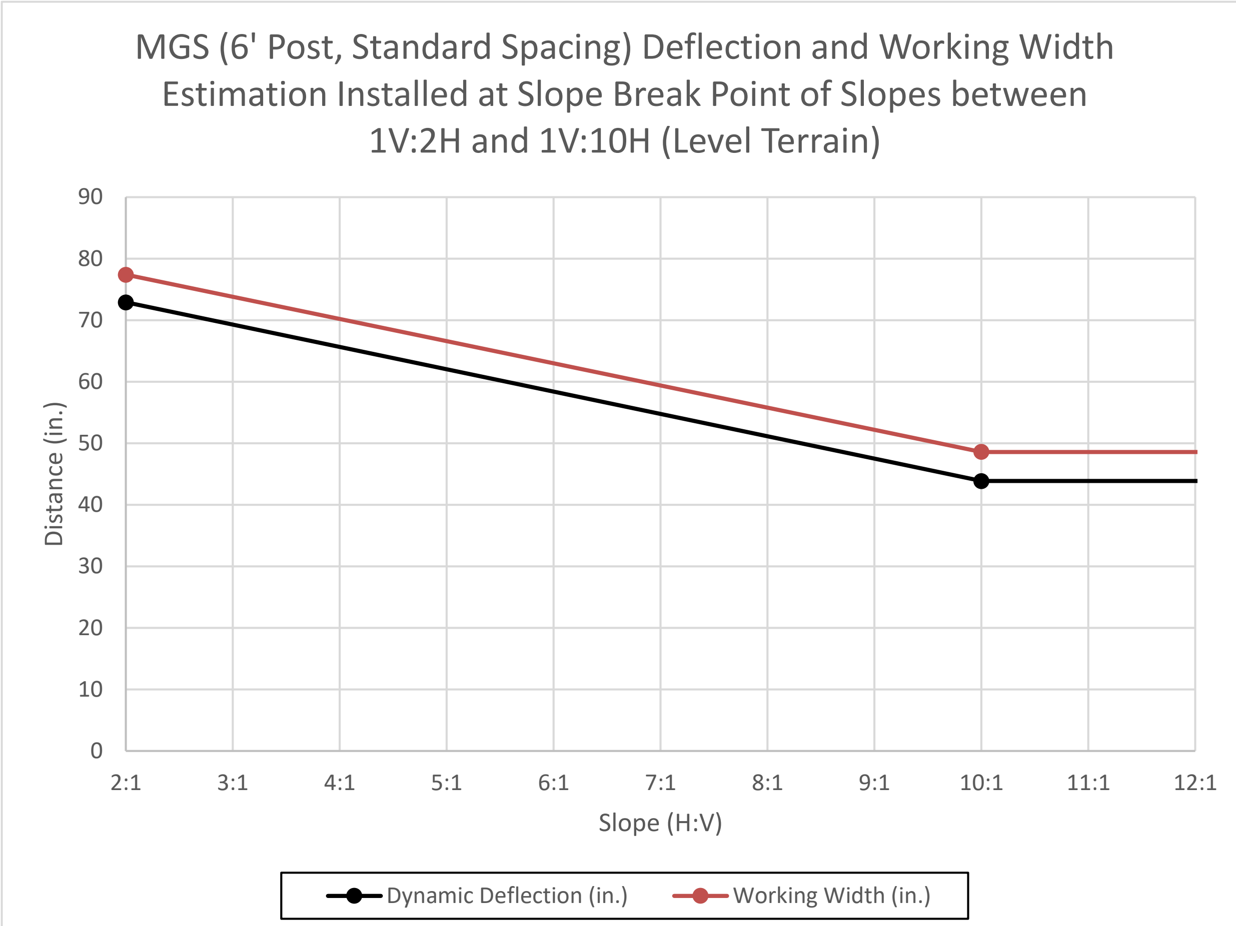
Note that the use of non-blocked MGS with wood posts may not be MASH TL-3 compliant and may require further research to verify its safety performance due to differences in the weak-axis post strength between steel and wood sections and the lack of research and crash testing regarding this topic.

3.2.4 Estimated Dynamic Deflection and Working Width for MGS Adjacent to Slopes

End users may also wish to determine or estimate dynamic deflections and working widths for various MGS configurations when installed adjacent to slopes. While full-scale crash test data was not available for all potential configurations, dynamic deflections and working widths were available from full-scale crash testing of the MGS on level terrain and adjacent to a 1V:2H fill slope with both 6-ft long and 9-ft long, W6x8.5 or W6x9 steel posts. This data was linearly interpolated to estimate dynamic deflections and working widths for the MGS installed at the slope break point of various slopes, installed at the slope break point of a 1V:2H fill slope with various post lengths, and placed at various lateral offsets in front of the slope break point. While no full-scale crash testing of the MGS adjacent to slopes was available for wood posts, a previous paper compared the performance of the MGS on level terrain based on full-scale crash tests with steel posts and SYP and white pine wood posts [27]. Dynamic deflections, working widths, occupant risk values, and vehicle stability measures were generally unaffected by the change in the support post type. Based on the similarity of MGS performance with steel and wood posts on level terrain, as well as the fact that wood post lengths for the MGS adjacent to slope were selected to mitigate premature post fracture, it was believed that the dynamic deflection and working width estimates based on full-scale crash tests of the MGS with steel posts adjacent to slope may be applied to wood-post MGS configurations with similar post spacing.

3.2.4.1 MGS with 6-ft Long Posts and Standard Spacing Installed at Slope Break Point with Various Slopes

As noted previously, the standard MGS with 6-ft long posts spaced at 75 in. on centers may be installed at the slope break point of slopes ranging from level terrain to 1V:2H. More gradual slopes should provide increased post-soil resistive forces and corresponding reductions in dynamic deflection and working width. Dynamic deflections and working widths were estimated for the standard MGS with 6-ft long posts spaced at 75 in. on centers and installed at the slope break point for slopes ranging from 1V:2H to level terrain, as shown in Figure 16. These estimates were developed based on linear interpolation between MASH TL-3 full-scale crash test results for the MGS on level terrain and installed at the slope break point for a 1V:2H fill slope. End users may apply these reductions in dynamic deflection and working width when installing the standard MGS adjacent to slopes more gradual than 1V:2H.



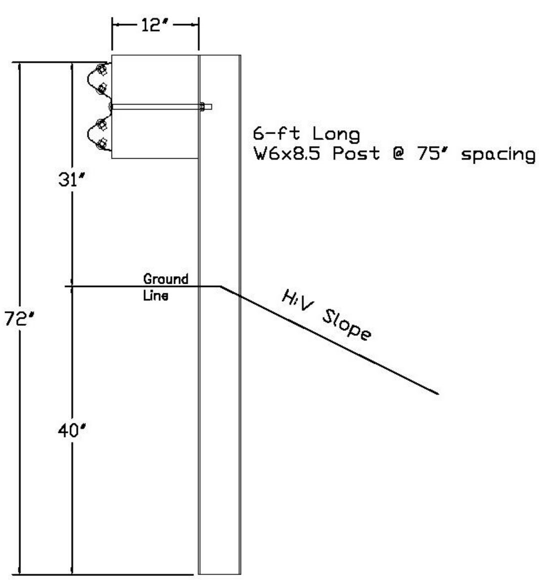


Figure 16. Dynamic Deflection and Working Width for Standard MGS Installed at Slope Break Point of Fill Slopes between Level Terrain and 1V:2H

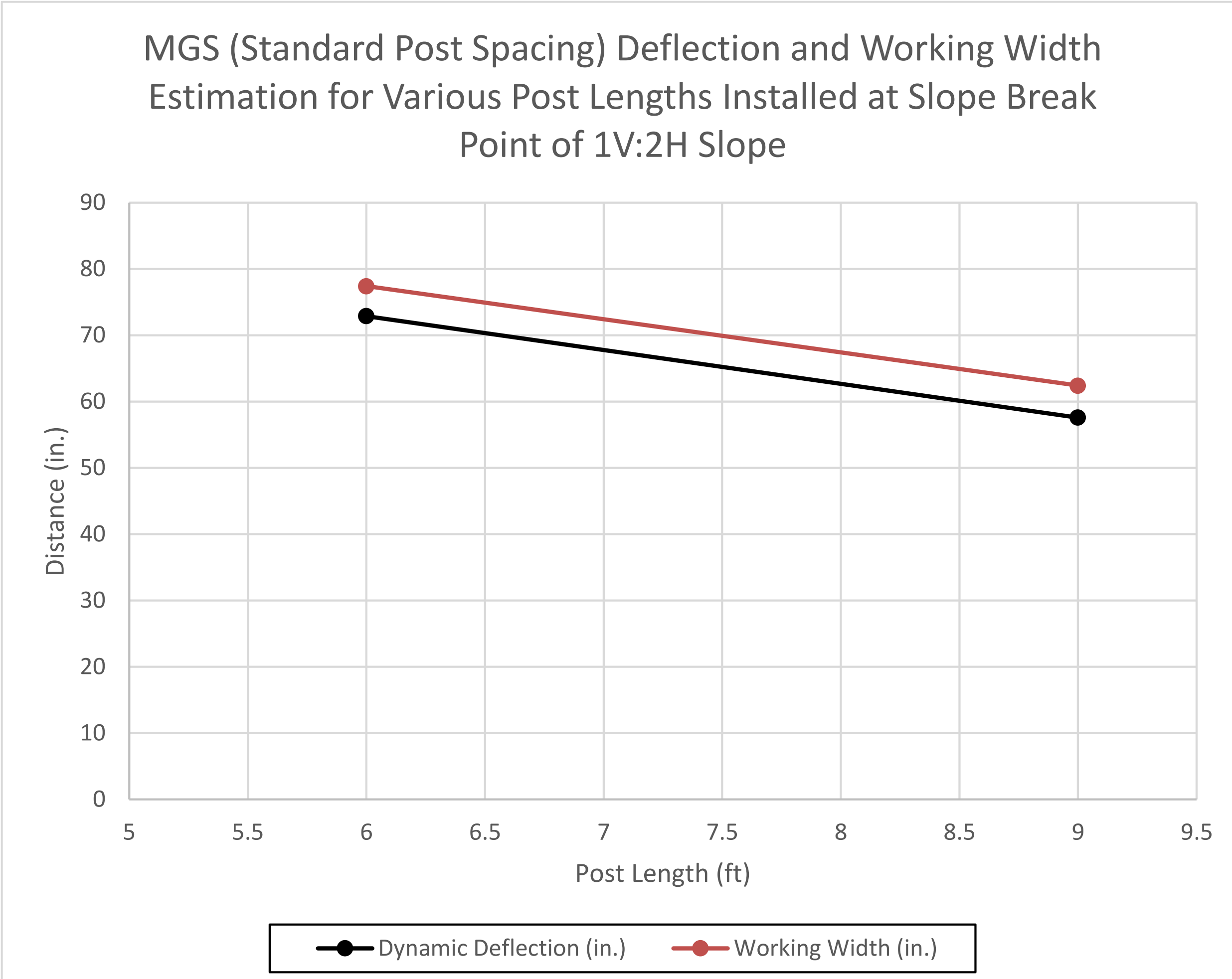
End users may desire to further reduce the dynamic deflection and working width of installations adjacent to slopes through increased post length and/or reduced post spacing. However, recent full-scale crash testing of stiffened or reduced deflection MGS systems have resulted in rail ruptures. TTI has recently conducted testing on the MGS with reduced post spacing and transitions from standard post spacing to reduced post spacing. TTI researchers first evaluated a quarter-post spacing system (18¾ in.) with MASH test designation nos. 3-11 and 3-10. The quarter-post spacing system successfully passed both MASH tests. TTI researchers also tested a transition between quarter-(18¾ in.) and full-(75 in.) spacing according to MASH test designation no. 3-21 impact conditions. This transition used single, W-beam rail elements and did not incorporate any nested rail sections. In this test, the pickup truck ruptured the rail and penetrated beyond the barrier. TTI researchers attributed the failure to rail pocketing caused by the short transition in lateral barrier stiffness. Finally, TTI researchers also tested a half-post spacing (37½ in.) variation of the MGS under this project. In this test, the pickup truck ruptured the rail and penetrated beyond the barrier.

These recent test failures involving 2270P impacts into the MGS with reduced post spacing suggests that the there is potential for rail failure during impacts into stiffened MGS applications and/or applications where increased localized rail deflection and pocketing may occur. The use of increased post length and embedment and/or reduced post spacing at the slope break point of shallower slopes than those that have been full-scale crash tested may result in similar W-beam rail loading and the potential for rail rupture. As such, the application of reduced post spacing and/or increased post length and embedment depth for the MGS installed at the slope break point of slopes shallower than 1V:2H may not be MASH TL-3 compliant and may require further research to verify its safety performance.

3.2.4.2 Deflection and Working Width Estimation for MGS Installed at Slope Break Point of a 1V:2H Fill Slope with Various Post Lengths

Some users may wish to reduce the dynamic deflection and of the standard MGS installed at the slope break point of a 1V:2H fill slope by utilizing posts longer than 6 ft to provide increased post-soil resistive forces. Estimated dynamic deflections and working widths for the MGS with various post lengths installed at the slope break point of a 1V:2H fill slope were interpolated from existing full-scale crash test results for the MGS adjacent to 1V:2H fill slopes with 6-ft long and 9-ft long posts and standard post spacing. These estimated values are shown in Figure 17.

Based on the discussion regarding rail rupture concerns for the stiffened MGS in the previous section, the application of increased post length and embedment depth for the MGS adjacent to slopes flatter than 1V:2H or at lateral offsets outside of the slope break point may not be MASH TL-3 compliant and may require further research to verify its safety performance.



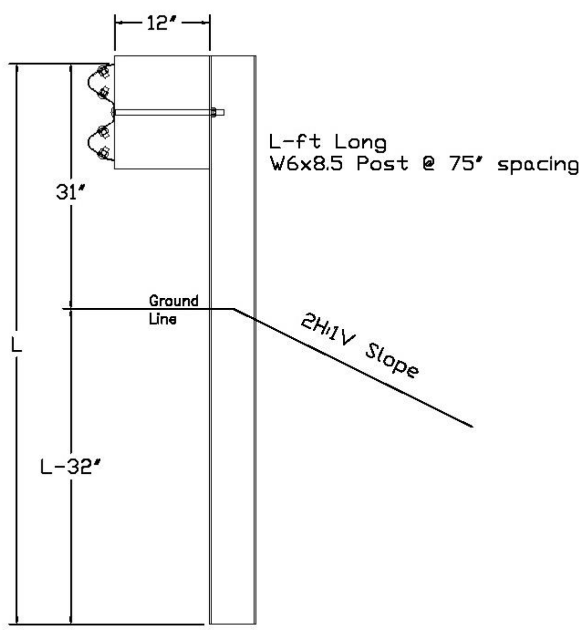
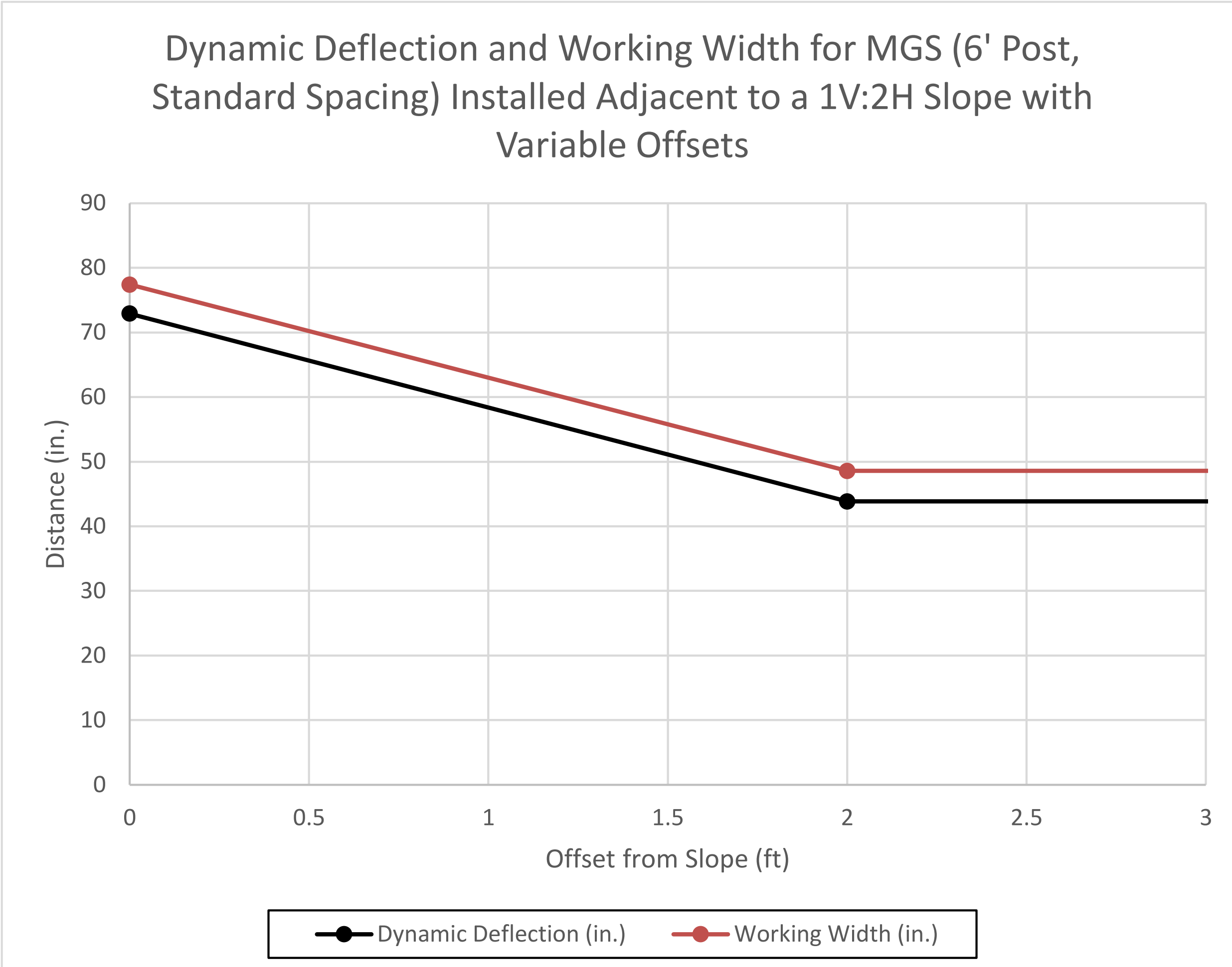


Figure 17. Dynamic Deflection and Working Width for MGS Installed at Slope Break Point of a 1V:2H Fill Slope with Variable Post Lengths

3.2.4.3 Deflection and Working Width Estimation for MGS with 6-ft Long Posts and Standard Spacing Offset from Slope Break Point of a 1V:2H Fill Slope

The lateral offset of the MGS in front of a slope break point affects the post-soil resistive forces. Previous guidance in the 2011 AASHTO *Roadside Design Guide* recommended that systems installed adjacent to steeper slopes should be installed a minimum of 2 ft in front of the slope break point to provide for proper vehicle stability and development of adequate post-soil resistive forces. The more recent crash testing detailed herein suggests that the standard MGS system can be safely applied at reduced lateral offsets with a corresponding increase in dynamic deflection and working width. Dynamic deflections and working widths for the standard MGS with variable lateral offsets adjacent to a 1V:2H fill slope were estimated based on the existing crash test data, as shown in Figure 18. Note that these estimated dynamic deflections and working widths for slopes flatter than 1V:2H would be expected to follow a similar trend but should be modified to account for the more flatter slopes based on Figure 16.

Based on the discussion regarding rail rupture concerns for the stiffened MGS in the previous section, the application of increased post length and embedment depth or reduced post spacing for the MGS adjacent to slopes flatter than 1V:2H or at lateral offsets outside the slope break point may not be MASH TL-3 compliant and may require further research to verify its safety performance.



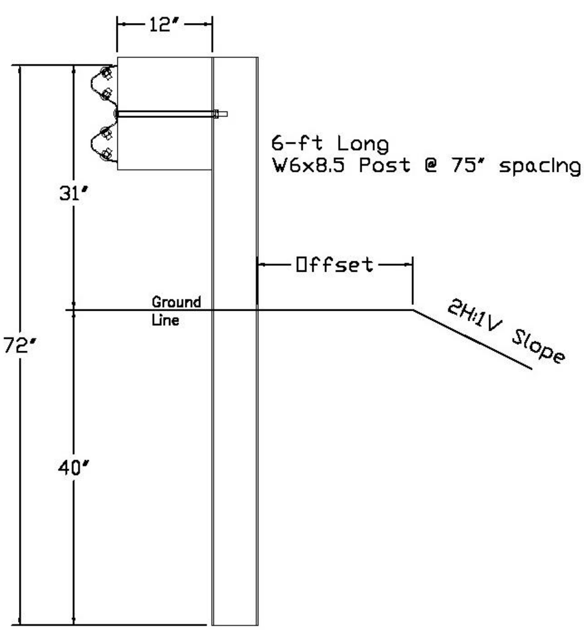


Figure 18. Dynamic Deflection and Working Width for MGS Installed Adjacent to a 1V:2H Fill Slope with Variable Offsets

3.3 Guidance for MGS Lateral Offset Beyond the Slope Break Point

There is limited data available with respect to the MGS installed beyond the slope break point of a fill slope. The sections below detail recommendations for the application of the MGS beyond the slope break point.

3.3.1 1V:2H Fill Slopes

The modified MGS evaluated at TTI is the only system to be developed and crash tested with the posts installed beyond the slope break point of a 1V:2H fill slope. The system utilized 8-in. blockouts and 8-ft long, W6x8.5 posts spaced at 75 in. on centers and the center of the post offset 15 in. down a 1V:2H fill slope [19]. Thus, the face of the rail was located directly above the slope break point. Due to a lack of dynamic testing on timber posts positioned beyond the slope break point, which effectively increases the moment arm in the post from the center of the rail to the soil support and increases the possibility of post fracture, there have not been any wood posts identified for use with this system. Non-blocked guardrail located beyond the slope break point has not yet been evaluated but may affect the relative height of the W-beam rail as system deflects during impacts. Specifically, the rail may be pulled downward as the posts deflect backward, which increases the possibility of vehicle override. As such, installation of this system as a non-blocked installation may not be MASH TL-3 compliant and may require further research to verify its safety performance. Finally, application of increased post lengths and/or reduced post spacing for reducing dynamic deflections and working widths of this system may not be MASH TL-3 compliant and may require further research to verify its safety performance.

3.3.2 MGS Installed on Shallower Approach Slopes

Guidance provided in the 2011 AASHTO *Roadside Design Guide* recommends that guardrail systems can be safely installed on 1V:10H or flatter approach slopes. Additional research and full-scale crash testing were conducted with respect to the steel-post version of the MGS installed on an 8:1 approach slope with the W-beam positioned 5 ft laterally behind the slope break point [14]. The testing program was conducted according to the NCHRP Report 350 impact safety standards using both an 820C small car and a 2000P pickup truck, and both test designation nos. 3-10 and 3-11 successfully met TL-3 safety requirements. From the crash testing program, the mounting height of the blocked MGS relative to the airborne trajectory of the front bumper and impact-side wheels was deemed critical for satisfactorily containing the 2000P pickup truck. Arguably, the test results may have also demonstrated that the 31-in. top railing height greatly contributed to adequate vehicle containment and stable redirection.

Because the MGS on 8:1 approach slope has not been evaluated under the MASH criteria, there is uncertainty as to whether this system would perform satisfactory under testing with the increased mass and CG height of the 2270P vehicle and the increased mass and impact angle of the 1100C vehicle test. As such, the MGS on approach slopes steeper than 1V:10H cannot be considered MASH compliant without further research and analysis. End users may elect to continue using the system as NCHRP Report 350 compliant until such time that further research on this topic is available.

3.4 MGS Special Applications Adjacent to Slopes

The following sections provide suggested implementation guidance and/or recommendations regarding the use other MGS special applications adjacent to slopes. These recommendations are intended to ensure comparable safety performance of the guardrail systems and are based on the full-scale crash testing and any associated research available at the conclusion of this project. Although some installation sites will require systems outside the bounds of these recommendations, the reasoning behind these recommendations should be considered along with other roadside treatments when selecting the final site-specific design.

3.4.1 MGS Adjacent to Curb

The standard MGS was successfully crash tested and evaluated with the front face of the W-beam rail placed 6 in. behind the front face of a 6-in. tall concrete curb according to MASH TL-3 criteria [29]. The use of the MGS installed at the slope break point of a 1V:2H fill slope with a concrete curb causes potential concerns with respect to barrier performance. Note that higher barrier deflection would be expected when installed at the slope break point of a 1V:2H fill slope. The vehicle's traversal of the curb during impact and impact with the barrier adjacent to slopes may also pose additional risks, such as vehicle instabilities and barrier override, which were not evaluated during the MASH testing on level terrain. Previous MASH TL-3 full-scale testing of the MGS with 9-ft long steel posts, a 27¾-in. top rail height, and installed at the slope break point of a 1V:2H slope failed due to vehicle override of the barrier [15]. This result would tend to indicate potential concerns for vehicle capture when the impacting vehicle's bumper height was higher with respect to the guardrail, which may occur due to vehicle traversal of a curb. As such, installation of the MGS at the slope break point of a 1V:2H fill slope adjacent to curb may not be MASH TL-3 compliant and may require further research to verify its safety performance.

3.4.2 MGS Long-Span Guardrail

The MGS long-span guardrail system was successfully full-scale crash tested to MASH TL-3 using an unsupported length of 25 ft and three controlled releasing terminal (CRT) posts with 12-in. deep blockouts adjacent to each end of the unsupported span [30]. These CRT posts were incorporated into the system in order to mitigate concerns for wheel snag on posts adjacent to the unsupported span when traversing from the unsupported span to the downstream standard guardrail. Adjacent to the CRT posts, the standard MGS utilized 12-in. deep blockouts. The MGS long-span guardrail system was installed with the back of the CRT posts positioned flush with the front face of the culvert headwall. The posts upstream and downstream from the culvert were installed 2 ft away from the slope break point of a 1V:3H fill slope.

End users may desire to install the standard MGS installed at the slope break point of a 1V:2H fill slope with 6-ft long steel posts or utilize reduced lateral offsets with flatter slopes with the MGS long-span guardrail system. There is concern that the use of these variations with the MGS long span may allow for dynamic barrier deflections that are too large for safe vehicle redirection. The MGS long span already has the largest dynamic deflection of any previously tested MGS application. Combining that system with the MGS installed at the slope break point of a 1V:2H fill slope with 6-ft long steel posts or with reduced lateral offsets to the slope break point of flatter slopes may result in even greater barrier deflections. Additionally, the CRT posts used in the MGS long span adjacent to the unsupported rail would behave differently when installed at the slope break point of a 1V:2H fill slope or at reduced lateral offsets to the slope break point. The expected increase in barrier deflection could affect vehicle capture and stability in a manner that is difficult to predict without further research. As such, application of the standard MGS installed at the slope break point of a 1V:2H fill slope with 6-ft long steel posts or to reduce the lateral offset to the slope break point below 2 ft for flatter slopes in conjunction with the MGS long span may not be MASH TL-3 compliant and may require further research to verify its safety performance.

3.4.3 MGS with an Omitted Post

Recent research at MwRSF consisted of the evaluation of the standard MGS with an omitted post [31]. The omitted post created an unsupported span of 12.5 ft. No other modifications were made to the MGS. One full-scale crash test was performed according to the TL-3 safety performance criteria defined in MASH, test designation no. 3-11, and the MGS with an omitted post performed in an acceptable and safe manner.

Concerns for the use of the MGS installed adjacent to slopes in combination with an omitted post are similar to those noted previously for the MGS long span. Omission of a post in this type of system would tend to increase rail deflections over the MGS adjacent to slopes described herein, and this increase in deflection could adversely affect the barrier’s performance in terms of vehicle capture and stability. As such, installation of the MGS adjacent to slope in combination with a single omitted post may not be MASH TL-3 compliant and may require further research to verify its safety performance. It is recommended that if an omitted post is utilized, that the minimum 2-ft offset to the slot break point be applied to provide adequate post-soil resistive forces.

3.4.4 MGS Stiffness Transition to Approach Guardrail Transitions

Several options for approach guardrail transitions for the MGS have been developed [32-35]. As part of those efforts, a steel-post MGS stiffness transition was found to satisfy all of the TL-3 safety performance criteria of MASH through a full-scale crash testing program. This transition design utilized standard, 6-ft long, W6x8.5 posts for a majority of the upstream stiffness transition. Subsequent bogie testing and BARRIER VII analysis developed a wood-post transition system that behaved similarly and without increases in barrier deflections, pocketing, or snag. Thus, it was believed that the wood-post transition system would also satisfy the MASH performance criteria, and the wood-post MGS stiffness transition was recommended for use as a TL-3 safety barrier.

The performance of approach guardrail transitions is directly related to the effectiveness of the system in providing a gradual transition in lateral barrier stiffness between the approach guardrail and the bridge parapet or bridge rail end. The previously-described MGS transitions were designed to rely on post-soil resistive forces to develop the proper stiffness transition. Installation of this type of transition or portions of the approach guardrail upstream of the transition adjacent to slopes could alter the lateral stiffness and performance of the transition system. Previous research at MwRSF investigated deviations in actual, installed transition systems as compared to the as-tested design [36]. For these real-world installations on slopes, researchers found an increased propensity for greater barrier deflection, rail pocketing, and vehicle snag. As such, application of the MGS adjacent to slope in any region inside the MGS approach guardrail transition may not be MASH TL-3 compliant and may require further research to verify its safety performance. However, slopes could be accommodated if the minimum 2-ft lateral barrier offset from the MGS to the slope break point is maintained.

Additionally, previous guidance for the MGS approach guardrail transition has noted that a minimum of 25 ft of standard MGS be installed upstream from the asymmetric W-to-thrie beam transition piece prior to switching to another MGS special application [33,35]. Thus, it is recommended that the MGS adjacent to slope should be placed no closer to the MGS approach guardrail transition than a minimum of 25 ft from the asymmetric W-to-thrie beam transition section, as shown in Figure 19.

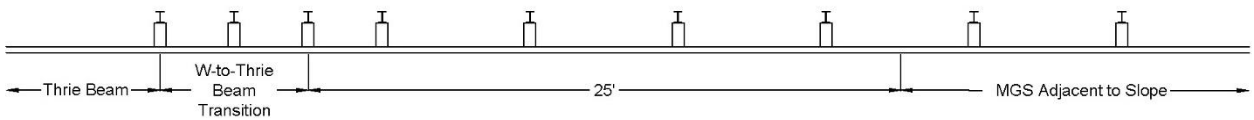


Figure 19. MGS Adjacent to Slope Offset from W-to-Thrie Beam Transition

3.4.5 MGS End Terminals Adjacent to Slopes

Finally, there may be a desire to implement the MGS installed adjacent to slopes near the ends of guardrail systems, which are typically anchored with some form of crashworthy end terminal or end anchorage. Installation of anchorage systems, such as generic, trailing-end anchorages, directly adjacent to a slope may not be MASH TL-3 compliant and may require further research to verify its safety performance as the reduction in soil near the anchorage may adversely affect its ability to develop the necessary tensile loads to restrain the barrier system and redirect impacting vehicles. Additionally, 1V:2H fill slopes are not considered to be safely traversable. Thus, any guardrail system shielding this type of steep slope should provide tensile anchorage outside the sloped area.

Crashworthy end terminals require specific grading requirement surrounding the end terminal to function properly. As such, it is recommended that guidance from any end terminal manufacturer be followed with respect to placement of their respective system adjacent to slopes. Additionally, the 2011 AASHTO *Roadside Design Guide* provides guidance regarding grading surrounding end terminals based on previous Federal Highway Administration (FHWA) memos [37,38]. This guidance would also be relevant for MGS end terminal applications if specific manufacturer guidance is not available.

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