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Non-Blocked, Midwest Guardrail System for Wire-Faced, MSE Walls

by

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ABSTRACT

Wire-faced, mechanically-stabilized earth (MSE) walls provide an economical method for constructing vertical structures for supporting roadways where local topography or high land costs preclude the use of conventional fill slopes. W-beam guardrail systems are often used for shielding high vertical drop-offs associated with MSE walls. For this study, the Midwest Guardrail System (MGS) was modified to decrease the overall width of the MSE wall structure. 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. Twenty-six dynamic tests were performed to evaluate the propensity for MSE wall damage, select post length, and determine the preferred post material and section.

The standard MGS was modified by removing the 12-in. (305-mm) deep wood spacer blocks and by incorporating W-beam backup plates. All other MGS features were maintained, including the 6-ft (1.8-m) long W6x8.5 (W152x12.6) steel posts, rail splices at mid-span locations, 31-in. (787-mm) top mounting height, and 75-in. (1,905-mm) post spacing. The non-blocked MGS was installed with the posts driven at the slope break point of a 3H:1V fill slope. The modified MGS was successfully crash tested using both 1100C small car and 2270P pickup truck vehicles according to Test Level 3 (TL-3) safety performance guidelines provided in the *Manual for Assessing Safety Hardware* (MASH). The MSE wall was not damaged during the testing programs. The non-blocked MGS is 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.

Keywords: Roadside Safety, Midwest Guardrail System, MGS, Non-Blocked Guardrail, Fill Slope, Rock Gabion, MSE Wall, MASH, Post Testing, Crash Testing

INTRODUCTION

Wire-faced, rock gabion or mechanically-stabilized earth (MSE) walls provide an economical method for constructing nearly vertical walls adjacent to roadways where the local topography or the high cost of land precludes the use of conventional fill slopes. These gabion walls incorporate wire mesh layers, cages, or baskets for surrounding and containing the angular aggregate or larger stones. The sequential placement of these layers or cages allow for a nearly vertical surface to be formed at the outside edge of the structure. While an economical solution for slope stability, gabion walls create safety issues by producing deep vertical drop offs adjacent to the roadway. Furthermore, the Federal Lands Highway Division (FLHD) of the Federal Highway Administration (FHWA) designs and constructs a large number of wire-faced, MSE walls throughout the United States (U.S.). The accepted practice of the FLHD is to install conventional guardrail more than 6 ft (1.8 m) from the exterior face of the gabion wall, as measured to the back of the wood posts. This required lateral offset increases project costs and can result in additional environmental impacts on FLHD projects. Unfortunately, a method for anchoring crashworthy barrier systems at or near the outside face of a wire-faced, MSE wall is unavailable. Therefore, there existed a need to develop an economical barrier system that would either reduce the large lateral offset currently required when placing standard guardrails on MSE walls or decrease the overall width of the MSE wall structure.

W-beam guardrail systems are normally used to prevent motorists from striking serious hazards adjacent to low and medium service level highways. However, these barriers rely on energy dissipation associated with the rotation of guardrail posts in soil and incur significant dynamic deflections during design impact events. The economics of MSE wall construction would dictate minimizing the lateral width required for the shoulder, guardrail system, and soil fill placed behind the guardrail. Additionally, the tradeoff between damage incurred to the MSE wall during a vehicular impact event and the initial cost of construction is an important consideration. Some barrier systems have been designed for attachment to the exterior vertical surface of wire-faced, MSE walls with the intent to mitigate damage to the MSE wall system. These modified barriers have incorporated long, exterior-mounted, vertical posts and/or rigid sleeves for anchoring guardrail posts, as well as costly foundation hardware placed within the MSE wall, such as long steel anchor rods, plates, and reinforced concrete beams. Unfortunately, these unique barrier and anchorage systems have not been evaluated according to impact safety standards using full-scale crash testing.

Full-scale crash testing of strong-post, W-beam guardrails installed in rigid foundations, such as solid rock, asphalt pavements, and concrete mow strips, has shown that preventing the posts from absorbing energy by rotating in the soil severely limits the barrier's ability to contain and redirect large passenger vehicles, such as light trucks and SUVs [1-2]. Therefore, the optimum barrier system would minimize damage to the MSE wall structure and decrease the required lateral offset between the guardrail face and the outside vertical edge of the MSE wall system.

The Midwest Guardrail System (MGS) has demonstrated improved vehicle containment, safety performance, and redirective capacity over that provided by conventional, strong-post, W-beam guardrail systems [3-12]. The MGS utilizes mid-span guardrail splices, an increased top rail mounting height of 31 in. (787 mm), an increased blockout depth of 12 in. (305 mm), and a reduced post embedment of 40 in. (1,016 mm). From the seemingly simple design changes, the redirective capacity of the MGS has proven to more than double that provided by standard W-beam guardrail systems [3-12]. The MGS has also been shown to provide satisfactory safety performance when used in combination with curbs, culverts, slopes, and other roadside anomalies. Thus, a modified MGS was considered for use in shielding the hazardous, vertical drop-offs created by the construction of wire-faced, MSE walls.

RESEARCH OBJECTIVES

The primary research objective was to develop an economical barrier system for safely treating vertical drop-offs located at the outside edge of gabion wall systems. During high-speed, high-energy impacts with passenger vehicles, the new barrier system should not impart unreasonable damage to the MSE wall system. In addition, the new barrier system should be easily replaced or repaired without requiring extensive repairs to the MSE wall structure. As a result, the standard MGS was to be considered for modification and use on or near the edge of wire-faced, MSE walls. 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) [13]. This study was performed by the Midwest Roadside Safety Facility (MwRSF) in cooperation with the FHWA, FLHD. Further details pertaining to this research study can be found in two MwRSF research reports [14-15].

MIDWEST GUARDRAIL SYSTEM (MGS)

The MGS has demonstrated excellent safety performance when modified for use in treating hazardous terrain. More specifically, full-scale crash testing has demonstrated that the MGS can successfully contain and redirect heavy passenger vehicles when placed in close proximity to both vertical drop-offs adjacent culverts headwalls and 2H:1V fill slopes [16-19].

First, the MGS was adapted to span across concrete box culverts measuring 24-ft (7.3 m) wide or less, as measured parallel to the roadway [16-17]. The long-span MGS system utilized three timber breakaway CRT posts, measuring 6 in. (152 mm) wide by 8 in. (203 mm) deep by 6 ft (1,829 mm) long and spaced on 6 ft – 3 in. (1,905 mm) centers, both on the upstream and downstream ends of the culvert system. During the crash testing program, the MGS contained a 2270P pickup truck even after allowing it to extend approximately 3 ft (0.9 m) beyond the edge of the vertical drop off and later redirected it back onto the traveled-way without serious risk to the occupants.

The MGS was also modified to allow for post placement at the slope break point of a 2H:1V fill slope [18-19]. This MGS design variation incorporated W6x9 (W152x13.4) steel posts measuring 9 ft (2.7 m) long and spaced on 6 ft – 3 in. (1,905 mm) centers. For this study, the modified MGS safely contained and redirected a 2270P pickup truck even when a maximum dynamic barrier deflection of 57.6 in. (1,463 mm) was observed.

Both MGS design variations were successfully crash tested and evaluated according to the TL-3 safety performance guidelines provided in MASH. Based on these results, the research team believed that the MGS could also be modified for use on top of or near the edge of wire-faced, MSE gabion walls.

DESIGN CONSIDERATIONS

Design concepts were developed for use in treating vertical drop-offs created with the construction of wire-faced, MSE wall systems. These concepts considered several factors, including: (1) control of project costs through a reduction in the lateral offset used for placing barrier systems or a decrease in the overall width of the gabion wall structure; (2) environmental impacts on FLHD projects, such as increased excavation into mountainous terrain or increased structure encroachment into nearby streams and forests; (3) use of an economical barrier system; (4) concerns for damage to the MSE wall structure; (5) placement of an approximately 6-ft (1.8-m) wide, 3H:1V fill slope at the top outer edge of MSE wall structure to help control erosion and mitigate structure damage; and (6) use of beam and post barriers either possessing flexibility to address aesthetics or providing openness for enhanced visualization of surroundings.

Using the noted design considerations, four similar barrier concepts were proposed that were based on the use of the MGS. Concept no. 1 consisted of a standard MGS located 24 in. (610 mm) forward from the slope break point (SBP), as measured to back of post. Concept no. 2 consisted of a non-blocked MGS located 24 in. (610 mm) forward from the slope break point, as measured to back of post. A standard MGS with the post centered at the slope break point was selected for Concept no. 3. Finally, Concept no. 4 utilized a non-blocked MGS with the post centered at the slope break point.

One additional barrier concept was proposed which did not utilize the 6-ft (1.8-m) wide, 3H:1V fill slope. Instead, the barrier concept utilized a heavily-reinforced concrete slab and grade beam system that was placed on a mostly level surface. Concept no. 5 incorporated an aesthetic, glue-laminated (glulam) timber rail and post system which was placed at the top exterior edge of the MSE wall system using steel mounting brackets which attached to the concrete slab and grade beam.

The five barrier concepts were compared using relative reductions in the required width of the gabion wall structure as the primary metric along with reductions in the cost of the gabion wall structure as a function of width and changes in the installation cost for the various barrier systems. Concept no. 1 served as the basis for comparison; since, the barrier face was farthest from the outside edge of the gabion wall structure and required the greatest structure width.

A comparison of five barrier concepts is shown in Table 1. From this information, an incremental decrease in the required width of gabion wall structure was observed with the progression of Concept nos. 1 through 5. For example, Concept no. 2 provides a 1 ft (0.3 m) reduction in wall width as compared to Concept no. 1 due to the elimination of the 12-in. (305-mm) deep timber spacer blocks. Thus, the front face of the barrier is placed 1 ft (0.3 m) closer to the outside edge of the gabion wall system. When compared to Concept no. 1, the greatest cost reduction for the gabion wall structure was determined as $450/ft for Concept no. 5.

When the costs of barrier construction were evaluated, only one barrier concept (Concept no. 2) was found to be more economical than a standard MGS guardrail. The net cost reduction for this concept was found to be less than $2/ft and occurring from the removal of the timber spacer blocks, the use of shorter guardrail bolts, and the addition of a steel backup plate. Concept nos. 3 and 4 were estimated to be more costly than Concept no. 1 as a result of the anticipated need to increase post length near the 3H:1V fill slope. Concept no. 5 provided the greatest increase in barrier costs, $800/ft, as compared to Concept no. 1. This large increase resulted from the high material and labor costs associated with the construction of a side-mounted, glulam timber beam and post system with attachment to the heavily-reinforced, concrete slab and grade beam system.

Barrier costs and savings in gabion wall construction were combined to produce a net reduction in construction costs for each option. Each of the MGS barrier alternatives (Concept nos. 2 through 4) provided a net cost reduction for the gabion wall and barrier systems when compared to the baseline condition of Concept no. 1. For example, Concept no. 4 (i.e., non-blocked MGS with steel posts placed at the slope break point) provided the greatest net cost reduction of $158/ft when compared to the baseline configuration. Alternatively, the glulam timber beam and post configuration (Concept no. 5) actually produced a net cost increase when compared to baseline configuration (Concept no. 1). Based on the cost analysis and system comparison, the FLHD-MwRSF project team selected Concept no. 4 for further development and use on wire-faced, MSE walls.

TABLE 1 Comparison of Barrier Concepts for Use on Wire-Faced, MSE Wall System

Concept No.	System Description	Reduction Wall Width (ft)	Reduction Wall Cost ($/lineal ft)	Reduction Barrier Cost ($/lineal ft)	Net Cost Reduction ($/ft)
1	Standard MGS - Steel Post - 2 ft from SBP to Back of Post - 6 ft Post Length	NA	NA	NA	NA
2	Non-Blocked MGS - Steel Post - 2 ft from SBP to Back of Post - 6 ft Post Length	1	$50/ft	$2/ft	$52/ft
3	Standard MGS - Steel Post - Post Centered @ SBP - Est. 7 to 8 ft Post Length	2.25	$112/ft	($8/ft)	$104/ft
4	Non-Blocked MGS - Steel Post - Post Centered @ SBP - Est. 7 to 8 ft Post Length	3.25	$162/ft	($4/ft)	$158/ft
5	Glulam Timber Rail and Post - 1 ft from Rail Face to Edge	9	$450/ft	($800/ft)	($350/ft)

BARRIER DESIGN ISSUES

The implementation of Concept no. 4 for use with a MSE wall system presents three potential problems, including: (1) failure of the rail to release from the posts; (2) rail rupture arising from contact with a post flange; and (3) overly stiff guardrail posts.

If a guardrail fails to release from a post, the rail element can be pulled down when the post rotates in the soil. In extreme cases, the rail will become disengaged from the vehicle and allow it to override the barrier. Standard MGS guardrail incorporates a button head post bolt and a wooden spacer block. The small button head is more easily pulled through the post bolt slot, and the soft wood behind the rail eliminates the risk of the rail becoming pinched between the bolt head and the post flange. Elimination of the blockout could allow the rail to be pinched which would alter rail release characteristics. Further, removing the blockout and placing the posts in very stiff soil, such as in a MSE wall system, would be expected to change the nature of post deformation during an impact. The stiffened post would not deflect in advance of the impacting vehicle. Thus, the stiff post would be more likely to be contacted by the front wheel and pushed down parallel to the rail. In this situation, the post bolt could be pushed parallel to the rail without generating a significant pull-out force.

The post bolt pullout problem was examined using first principles. Initially the size of the shoulder on a standard post bolt was examined to determine if the rail element could actually become tightly pinched between the bolt head and the post flange. This dimensional analysis showed that a single layer of guardrail could not become tightly pinched and thus, a standard post bolt with underside lug could possibly be used with the MGS without blocks.

The second post bolt pull-out issue that was investigated related to the potential motion of the post parallel to the rail. In this situation, the post bolt would quickly reach the end of the slot in the rail. In this loading condition, the post bolt would need to begin to tear out the end of the slot in order to release the rail from the post. The shear force required to yield the region of the guardrail in contact with the side of the bolt was calculated using the bolt bearing equation shown below:

$$F_v = (\sigma_w)(t_w)(D_b) = 3{,}400 \text{ lbs } (15.1 \text{ kN})$$

where σ_w = yield strength of W-beam rail = 50 ksi
t_w = thickness of W-beam rail = 0.109 in.
D_b = bolt diameter = 0.625 in.

After the W-beam begins to yield, it will initially begin to buckle, which would produce out-of-plane tearing in the guardrail. A great number of out-of-plane tearing tests were conducted during development of the BEST guardrail end terminal [20-22]. The BEST impact head causes out-of-plane tearing to cut a W-beam guardrail into four longitudinal strips. Static compression tests with the W-beam rail pushed over the hardened cutters demonstrated that out-of-plane tearing forces were generally below the estimated bearing yield force shown above. Never-the-less, a 25 percent dynamic load factor was applied to the bearing force to produce a tear-out force estimate of 4,200 lbs (18.7 kN).

The post was modeled as a cantilever with a 4,200 lb (18.7 kN) resistive force at the top and a tire impact load applied 16 in. (406 mm) above the ground. This load condition was found to produce a plastic moment at the base of the post when the tire load approached 13,000 pounds (57.8 kN). This loading would produce approximately 5.5 g's on the MASH 1100C test vehicle. Note that this acceleration is only slightly higher those experienced on some roller coasters. Hence, the force required to reduce bolt tear out along the rail should not produce unsafe decelerations, even for impacts with an 1100C small car vehicle.

The concern for guardrail tearing when contacted by a post flange was resolved by reviewing prior crash test findings. Historical testing has shown that small cuts can be produced in a W-beam guardrail when it becomes trapped between the edge of a post flange and an impacting vehicle [23]. The traditional solution to this problem has been to incorporate plates to prevent the rail from directly contacting a post. This inexpensive solution was incorporated into the new barrier.

The final concern was that excessively stiff guardrail posts would not absorb enough energy and thereby lead to rail rupture. Note that guardrail posts were expected to be significantly stiffer because the posts were driven into a well-compacted, crushed limestone soil material adjacent to the baskets of large rocks and with the bottoms of the posts penetrating into the wire-mesh layers of compacted, crushed limestone. The large rocks inside the wire baskets were essentially constrained from any significant movement. Thus, the base of the posts adjacent to the baskets of rocks and penetrating into the wire-mesh layers would likely be constrained against lateral movement and rotation, thus potentially resulting in premature lateral torsional buckling and reduced energy dissipation. In order to investigate the post stiffness when installed in a MSE wall system, a series of dynamic bogie tests were conducted to determine the appropriate guardrail post length to support the guardrail and prevent damage to the MSE wall system. As summarized below, these dynamic post tests in the MSE wall produced high soil resistance, but the posts did not fail in lateral torsional buckling.

DYNAMIC COMPONENT TESTING

Dynamic component testing was utilized to determine the post-soil behavior of steel and wood posts placed in compacted, soil material representative of that used for constructing wire-faced, MSE walls. This post testing program was also used to: (1) investigate the dynamic response of posts placed on 3H:1V fill slopes using alternative post installation methods; (2) evaluate the propensity for rotating posts to inflict damage to the MSE wall system; (3) select the appropriate post length ranging between 6 and 9 ft (1.8 and 2.7 m); and (4) evaluate common guardrail post sections, including 6-in. x 8-in. (152-mm x 203-mm) wood posts as well as W6x9 (W152x13.4) and W6x8.5 (W152 x 12.6) steel sections [15].

A total of twenty-six dynamic tests were conducted during four rounds of testing on 6-in. x 8-in. (152-mm x 203-mm) wood posts, W6x16 (W152x23.8) steel posts, W6x9 (W152x13.4) steel posts, and W6x8.5 (W152 x 12.6) steel posts of multiple lengths and soil embedment depths. The posts were impacted 24⅞ in. (632 mm) above the ground line.

For each bogie test, raw acceleration data was acquired and filtered, and then force vs. displacement and energy vs. displacement graphs were plotted. From the energy vs. displacement graphs, the average post-soil forces were calculated for displacements of 15 and 20 in. (381 and 508 mm) at the center rail height. Different soil gradations, terrain (i.e., level or sloped fill), installation methods, and levels of soil compaction were evaluated. A summary of the results from the four rounds of post testing can be found in the two MwRSF research reports [14-15]. The force versus deflection results from the dynamic component testing program and pertaining to driven steel posts placed in the MSE wall system are shown graphical in Figure 1. In addition, typical post and soil deformations are shown for a 6-ft (1.8-m) long W6x8.5 (W152x12.6) steel section installed at the slope break point of a 3H:1V fill slope.

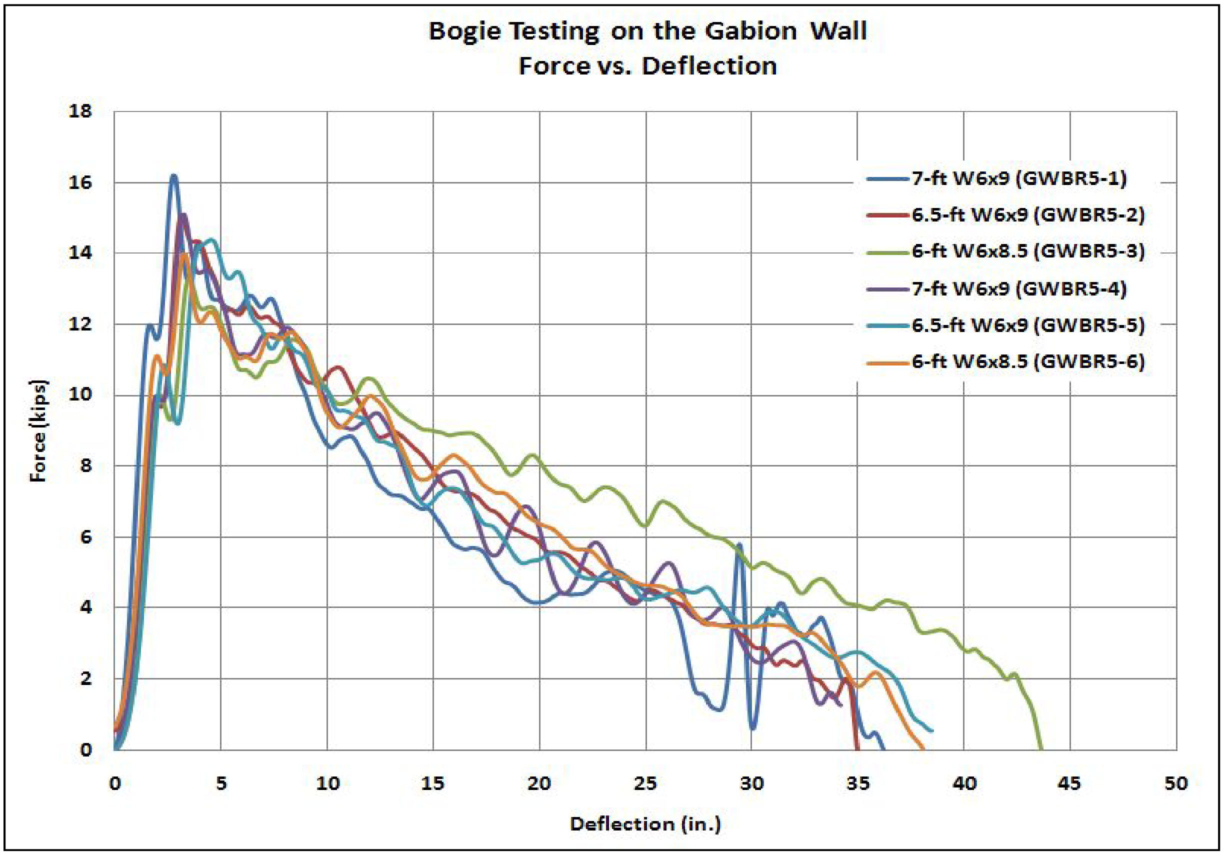
From the component testing program, post-soil forces and energy dissipation characteristics for steel posts were compared to those results obtained from the original MGS research and development program [3-5, 24]. From that original study, the baseline average post-soil resistance for standard steel posts installed in level terrain was found to be approximately 6.4 kips (28.5 kN) over 15 in. (381 mm) of deflection. From the FHWA testing program described herein, a standard 6-ft (1.8-m) long steel guardrail post installed at the slope break point of the sloped MSE wall system provided an average post-soil resistance of 9.8 kips (43.6 kN) over 15 in. (381 mm) of deflection. Thus, the research team believed that the 6-ft (1.8-m) long steel post would allow the MGS to perform in an acceptable manner and meet current impact safety standards but with reduced barrier deflections from those observed in the original R&D program.

Following the completion of 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, rock gabion or MSE wall; and (4) posts installed using a 40-in. (1,016-mm) embedment depth.

TEST REQUIREMENTS AND EVALUATION CRITERIA

Longitudinal barriers, such as W-beam guardrails, have been required to satisfy the impact safety standards provided in MASH to be accepted by the FHWA for use on National Highway System (NHS) construction projects or as a replacement for existing designs not meeting current safety standards. According to TL-3 criteria found in MASH, longitudinal barriers must be subjected to two full-scale vehicle crash tests: (1) a 2,425-lb (1,100-kg) passenger car impacting at a speed of 62 mph (100 km/h) and at an angle of 25 degrees and (2) a 5,000-lb (2,268-kg) pickup truck impacting at a speed of 62 mph (100 km/h) and at an angle of 25 degrees.

The evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the guardrail to contain and redirect the vehicle. In addition, controlled lateral deflection of the test article is acceptable. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Vehicle trajectory after collision is a measure of the potential for the post-impact trajectory of the vehicle to result in multi-vehicle accidents. This criterion also indicates the potential for safety hazard for the occupants of other vehicles or occupants of the crash vehicle when subjected to secondary collisions with other fixed objects. These three evaluation criteria are described in greater detail in MASH. Finally, the full-scale vehicle crash tests were conducted and reported in accordance with the procedures provided in MASH.



(a)

(b)

FIGURE 1 (a) Force Versus Deflection Results for Posts Driven into Sloped MSE Wall and (b) Typical Post-Soil Deformation

DESIGN DETAILS

The standard MGS formed the basis for the barrier system utilized with the wire-faced, MSE wall system. However, the MGS was modified by removing the 12-in. (305-mm) deep wood spacer blocks and incorporating W-beam backup plates. In addition, all other MGS features were maintained, including the use of 6-ft (1.8-m) long W6x8.5 (W152x12.6) steel posts, rail splices at mid-span locations, a 31-in. (787-mm) top mounting height, as well as the 75-in. (1,905-mm) post spacing. The non-blocked MGS was installed at the slope break point of a 3H:1V fill slope using an approximate lateral offset of 6 ft (1.8 m) to the outer edge of the wire-faced, MSE wall.

Design details and photographs of the non-blocked MGS installed on top of a MSE wall system are shown in Figure 2. The test installation was 175 ft (53.3 m) long and consisted of standard 12-gauge (2.66-mm thick) corrugated W-beam guardrail supported by steel posts. The entire system was constructed with twenty-nine posts. Post nos. 3 through 27 were galvanized ASTM A36 W6x8.5 (W152x12.6) steel sections measuring 72 in. (1,829 mm) long. Post nos. 1, 2, 28, and 29 utilized timber Breakaway Cable Terminal (BCT) posts measuring 5½ in. wide x 7½ in. deep x 46 in. long (140 mm x 190 mm x 1,168 mm) and were placed in 72-in. (1,829-mm) long steel foundation tubes. A tangent anchorage system was utilized on the upstream and downstream ends of the guardrail system in order to develop the barrier's tensile capacity. The anchorage system consisted of timber posts, foundation tubes, anchor cables, bearing plates, rail brackets, and channel struts, which closely resembled the hardware used in the Modified BCT system.

Post nos. 1 through 29 were spaced on 75 in. (1,905 mm) centers. For post nos. 3 through 27, the soil embedment depth was 40 in. (1,016 mm), and the posts were driven into the soil at the slope break point of a 6-ft (1,829-mm) wide, 3H:1V fill slope located on the wire-faced, rock gabion wall. Wood spacer blocks were not used to offset the rail away from the front face of the steel posts. However, 12-gauge (2.66-mm thick) W-beam backup plates, measuring 12 in. (305 mm) in length, were located between the rail and the front face of the steel posts.

The center rail mounting height of the W-beam rail was 24⅞ in. (632 mm). All guardrail splice connections between the rail sections were lapped in the direction of traffic to reduce vehicle snag at the splice during the crash tests.

The actual, wire-faced, rock gabion wall system measured 84 ft (25.6 m) in length and was configured with a 3H:1V fill slope at its outer edge. The gabion wall was located behind post nos. 9 through 21, as shown in Figure 2. The gabion wall was placed in an excavated pit measuring 11 ft – 10 in. (3.6 m) wide by 7 ft (2.1 m) deep with three 2-ft (0.6-m) thick layers of roller-compacted, course, crushed limestone material that met Grading B of AASHTO M147-65 denoted in MASH [13] and NCHRP Report No. 350 [25], which also closely conformed to select wall backfill material denoted in Sections 255 and 704 of the 2003 FHWA Standards Specifications for Highway Construction of Roads and Bridges on Federal Highway Projects [26]. The outer region of the bottom two layers contained a wall facing fill material that consisted of 4 to 6-in. (102 to 152-mm) diameter rocks that were placed by hand. A 4-ft (1.2-m) wide void space was excavated behind the MSE wall system. Steel-wire reinforcement mats were used to construct and stabilize the MSE wall system. Further details on the construction of the MSE wall system can be found in the MwRSF research report [14].

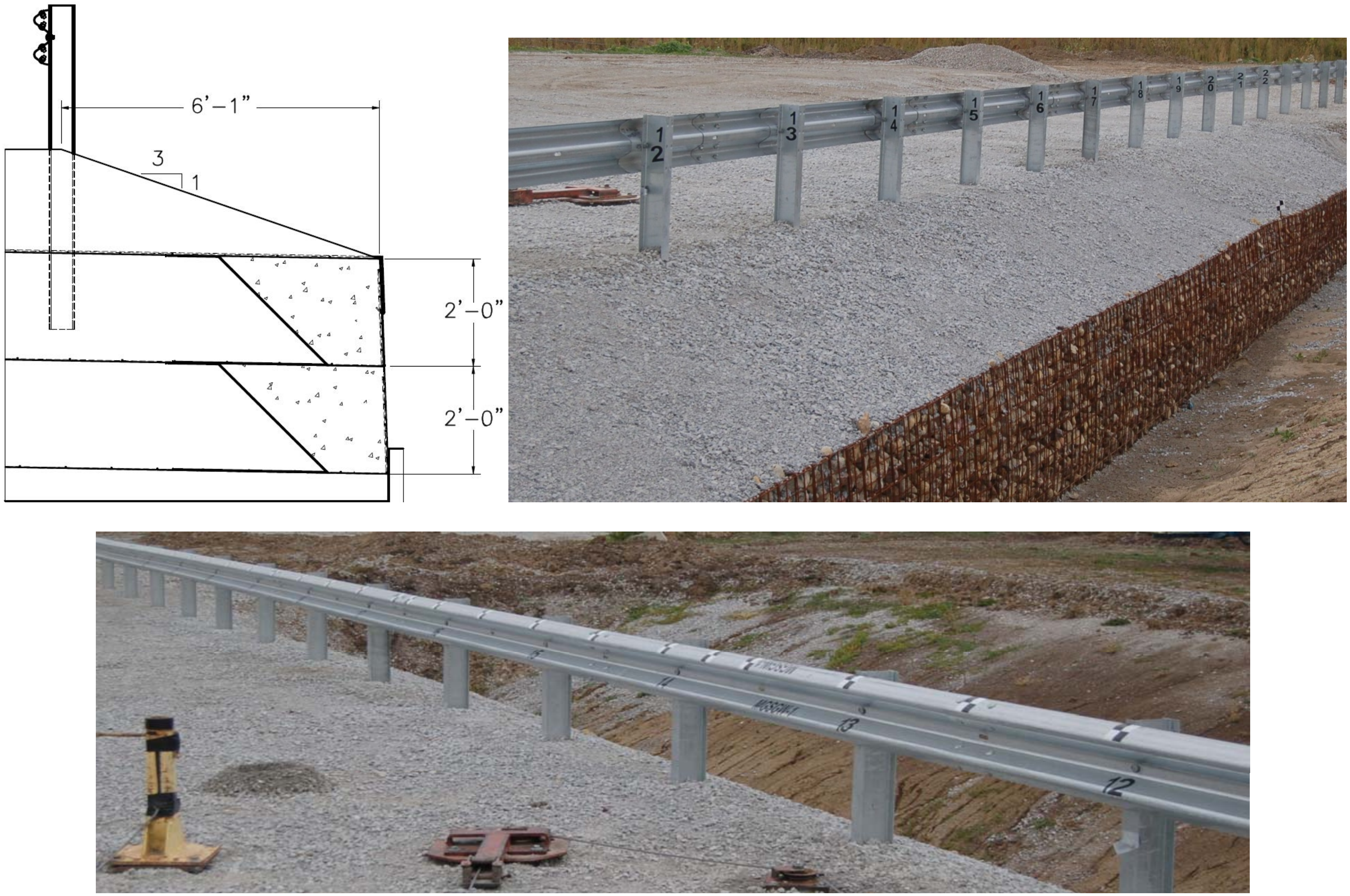


FIGURE 2 Non-Blocked MGS for MSE Wall Systems

FULL-SCALE CRASH TESTING

Test No. MGSGW-1 – Small Car Test

For test no. MGSGW-1, a 2,596-lb (1,178-kg) small car with a simulated occupant seated in the right-front seat, impacted the non-blocked MGS placed on top of the gabion wall system at a speed of 61.0 mph (98.2 km/h) and at an angle of 25.3 degrees. A summary of the test results and the sequential photographs are shown in Figure 3. Initial impact occurred at 4 ft – 5 in. (1.3 m) upstream from the centerline of the splice between post nos. 14 and 15. By 0.238 sec after impact, the vehicle was redirecting and nearly parallel to the guardrail. At this point, the vehicle snagged on post no. 14 and yawed about the front of the vehicle. At 0.726 sec and after yawing significantly, the vehicle exited the guardrail at an angle of 58.3 degrees and at a speed of 10.2 mph (16.3 km/h). The exterior vehicle damage, as shown in Figure 4, was moderate, and the interior occupant compartment deformations were minimal, with a maximum deformation of 1¼ in. (32 mm), consequently not violating the limits established in MASH. As shown in Figure 4, damage to the barrier was moderate, consisting mostly of deformed W-beam rail and steel guardrail posts as well as contact marks on guardrail and posts. The maximum lateral dynamic rail and post deflections were 27.4 in. (696 mm) at the mid-span between post nos. 15 and 16 and 26.2 in. (665 mm) at the centerline of post no. 14, respectively, as determined from high-speed digital video analysis. The working width of the system was 35.7 in. (907 mm), as determined from high-speed digital video analysis. All occupant risk measures were well below recommended values, and the test vehicle showed no tendency to roll over. A summary of the impact conditions and test results are shown in Table 3. Therefore, test no. MGSGW-1 was determined to be acceptable according to the TL-3 safety performance criteria found in MASH.

Test No. MGSGW-2 – Pickup Truck Test

For test no. MGSGW-2, a 5,169-lb (2,345-kg) pickup truck with a simulated occupant seated in the right-front seat, impacted the non-blocked MGS placed on top of the gabion wall system at a speed of 65.3 mph (105.0 km/h) and at an angle of 25.1 degrees. A summary of the test results and the sequential photographs are shown in Figure 5. Initial impact occurred at 16 ft (4.9 m) upstream from the centerline of the splice between post nos. 14 and 15. At 0.230 sec after impact, the vehicle became parallel to the guardrail with a speed of 46.7 mph (75.2 km/h). At 0.452 sec, the vehicle exited the guardrail at an angle of 20.4 degrees and at a speed of 43.8 mph (70.5 km/h). The vehicle was smoothly redirected even though the vehicle encountered moderate pitching. Vehicle pitching occurred when the driveshaft was disconnected and lodged in the ground, thus allowing the vehicle's undercarriage to snag on the shaft's exposed end. The exterior vehicle damage, as shown in Figure 6, was moderate, and the interior occupant compartment deformations were minimal, with a maximum of 1½ in. (38 mm), consequently not violating the limits established in MASH. As shown in Figure 6, damage to the barrier was moderate, consisting mostly of deformed W-beam and guardrail posts as well as contact marks on guardrail and posts.

During this test, the locations of the post bolts were varied within the rail slots in order to investigate rail release away from the posts. As a result of this variance, maximum rail tearing due to post bolt pulling through the slot occurred when the post bolt was located at the upstream end of the rail slot, as shown in Figure 7. The maximum lateral dynamic rail and post deflections were 35.7 in. (907 mm) at the mid-span between post nos. 13 and 14 and 35.7 in. (907 mm) at the centerline of post no. 14, respectively, as determined from high-speed digital video analysis. The working width of the system was 45.2 in. (1,148 mm), as determined from high-speed digital video analysis. All occupant risk measures were well below recommended values, and the test vehicle showed no tendency to roll over. A summary of the impact conditions and test results are shown in Table 3. Therefore, test no. MGSGW-2 was determined to be acceptable according to the TL-3 safety performance criteria found in MASH.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A design review, cost comparison, and evaluation was performed on existing barriers and new barrier concepts for consideration in protecting hazardous conditions that arise from the construction of wire-faced, MSE walls. From this effort, a non-blocked MGS with steel posts placed at the slope break point of a 3H:1V fill slope (Concept no. 4) was found to provide the greatest net cost reduction, or $158/ft, when compared to the baseline configuration of standard MGS with steel posts and a 2-ft (610-mm) lateral offset to the slope break point (Concept no. 1). Based on the cost analysis and system comparison, the FLHD-MwRSF project team selected Concept no. 4 for further development and use in protecting vertical drop-offs associated with wire-faced, MSE walls.

A total of 26 dynamic bogie tests were conducted to determine the post-soil behavior of steel and wood posts embedded in level and/or sloped terrain using a compacted soil material similar to that used for the construction of wire-faced, MSE walls. This post testing program was also used to evaluate different post placement methods, such as the auger, backfill, and tamp method versus driven posts, as well as to select the appropriate post length, determine the preferred post material, and evaluate the propensity for damage to occur to wire-faced, MSE walls during vehicular impacts into the barrier system. From this effort, a 6-ft (1.8-m) long steel guardrail post with a 40-in. (1,016-mm) embedment depth was selected for use in the MGS when located at the slope break point of a 3H:1V fill slope. A 6-ft (1.8-m) long steel guardrail post embedded into a roller-compacted, special MSE wall fill material, driven through the upper wire-mesh layer, and placed at the slope break point was found to provide adequate post-soil resistance for use in the MGS. In addition, dynamic component testing of steel posts driven at the slope break point did not reveal any concerns for damage to the wire-faced, MSE wall system.

The MGS was modified for use with a wire-faced, MSE wall system. The modified barrier system utilized 6-ft (1.8-m) long steel posts spaced on 75 in. (1,905 mm) centers, a top mounting height of 31 in. (787 mm) for the W-beam rail, and steel W-beam backup plates at the steel post locations. The 12-in. (305-mm) deep wood spacer or offset blocks were not utilized in this barrier system.

The non-blocked MGS was successfully crash tested using both the 1100C small car and 2270P pickup truck vehicles according to TL-3 safety performance guidelines provided in MASH. After the first full-scale crash test, the deformed posts were removed from the wire-faced, MSE wall. Subsequently, the soil region surrounding the locations of the damaged posts were filled with soil and re-compacted. Then, new steel posts were driven into the wire-faced, MSE wall at the slope break point in order to repair the MGS and for use in the second full-scale crash test. Following both crash tests, no damage was observed in the wire-faced, MSE wall system.

Based on this research program, the non-blocked MGS is recommended for use on top of wire-faced, MSE wall systems when the steel posts are placed at the slope break point of a 3H:1V fill slope. The non-blocked MGS provides an economical design variation of the MGS as well as compared to exterior-mounted, aesthetic, beam and post railing systems. In addition, the non-blocked MGS provides adequate vehicle containment, reduces the required width of the MSE wall with the elimination of a timber blockout, and results in decreased construction costs for the overall barrier and MSE wall system.

The roller-compacted soil fill material and mesh reinforcement within the wire-faced, MSE wall provided a stiff foundation for the driven, steel guardrail posts. This finding was made upon review of the post-soil responses observed in selected dynamic bogie tests as well as from the barrier deflections and working widths observed during the full-scale crash testing program. From the successful MASH crash testing program reported herein, it is the researcher's opinion that a non-blocked MGS would also perform satisfactorily when installed in standard soil placed on level terrain. However, the safety performance of a non-blocked MGS installed on level terrain can only be verified through full-scale crash testing.

Previously, it has been demonstrated that wood blockouts used in combination with the MGS greatly increases barrier capacity, reduces occupant risk, and improves the vehicle post-impact trajectory. Thus, the researchers recommend that 12-in. (305-mm) deep wood spacer blocks, or acceptable alternatives, be used with the MGS when the roadside geometry can accommodate a guardrail system with increased width.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration, Federal Lands Highway Division. This report does not constitute a standard, specification, or regulation.

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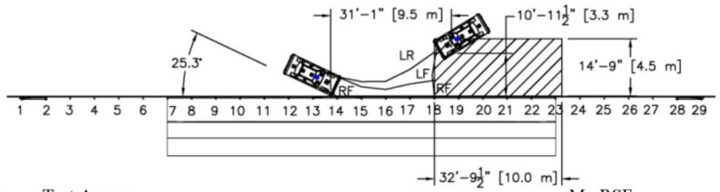
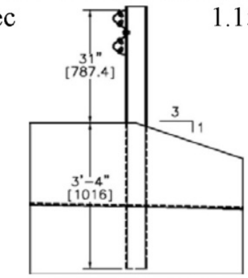


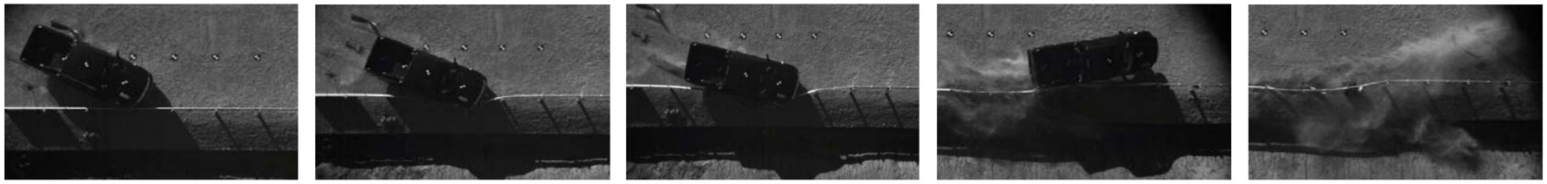


- Test Agency .... MwRSF
- Test Number MGSGW-1
- Date 10/20/2009
- MASH Test Designation 3-10
- Test Article .... Non-blocked MGS adjacent 3:1 slope of gabion wall
- Total Length .... 175 ft (53.4 m)
- Key Component – Steel W-Beam
  - Thickness .... 12 gauge (2.66 mm)
  - Top Mounting Height .... 31 in. (787 mm)
- Key Component – Steel Posts
  - Post nos. 3-27 .... W6x8.5 (W152x12.6) by 6 ft (1.8 m) long
  - Post Location .... Centerline of posts at slope break point
  - Spacing .... 6 ft - 3in. (1.9 m)
  - Blockout .... None
- Key Component – BCT Posts
  - Post nos. 1-2, 28-29 .... 5½ by 7½ by 46 in. (140x191x1, 168 mm)
  - Foundation Tube .... 6 ft (1.8 m) long
- Soil Type .... AASHTO M147-65 Grading B
- Vehicle Model .... 2003 Kia Rio Sedan
  - Curb .... 2,302 lb (1,044 kg)
  - Test Inertial .... 2,426 lb (1,101 kg)
  - Gross Static .... 2,596 lb (1,178 kg)
- Impact Conditions
  - Speed .... 61.0 mph (98.2 km/h)
  - Angle .... 25.3 deg
  - Impact Location ...... 4 ft - 5 in. (1.4 m) US of splice btwn posts 14 & 15
- Exit Conditions
  - Speed .... 10.2 mph (16.3 km/h)
  - Angle .... 58.3 deg
  - Exit Box .... Pass
- Vehicle Stability .... Satisfactory
- Vehicle Stopping Distance .... 31 ft-1 in. downstream
  .... 11 ft-3 in. (3.4 m) laterally from traffic-side face
- Vehicle Damage .... Moderate
  - VDS 1-FR-5
  - CDC 01-FZEW4
  - Maximum Interior Deformation .... 1¼ in. (32 mm) Right Toe Pan
- Test Article Damage .... Moderate
- Test Article Deflections
  - Permanent Set .... 20⅛ in. (511 mm)
  - Dynamic .... 27.4 in. (696 mm)
  - Working Width .... 35.7 in. (906 mm)
- Maximum Angular Displacements (DTS)
  - Roll .... -11.2° < 75°
  - Pitch .... -5.4° < 75°
  - Yaw .... 126.0°
- IS .... 58.97 kip-ft (80 kJ)
- Transducer Data

Evaluation Criteria		Transducer			MASH Limit
		EDR-3	DTS set 1	DTS set 2	
OIV ft/s (m/s)	Longitudinal	-22.62 (-6.89)	-25.87 (-7.89)	-22.45 (-6.84)	≤ 40 (12.2)
	Lateral	-16.51 (-5.03)	-17.07 (-5.20)	-16.53 (-5.04)	≤ 40 (12.2)
ORA g's	Longitudinal	-9.94	-13.78	-10.25	≤ 20.49
	Lateral	-6.54	-7.81	-7.40	≤ 20.49
THIV – ft/s (m/s)		NA	30.10 (9.17)	NA	not required
PHD – g's		NA	14.55	NA	not required
ASI		0.74	0.92	0.78	not required

FIGURE 3 Summary of Test Results and Sequential Photographs, Test MGSGW-1

FIGURE 4 Impact Location, Vehicle Damage, and Barrier Damage, Test MGSGW-1



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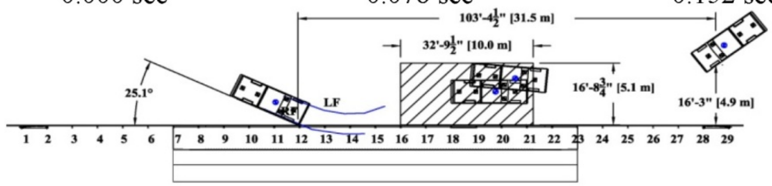

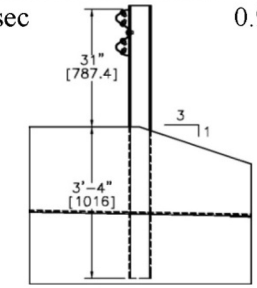

- Test Agency .... MwRSF
- Test Number MGSGW-2
- Date 11/20/2009
- MASH Test Designation 3-11
- Test Article .... Non-blocked MGS adjacent to 3:1 slope of gabion wall
- Total Length .... 175ft (53.4 m)
- Key Component – Steel W-Beam
  - Thickness .... 12-guage (2.66 mm)
  - Top Mounting Height .... 31 in. (787 mm)
- Key Component – Steel Posts
  - Post nos. 3-27 .... W6x8.5 (W152x12.6) by 6 ft (1.8 m) long
  - Post Location .... Centerline of posts at slope break point
  - Spacing .... 6 ft - 3 in. (1.9 m)
  - Blockouts .... None
- Key Component – BCT Posts
  - Post nos. 1-2, 28-29....... 5½ by 7½ by 46 in. long (140x191x1,186 mm)
  - Foundation Tube .... 6 ft (1.8 m) long
- Soil Type .... AASHTO M147-65 Grading B
- Vehicle Model .... 2003 Dodge Ram 1500 Quad Cab
  - Curb .... 5,081 lb (2305 kg)
  - Test Inertial .... 4,999 lb (2268 kg)
  - Gross Static .... 5,169 lb (2345 kg)
- Impact Conditions
  - Speed .... 65.27 mph (105.04 km/h)
  - Angle .... 25.1 deg
  - Impact Location .... 16 ft (4.9 m) US of splice btwn posts 14 & 15
- Exit Conditions
  - Speed .... 43.78 mph (70.46 km/h)
  - Angle .... 20.4 deg
  - Exit Box Criteria .... Fail
- Vehicle Stability .... Satisfactory
- Vehicle Stopping Distance .... 103 ft 4 ½ in.(31.5 m) downstream
  16 ft - 3 in. (4.9 m) laterally in front of traffic-side face
- Vehicle Damage .... Moderate
  - VDS 1-RFQ-3
  - CDC 01-RDEW2
  - Maximum Interior Deformation .... 1 1/4 in. (32 mm) right toe pan
- Test Article Damage .... Moderate
- Test Article Deflections
  - Permanent Set .... 26¼ in. (667 mm)
  - Dynamic .... 35.7 in. (907 mm)
  - Working Width .... 45.2 in. (1148 mm)
- Maximum Angular Displacements (DTS)
  - Roll .... 16.4 deg <75°
  - Pitch .... -15.7 deg <75°
  - Yaw .... 38.0 deg
- IS .... 132.3 kip-ft (180 kJ)
- Transducer Data

Evaluation Criteria		Transducer			MASH Limit
		EDR-3	DTS set 1	DTS set 2	
OIV ft/s (m/s)	Longitudinal	-17.25 (-5.26)	-17.85 (-5.44)	-16.91 (-5.15)	≤ 40 (12.2)
	Lateral	-17.71 (-5.40)	-18.26 (-5.57)	-17.56 (-5.35)	≤ 40 (12.2)
ORA g's	Longitudinal	-11.15	-11.99	-10.98	≤ 20.49
	Lateral	-8.76	-8.91	-10.37	≤ 20.49
THIV – ft/s (m/s)		NA	24.1 (7.35)	NA	Not required
PHD – g's		NA	12.73	NA	Not required
ASI		0.76	0.81	0.84	Not required

FIGURE 5 Summary of Test Results and Sequential Photographs, Test MGSGW-2

FIGURE 6 Impact Location, Vehicle Damage, and Barrier Damage, Test MGSGW-2

FIGURE 7 Damage Comparison of Varying Post Bolt Location

TABLE 2 Summary of Impact Conditions and Crash Test Results

Test No.	Test Designation and Description	Actual Impact Conditions		Occupant Risk				Comments	Assessment
		Speed mph (km/h)	Angle (deg.)	OIV ft/s (m/s)		ORA (g's)			
				Long.	Lat.	Long.	Lat.		
MGSGW-1	Test 3-10 1100C Small Car	61.0 (98.2)	25.3	-25.87 (-7.89)	-17.07 (-5.20)	-13.78	-7.81	The vehicle was safely contained and redirected with minor post snag.	**PASS**
MGSGW-2	Test 3-11 2270P Pickup Truck	65.3 (105.0)	25.1	-17.85 (-5.44)	-18.26 (-5.57)	-11.99	-8.91	The vehicle was safely contained and smoothly redirected.	**PASS**

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