APPLICATION OF A PRECAST CONCRETE BARRIER ADJACENT TO A STEEP ROADSIDE SLOPE

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ABSTRACT

When concrete barriers are installed adjacent to drop-offs or steep roadside slopes such as 1.5H:1V, a cast-in-place concrete moment slab is usually attached to the base of the barrier to resist lateral and overturning forces during vehicle impact. Cast-in-place construction can require more time on site to build forms, pour the concrete, and allow for curing. This results in an increase in disruption to traffic and more exposure for construction workers. Furthermore, the installation of a moment slab is very costly and requires an additional construction phase to build the slab. Since the slab is normally under the shoulder and possibly the lanes, the disruption of traffic flow is increased. This paper presents a new application of a precast 42-inch tall single slope concrete barrier for use in front of steep slopes, without requiring a moment slab. The lateral movement of the barrier is restricted by embedding it in soil. This design also reduces the embankment behind the barrier to two feet. The embedded barrier application was successfully evaluated under Manual for Assessing Safety Hardware test level 3 criteria. The permanent deflection of the barrier was 5.5 inches. The use of the embedded concrete barrier in lieu of the typically installed barrier with a moment slab is expected to result in cost savings of approximately $300 per linear foot and reduced time to construct.

INTRODUCTION

Roadside barriers are used to shield motorists from hazards located off the traveled way. A naturally occurring hazard common in mountainous regions and constrained environments is a steep, non-traversable roadside slope. Available right-of-way along highways in these regions is often restricted. Thus, it is desirable to place the barrier as close to the slope break point as possible in order to maximize available space for travel lanes and shoulders.

There are various types of roadside barriers that have met current crash test criteria and been accepted for use on the National Highway System. These barriers are generally categorized as flexible, semi-rigid, or rigid depending on their deflection characteristics. While flexible systems typically have lower injury probability due to their more forgiving nature, their use is often limited as a result of the space required to accommodate their high design deflections. Thus, when installing a barrier in close proximity to a steep, non-traversable slope, a semi-rigid or rigid system is often preferred.

Semi-rigid barriers include strong-post, corrugated beam (e.g. W-beam, thrie beam) guardrail systems. While variations of these systems have been successfully tested in close proximity to steep slopes *(1)*, their installation can be difficult due to deep embedment depths of the posts and/or smaller post spacing that are characteristic of these designs. Further, the maintenance and repair of impact damage required for these semi-rigid systems can pose additional risk to workers due to the close proximity of both traffic and the hazardous slope condition.

Use of a more rigid concrete barrier system can mitigate the cost and risk of maintenance and repair. They are often selected where space is constrained and only a small amount of deflection is allowable. These systems are also used where there is a frequent occurrence of impacts and a reduced maintenance is desired.

Concrete barriers can be cast in place or installed in precast sections. Cast-in-place construction can require more time on site to build forms, pour the concrete, and allow for curing. This results in an increase in disruption to traffic and more exposure for construction workers. Concrete barriers are typically designed with the barrier embedded in the ground, keyed in the pavement, or with some type of foundation to make them rigid. This configuration is fairly typical for median applications. However, there has not been any testing performed for these keyed or embedded barriers in a configuration where the barrier is installed on the roadside adjacent to a steep slope. Some of the concrete barriers designs have used vertical steel pins that pass through holes in the barrier and continue some distance into the ground to restrict lateral barrier movement. The barriers in these designs were tested while placed on asphalt or concrete pavements, which helped reduce deflections during vehicle impacts. Such designs however are typically used in temporary barrier applications.

In the absence of a restraining mechanism, designers recommend several feet of embankment behind a concrete barrier to develop the required strength and barrier stability during an impact. When this space is not available, current design practice requires the use of a below grade moment slab similar to the one depicted in Figure 1. However, the installation of a cast-in-place moment slab (which includes excavation, forming, concrete placement, and compaction of soil backfill) can be very expensive and requires an additional construction phase to build the slab. Since the slab is normally under the shoulder and possibly the lanes, the disruption of traffic flow is increased. There is a need for a cost-effective barrier system for use adjacent to steep slopes that has limited deflection and low maintenance and repair needs.

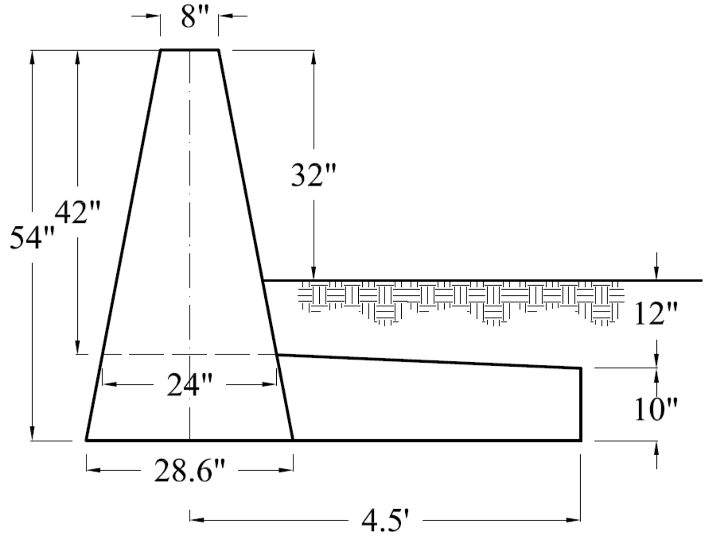


Figure 1: Single slope barrier with a moment slab.

OBJECTIVE

The objective of the research presented in this paper was to develop a cost-effective, concrete barrier system that can be placed in front of slopes as steep as 1.5H:1V. The design constraints excluded use of a moment slab and permitted no more than 2 ft of offset from the slope break point. The barrier system was required to meet the impact performance criteria recommended in the AASHTO Manual for Assessing Safety Hardware (MASH) *(2)*, and have a deflection of less than 12 inches for a design impact. If embedment of the barrier was required, the depth of embedment was limited to 10 inches.

DESIGN AND ANALYSIS

The design and analysis was performed using the single or constant slope barrier profile. This profile was used due to the ease of embedment if needed. A standard single slope barrier is 42 inches tall and can be embedded 10 inches without needing a change in its profile. At a 10 inch embedment, the barrier would still have a height of 32 inches above the ground, which is typical of most other concrete barriers such as the New Jersey and F-shape barriers. The barrier used in this research was precast with a 20-ft segment length. Adjacent barrier segments were connected using the grouted rebar-grid connection. This connection type and segment length is typically used by the participating pooled fund states.

Evaluation of the free-standing barrier

In 1989, Texas Transportation Institute performed crash testing of the single-slope barrier with the grouted rebar-grid connection, but the barrier was keyed into an asphalt layer which prevented its lateral movement. Another test was performed under the same project with the free-standing single slope barrier, but the rebar grid connection was not grouted *(3)*. To date, no testing has been performed with the single slope barrier using the grouted rebar-grid slot connection in a free-standing condition. As a first step, the researchers evaluated the performance of the free-standing single slope barrier. The objective of this evaluation was to determine if this connection provided sufficient strength to transfer moments between adjacent barrier segments and cause them to deflect as a single body during vehicle impact, without significant rotation at the joints. If this could be achieved, it was believed that the impacting vehicle can be contained and redirected without significant barrier deflection simply using the weight of the concrete barrier. This would have also rendered easiest solution to the design problem and allowed maximum flexibility in the use of the barrier.

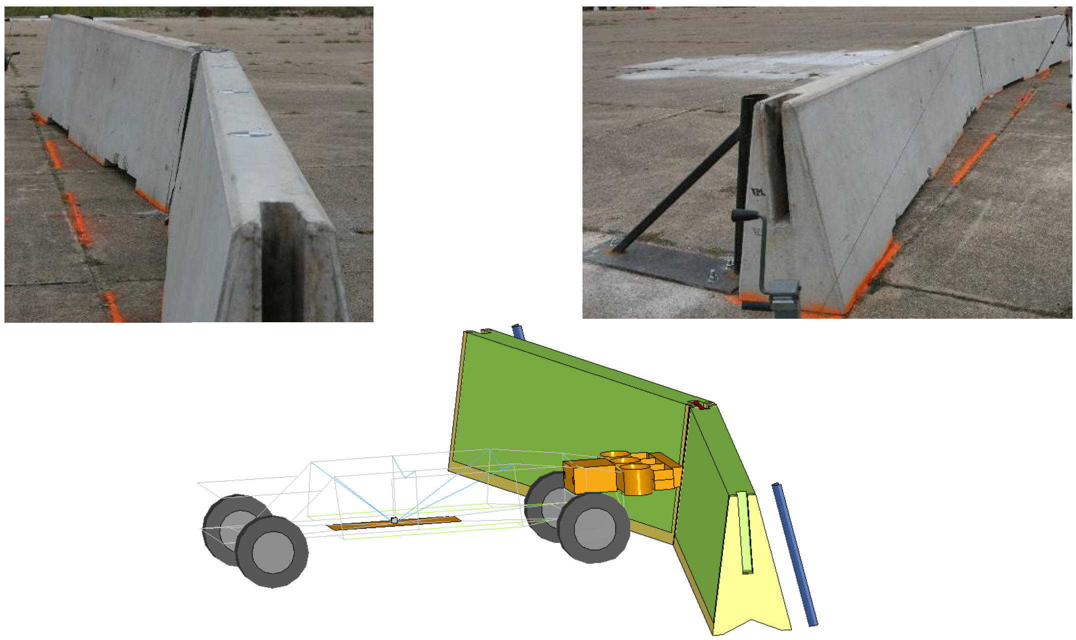
To evaluate the performance of the free-standing single slope barrier with grouted rebar-grid connection, the researchers first determined the response of a single barrier connection using surrogate bogie vehicle testing. Two 42-inch tall and 20-ft long single-slope barrier segments were connected using the grouted rebar-grid connection. The outside ends of the barrier segments were constrained from moving laterally by a 5 inch diameter pipe that was anchored to the concrete pavement as shown in Figure 2-a. A 5000-lb bogie vehicle impacted the barrier at the connection with an impact speed of 14 mi/h and an angle of 90 degrees. The impact in the test resulted in a maximum permanent lateral deflection of 22 inches. Due to the impact, the grouted rebar-grid connection cracked near the centerline of the connection.

The researchers used finite element modeling analysis for the evaluating the barrier performance during different stages of this research. General modeling and simulation approach are presented in this paper. Greater specifics about finite element modeling and analysis can be found elsewhere *(4)*.

A finite element model of the barrier installation used in the bogie test was developed. A surrogate grouted rebar-grid connection was modeled with a block of bi-linear elastic-plastic material and a rebar-grid comprising of beam elements. Simulations were performed with a 5000-lb bogie vehicle impacting the barrier connection at test speed and location. The properties of the surrogate connection in the simulation were calibrated to match the lateral deflection of the barrier observed in the test. Figure 2-b shows the calibrated simulation results compared to the crash test results.

Once the response of a single grouted rebar-grid connection was calibrated, the researchers used it to develop a full-scale barrier system model of a 100-ft long installation of the free-standing single slope barrier. It was then evaluated under MASH Test Level 3 impact conditions (i.e. impact with a 5000-lb vehicle at 62 mi/h and 25 degrees). The objective of this simulation was to determine if the overall lateral deflection of the free-standing barrier installation was small enough to allow its use adjacent to steep slopes. The barrier system model comprised of five 20-ft long single slope barrier segments that were connected using the calibrated grouted rebar-grid connection model. A 5000-lb vehicle impacted the barrier 4 ft upstream of the connection between the second and the third barrier segment. Simulation results indicated that the free standing barrier will result in deflection of greater than 30 inches in a full-scale 5000-lb vehicle impact at 62 mi/h and 25-degrees. This deflection was much higher than acceptable as per the objectives of this research. Hence the researchers started evaluating the performance of the barrier when restrained by embedding it in soil.

(a) Bogie test setup



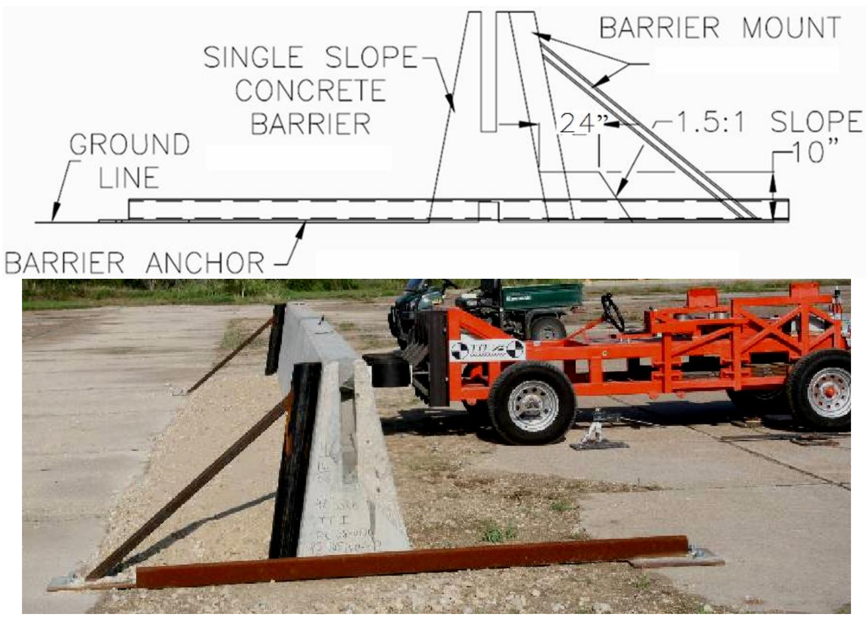
(b) Test and simulation results

Figure 2: Evaluation of free standing rebar-grid connection using bogie testing and simulation analysis.

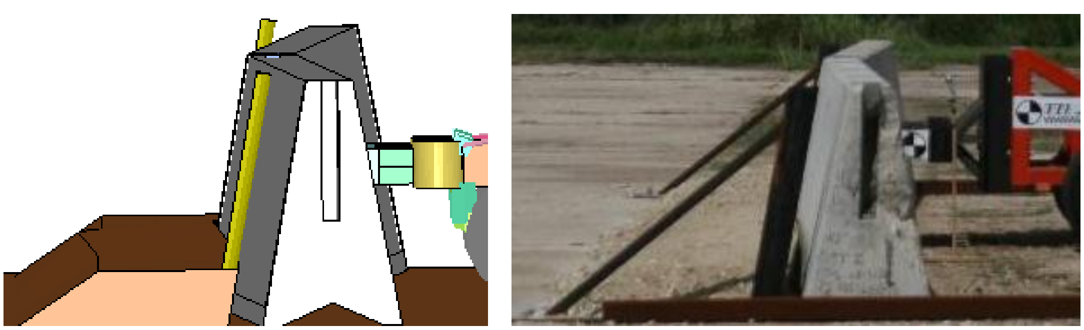
The vehicle model used in the simulation analysis was originally developed by National Crash Analysis Center with further modifications from TTI researchers. This 4409-lb pickup truck model was developed and widely used as a design vehicle model specified in National Cooperative Highway Research Program (NCHRP) Report 350 criteria *(5)*, which preceded the more recent MASH criteria. While NCHRP Report 350 required a 4409-lb, ¾-ton, standard cab pickup truck, MASH requires a 5000-lb, ½-ton, 4-door pickup truck. A public domain finite element model of the 5000-lb, ½-ton, 4-door pickup truck was not available during the period of this research. The researchers increased the mass of the available 4409-lb pickup truck model by distributing additional mass over different parts of the vehicle and bringing the total vehicle mass to 5000-lb. Doing so enabled the researchers to impart the same level of impact energy into the barrier system as required by MASH. Due to the differences in vehicle types and vehicle inertia characteristics, it was expected that the vehicle dynamics response of the 5000-lb vehicle model will not match the vehicle response observed in a crash test. However, previous testing of the single-slope barrier had shown that the vehicle remains fairly stable during the impact *(3)*. Thus the vehicle dynamic characteristics were not deemed as critical and accounting for the increased vehicle mass was expected to enable a successful evaluation of the barrier system for the MASH criteria.

Evaluation of the embedded barrier

To evaluate the barrier in embedded configuration, the researchers conducted another bogie impact test with two single-slope barrier segments connected via grouted rebar-grid connection and embedded 10 inches in soil behind the barrier. The width of the soil was 24 inches behind the barrier and a 1.5H:1V slope was used for the soil cut, as shown in the test setup in Figure 3-a. The type of soil and the compaction method used were as specified in the MASH criteria. Use of this bogie test helped evaluate the response of a single grouted rebar-grid connection when embedded in a 10-inch soil layer. As a result of the impact from a 5004-lb bogie vehicle at a speed of 14.4 mi/h, the maximum permanent barrier deflection was 4.45 inches at the joint. The researchers then incorporated the 10-inch soil layer into the finite element model of the bogie test and calibrated soil properties to match the barrier deflection observed in the test (see Figure 3-b).



(a) Bogie test setup



(b) Test and simulation results

Figure 3: Evaluation of the embedded barrier with grouted rebar-grid connection using bogie testing and simulation analysis.

Once the response of a single grouted rebar-grid connection with soil behind the barrier was calibrated, the researchers developed a full-scale system model to evaluate a 100-ft long installation. The installation model comprised of five 20-ft long single-slope barrier segments connected using grouted rebar-grid connection and embedded 10 inches in soil in front and behind the barrier. The widening of the soil behind the barriers was two feet and the slope of the soil embankment was 1.5H:1V, as in the bogie test. A simulation was performed with a 5000-lb vehicle impacting the barrier at 25 degrees and 62 mi/h. The vehicle impacted the barrier 4 ft upstream of the connection between the second and the third barrier segment. The vehicle was successfully contained and redirected by the embedded barrier system in a stable manner (see Figure 4). The maximum permanent deflection of the barrier was 9.75 inches, which was within the 12-inch limit specified in the design objectives.

Based on results of the simulation analysis, the researchers recommended performing a crash test with the single slope barrier by embedding it 10 inches in soil.

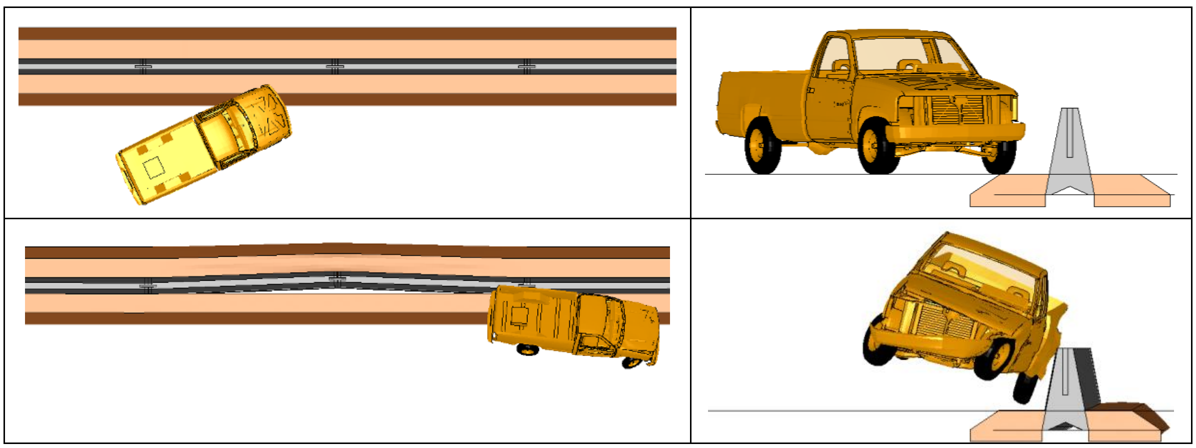


Figure 4: Simulation results with 100-ft installation of single slope barrier embedded 10 inches in soil (initial (top) and final (bottom) states).

FULL-SCALE CRASH TEST

Test Article Design and Construction

The test article comprised of a 100-ft long installation of single-slope concrete barrier that was embedded 10 inches in soil. Five 20-ft long barrier segments were connected using the grouted rebar-grid slot connection to achieve the 100-ft installation length.

The single-slope barrier segments were 42 inches tall, 24 inches wide at the base and 8 inches wide at the top. At each end of the barrier segments, a 3-inch wide, 24-inch deep, and 10.5-inch long slot was cast into the barrier to incorporate the grouted rebar-grid connection. The concrete reinforcement of the barrier segments comprised of #4 vertical bars that were bent to approximately match the profile of the barrier faces and were spaced 12 inches apart along the length of the barrier. The spacing of the vertical bars was reduced around the slot cast at each end for the grouted rebar-grid connection. In addition to the vertical bars, ten #5 longitudinal bars were located along the height of the barrier. The barrier segments had a 4-inch wide and a 2-inch high slot cast at the bottom.

The barrier was embedded in crushed limestone road base material that conformed to MASH standard soil. To embed the barrier a 2-ft depth of the native soil adjacent to the testing facility's concrete pavement was excavated. The excavated area was then backfilled with standard MASH soil and compacted in approximately 6-inch lifts. Once the backfill soil reached a level of 10 inches below the concrete pavement surface, the barrier was set in place and further soil was added and compacted in front and back of the barrier. The barrier was placed adjacent to the concrete pavement at a 1-ft lateral offset. The soil widening behind the barrier was 2 ft. As the soil was backfilled, a 1.5H:1V slope was built into the embankment.

A rebar-grid was then dropped into the slot at each barrier connection location. It comprised of two vertical #6 bars that were spaced 10 inches apart, and three longitudinal #8 bars that were spaced eight inches apart. With the rebar-grid in place, the connection was grouted using a non-shrink grout. Details of the test article and its installation are shown in Figure 5.

The concrete of the barrier was specified to have a minimum compressive strength of 4000 psi. The reinforcing steel was specified to be grade 60 steel. The steel material used for manufacturing the rebar-grid was also specified to be grade 60. The grout used for making the connection was a non-shrink grout with a minimum strength of 4000 psi. The soil used for embedding the barriers was crushed limestone road base material that conforms to standard MASH soil. The moisture content of the soil on the day of the test was 8.5%.

The process of embedding the barrier in the field may be different from the test. The barrier can be installed by first compacting the soil to roadway surface and then excavating a 2-ft wide area for embedding the barrier. Once the barrier has been placed, some level of compaction may be needed depending on site conditions. If compaction is needed behind the barrier, a compactor placed on a swing arm can be used.

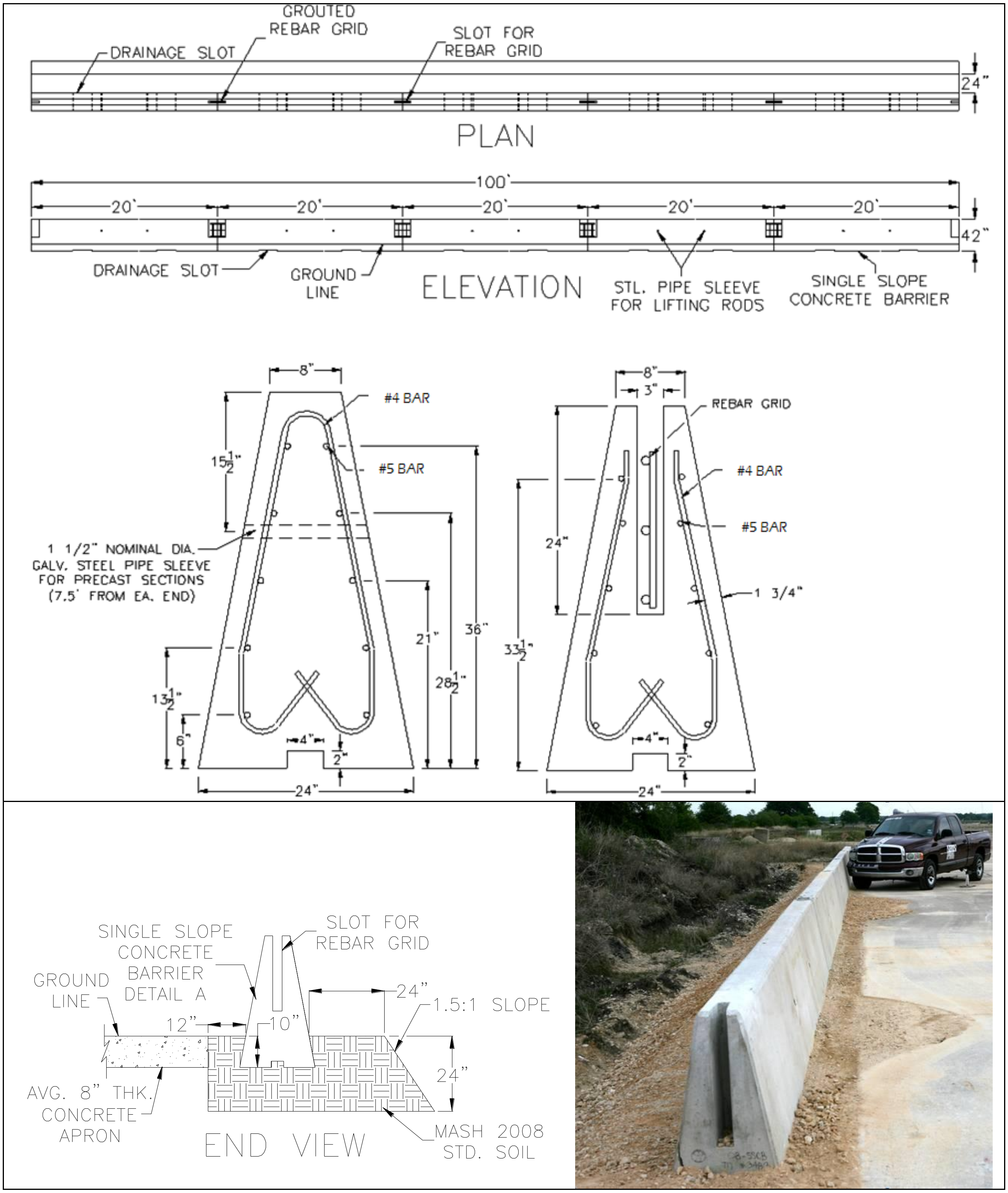


Figure 5: Test article details and barrier installation.

Testing Requirements

According to MASH, two tests are recommended to evaluate longitudinal barriers for test level three (TL-3) as described below.

1. MASH Test Designation 3-10: 2425 lb vehicle impacting the critical impact point (CIP) of the length of need section at a speed of 62 mi/h and an angle of 25 degrees.
2. MASH Test Designation 3-11: 5000 lb pickup truck impacting the CIP of the length of need section at a speed of 62 mi/h and an angle of 25 degrees.

The researchers performed test 3-11 of MASH (i.e. 5000 lb vehicle, 62 mi/h, 25 degrees) on the design finalized from the simulation effort to verify simulation results. It was argued that this is the critical test for the design and the test with smaller 2425 lb vehicle is not needed. Due to higher impact energy, the test with the 5000 lb pickup truck will result in greater lateral deflection and help evaluate connection strength and the tendency of the barriers to rotate. An impact resulting from the lighter 2425 lb passenger car under same impact speed and angle will not result in any increase in lateral deflection of the barrier nor will it impart a higher force on the barrier to evaluate connection strength and barrier rotation. Furthermore, due to the small deflection expected in the test, the small car impact with the embedded single-slope barrier will be no different than the rigid single-slope barrier. Thus, the test was conducted with the 5000 lb pickup only.

Test Description

MASH test 3-11 involves a 2270P vehicle weighing 5000 lb ±100 lb and impacting the barrier at an impact speed of 62.2 mi/h ±2.5 mi/h and an angle of 25 degrees ±1.5 degrees. A 2002 Dodge pickup truck was used in the test, which weighed 4953 lb. The vehicle impacted the barrier with a speed and angle of 63.1 mi/h and 24.2 degrees, respectively. The test impact point was 62.0 inches upstream of the joint between segments 2 and 3. At approximately 0.042 s, the left front tire began to climb the face of the barrier and the vehicle began to redirect. At 0.169 s, the vehicle began to travel parallel to the barrier while traveling at a speed of 58.7 mi/h. At 0.173 s, the right rear of the vehicle contacted the barrier, and at 0.176 s, the vehicle began to roll clockwise. The right rear corner of the bed of the vehicle contacted the top of the barrier at 0.616 s, and after that, dust obscured the view in all camera views. Brakes on the vehicle were applied at 1.5 s after impact, and the vehicle came to rest 247 ft downstream of impact and 10 ft toward traffic lanes.

Damage to Test Installation

Damage to the impacted barrier segments was minimal as shown in Figure 6-a. Tire marks were on the traffic face of the barrier and there was no evidence of cracking in the barrier. Length of contact of the vehicle with the barrier was 14.0 ft. Maximum permanent deflection of the barrier was 5.5 inches. The working width was 19.6 inches. Maximum dynamic deflection during the test was 5.6 inches.

Vehicle Damage

The 2270P vehicle sustained damage to the right front corner and along the right side, as shown in Figure 6-b. The right upper A-arm, right tie rod end, and sway bar were deformed. Also damaged were the front bumper, grill, right front fender, right front and rear doors, right exterior side of bed, rear bumper, and tailgate. The right front and rear wheel rims were deformed and the right front tire was deflated. Maximum exterior crush to the vehicle was 14.0

inches in the side plane at the right front corner at bumper height. Maximum occupant compartment deformation was 0.5 inches in the right front door at hip height.

Occupant Risk Factors

Data from the accelerometer, located at the vehicle's center of gravity, were digitized for evaluation of occupant risk and were computed as follows. In the longitudinal direction, the occupant impact velocity was 12.1 ft/s (3.7 m/s) at 0.090 s, the highest 0.010-s occupant ridedown acceleration was -2.4 Gs from 0.173 to 0.183 s, and the maximum 0.050-s average acceleration was -6.5 Gs between 0.009 and 0.059 s. In the lateral direction, the occupant impact velocity was 24.6 ft/s (7.5 m/s) at 0.090 s, the highest 0.010-s occupant ridedown acceleration was -11.3 Gs from 0.187 to 0.197 s, and the maximum 0.050-s average was -13.0 Gs between 0.026 and 0.076 s. These data and other pertinent information from the test are summarized in Figure 7.

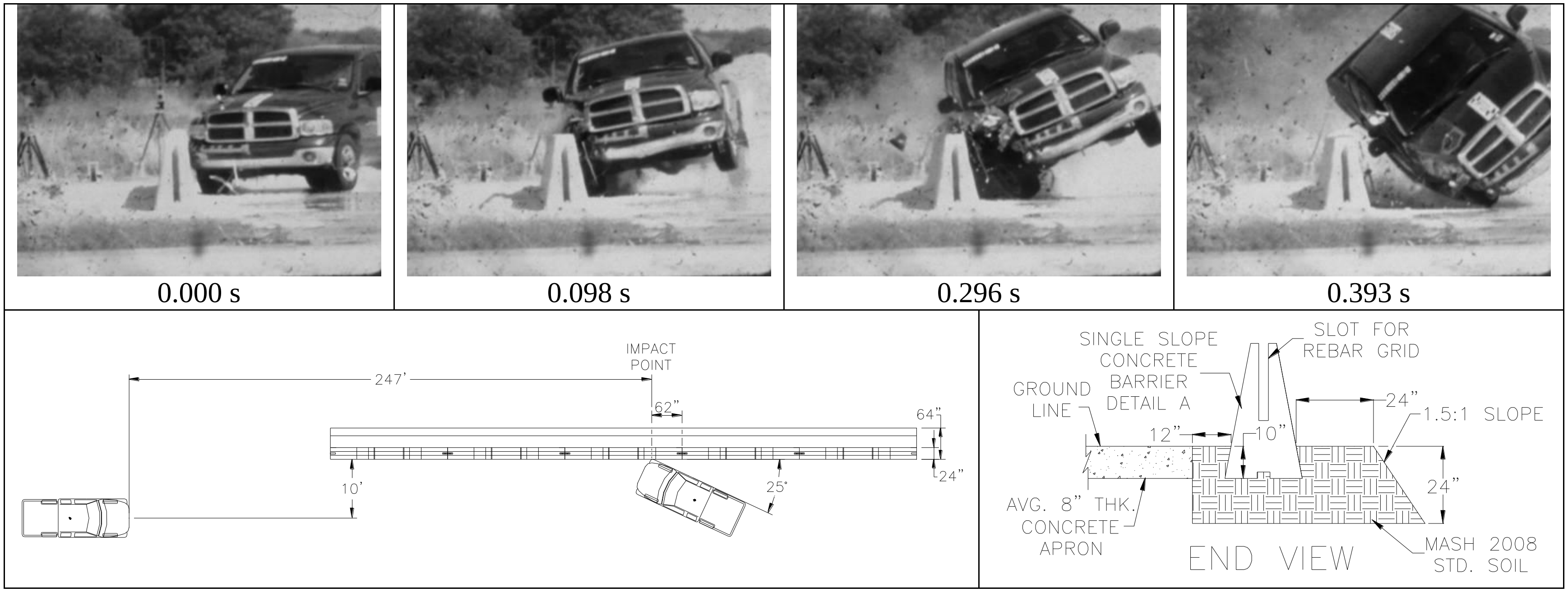
Assessment of Test Results

An assessment of the crash test based on the applicable *MASH08* safety evaluation criteria is presented in Table 1. As shown, the embedded single slope barrier with grouted rebar grid connection was judged to meet all the required impact performance criteria for a TL-3 impact.

(a) Test article damage

(b) Vehicle damage

Figure 6: Test article and vehicle damage.



General Information

Test Agency	Texas Transportation Institute
Test No.	40516-13-1
Date	April 16, 2009

Test Article

Type	Concrete Barrier
Name	Single-Slope Barrier on 1.5H:1V Slope
Installation Length	100 ft
Material or Key Elements	42-inch tall x 20 ft long single-slope concrete barrier embedded 10 inches in soil in front of 1.5H:1V slope
Soil Type and Condition	Standard Soil, Dry

Test Vehicle

Type/Designation	2270P
Make and Model	2002 Dodge Ram 1500 Pickup
Curb	4630 lb
Test Inertial	4953 lb
Dummy	No Dummy
Gross Static	4953 lb

Impact Conditions

Speed	63.1 mi/h
Angle	24.2 degrees
Location/Orientation	62 inch upstrm Joint 2-3

Exit Conditions

Speed	Out of view
Angle	Out of view

Occupant Risk Values

Impact Velocity	
Longitudinal	12.1 ft/s
Lateral	24.6 ft/s
Ridedown Accelerations	
Longitudinal	-2.4 G
Lateral	-11.3 G
THIV	29.6 km/h
PHD	11.3 G
Max. 0.050-s Average	
Longitudinal	-6.5 G
Lateral	-13.0 G
Vertical	-4.2 G

Post-Impact Trajectory

Stopping Distance	247 ft dwnstrm 10 ft fwd

Vehicle Stability

Maximum Yaw Angle	-42 degrees
Maximum Pitch Angle	-11 degrees
Maximum Roll Angle	44 degrees
Vehicle Snagging	No
Vehicle Pocketing	No

Test Article Deflections

Dynamic	5.6 inches
Permanent	5.5 inches
Working Width	19.6 inches

Vehicle Damage

VDS	01RFQ5
CDC	01RFEW4
Max. Exterior Deformation	14.0 inches
Max. Occupant Compartment Deformation	0.56 inch

Figure 7: Summary of results for MASH08 test 3-11 on the single-slope barrier on 1.5H:1V slope.

Table 1 Performance evaluation summary for *MASH08* test 3-11 on the single-slope barrier on slope.

Test Agency: Texas Transportation Institute | Test No.: 405160-13-1 | Test Date: 2009-04-16

***MASH08* Evaluation Criteria**	*Test Results*	*Assessment*
Structural Adequacy		
A. *Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable*	The single-slope barrier in front of 1.5H:1V slope contained and redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 5.6 inches.	Pass
Occupant Risk		
D. *Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.*	No detached elements, fragments, or other debris were present to penetrate or show potential to penetrate the occupant compartment, or to present undue hazard to others in the area.	Pass
Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH08.	Maximum occupant compartment deformation was 5.5 inches.	Pass
F. *The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.*	The 2270P vehicle remained upright during and after the collision event. Maximum roll was 44 degrees.	Pass
H. *Longitudinal and lateral occupant impact velocities should fall below the preferred value of 9.1 m/s (30 ft/s), or at least below the maximum allowable value of 12.2 m/s (40 ft/s).*	Longitudinal occupant impact velocity was 12.1 ft/s, and lateral occupant impact velocity was 24.6 ft/s.	Pass
I. *Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15.0 Gs, or at least below the maximum allowable value of 20.49 Gs.*	Longitudinal ridedown acceleration was -2.4 G, and lateral ridedown acceleration was -11.3 G.	Pass
Vehicle Trajectory		
For redirective devices, the vehicle shall exit the barrier within the exit box.	The vehicle remained within the exit box.	Pass

SUMMARY AND CONCLUSIONS

The objective of the this research to develop a precast concrete barrier that can be placed adjacent to steep slopes such as 1.5H:1V, without using a concrete moment slab.

The final design was incorporated 20-ft long precast single slope barrier segments with grouted rebar grid connection. The 42-inch tall single slope barrier was preferred over other concrete barrier types due to the ease of embedment without requiring changes in the barrier's profile. Since the performance of the grouted rebar-grid connection in a free-standing single slope barrier was not known under MASH evaluation criteria, the researchers evaluated its performance using a smaller scale bogie impact test and simulation analysis. It was determined that the grouted rebar grid connection did not provide enough strength to restrict lateral deflections. Results of the simulation analysis showed that large lateral deflection was expected with the grouted rebar-grid connection when used with the single slope barrier in a free-standing mode.

The researchers then evaluated restricting the deflection of the barrier by embedding it 10 inches in soil. The barrier was placed in front of a 1.5H:1V slope. The offset of the barrier from the slope break point of the soil embankment was restricted to two feet. Another phase of bogie testing and simulation analysis was performed to evaluate the performance of the grouted rebar grid connection in the embedded barrier configuration. Results of the simulation analysis showed that the embedded barrier system will result in acceptably reduced lateral deflections.

A full-scale crash test was subsequently performed to validate the design. The embedded single-slope barrier in front of 1.5H:1V slope performed acceptably according to the requirements of MASH. The permanent lateral deflection of the barrier was 5.5 inches.

The embedded single slope barrier application developed in this research is expected to result in significant cost savings for the user transportation agencies. The benefit of this application comes from the elimination of the use of a moment slab to restrict lateral barrier deflection. The cost of constructing and installing the single slope barrier with a moment slab is typically $375 per linear foot (based on recent bids received by Washington State Department of Transportation). The cost of constructing and installing the embedded single slope barrier on the other hand is approximately $75 per linear foot (based on test article construction in this research). This implies a cost saving of nearly 80%. In addition, the use of a precast barrier minimizes the amount of time to construct in traffic, which reduces traffic disruptions and worker exposure. Eliminating the moment slab further reduces time by eliminating a construction phase.

In comparison to some of the metal guardrail systems developed for use on slopes, the initial cost of installing the embedded single slope barrier will be higher. However, due to its small permanent deflection, the embedded barrier design is expected to require little or no maintenance under most vehicle impacts. Since metal guardrail systems require significant repair time and cost, the embedded barrier design developed in this research is expected to result in significant lifecycle cost savings in areas where frequent vehicle hits are encountered.

ACKNOWLEDGMENTS

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