LS-DYNA® Analysis of a Sacrificial Wall Designed to Protect Mechanically Stabilized Earth Retaining Walls

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Abstract

Mechanically Stabilized Earth (MSE) retaining walls are used to provide roadway elevation for bridge approaches, underpass frontage roads and other roadway elevation applications. Vehicular traffic may exist on the high (fill) side of the MSE retaining wall, on the low side, or both sides. For traffic on the high side, a conventional traffic barrier might be placed on or near the top of the wall and mounted on a moment slab or a bridge deck. For traffic on the low side, a conventional traffic barrier might be installed adjacent to the wall or the wall itself may serve as the traffic barrier. Typical MSE wall panels are not designed to resist vehicle impacts. Therefore, structural damage to the wall panels and the earth fill would require complicated and expensive repairs. A simple reinforced concrete crash wall constructed in front of the MSE wall panels can significantly reduce damage to them. It may prove practical to implement such a design in order to reduce costly repair to the MSE wall structure.

In this paper, LS-DYNA was used to model and analyze a sacrificial crash wall design to determine its effectiveness of protecting the MSE retaining wall. Based on the LS-DYNA simulations, a 0.2 m. thick crash wall is considered adequately designed to reduce damage to the MSE wall.

Introduction

MSE walls typically consist of backfill soil reinforced with steel strips, a steel bar mat, or polymeric materials. The reinforcement is attached to the retaining wall (panels) to provide stability of the MSE structure as shown Figure 1 *(1).* On top of the retaining wall and the backfill soil, a barrier–moment slab subsystem is installed to protect the errant vehicular impact. An example of a MSE wall in the highway in Long Beach, California is shown in Figure 2 *(2.) C*urrently there is no guideline on how to protect the MSE wall panels from heavy vehicle impacts. A sacrificial crash wall constructed of reinforced concrete can be practically cast against the MSE wall panels using steel anchors embedded between the sacrificial crash wall and the MSE panels. This sacrificial crash wall design is the focus of this numerical investigation. It may prove practical to implement such a design in order to prevent the complexity and the costs involved in repairing the MSE retaining wall structure.

Figure 1 MSE retaining wall key component and construction (TTI 475350) (*3*)

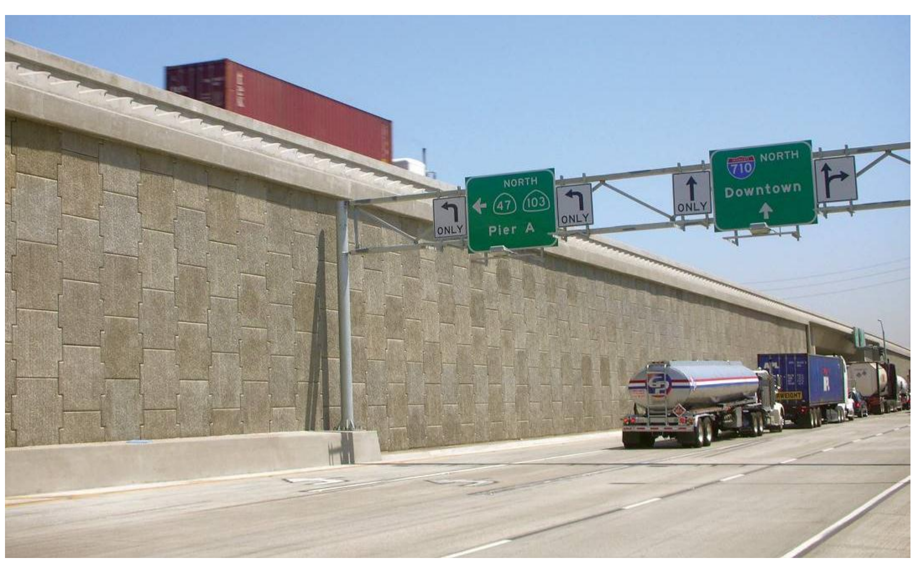


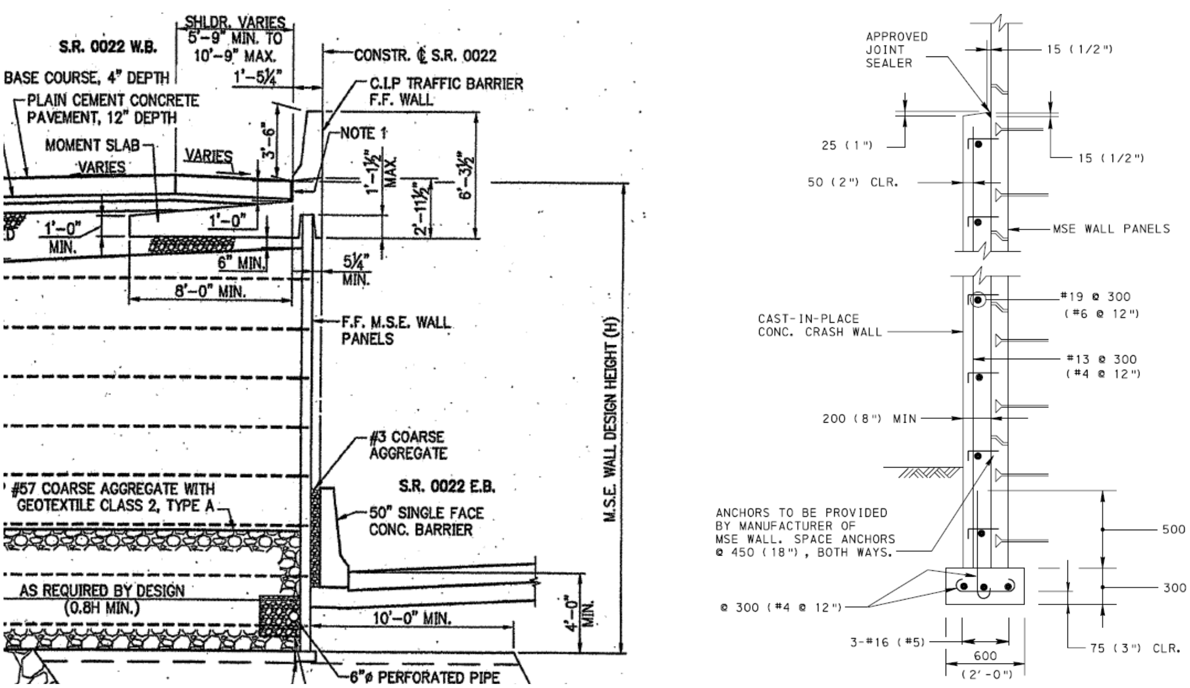
Figure 2 MSE wall in Long Beach, CA *(2)*

For this study, a typical MSE retaining wall design was modeled (5*)*. The drawing for the sacrificial crash wall was obtained from Pennsylvania Department of Transportation (PennDOT) Precast Concrete Wall Panels drawing (*3*). This 0.2 m. thick sacrificial crash wall is placed in front of the MSE wall panels (*4*). The cast-in-place crash wall is connected to the precast wall panels by anchors. The crash wall is embedded 0.5 m into the ground. The reinforcing bars in the crash wall consist of longitudinal No. 6 bars at 304.8 mm and vertical No. 4 bars at 304.8 mm as shown in Figure 3(b).

Analysis Methodology

A finite element model of the MSE wall with a crash wall was developed to evaluate the sacrificial crash wall structural response to vehicular impact. The analyses were performed using LS-DYNA *(5)*. The methodology used to model the MSE wall and the sacrificial crash wall consisted of six steps:

1) Construct the finite element models of the MSE wall and the sacrificial crash wall.
2) Initialize the model of the MSE wall and the sacrificial crash wall to account for steady state gravitational loading.
3) Modify the Single Unit Truck (SUT) model to reflect current testing guidelines *MASH (6)* and establish the performance envelope of the SUT model.
4) Simulate the SUT impact against the MSE wall panels (without the sacrificial crash wall). Analyze the performance of the MSE wall.
5) Simulate the SUT impact against the sacrificial crash wall constructed in front of the MSE wall. Analyze the performance of the sacrificial crash wall.
6) Identify any further investigation needed.

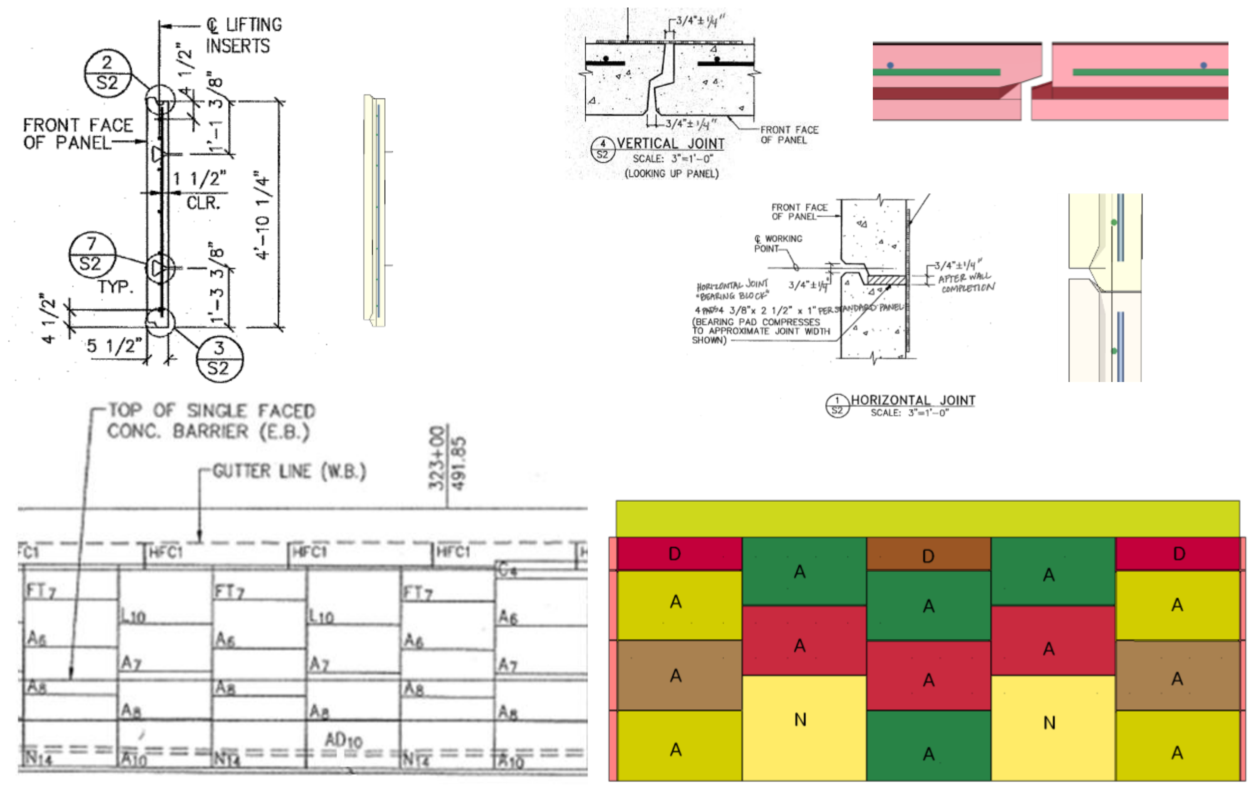


(a) (b)

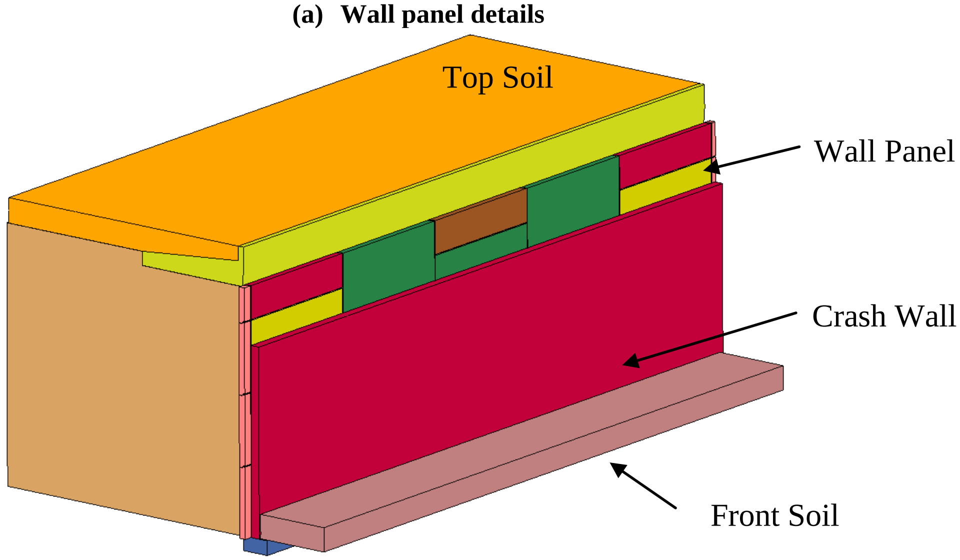
Figure 3 Detail drawing of a crash wall (a) MSE wall section drawing *(3)* and (b) typical crash wall section from PennDOT drawing *(4)*

The finite element representation of the MSE retaining wall incorporated these key structural components:

1. The precast concrete panels with rebar reinforcement.
2. The concrete leveling pad
3. The cast-in-place moment slabs.
4. The backfill soil and front soil.
5. The reinforcements in the soil to the wall panels.
6. The sacrificial crash wall.



(a) Wall panel details



(b) Overall view of MSE wall and crash wall model

Figure 4 MSE wall and crash wall model

The finite element model represented an MSE wall system that was 15.1 m long and 5.2 m tall as shown in Figure 4. The barrier and moment slab were located on the top of the MSE wall panels and backfill soil. Since the impact location was at the bottom part of the panels, the barriers and the interaction of the coping of the barrier and panels were not modeled in this study. The MSE wall components such as soil, wall panels, the pedestal and the moment slab were modeled using solid elements. Beam elements were used to model the rebars of the wall panels, the crash wall, and the pedestal. The steel strip reinforcements for the MSE wall were modeled using shell elements. The overall model of the MSE wall is shown in Figure 4.

Three types of panels were selected to build the model. All three panels have the same width and thickness of 2.98 m and 140 mm, respectively. The height of panels varied from 0.73 m to 2.23 m. Three different panel shapes, "A", "D", and "N", were shown using an alphabetical indicator as depicted in Figure 4.

To account for realistic interaction between the wall panels, the panels' joints along both vertical and horizontal directions were explicitly modeled as shown in Figure 4(a). Finally, the 15.1 m long, 203.2 mm thick and 4 m high sacrificial crash wall was constructed next to the MSE wall panels. The sacrificial wall construction drawing and its LS-DYNA model are shown in Figure 5.

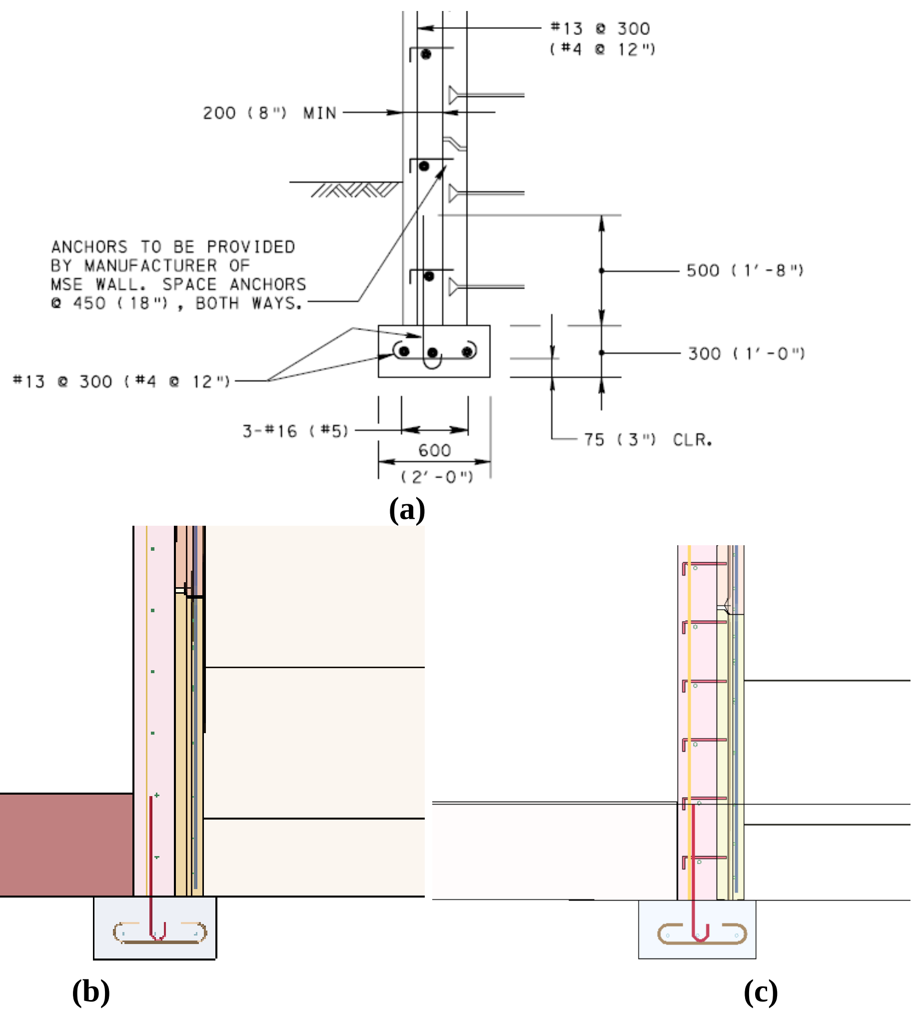


Figure 5 Crash wall details and model

Components Interactions and Boundary Condition

In order to eliminate the requirement of matching nodes to merge the reinforcing steel inside the concrete continuum, the steel re-bars were coupled to the surrounding concrete using *CONSTRAINED_LAGRANGE_IN_SOLID card in LS-DYNA. Hence, we would avoid the creation of elements with poor aspect ratios and the creation of unnecessarily small element sizes, which has a significant effect on the time step (*7)*. The wall reinforcements were coupled to the backfill soil in the same manner. The anchors were coupled to both the crash wall and the wall panels.

The interaction between the soil and concrete was modeled using contact definition *AUTOMATIC_NODES_TO_SURFACE. The contact friction was based on the estimated backfill soil internal friction angle. The soil friction angle, ϕ, was estimated to 35 degrees and thus the contact friction angle was calculated to be 0.7 (tan ϕ).

During gravitational initialization, the front elements of wall reinforcing strip developed unrealistic bending stresses. Therefore, dummy sliding shells were added to enable the strip to slide downward without bending to better reflect construction methods. It exhibited significant reduction in artificial bending by incorporation this sliding mechanism in the model. Once initialization was completed, these dummy sliding shells were removed. Afterward, the connection between the panels and the wall reinforcing strips was established via *TIED_NODES_TO_SURFACE. Directional translational constraints were applied on the boundary surfaces to account for boundary conditions of the structures as needed at other faces of the MSE wall system.

Material Models and Parameters

The outside wall panels, the moment slab, and the leveling pad were modeled using elastic material. The parameters of the elastic model were density, elastic modulus, and Poisson's ratio. The center wall panels, that were subjected to direct impact, were modeled using *MAT_CSCM concrete material model definition *(8)*. The parameters of this concrete can be assigned using two basic concrete properties, the confined compressive strength of concrete *f'c* and the maximum aggregate size of the mix.

All steel rebar and steel strips were modeled using the commonly used elasto-plastic material model (*MAT_PIECEWISE_LINEAR_PLASTICITY).

The soil was modeled using the two-invariant geological cap material model *MAT_GEOLOGIC_CAP_MODEL. Typical backfill soil properties were used from Hofstetter and Simo *(9)* and NCHRP Report 556 *(10)*.

Verification of the Model under Steady State Conditions

The MSE wall and barrier model had to be initialized first to account for gravitational loading. Gravitational loading affects soil pressure on the wall panels and builds the steady state stresses in the steel strips. Therefore, the initialization step had to be performed prior to any impact simulation process. Initialization was achieved by gradually ramping up gravitational load on the system while imposing a diminishing damping on the soil mass to prevent oscillatory forces from developing.

The difference between the total vertical reaction and the calculated weight of the system was used as a convergence criterion for achieving the steady state solution of the MSE wall model. In this model, the total mass of MSE wall model is 1,180,570 kg which corresponds to a weight of 11,576.7 kN . The total vertical reaction of the finite element model was 11,241 kN at the end of the initialization process which is less than 3 percent different from the calculated total weight. This was considered a reasonable agreement between the calculated weight and the total vertical reaction from the finite element analysis as shown in Figure 6 below.

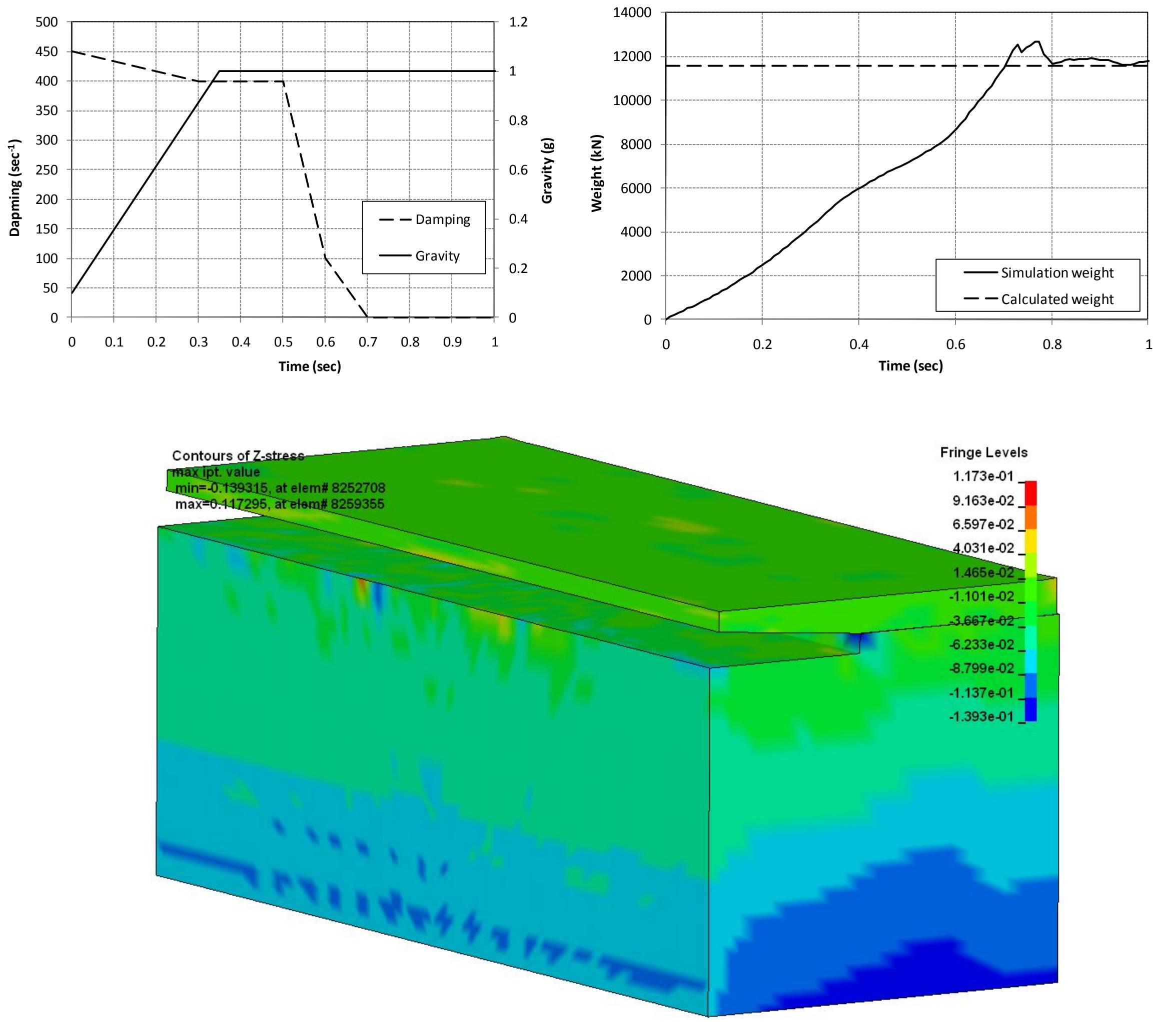


Figure 6 Initialization of the MSE wall soil continuum.

Once the gravitational initialization was completed, the loads in the wall strips from simulation were compared to the unfactored loads from *AASHTO LRFD* specification *(11)* as another check of the steady state simulation results.

The following equation in *AASHTO LRFD* was used (*AASHTO LRFD* Equation 11.10.6.2.1-2) to determine the unfactored load (T) expected per wall strips.

$$T = \sigma_h \times A_t \tag{1}$$

where σ_h is the horizontal stress due to the soil ($\sigma_h = K_r \times \sigma_v$), K_r is lateral earth pressure coefficient, and A_t is tributary area of the reinforcement.

The forces in the strips using the using *AASHTO LRFD* and LS-DYNA simulation are presented in Table 1. Overall, the difference is acceptable given the size of the structure being analyzed and the intrinsic uncertainties in large soil systems.

Table 1 Static Load on the MSE wall.

Rein. Layer NO.	Depth (m)	Unfactored T (*AASHTO LRFD*) (kN)	Load in the strip from simulation (kN)	Difference (%)
1	1.21	5.38	7.56	28.8
2	1.88	8.10	8.10	0.1
3	2.64	12.1	11.12	8.7
4	3.38	14.89	14.23	4.6
5	4.13	17.40	17.35	0.3
6	4.88	19.64	21.35	8.0
7	5.63	21.58	24.47	11.8

Validation of the Truck Model

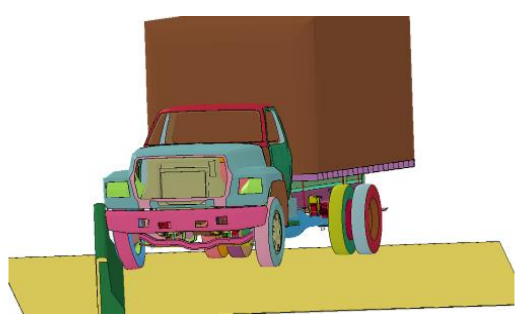
The SUT vehicle model was developed by the National Crash Analysis Center (NCAC) *(11)*. The Ford F800 Series Truck which meets the *NCHRP Report 350* criteria *(13)* of the 8000S test vehicle specification. However, *NCHRP Report 350* was replaced by *MASH (6)* which has different SUT test vehicle specification. Thus, the SUT model needed to be modified to reflect the *MASH* 10000S test vehicle specification. In *MASH*, the mass of the SUT increased from 8,000 kg to 10,000 kg and the impact speed increased from 80.47 km/h) to 90.12 km/h.

The existing 8000S vehicle model was modified and then corroborated using crash test results of TTI Project 476460-1b *(14)* which used *MASH* 10000S test vehicle in a barrier impact. The performance of the modified SUT model was investigated by performing a full-scale vehicle impact simulation and comparing the results to the aforementioned crash test. The crash test used for this investigation was conducted at TTI using *MASH* TL-4 impact conditions. The test vehicle impacted the barrier at a speed of 92.4 km/h and at an impact angle of 14.4 degrees.

Vehicle Impact Simulation

To quantify the performance of the modified 10000S vehicle model, an impact simulation was performed of the aforementioned full-scale crash test as shown in Figure 7. In the model, the vehicle impacted the N.J. bridge rail at a speed of 92.4 km/h and an angle of 14.4 degrees to represent the test initial conditions. The vehicular dynamics in the simulation correlated reasonably well with that observed in the crash test..

0.000 s



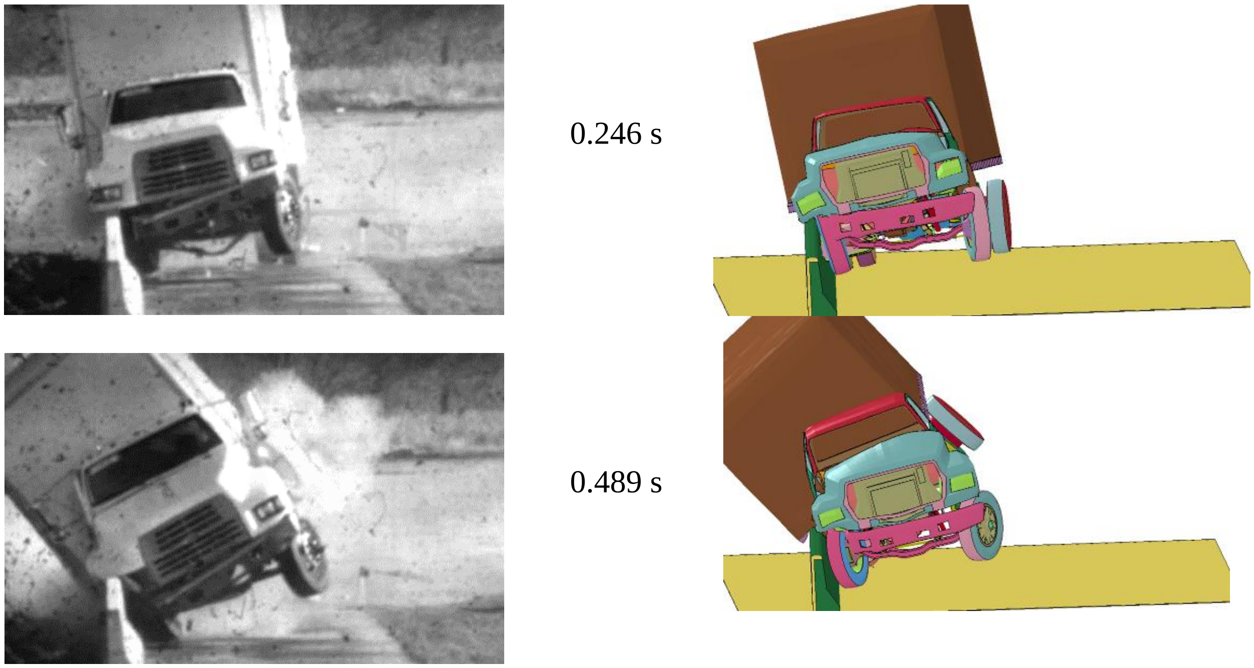
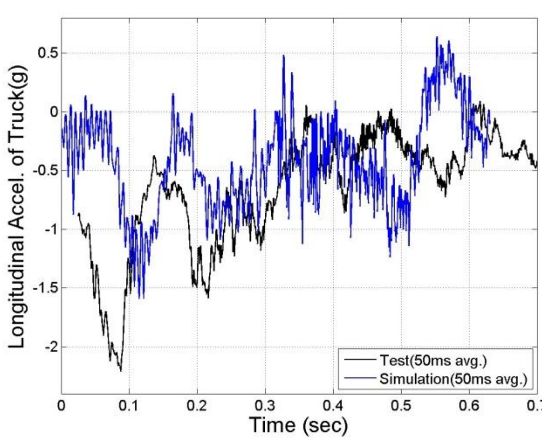
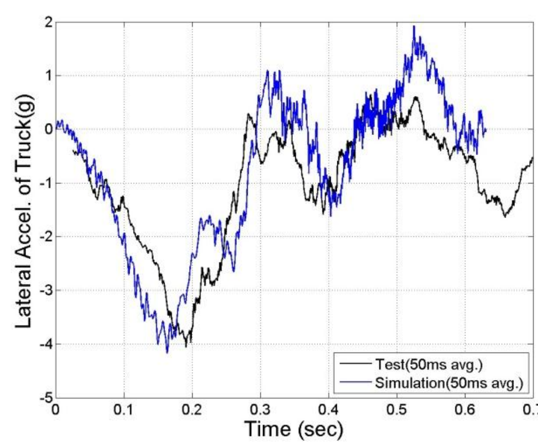


Figure 7 Time sequential comparison for test and simulation

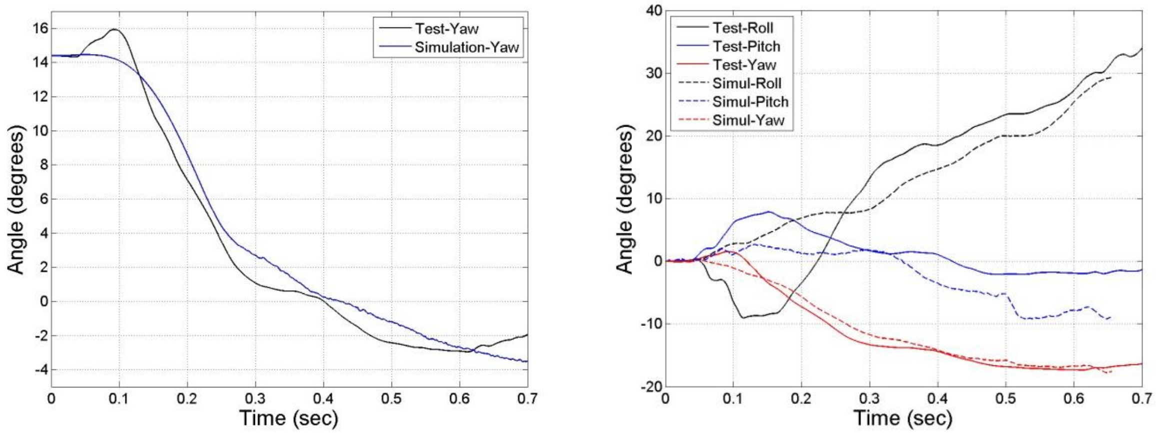
Data obtained from the accelerometer were analyzed and the results are presented in Figure 8 using SAE 60 Hz digital filter and a 50 milli-second (msec) average. Figure 8 shows the longitudinal and lateral accelerations ((a) and (b)) using the SAE 60 Hz digital filter and 50 msec average. The vehicle yaw, pitch, and roll angles of both test and simulation were calculated using TRAP as shown in Figure 8(c). The test vehicle rolled outward as much as 9.8 degrees first and then rolled over the barrier. The maximum roll angle of the test vehicle was 33.8 degrees is compared to 51.8 degrees of the vehicle model at 0.7 sec. The peak pitch angles in test and simulation were 7.8 degrees at 0.152 sec and -9.7 degrees, respectively. The minimum yaw angles in test and simulation were -15.9 and -18.4 degrees at 0.6 sec, respectively. The vehicle's yaw angle obtained from the simulation reasonably followed the test results.



(a) Longitudinal acceleration



(b) Lateral acceleration



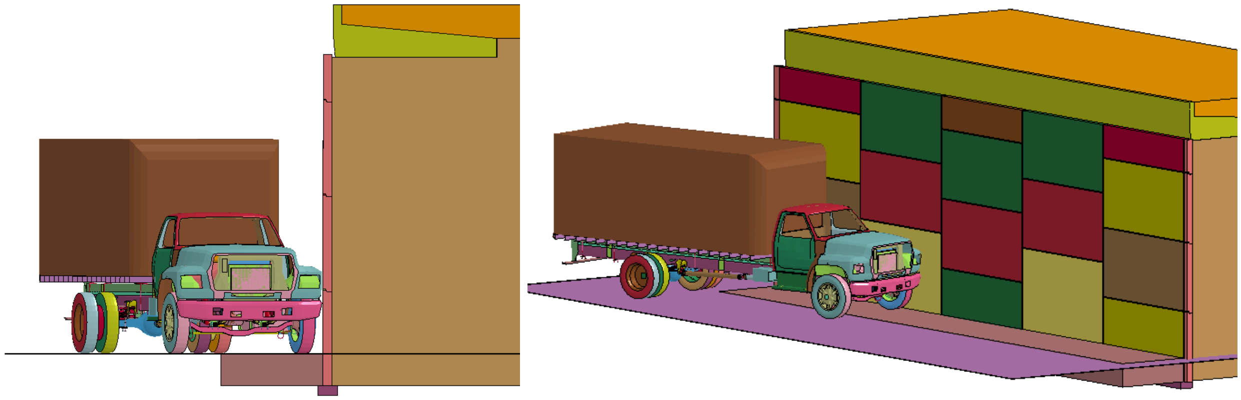
(c) Angular displacement of vehicle

Figure 8 Comparison of accelerometer data and angular displacement of the truck

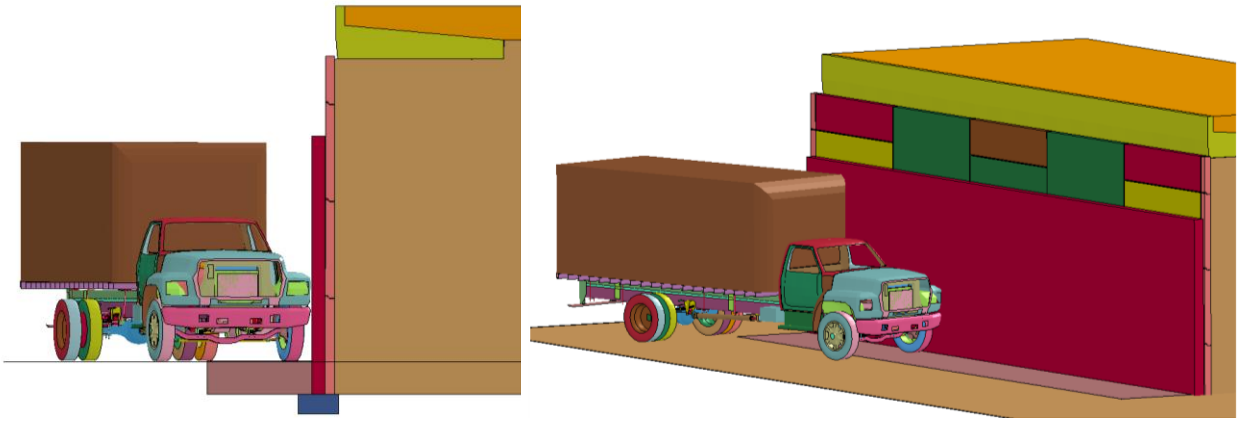
System Set-Up of Full-Scale Crash Simulation

Once the initialization process was completed, the vehicle model was combined with the initialized MSE model to conduct the impact simulation. The initialized model included soil and strips stresses from `dynain` output file generated by *INTERFACE_SPRINGBACK keyword used in the initialization simulation. The vehicle impact point against the wall panels was located on the second panel from the left. The distance from the end of the wall panel from the left was to be 5.35 m. This point was chosen to maximize the severity of impact by making the impact point closer to a joint.

Three LS-DYNA simulations of the MSE wall were conducted in the course of this study. The first simulation was for a model of a typical section of an MSE wall as shown in Figure 9(a). This simulation would be used to quantify damage profile of the wall panels during a direct vehicular impact as a reference case. The next two simulations incorporated the same MSE wall model in addition to the sacrificial crash wall model to quantify damage profile of the wall panels due to a vehicular impact on the crash wall as shown in Figure 9(b). Two different methods were used to represent the interaction between the wall panels and a crash wall. Contact definition was used in one model to represent compressive only interaction while embedded anchors were added in the other model to represent compressive interaction and positive anchorage.



(a) FE Model of a typical MSE wall

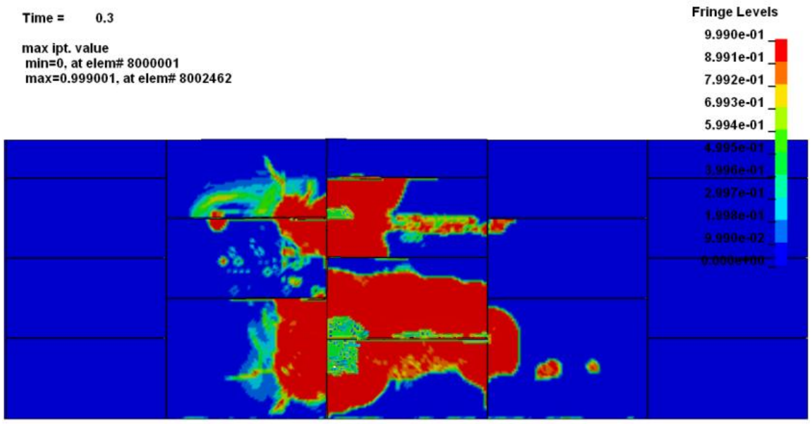


(b) FE Model of an MSE wall with a crash wall

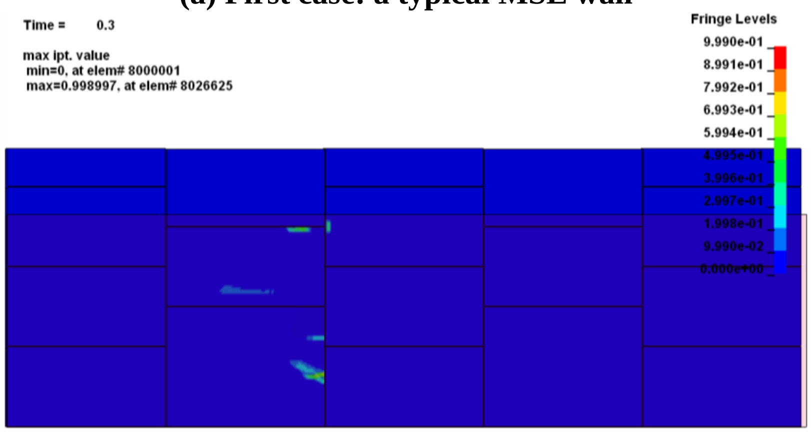
Figure 9 Set-up of SUT vehicle with MSE wall models

Simulations Results

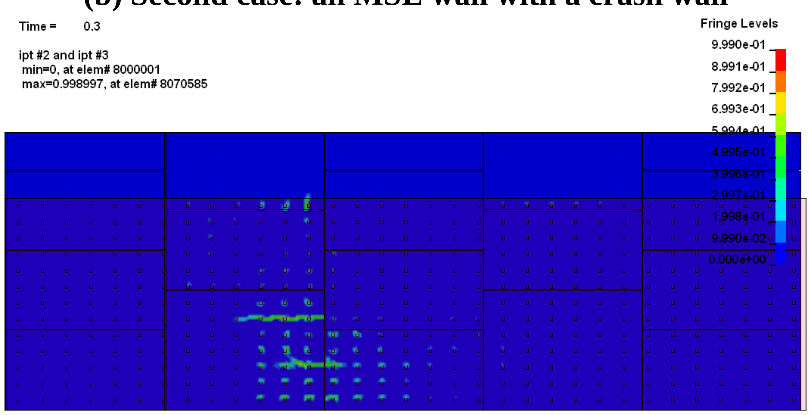
The wall panels exhibited significant damage once impacted by the 10000S vehicle as shown in Figure 10(a). This indicates that the panels alone cannot resist direct impact of such severity. However, once the 0.2 m thick continuous sacrificial crash wall was added in front of the panels, the panels exhibited minor damage profile as shown in Figure 10(b). Similarly, in the case of an MSE wall with the sacrificial crash wall and anchors, the panels exhibited minor damage profile as shown in Figure 10(c).



(a) First case: a typical MSE wall



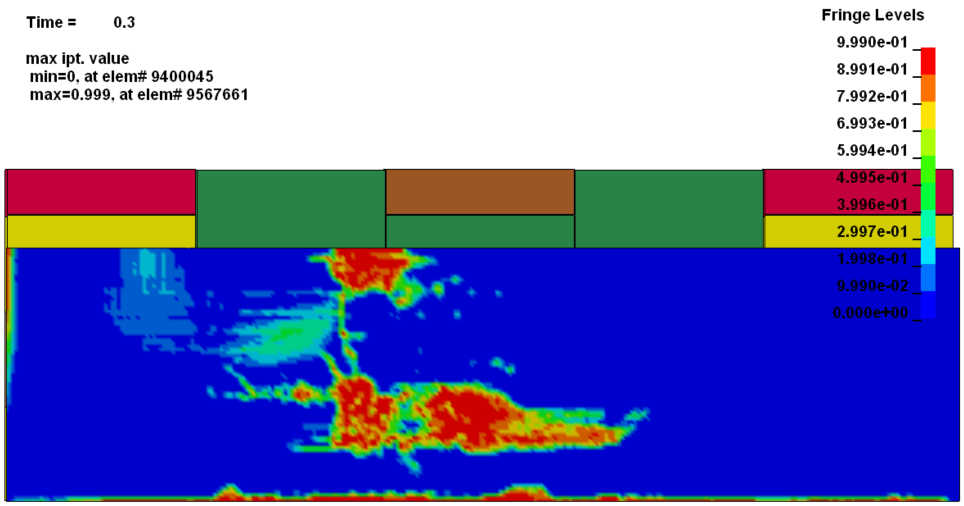
(b) Second case: an MSE wall with a crash wall



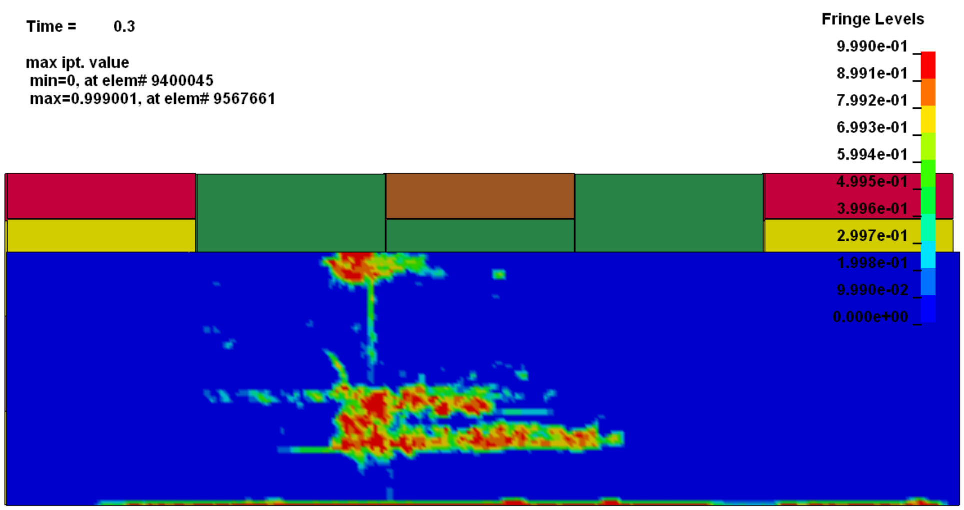
(c) Third case: an MSE wall with a crash wall and anchors

Figure 10 Comparison of damage profile on the wall panels

The damage was limited to the sacrificial crash wall instead of the panels as expected. However, this damage of the sacrificial crash wall was spread over smaller surface area of the sacrificial crash wall than the damaged area developed in the case of direct impact on the MSE wall panels. This comparison was identified from comparing Figure 11(a) with Figure 10(a). Moreover, adding the anchors reduced the damaged area to the sacrificial crash wall as shown in Figure 11(b) with respect to Figure 11(a).



(a) Second case: an MSE wall with the sacrificial crash wall



(b) Third case: an MSE wall with the sacrificial crash wall anchored to the MSE wall panels

Figure 11 Comparison of damage profile on the crash wall (Impact side)

Summary and Conclusion

This study was undertaken to evaluate the effectiveness of a sacrificial crash wall design installed in the front of MSE wall panels using LS-DYNA. A 0.2 m thick crash wall was shown to be effective in reducing damage to the MSE wall panels from direct vehicular impact.

In order to evaluate the crash wall design on the MSE wall, three simulations were conducted: (1) a typical MSE wall structure, (2) an MSE wall with a sacrificial crash wall, and (3) an MSE wall with a sacrificial crash wall that is tied with anchors to the panels. An SUT vehicle model that represents *MASH* 10000S vehicle specifications was used for these simulations as the errant truck.

The analysis results showed that the wall panels exhibited considerable damage by the direct impact. This indicates that the wall panels alone cannot prevent the direct impact of such severity. However, once the 0.2 m thick sacrificial crash wall was added in front of the MSE wall panels, the MSE wall panels exhibited much reduced damage profile. The damage was rather spread on the sacrificial crash wall instead of the MSE wall panels. Moreover, the damage on the sacrificial crash wall had smaller spread than the damage spread of the MSE wall panels when impacted directly.

When the wall panels have damage due to a direct impact, the reconstruction work for the panels is complicated because this damage might affect the whole MSE wall system. The reconstruction cost also would be high to repair large section of the MSE wall system. However, the simulation analysis showed that the sacrificial crash wall placed in front of the panels significantly helped to reduce damage to wall panels. Reconstruction of the sacrificial crash wall is less complicated than reconstruction of the MSE wall structure because casting concrete can be accomplished from the outside area without rebuilding the wall panels. This would results in reducing construction time experienced by the traveling public as well significant reduction in repair cost for the user agency.

Acknowledgment

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