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AT-GRADE MOMENT SLAB FOUNDATION FOR MASH TL-4 CONCRETE BARRIER

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Introduction and Objective

The Minnesota Department of Transportation (MnDOT) has applications for a concrete roadside barrier with a structurally independent foundation. A moment slab foundation was successfully developed for a single slope traffic rail (SSTR) under a research project sponsored by the Texas Department of Transportation (TxDOT) (*1*). This system, which had a 20-ft segment length and the moment slab embedded in the soil, satisfies Test Level 4 (TL-4) criteria of the American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (*MASH)* (*2*).

MnDOT prefers to avoid burying the moment slab under pavement due to freeze/thaw issues associated with their northern climate. The soil resistance achieved from the embedment of the moment slab helps reduce sliding and rotation of the barrier-moment slab system during an impact. MnDOT asked how long a segment length is needed to satisfy *MASH* TL-4 criteria if the groundline elevation on the field side of the system is at the base of the moment slab as shown in Figure 1.

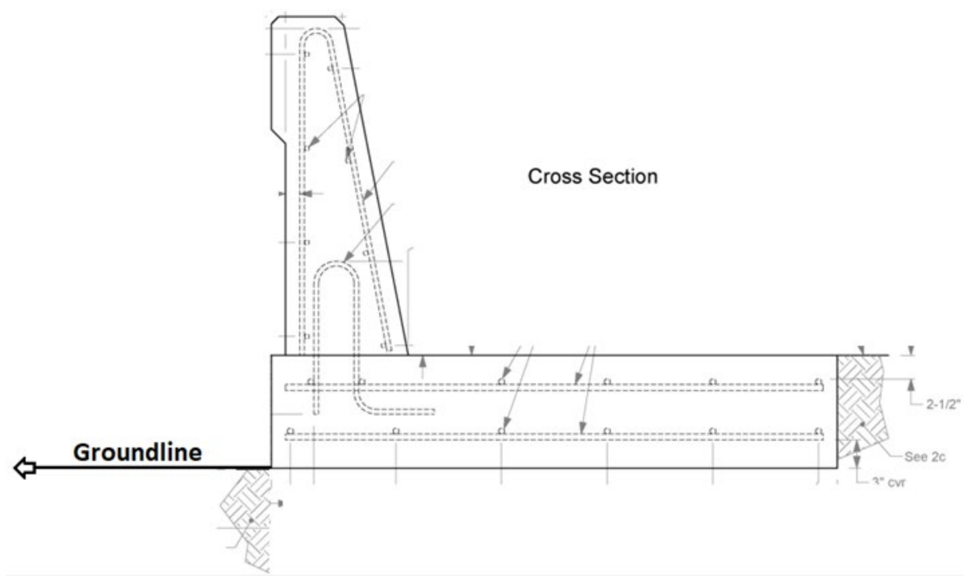


Figure 1. Barrier-Moment Slab System without Soil Embedment on Field Side of Moment Slab

Analysis Approach

The successfully tested *MASH* TL-4 barrier-moment slab system provides a baseline for comparison of alternate design configurations (*1*). As part of the development of that system, Texas A&M Transportation Institute (TTI) researchers developed a finite element model of the system and performed *MASH* Test 4-12 impact simulations.

The approach used to assess the *MASH* compliance of a similar barrier-moment slab system without soil embedment on the field side of the system was to modify the existing finite element model to remove the soil constraint on the field side edge of the moment slab and increase the overall segment length to compensate for the loss of soil resistance. An acceptable segment length is one that provides dynamic deflection less than or equal to the simulated dynamic deflection of the successfully tested configuration.

A foundation design analysis procedure using static equivalent loads developed under NCHRP Project 22-20(02) was used to an initial starting segment length for the simulation analysis (*3*). This analysis procedure, which was developed to design moment slab foundations on top of MSE wall systems, was adjusted to account for the different soil support conditions associated with the MnDOT slab on grade.

System Design Review

Under TxDOT research project 0-6968, TTI researchers developed a structurally independent moment slab foundation for a 36-inch-tall single slope traffic rail (SSTR) (*1*). The SSTR has an 11-degree slope on the traffic-side face.

The moment slab foundation (shown in Figure 2) for the 20-ft long barrier segment was comprised of a 12-inch deep × 5-ft wide concrete foundation embedded in soil. Note that the presence of the soil behind the moment slab helps resist motion of the barrier-moment slab system during an impact.

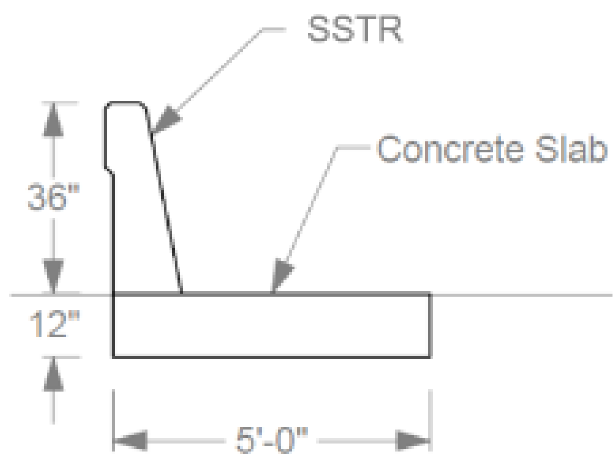


Figure 2. Independent Moment Slab Foundation for SSTR (1)

Finite element modeling and simulation was used during the design effort to investigate several variables including segment length, moment slab width, and moment slab depth. The barrier-moment slab system was designed to satisfy *MASH* Test Level 4 (TL-4) criteria and require minimal maintenance after a design impact. A primary objective in the design of the barrier foundation was to have minimal movement of the barrier during impact to minimize maintenance and repair.

TTI researchers developed a full-scale finite element model of the barrier-moment slab system and performed a vehicle impact simulation following *MASH* Test 4-12 impact conditions. This test involves a 22,000-lb single-unit truck impacting the barrier at a speed of 56 mi/h and an angle of 15°. In the simulation, the SUT was successfully contained and redirected. The predicted maximum dynamic deflection at the top of the barrier was 1.4 inches, and the predicted permanent deflection was 0.1 inch.

Based on the successful simulation results, the barrier-moment slab system was detailed and a prototype installation was constructed for full-scale crash testing. Details of the tested system are shown in *Figure 3*.

The barrier-moment slab system successfully contained and redirected the SUT under *MASH* Test 4-12 impact conditions (*1*). A slight but unmeasurable dynamic deflection was noted.

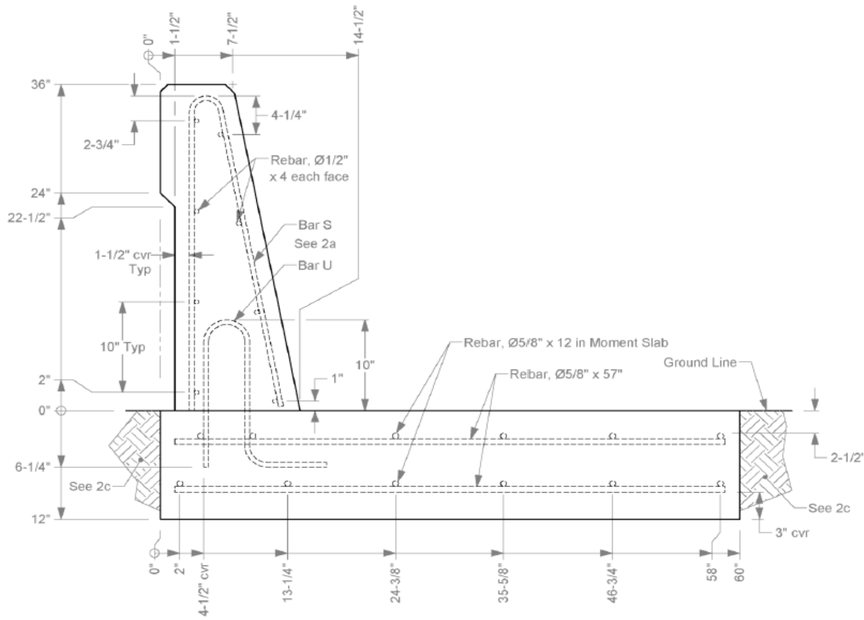


Figure 3. Crash Tested Moment Slab Foundation for SSTR (1)

Engineering Analysis of Foundation System

Under NCHRP Project 22-20(02), Bligh et al. developed design recommendations for barrier moment slab (BMS) systems mounted on MSE walls for impact conditions ranging from *MASH* TL-3 to TL-5 (*3*). During an impact, the BMS system can experience displacement through both sliding and rotation with the rotation occurring about a specific rotation point. Determining the required BMS system design parameters involves applying an equivalent static load to the barrier and performing equilibrium analyses that consider both sliding and overturning. Figure 4 presents a free-body diagram (FBD) defining the variables relevant to the static equilibrium analysis of a BMS system for an MSE wall application.

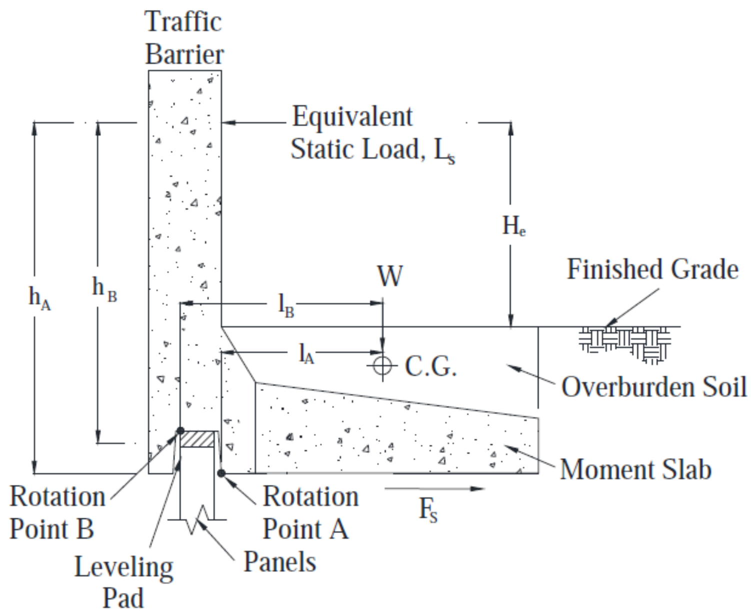


*Figure 4. Application of static **e**quivalent load on BMS system (3)*

Figure 5 provides the recommended equivalent static design loads for a BMS system for different *MASH* test levels. The recommended equivalent static load is based on the static resistance of selected TL-3, TL-4, and TL-5 BMS systems that satisfied *MASH* crash test criteria. For a specific BMS system, either rotation or sliding will be the critical mode that controls the design. The recommended moment slab width is the width corresponding to the controlling failure mode, which will be the larger of the widths required to resist sliding and overturning.

Test Designation	L_d (1) (kips)	L_s (2) (kips)	H_{min} (3) (in.)	H_e (4) (in.)	W_{min} (5) (ft)	B_L (6) (ft)
TL-3(7)	70	23	32	24	4	10
TL-4-1	70	28	36	25	4.5	10
TL4-2	80	28	>36	30	4.5	10
TL-5-1	160	80	42	34	7	15
TL-5-2	260	132	>42	43	12	15

(1) Dynamic Load L_d
(2) Equivalent static load (Ls) applied at height He, calculated based on the static resistance deemed more critical for the barrier as follows: the overturning resistance for TL-3, TL-4 and TL-5-1 barriers and the sliding resistance for TL-5-2 barrier.
(3) Minimum barrier height H_{min}
(4) Effective barrier height H_e
(5) Minimum moment slab width W_{min}
(6) Minimum length of the precast barrier B_L
(7) Revised from the recommendations in NCHRP Report 663, Figure 7.1 (*2*)

Figure 5. Recommended equivalent static load (L_s) for TL-3 through TL-5 (3).

The BMS system must resist the two modes of stability failure (sliding and overturning) when the static equivalent load, L_s, is applied. The static equivalent load is applied at a resultant height (H_e) corresponding to the resultant height of the dynamic impact load, L_d.

The factored static resistance (φ P) to sliding of the BMS system along its base should be greater than or equal to the factored equivalent static load (γL_s) due to the dynamic impact force. The static resistance is calculated as follows:

$$\varphi P = \varphi W \tan(\phi_r) \geq \gamma L_s \quad \text{(eq.1)}$$

where φ = resistant factor of 1 defined in AASHTO LRFD 10.5.5.3.3
W = weight of the monolithic section of barrier and moment slab plus any overburden on top of the moment slab (kips)
ϕ_r = friction angle of the soil-moment slab interface
γ = load factor of 1.0 for extreme event defined in AASHTO LRFD 10.5.5.3.3
L_s = equivalent static load.

The factored equivalent static load is applied to the length of the moment slab between joints. Any coupling between adjacent moment slabs or friction that may exist between free edges of the moment slab and the surrounding soil are neglected. If the soil–moment slab interface is rough (e.g., cast in place), ϕ_r is equal to the friction angle of the soil ϕ_s. If the soil–moment slab interface is smooth (e.g., precast), ϕ_r should be reduced according to the following relationship: $\tan(\phi_r) = 2/3 \tan(\phi_s)$.

The factored static moment resistance (φM) to overturning of the BMS system should be greater than or equal to the moment associated with the application of the static equivalent load. The moment contribution due to any coupling between adjacent moment slabs, shear strength of the overburden soil, or friction that may exist between the backside of the moment slab and the surrounding soil are neglected. The static moment resistance is calculated as follows:

$$\varphi M = \varphi W l_m \geq \gamma Ls h \quad \text{(eq.2)}$$

where φ = resistant factor of 1 defined in AASHTO LRFD 10.5.5.3.3
W= weight of the monolithic section of barrier and moment slab plus any overburden on top of the moment slab (kips)
l_m = horizontal distance from the CG (c.g.) of the weight W to the point of rotation (ft)
γ = load factor of 1.0 for extreme event defined in AASHTO LRFD 10.5.5.3.3
L_s = equivalent static load
h = the moment arm (h_A or h_B in Figure 1) taken as the vertical distance from the resultant height of the dynamic impact force (effective height, H_e) to the point of rotation (Figure 4).

The FBD for the 36-inch-tall single slope BMS system on grade without soil embedment investigated herein is illustrated in Figure 6. The rotation point was selected at the bottom field-side corner of the moment slab.

Various properties were calculated and variables defined for use in the static equilibrium analysis of the MnDOT system. Table 1 lists these values and their designated units.

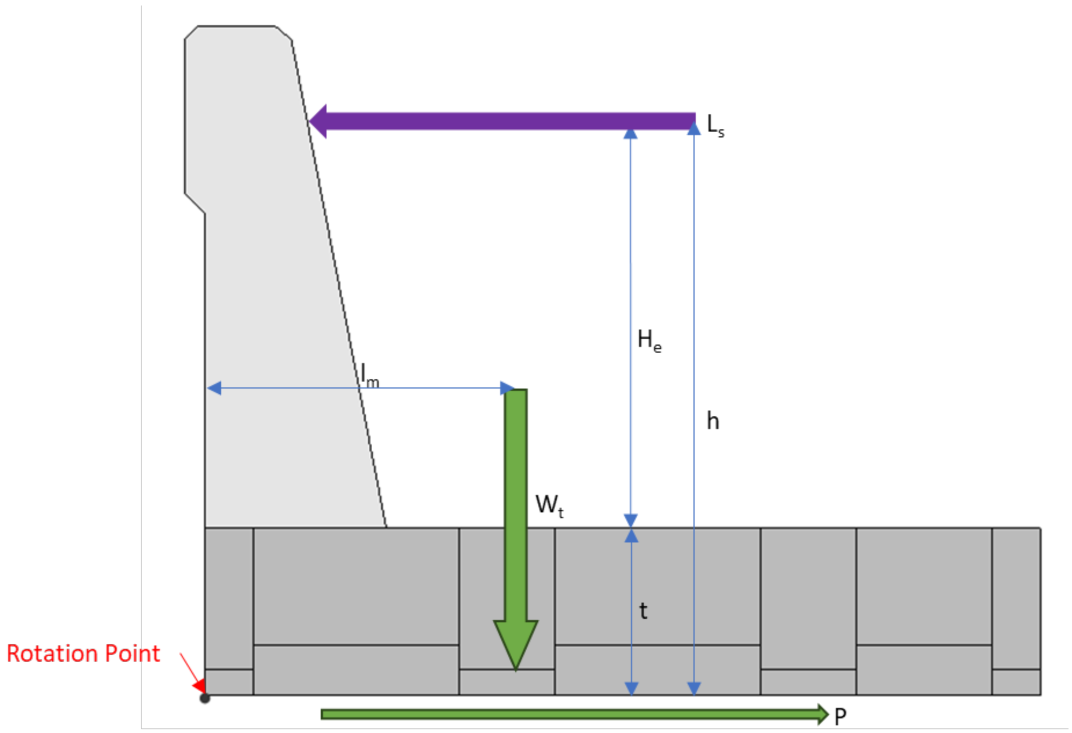


Figure 6. Free-body Diagram showing static equilibrium for 36-inch-tall single slope BMS system

Table 1. Properties of BMS System Used in Static Equilibrium Analysis

Variables	Known Values
Barrier cross-section area (in^2)	360.18
Concrete density (lbs/in^3)	0.0868
Slab thickness, t (in)	12
Friction angle of the soil for cast-in-place, ϕ_r (rad)	0.6981
$\tan(\phi_r)$	0.8390
L_s for TL-4 (kips)	28
H_e for TL-4 (in)	25
Moment arm, h = He + t (in)	37
$L_s \cdot h$ (kips·ft)	86.3

Using the values from Table 1, the sliding force and overturning moment were checked using eq.1 and eq.2, respectively. Table 2 and Table 3 show the design parameters investigated and the corresponding analysis results. The initial BMS system parameters were based on the TxDOT 36-inch-tall single slope BMS system. As described above, this system had a 20 ft segment length and a 5-ft wide × 1-ft thick moment slab (*1*). The resistance was checked without any soil behind the BMS system based on the design constraints provided by MnDOT.

Based on the static analyses, the TxDOT design configuration with 20-ft segment length cannot resist the TL-4 vehicle impact sliding force without the embedment of the moment slab. When the barrier segment length was increased to 40 ft with the same moment slab configuration, the design conditions were satisfied. If a 20-ft segment length is desired, the moment slab width could be increased to 9 ft (design option 3) or the moment slab thickness could be increased to 24 in (design option 4).

Table 2. Sliding Resistance Check Using eq.1

Design option	Barrier segment length (ft)	Slab thickness (in)	Slab width (ft)	Barrier weight (kips)	Slab weight (kips)	BMS total weight, W_t (kips)	P (kips)	$\varphi P > \gamma Ls$
TxDOT Design	20	12	5.0	7.5	15.0	22.5	18.88	Fail
1	40	12	5.0	15.0	30.0	45.0	37.76	Pass
2	20	12	6.0	7.5	18.0	25.5	21.39	Fail
3	20	12	9.0	7.5	27.0	34.5	28.94	Pass
4	20	24	5.0	7.5	30.0	37.5	31.46	Pass
5	80	12	5.0	30.0	60.0	90.0	75.51	Pass

Table 3. Moment Resistance Check Using eq.2

Design option	Slab C.G.x (ft)	Lateral distance from rotation point to C.G., l_m (ft)	M (kips·ft)	$\varphi M > \gamma Ls \cdot h$
TxDOT Design	2.5	2.26	50.86	Fail
1	2.5	2.26	101.73	Pass
2	3.0	2.64	67.36	Fail
3	4.5	3.91	134.85	Pass
4	2.5	2.36	88.36	Pass
5	2.5	2.26	203.45	Pass

After consultation with MnDOT it was decided to further analyze the configuration with 40-ft segment length with a 5-ft wide x 1-ft thick moment slab using finite element simulation.

MASH Compliance Assessment

Based on the preliminary analysis results and design feedback from MnDOT, the research team performed a finite element impact simulation to further assess the *MASH* compliance of the 36-inch-tall single slope BMS system with 40 ft segment length and a 5 ft-wide × 12-inch-thick moment slab. An existing finite element (FE) model of the BMS system was modified for this purpose.

The FE model was previously developed and used as a predictive design tool to arrive at the final design of the 36-inch tall BMS system with the 20 ft segment length and a 5-ft-wide moment slab with soil behind it (*1*). To evaluate the performance of the BMS system with 40-ft segments without soil constraint behind the system, the research team modified the FE model to increase the segment and remove the soil behind the moment slab. It should be noted that the scope of this assessment did not include making extensive changes to the model to improve model validation with the crash test.

An impact simulation following *MASH* Test 4-12 impact conditions was performed using the modified model. *MASH* Test 4-12 involves a 22,000-lb single-unit-truck impacting the barrier at an impact speed of 56 mi/h and angle of 15 degrees. The impact location was 5 ft upstream of the midpoint of the 40-ft long segment. The simulation results of the BMS with 40-ft-long segments without soil behind the moment slab was assessed using *MASH* structural adequacy criteria, vehicle stability, and dynamic deflection of the barrier-moment slab system. The results were compared to the previous simulation and crash test performed on the BMS with 20-ft segments with soil constraint behind the moment slab.

Figure 7 provides a comparison of the SUT behavior in the test and the simulations. In the test of the 20-ft segment with soil support, there was slight dynamic movement of the barrier noted but it was too small to be measurable in the video analysis. There was no measurable permanent deflection. In the associated simulation of the 20-ft segment with soil support, there was 1.4 inches of dynamic deflection and 0.1 inches of permanent deflection. These values established the range of deflections used for assessment of *MASH* compliance of the longer segment lengths without soil support.

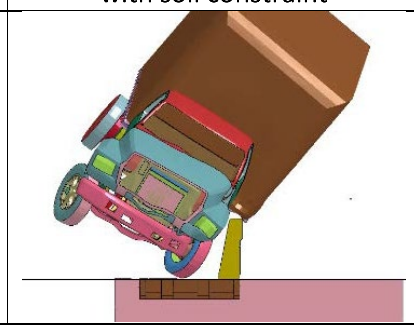
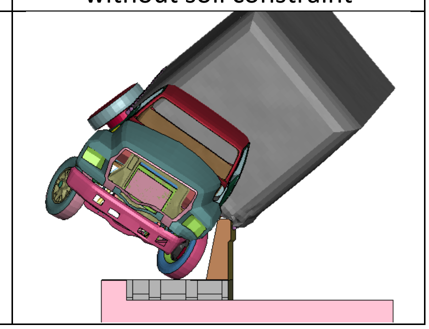
Test with 20-ft segment with soil constraint	Simulation with 20-ft segment with soil constraint	Simulation with 40-ft segment without soil constraint
		

Figure 7. Comparison of vehicle behavior.

In the simulation of the 40-ft segment without soil support, larger deflections were obtained. The maximum dynamic deflection was 3.81 inches, and the permanent deflection was 2.92 inches. This increased deflection resulted in more roll of the single unit truck as shown in Figure 7.

Because the dynamic barrier deflection and roll angle of the SUT were beyond the level observed for the simulation of the successfully tested system, there was not enough engineering confidence to accept this configuration without a test. After discussing the results with MnDOT, it was decided to evaluate an 80-ft long contiguous segment with the same moment slab dimensions and no soil support behind the moment slab.

A comparison of the SUT behavior between the 40-ft long and 80-ft long systems without soil support is shown in Figure 8. The simulation of the 80-ft long system without soil support resulted in a maximum dynamic deflection of 0.5 inches and negligible permanent deflection. This was within the range of the movement of the simulation of the successfully tested system and resulted in improved stability of the SUT as shown in Figure 8.

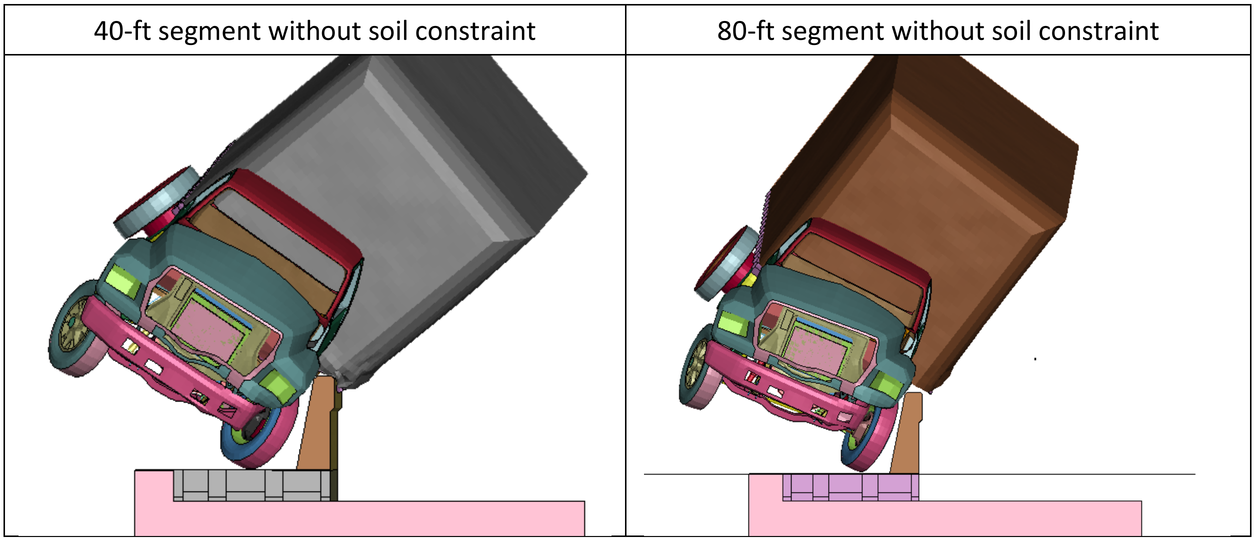


Figure 8. Comparison of the vehicle behavior for 40-ft and 80-ft long systems without soil constraint.

Table 4 lists the evaluation criteria required for *MASH* Test 4-12. Based on the simulation results, the BMS system with 80-ft segments without soil constraint satisfied *MASH* Test 4-12 evaluation criteria. The BMS system was able to contain and redirect the 10000S vehicle. The vehicle remained upright and there was no observed occupant compartment deformation.

Table 4. Evaluation Criteria Required for MASH Test 4-12.

Evaluation Factors	**Evaluation Criteria**
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.*
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 undue hazard to other traffic, pedestrians, or personnel in a work zone.* *Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.*
	G. It is preferable, although not essential, that the vehicle remains upright during and after the collision.

Conclusion

Based on the simulation results and comparison of these results to a successfully crash tested barrier system, the research team concluded that the BMS system with 80-ft segments without soil constraint is, within a reasonable degree of engineering certainty, *MASH* TL-4 criteria.

References

1. Sheikh, N.M., Bligh, R.P., Kovar, J.C., Cakalli, S., Menges, W.L., Schroeder, G.E., and Kuhn, D.L. (2020). *Development of Structurally Independent Foundations for 36-inch Tall Single Slope Traffic Rail (SSTR) for MASH TL-4.* Report No. FHWA/TX-19/0-6968-R7. Texas A&M Transportation Institute, College Station, TX.
2. AASHTO. (2016). *Manual for Assessing Roadside Safety Hardware*: Second Edition, 2016. American Association of State Highway and Transportation Officials. Washington, D.C.
3. Bligh, R.P., Briaud, J.L., Abu-Odeh, A., Saez, D.O., Maddah, L.S., and Kim, K.M. (2022). *Design Guidelines for Test Level 3 through Test Level 5 Roadside Barrier Systems Placed on Mechanically Stabilized Earth Retaining Walls*. NCHRP Web-Only Document 326. Washington, DC: The National Academies Press. https://doi.org/10.17226/26580.