MSE Wall Behavior during Large Truck Impact at High Speed against Barrier on Top of Wall

Jean-Louis Briaud, *Professor, Texas A&M University, College Station, TX, U.S.A.; email: briaud@tamu.edu*
Roger Bligh, *Research Engineer, Texas A&M Transportation Institute, College Station, TX, U.S.A.; email: rbligh@tamu.edu*
Layal Maddah, *Geotechnical Engineer, Fugro, Houston, TX, U.S.A.; email: l.maddah@fugro.com*

ABSTRACT: *Some 45 years ago, the total number of annual deaths on U.S. roadways was slightly over 50,000. In 2020, this number was reduced to less than 39,000 despite the fact that the number of kilometers traveled almost doubled. One of the major contributing factors to this life-saving improvement is the development of better roadside safety barriers. This paper describes one of the largest instrumented crash tests with a 352 kN truck hitting a 1.07 m high reinforced concrete barrier at 79.5 kph and a 15-degree angle. The barrier transferred the load to the Mechanically Stabilized Earth (MSE) wall through the sliding and rotation of the barrier-moment slab placed on top of the wall's edge. The instrumentation indicated that some of the MSE wall strips in the vicinity of the crash area were brought to the pull-out failure load during the impact. However, since the impact duration was very short, the displacement of the front of the wall and the barrier were tolerable and the wall needed only cosmetic repair. The maximum horizontal dynamic force on the barrier at impact was 712 kN and the maximum lateral permanent displacement of the barrier was 31 mm. The truck was properly redirected onto the road while the wall experienced minimal damage. As such, the barrier and wall design were considered successful. Design guidelines are suggested for a barrier-MSE wall assembly to resist such a large truck impact.*

KEYWORDS: MSE wall, pullout load, crash test, barrier, TL5, numerical simulation, measured behavior, full-scale test

SITE LOCATION: **Geo-Database**

INTRODUCTION

Roadside safety has progressed dramatically over the last 100 years. Common types of roadside barriers include metal guardrails, cable guardrails, and concrete barriers. These barriers are anchored in the soil or rigidly connected to a bridge deck. In the case of an MSE wall, the barrier cannot be anchored either way. Instead, the barrier is designed as a self-sufficient L-shaped barrier, where the vertical part of the L is the barrier hit by the vehicle, and the horizontal part of the L is the moment slab, which must be heavy enough and long enough to prevent excessive sliding or overturning of the barrier during the impact. When the barrier is hit by the vehicle, a dynamic load is transferred to the MSE wall below. Two questions to be answered in this article are: what is the load transferred to the soil reinforcing strips and what is the damage imparted to the wall? The goal is to ensure that both load and displacement are tolerable, and that minimal damage is imparted upon the permanent fixtures of the wall. From a roadside safety point of view, the goal is to redirect the truck back onto the roadway without it going through the barrier or rolling over the barrier. The behavior of the truck occupant is not addressed in this article.

Much work has been done on roadside safety barriers over the years. Some of the major references for barriers include NCHRP Report 350 by Ross et al. (1993) which set guidelines for evaluating barriers for trucks, followed by an AASHTO update (2009) that became the Manual for Assessing Safety Hardware (MASH). On the MSE wall side, some major references for design include Elias et al. (2001), updated by Berg et al. (2009). However, existing work specifically on MSE wall behavior during impact of a vehicle against a barrier placed on top of the wall is scarce.

One full-scale crash test on a precast barrier section atop of an MSE wall was conducted in 1982 by the Terre Armee Interna-

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tionale (TAI) in France (RECO, 1995). In this test, a 118 kN bus impacted the barrier at a speed of 70.8 kph and an angle of 20 degrees. The 1.52 m long precast concrete barrier sections used in the test were 0.81 m tall and had a New Jersey (NJ) profile. A 1.25 m wide moment slab was cast in place with a joint every 9.14 m. The underlying MSE wall was 3.05 m high with two levels of 1.52 m panels attached to 5 m long steel reinforcement strips at a density of 6 strips per 3 m of wall length. The first and second layers of soil reinforcement were at a depth of 0.38 m and 1.14 m below the bottom of the moment slab.

In the test, the MSE wall panels were not damaged and had only minimal movement. All damage was concentrated in the barrier sections. The maximum recorded strip load was 28.91 kN. In 1995, the Reinforced Earth Company (RECO) wrote a report outlining the results of this test, and it was concluded that the minimum density of soil reinforcement was adequate to resist the impact load. Another reference for this problem is Bligh et al. (2009) for a pickup truck weighing 22 kN hitting the barrier at 102 kph at a 25.6-degree angle. Further work by the authors (Bligh et al., 2017) included a single unit truck weighing 98 kN hitting the barrier at 94 kph at a 15.2-degree angle.

This article presents the results of a much larger tractor-van trailer truck, commonly known as an 18-wheeler, weighing 352 kN and going 79.5 kph with a 15-degree angle hitting a 1.07 m high reinforced concrete barrier-moment slab assembly sitting on top of a 3 m high instrumented MSE wall. These crash tests on barriers are classified by Test Level or TL in the MASH standard. The TL rating goes from TL1 to TL6. TL1 is a crash test for a small car at low speed progressing all the way to TL6 for a fully loaded tractor-tank trailer truck at high speed. The crash test reported here is a TL5 test.

SETTING UP THE NUMERICAL SIMULATION OF THE IMPACT

In roadside safety, the first half of the last sixty years consisted of full-scale tests and associated measurements performed according to evolving design guidelines. In the last 30 years, numerical simulation of the impact has grown significantly to the point where nowadays, vehicle impact research projects often start with numerical simulations of the full-scale impact. The reason is that numerical simulations are typically less expensive than the full-scale test and that the results of judiciously chosen numerical simulations can help optimize the design of the more expensive full-scale experiment.

The software used for the simulations was LS-DYNA (Hallquist, 2007). The Finite Element Method (FEM) models included the tractor-trailer truck, the L shape barrier and moment slab, and the MSE wall with soil and reinforcement strips (Figure 1). The truck drove over the pavement on top of the MSE wall, hit the barrier, and got redirected back on the pavement. The model of the tractor-trailer truck consisted of 583 parts with a total of about 400,000 elements, including the ballast in the trailer made of concrete beams rigidly tied to the trailer's floor. The L shape barrier-moment slab assembly and the reinforced MSE wall soil mass consisted of 4.57 m long precast steel reinforced concrete barrier-coping sections, the 9.15 m long cast-in-place reinforced concrete moment slab sections, the backfill and overburden soil material, the precast steel-reinforced concrete wall panels, the unreinforced concrete bearing pad and concrete levelling pad, the steel reinforcement shear dowels connecting the moment slab sections, and the steel soil reinforcement strips (Figure 2). The coping is the lower part of the barrier which straddles the top panels of the MSE wall. The finite elements of the barrier, the panels, and the soil surrounding the impact location had an average size of 20 to 40 mm for a total of about 1 million elements.

The dimensions of the model (Figure 1) were 27.45 m in length, 3.75 m in height, and 5.34 m in width. The barrier height from the pavement surface to the top of the barrier was 1.07 m and the width of the moment slab was varied but finally chosen as 2.13 m, measured from the back of the MSE wall panel to the end of the moment slab. The bottom of the moment slab was 1.02 m deep below the pavement surface, and the length of the reinforcement strips was 3.05 m. Referring to Figure 1, the boundary conditions were as follows: all boundaries were free of any constraints except for the vertical boundary at the back of the wall, at the bottom of the wall and on the side-ends of the wall.

Constitutive models were selected for the concrete, steel, and soil elements. The concrete constitutive model was elastic with a check on the tensile strength to ensure that the concrete stayed within the elastic range. The steel constitutive model was elastic up to the yield strength and perfectly plastic beyond that until the break strength. The soil constitutive model was elastic plastic using a two-invariant cap model with a convex yield surface consisting of a failure envelope, an elliptical cap, and a tension cutoff region (Bligh et al., 2017; Murray, 2007). The soil had a unit weight of 18.85 kN/m^3, a Young's modulus of 20 MPa (based on correlations, engineering judgment, and prior experience in matching observed crash test behavior on a compacted fill), a Poisson's ratio of 0.35, no cohesion, and cap model parameters based on triaxial tests which gave a friction angle of 34^o. All interfaces were deforming according to the elements themselves without any slip interface.

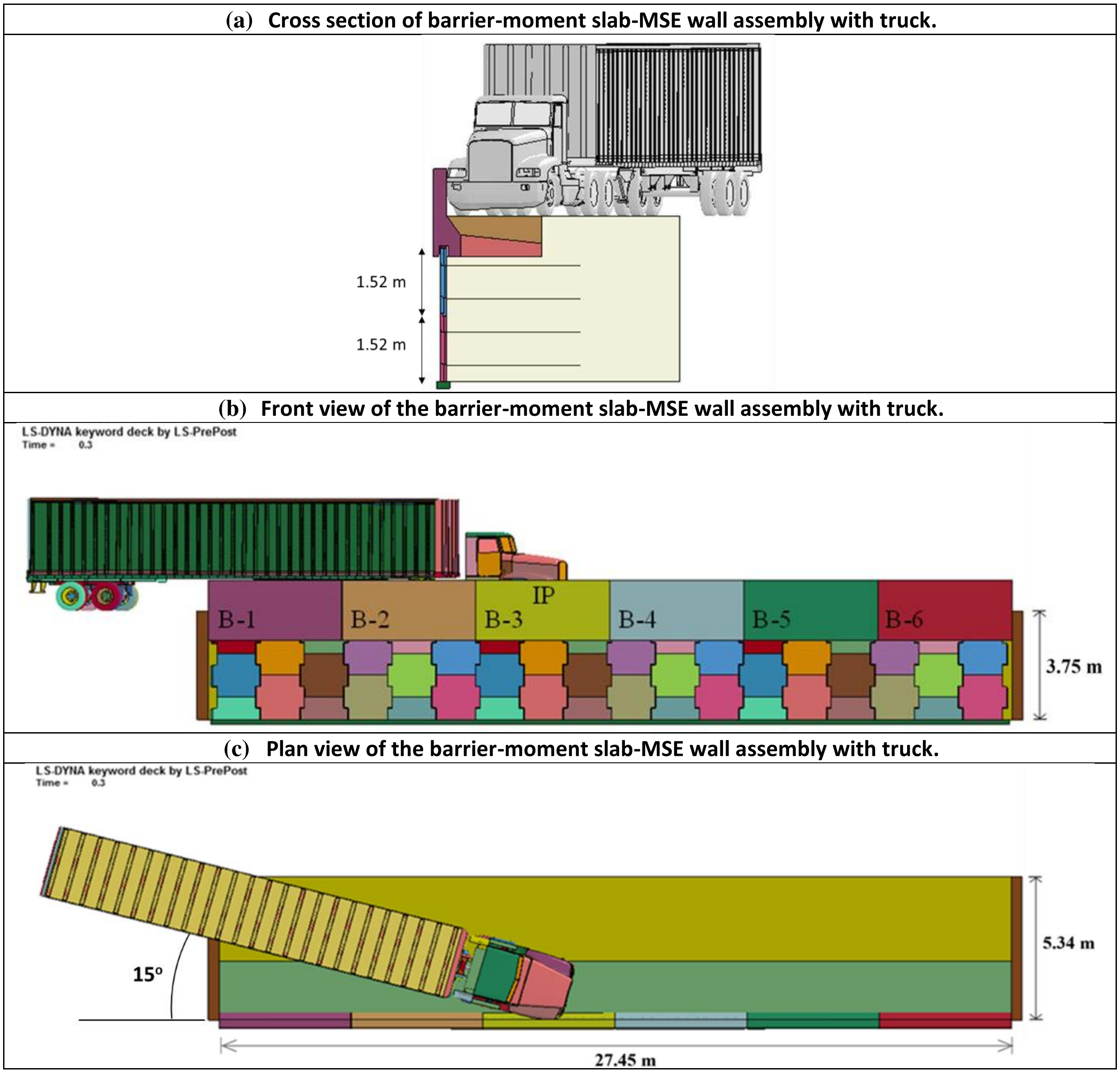


Figure 1. Finite element mesh for simulation of barrier-moment slab-MSE wall assembly with truck: (a) cross section of barrier-moment slab-MSE wall assembly with truck, (b) front view of the barrier-moment slab-MSE wall assembly with truck, and (c) plan view of the barrier-moment slab-MSE wall assembly with truck.

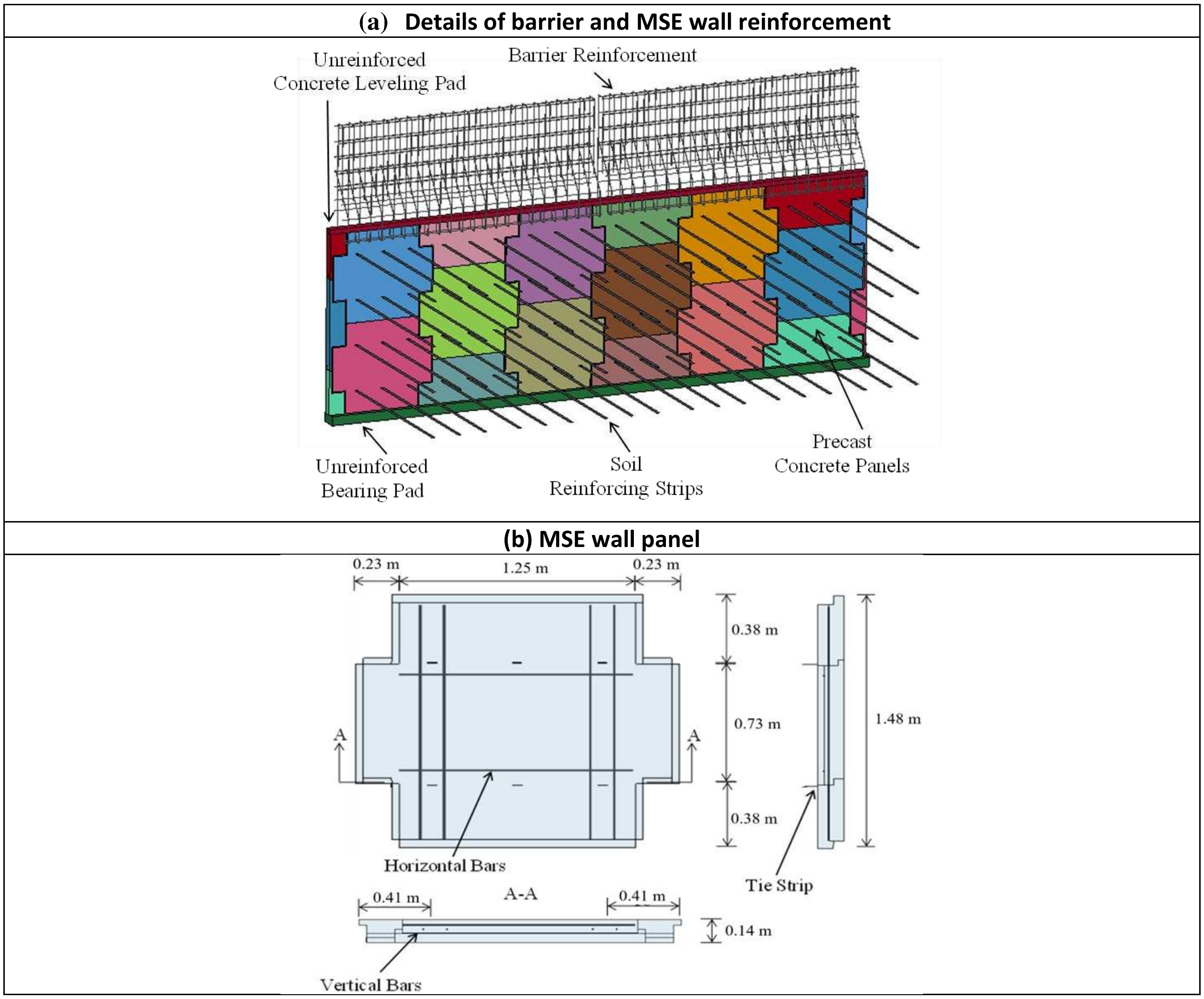


Figure 2. Barrier-moment slab and MSE wall model: (a) details of barrier and MSE wall reinforcement, and (b) MSE wall panel.

RESULTS OF THE NUMERICAL SIMULATION OF THE IMPACT

The most common height for a TL5 rated barrier on the highway is 1.07 m above the pavement surface. For higher barriers (e.g., 1.22 m), the impact load is much higher since the floor of the trailer hits the barrier; for a 1.07 m barrier it does not, and only the trailer axel hit the barrier. The results described next are for the most common 1.07 m high TL5 barrier. The concrete strength and the amount of steel reinforcement for the barrier were selected and designed to an ultimate capacity of 720 kN peak dynamic horizontal load; this load was estimated from numerical simulations, not a rigid barrier. The length of each of the six prefabricated barrier segments was 4.57 m, and the length of each of the three cast-in-place moment slab segments was 9.15 m (or two barrier segments). The moment slab segments were dowelled together but not the barrier segments as is done in practice. The width of the moment slab was 2.13 m, measured from the inside face of the MSE wall panels to the end of the moment slab. The average thickness of the moment slab was 0.381 m (0.483 m at the coping and 0.280 m at the far end), with the bottom of the moment slab at a depth of 1.02 m below the pavement surface. The length of the MSE wall reinforcement strips was selected to be the minimum length for low MSE walls, or 3.05 m, to see if this length would be sufficient to resist the impact. The truck weight was 352 kN, the impact speed was 80 kph, and the approach angle was 15^{o}.

The impact horizontal force on the barrier as a function of time is shown in Figure 3. Two lines can be seen: one shows rapid variations in the load which is the actual measured response, and the other shows a smoother variation. The smoother line corresponds to the 50-millisecond average of the signal, which is common practice in roadside safety data analysis. The 50-

ms signal identifies three distinct impacts associated with the front axle of the tractor at a peak dynamic force of 332 kN, the rear axle of the tractor (458.8 kN), and the rear axle of the trailer also known as the back slap (744.9 kN). Figure 4 shows the displacement at the top and at the bottom of the barrier. The main part of the impact lasted one second.

The total load in the MSE wall strips is the addition of the static load due to the earth pressure in the wall and the dynamic load due to the TL5 impact. The designation of the strips in the wall is given in Figure 5. For example, B3_B_1st refers to barrier segment B3, strip B in the first layer of strips. The top or first layer of strips is the one that is most severely influenced by the dynamic impact. The total load in the most heavily loaded individual strip in the first layer of strips during the impact and the dynamic component are shown in Figure 6a. The peak total load is 26.03 kN with a peak dynamic component of 22.02 kN. In the second layer of strips (Figure 6b), the corresponding peak total load and peak dynamic load were 15.4 and 8.5 kN respectively. The calculated maximum pullout resistance of the strips according to AASHTO LRFD (2014) was 10.14 kN for strips in the first layer and 15.57 kN for strips in the second layer. Therefore, according to the numerical simulation, the reinforcing strips of the first layer reached pull-out failure during the impact. The pull-out displacement of the strips is shown in Figure 7 and indicates a maximum displacement of 10 mm. Laboratory tests conducted on strips in a pressurized sand box showed displacements to failure of about 5 mm. This is consistent with the numerical simulations indicating that the reinforcement strips were at failure during the impact. The dynamic and permanent displacement of the wall panels are shown in Figure 8; the permanent displacement of the panels is limited to 7 mm, indicating that the wall could likely be reused without repair.

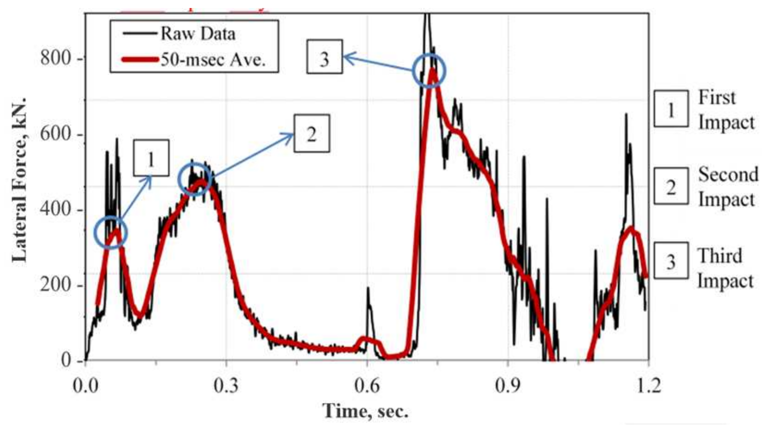


Figure 3. Horizontal impact force as a function of time in FEM simulation.

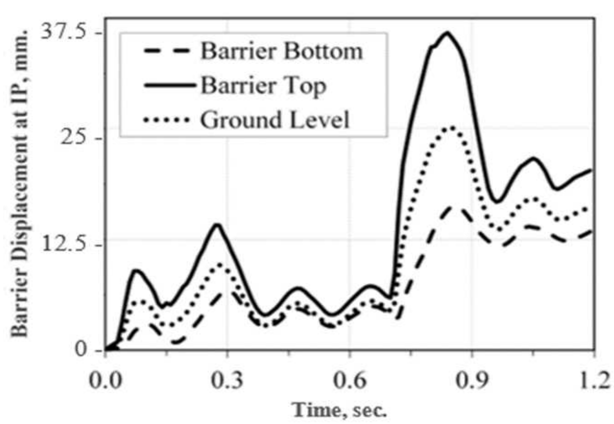


Figure 4. Barrier displacement during impact in FEM simulation.

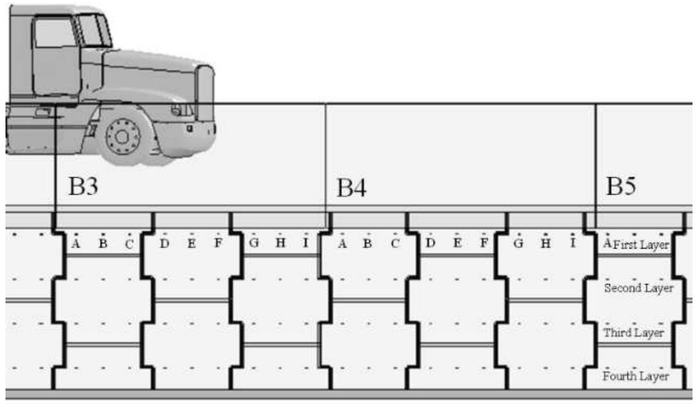
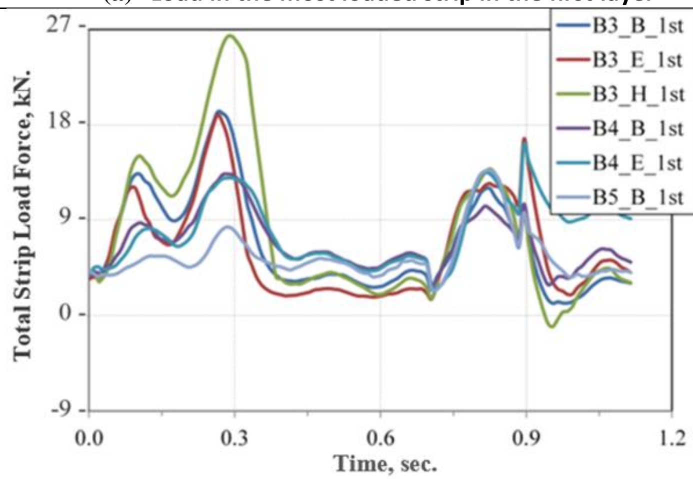


Figure 5. Reference designation for the strips in the wall.

(a) Load in the most loaded strip in the first layer



(b) Load in the most loaded strip in the second layer

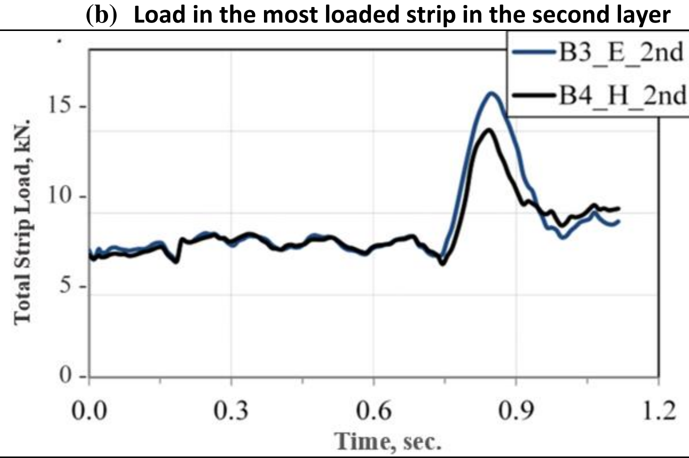


Figure 6. Total load in the most loaded strip for the first and second rows of strips in FEM simulation: (a) load in the most loaded strip in the first layer, and (b) load in the most loaded strip in the second layer.

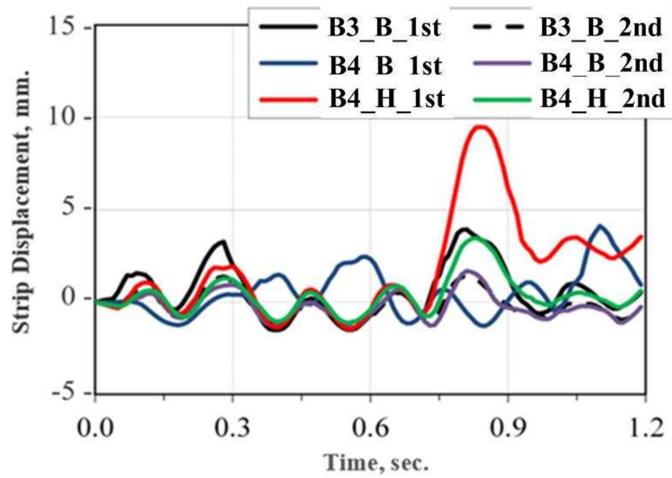


Figure 7. Displacement of the reinforcing strips (first level and second level) in FEM simulation.

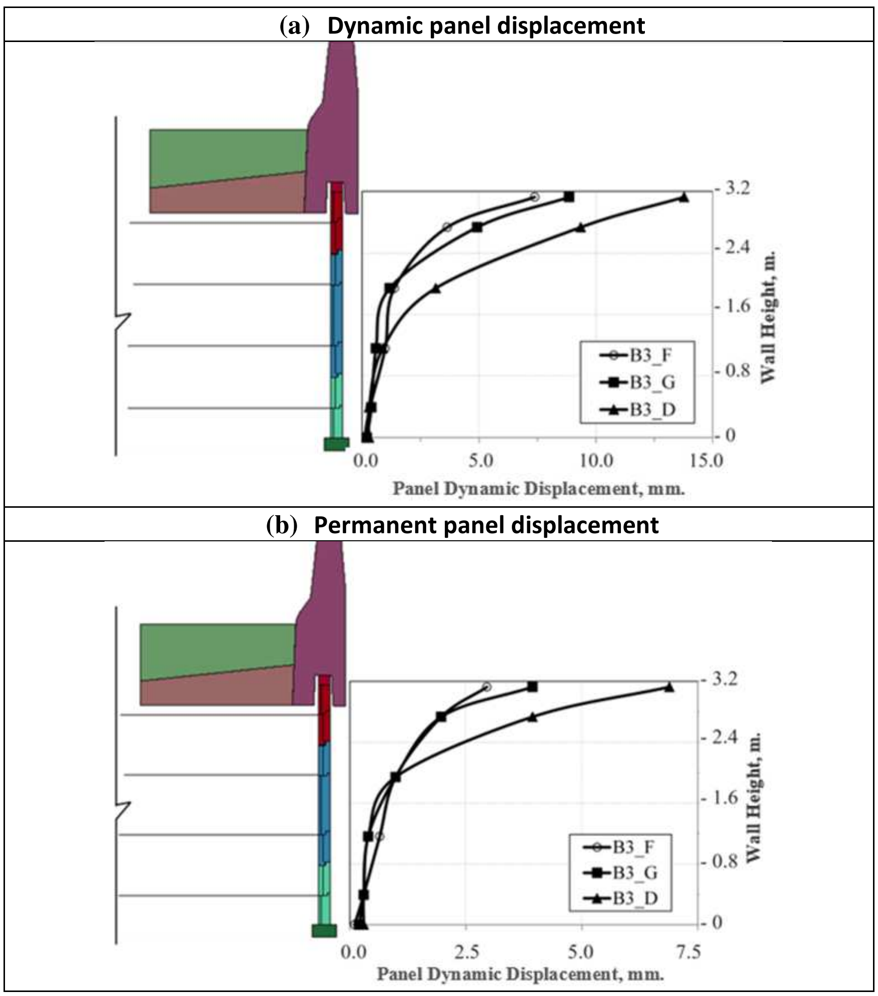


Figure 8. Displacement of the MSE wall panel in FEM simulation: (a) dynamic panel displacement, and (b) permanent panel displacement.

CONSTRUCTING THE WALL AND INSTRUMENTATION

The FEM simulation was the basis for the design of the full-scale TL5 crash test. The construction sequence consisted of digging a large 3 m deep hole, building the MSE wall from the bottom of the hole up such that the finished top level of the wall would be at grade with a runway pavement where the truck would gather speed, erecting the TL5 barrier prefabricated elements straddling the top panels, and casting and dowelling the moment slab elements. The instrumentation was inserted in various places as construction progressed.

The MSE wall was constructed with the help of the Reinforced Earth Company. After excavation of the native stiff clay down to a depth of 3 m, a 0.3 m wide and 0.15 m thick unreinforced concrete levelling pad was placed along the line where the bottom of the wall panels would rest. The concrete wall panels were cruciform, 1.52 m wide, 1.52 m high, and 0.14 m thick (see Figure 2). The wall was one and a half panels high, with the barrier sitting atop the top edge of the panels. Each panel had two levels of three 3.05 m long, 50 mm wide, and 4 mm thick galvanized steel strips each. These strips were ribbed and the strip spacing on each panel was 0.76 m vertically and 0.38 m horizontally.

Six 4.75 m long precast TL5 barrier segments were erected on top of the top panels and connected to three 9.15 m long, 2.13 m wide, and 0.381 m (on average) thick cast-in-place moment slabs at a depth of 1.02 m below the pavement surface. Details of the barrier are given in Figure 9. The three moment slabs were made of 27.6 MPa compressive strength concrete and dowelled together using three No.11 shear dowels across each joint. The barrier moment slab assembly continued 12.2 m beyond the end of the wall to help redirect the truck.

The backfill consisted of two soils: the clean sand used to build the wall from the bottom of the excavation to the bottom of the moment slab (1.98 m), and the crushed limestone from the bottom of the moment slab to the pavement surface (1.02 m). The clean sand was a poorly graded sand (SP) with a D_{50} of 0.51 mm, a coefficient of uniformity of 3.85, a coefficient of curvature of 0.84, and 3.1% passing sieve No. 200 (Figure 10a). The modulus of the sand was 14.8 MPa as measured with the BCD (Briaud et al., 2006), and the direct shear test friction angle was 34 degrees. The crushed limestone rock (also called road base) was a silty gravel with a D_{50} of 4 mm, a coefficient of uniformity of 216.7, a coefficient of curvature of 3.28, and 15.0 % passing sieve No. 200 (Figure 10b). The modulus of the crushed limestone was 55.2 MPa as measured with the BCD, and a large triaxial cell test gave a friction angle of 45 degrees. The sand was compacted in 150 mm thick lifts to a dry density of 17.4 kN/m^3 (95% of maximum dry density) and 3.03% water content, while the crushed limestone was compacted in lifts of 250 mm to a dry density of 20.1 kN/m^3 (95% of maximum dry density) and 5.81% water content.

The instrumentation consisted of strain gages on the reinforcement strips, a contact switch, accelerometers, high-speed cameras, and displacement gages. Based on the simulation results, 14 full-bridge strain gages were installed at 0.152 m and 0.915 m behind the connection of the strips to the wall panels at selected locations on the top two levels of strips near the impact point (Figure 11). A contact switch was installed between the top of the top panel and the coping to check if the coping of the barrier would come in contact with the top panel during the impact. Accelerometers were placed at various points on the truck to measure the three-dimensional decelerations during the impact. Two were on the tractor frame near the front axle and on the trailer frame between the two rear axles. One accelerometer was placed on the vertical edge at the end of the moment slab to indicate if the moment slab would move during the impact. Displacement and rotation of the barrier and wall panels were determined by high-speed video cameras at 1,000 frames per second. Fixed displacement gages were placed at the top and bottom of the wall panels to obtain the permanent movement of the panels and barrier after the test.

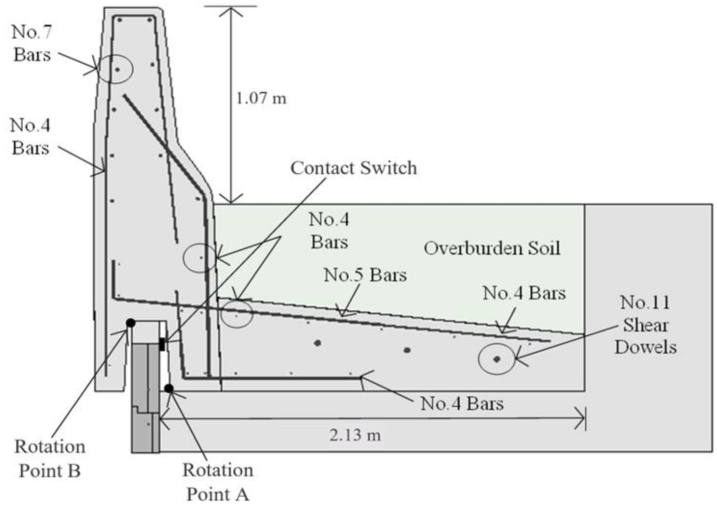


Figure 9. The TL5 barrier and moment slab as placed on the MSE wall.

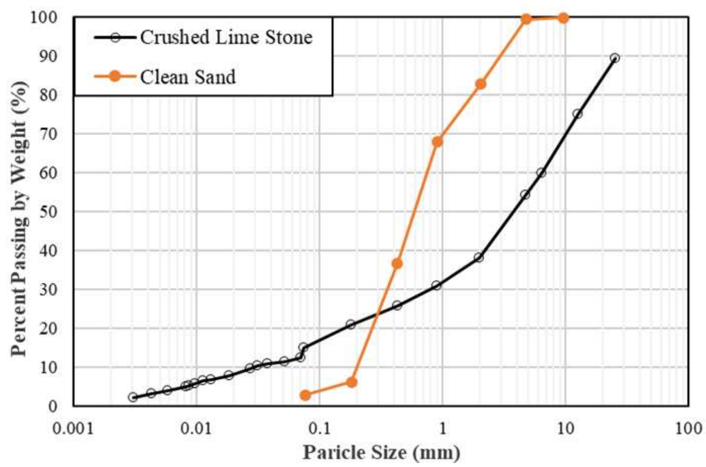


Figure 10. Particle size distribution curves for the clean sand and the crushed limestone rock

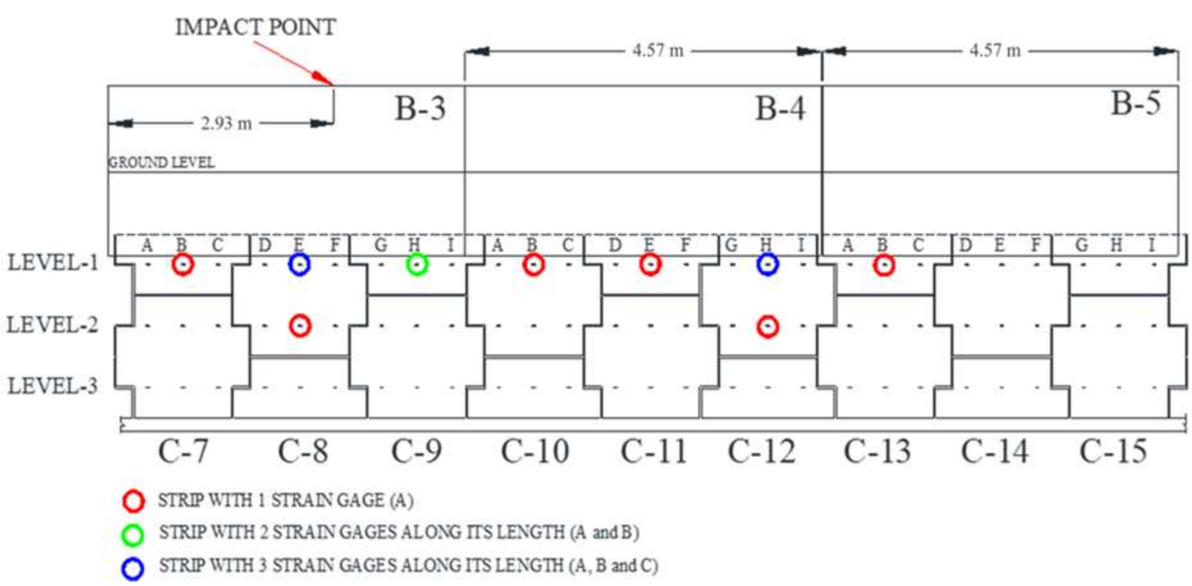


Figure 11. Location of the instrumented reinforcing strips.

CONDUCTING THE CRASH TEST AND MEASUREMENTS

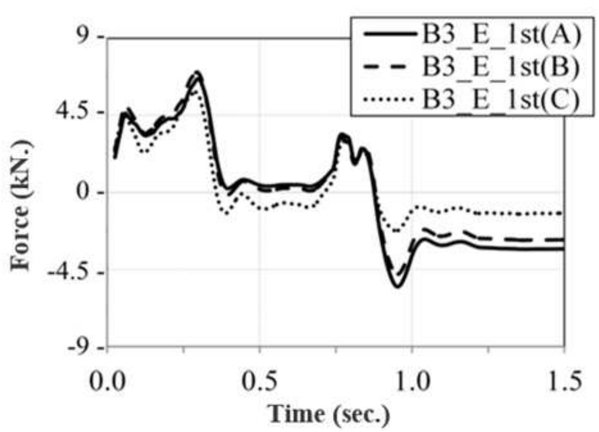
The TL5 test, also called MASH test 5-12, was conducted on 26 September 2012 under a clear sky and a temperature of 31.7°C (Figure 12). The tractor was a 2000 Sterling TF with a 1997 Stri 14.63 m long trailer. The tractor-trailer assembly weighed 352 kN and hit the barrier at 79.5 kph and at a 15° angle. The vehicle was directed into the test installation under power using a cable guidance system and was released to be free-wheeling and unrestrained just prior to impact. The tractor impacted the barrier 11.28 m from the upstream end of the barrier. At 0.070 sec after impact, the tire of the front axle of the tractor contacted the barrier and the tractor started to redirect. At 0.190 sec, the tire of the rear tandem of the tractor contacted the barrier, and at 0.757 sec the rear axle of the trailer contacted the barrier and created the highest dynamic horizontal load. The tractor-trailer rode off the end of the barrier and came to rest 53.8 m downstream of impact. The brakes on the vehicle were not applied.

The vehicle suffered significant exterior damage, but no measurable occupant compartment deformation. The maximum 50-msec average occupant ride-down acceleration was -4.4 g's in the lateral direction and -1.4 g's in the longitudinal direction. The vehicle rolled but did not overturn, and the maximum roll, pitch, and yaw angles were 32.5°, 6°, and 15° respectively. Using the mass of the vehicle and the lateral acceleration of the tractor and the trailer, the dynamic lateral force on the barrier can be computed ($F = ma$, where F is the force, m is the mass, and a is the acceleration). This force is an upper bound of the true force as it is assumed that the mass is rigid with no energy dissipated in strain energy associated with the vehicle deformation. These upper bound calculations give horizontal impact forces equal to 626.6 kN for the second impact (rear axle of tractor), and 895.4 kN for the third impact (rear axle of the loaded trailer). The permanent displacement of the top of the barrier ranged from 29.7 mm to 3 mm, while at the bottom of the barrier it ranged from 16.5 mm to 3 mm. After the crash test, the soil on top of the moment slab was removed to permit inspection of the moment slab and particularly the connection between the coping and the moment slab. A tension crack was observed in the barrier at the impact point but was not considered significant enough to require excavation and repair based on the crack size and length. Overall, redirecting the truck was deemed a success.

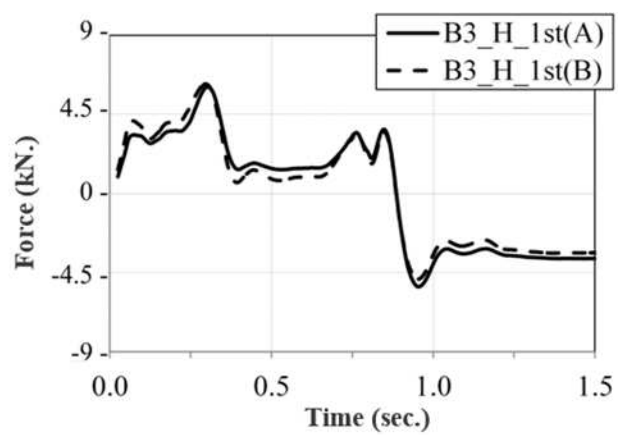
The location of the MSE wall reinforcing strips that were instrumented is shown in Figure 11. The total load in a strip in this project is defined as the addition of the static load due to the internal stability of the wall under gravity active pressure and the dynamic load induced by the truck impact. The load in the strips was measured 0.178 m behind the strip connection to the panel, and the dynamic load vs. time is shown in Figure 13. The maximum dynamic component of the loads in the strips is listed in Table 1 and the total load in Table 2. The dynamic load in the strips was maximum near the strip-to-panel connection point. As can be seen, the measured static loads are close to those calculated by AASHTO. The sum of the dynamic load and the static load is defined as the total load in the first layer of strips; the total load reaches the calculated ultimate resistance of the strip closest to the impact.

The dynamic displacement of the barrier and wall panels was to be recorded by the high-speed camera. Unfortunately, that camera did not trigger properly, and this information was not recorded. However, the permanent displacement of the wall panels associated with this ultimate pull-out load on the impact strip was 13.7 mm. The overall horizontal movement of the wall panels near the impact point varied from 0.25 to 13.7 mm. The most loaded strips were at or close to calculated failure for milliseconds and the resulting displacement was tolerable. Separate tests were conducted to quantify any possible rate effect on the pull-out capacity of the strips in a laboratory setting with clean dry sand backfill and 1.1 m long strips. No difference in ultimate capacity was found between pulling on the strip with a 1,200 s time to failure and pulling on the strip with a 0.05 s time to failure (Bligh et al., 2009). The panels also displaced in the longitudinal direction and in the vertical direction, but the displacements were minimal compared to the lateral displacements. These longitudinal and vertical displacements are due to the trailer box riding on top of the barrier for about 0.040 seconds. The wall panels were inspected after the test. A hairline crack was observed on two of the full-section panels at the level of the uppermost layer of reinforcing strips. The barrier segments were positioned with a horizontal gap of 19 to 25 mm between the coping of the barrier and the wall panels to avoid transferring impact loads into the wall panel. The contact switch between the coping and the panel face did not trigger, indicating that the coping did not touch the MSE wall panel during the impact. Overall, the performance of the wall panels and the relatively short 3.05 m long strips was satisfactory, and no restoration was deemed necessary.

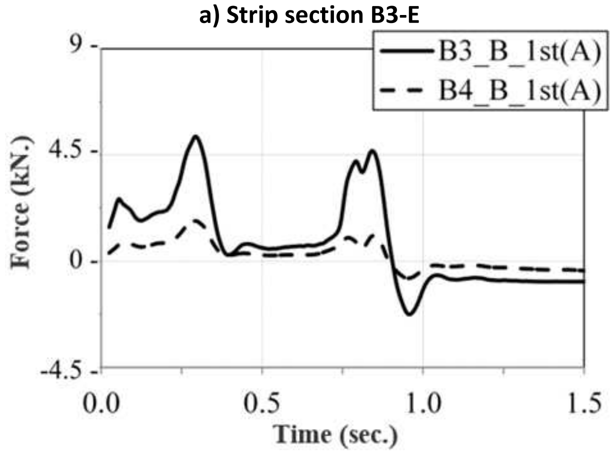
Figure 12. Test set up just before impact test.



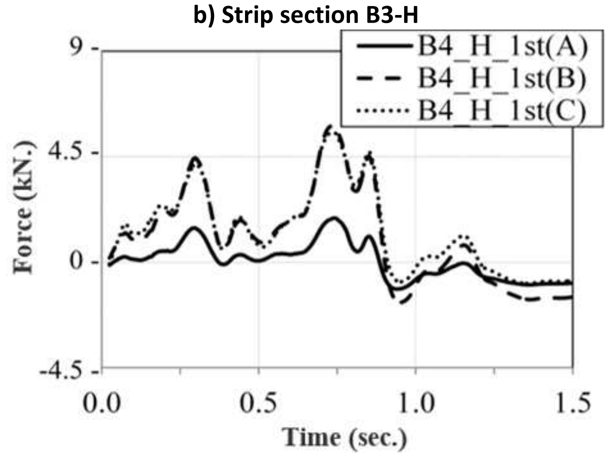
a) Strip section B3-E



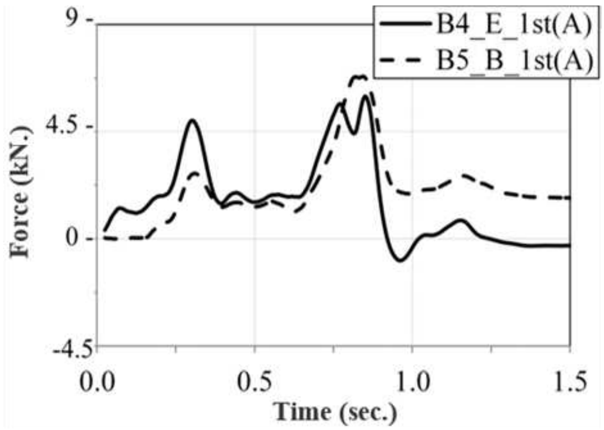
b) Strip section B3-H



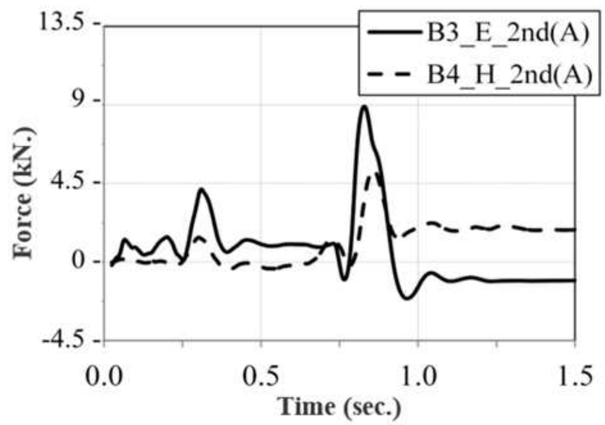
c) Strip sections B3-B and B4-B



d) Strip section B4-H



e) Strip sections B4-E and B5-B



f) Second layer of strips

Figure 13. Dynamic load in the wall reinforcing strips during the impact (50 msec average): (a) strip section B3-E, (b) strip section B3-H, (c) strip sections B3-B and B4-B, (d) strip section B4-H, (e) strip sections B4-E and B5-B, and (f) second layer of strips.

Table 1. Measured maximum dynamic loads in the strips during the impact.

Strip section	Layer of soil reinforcement	Location from the panel face (m)	Maximum load from raw data (kN)	Maximum load from 50-msec. ave. data (kN)
B3-B-1st(A)	First	0.178	6.138	5.204
B3-E-1st(A)	First	0.178	7.161	6.539
B3-E-1st(B)	First	0.914	7.562	7.117
B3-E-1st(C)	First	2.286	6.450	5.782
B3-E-2nd(A)	Second	0.178	12.10	8.807
B3-H-1st(A)	First	0.178	6.405	6.005
B3-H-1st(B)	First	0.914	6.628	6.138
B4-B-1st(A)	First	0.178	1.957	1.690
B4-E-1st(A)	First	0.178	7.161	5.916
B4-H-1st(A)	First	0.178	1.957	1.868
B4-H-1st(B)	First	0.914	6.049	5.782
B4-H-1st(C)	First	2.286	5.738	5.471
B4-H-2nd(A)	Second	0.178	5.649	5.249
B5-B-1st(A)	First	0.178	6.939	6.716

Table 2. Total maximum loads on the soil reinforcing strips.

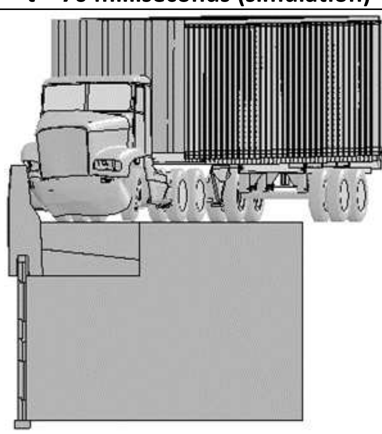
	Static load measured (kN)	Dynamic load [(1)] measured (kN)	Total load measured (kN)	Resistance by AASHTO[(2)] (kN)
Top layer	3.51	7.12	10.63	10.14
Second layer	4.00	8.81	12.81	15.57

(1) 50 ms average
(2) AASHTO (2014)

COMPARING NUMERICAL SIMULATION AND FULL-SCALE TEST

A comparison between the results of the full-scale test and the associated numerical simulation was conducted to establish confidence in the simulation and to develop the design guidelines. Note that the simulation was performed prior to running the test, thus representing a true class A prediction. There were minor physical differences between the simulation and the test (wall height, ballast in the trailer, coping wall panel spacing, and truck model), as not all decisions had been made for the test when the simulation was performed.

Qualitatively, the sequential views of the impact from the simulation and the test compare well, as seen in Figure 14. Quantitatively, the acceleration results were closer for the rear axle of the trailer, which corresponds to the highest load in the impact than for the rear axle of the tractor. Indeed, for the trailer, the longitudinal and lateral accelerations were -2.7 g's and -11.6 g's for the model, and -3.4 g's and -10.8 g's for the test; for the tractor, they were -2.1 g's and -5.3 g's for the longitudinal and lateral acceleration in the model, and -1.4 g's and -4.4 g's for the test. These acceleration values are 50 msec averages. The simulation predicted reasonably well the permanent displacement of the barrier, as shown in Table 3. The dynamic displacements of the wall panels during the test could not be measured due to problems in the instrumentation. The measured lateral permanent deflections of the wall panels after the test ranged from 0.25 mm to 13.72 mm. The dynamic and permanent deflection determined from the simulation ranged from 0.25 mm to 14.73 mm and from 0.25 mm to 7.11 mm, respectively. The simulation under-predicted the permanent displacement in some wall panels but predicted others reasonably well. In addition, the simulation predicted high bending stresses of the panels located underneath the impact point and, after the test, hairline cracks were observed at those locations. The simulation overpredicted the tension load in the top strips near the point of impact but did better at other locations (Figure 15), particularly in the second row of strips.

t = 70 milliseconds (simulation)	**t = 70 milliseconds (test)**
	

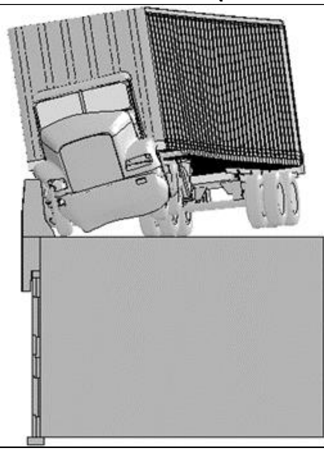
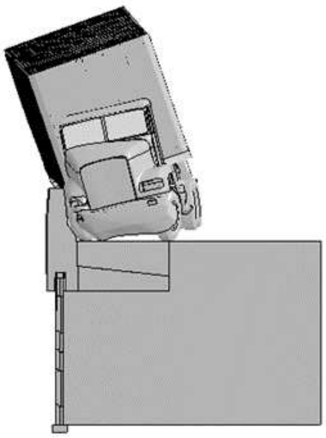
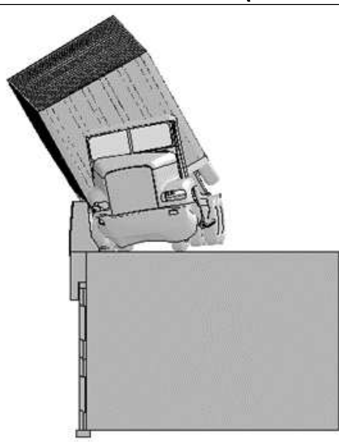
t = 370 milliseconds (simulation)	t = 370 milliseconds (test)
	
t = 740 milliseconds (simulation)	**t = 740 milliseconds (test)**
	
t = 920 milliseconds (simulation)	**t = 920 milliseconds (test)**
	

Figure 14. Comparison between simulation and test of sequential views of the impact.

Table 3. Comparisons between measured and simulated permanent displacement of the barrier at the impact point.

	Top (mm)	Ground level (mm)	Bottom (mm)
Measured	26.9	18.8	10.2
Simulated	21.6	16.5	13.5

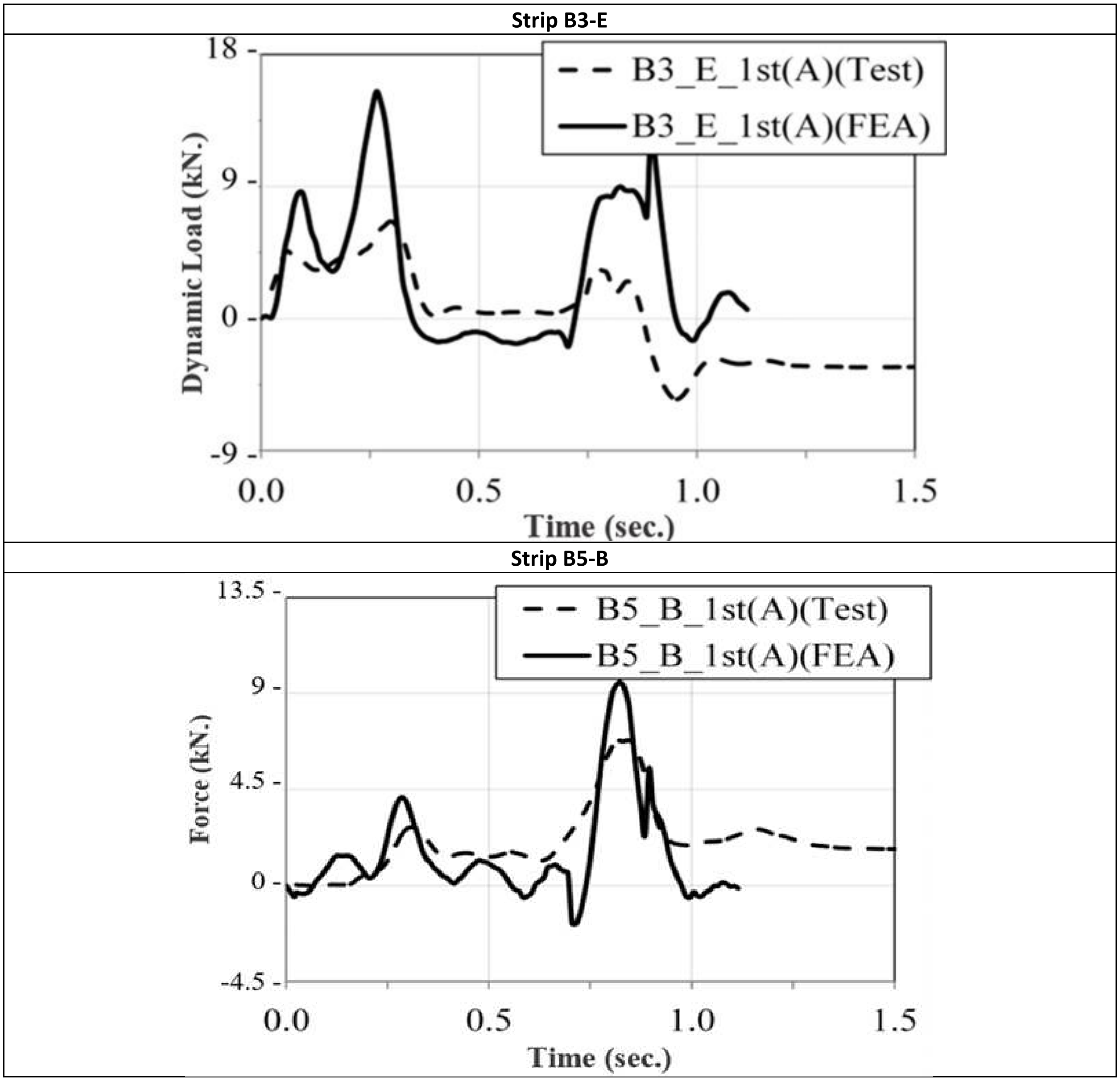


Figure 15. Comparison of the dynamic component of the strips' loads in the uppermost layer of soil reinforcement.

STATIC LOAD TEST ON THE BARRIER

After the full-scale impact test, a horizontal static load test was performed on the barrier moment slab system on top of the MSE wall (Figure 16). The objective was to assess the ultimate horizontal load of the system as an equivalent static load to the maximum horizontal dynamic load in the impact test. The section of barrier selected was one that had received minor loading from the impact of the truck (B5). The horizontal load was applied at a height of 0.864 m through a 3.05 m long spreader bar to engage a 9.15 m length of barrier and a 9.15 m length of moment slab in the load test. The load was applied in 22.25 kN increments lasting one minute each. The horizontal displacement of the top and the bottom of the barrier were recorded, as well as the horizontal displacement of the coping. The horizontal load-horizontal displacement curve for the load test is shown on Figure 17(a) along with the numerical simulation results. Figure 17(b) shows the displacements at different heights of the barrier. During the static load test, the load in the strip right below the loading point (B5_B_1st(A)) was recorded (Figure 18). The figure indicates that the load started to increase rapidly in the strip when the static load on the barrier exceeded 356 kN, which is assumed to be the point at which sliding of the barrier was prominently engaged. Because the barrier moment slab redirected the truck properly and without major repair needed, the static load considered to be equivalent to the maximum dynamic load on the barrier was the maximum load applied to the barrier in the horizontal static load test before the nonlinear behavior started, or 356 kN.

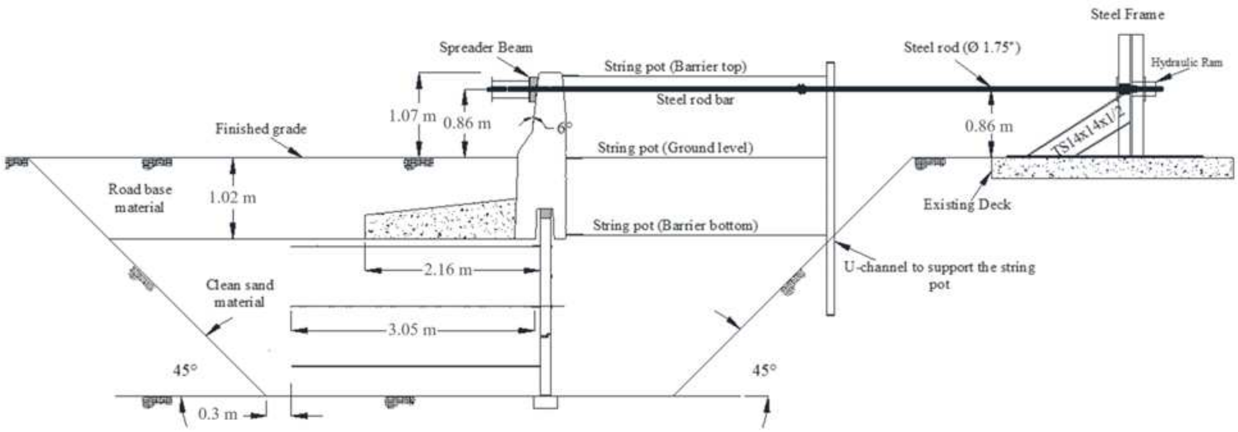
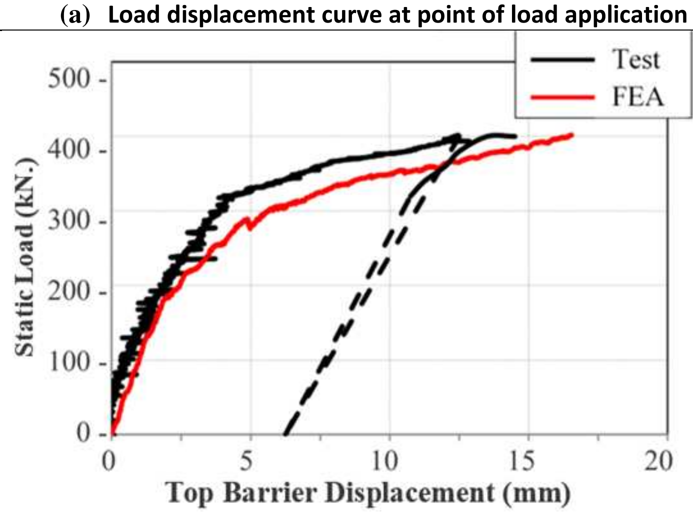


Figure 16. Set up for the horizontal static load test on the barrier.

(a) Load displacement curve at point of load application



(b) Load displacement curve at points along barrier height

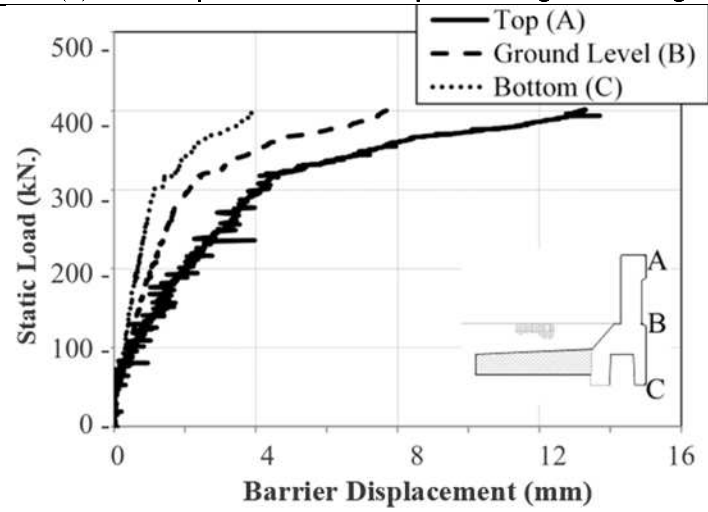


Figure 17. Horizontal load vs. horizontal displacement of the barrier: measurements and simulation: (a) load displacement curve at point of load application, and (b) load displacement curve at points along barrier height.

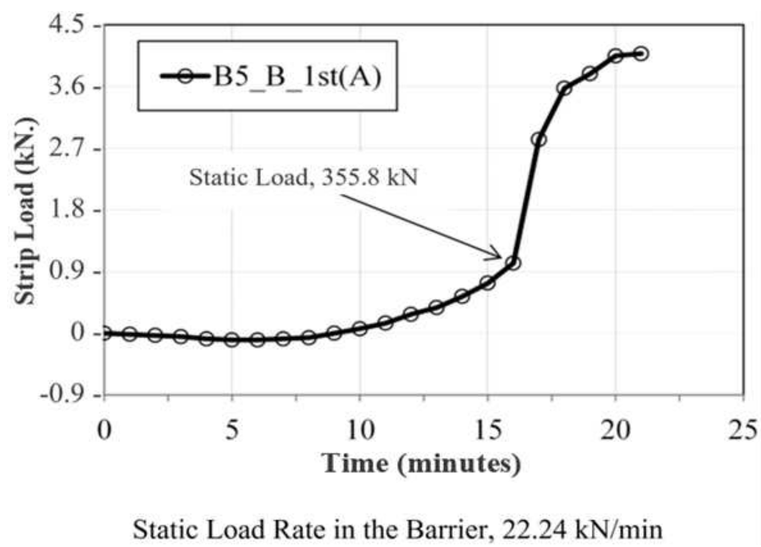


Figure 18. Load in top strip below barrier loading point.

DESIGN SUGGESTIONS AND CONCLUSIONS

Based on the TL5 full-scale impact test, the TL5 barrier static test, and the numerical simulation of the TL5 impact test, the following design suggestions are presented for MSE walls with barriers on top of them to withstand a TL5 impact:

1. The maximum dynamic load obtained in the numerical simulations is 712 kN. It is chosen for design purposes instead of the load of 895.4 kN obtained from the product of the truck mass and the measured acceleration during the crash test. Indeed, the 895.4 kN load ignores the crushing of the truck during the impact test and is thus an upper bound. The 712 kN load should be used for designing the barrier, coping, and moment slab components—including concrete and steel— as these components will be subjected to the full impact load dynamically. The barrier should be 1.07 m high, as taller barriers can be subjected to much higher loads (Bligh et al., 2017).

2. The width of the moment slab can be obtained through an equivalent static design by using the horizontal equivalent static load measured in the barrier static test (356 kN) and applied at a height of 0.864 m, as was the case for the

test. Both overturning and sliding of the barrier moment slab assembly should be checked. The 2.18 m wide moment slab worked well in the TL5 test.

3. The point of rotation of the barrier can be point A or B, as shown in Figure 9. Point A should be selected for overturning design if the top of the wall panel is not in contact with the coping. Point B should be used if there is direct bearing between the bottom of the coping and the top of the wall panel or level-up concrete.

4. The load and resistance factors should be consistent with extreme events loading.

5. The first two layers of the wall reinforcement should be designed to resist the dynamic load due to the impact in addition to the static load due to the earth pressure. The pull-out load should be calculated to resist the equivalent static pressures listed in Table 4 in addition to the earth pressures (Figure 19). Alternatively, a line load approach can be used (Table 5 and Figure 20). These suggestions come from the AASHTO calculated ultimate static pull out load on the 3.05 m long strips and their tributary areas after subtracting the static load due to the earth pressure load. Having the reinforcement working at maximum pullout resistance is considered acceptable given that the load duration is very short, and the observed displacements were tolerable.

6. The entire length of the strip should be used for the pull-out check on the dynamic loads as, during the impact, the maximum dynamic load occurs near the wall panel face.

7. Yield of the wall reinforcement in the top two layers of reinforcement should be checked against the dynamic pressures (or line loads) listed in Tables 6 and 7. These pressures and line loads come from the maximum dynamic loads and tributary areas on the reinforcement obtained in the crash test and the simulation.

8. Permanent displacements of 27 mm at the top of the barrier are allowable as they were measured in the crash test with minimal damage to the barrier-moment slab MSE wall system. The numerical simulation indicates that this corresponds to 39.1 mm of maximum dynamic movement during the impact.

Overall, the conclusion is that a 9.15 m long and 1.07 m high barrier mounted to a 9.15 m long and 2.18 m wide moment slab, founded at a depth of 1.02 m below the rolling surface on top of a 3.05 m high MSE wall with 3.05 m long strips, is capable of withstanding a TL5 impact with only minor damage to the installation. Note that the work presented here is for MSE walls with rigid inclusions only, and does not necessarily apply to geosynthetic reinforced MSE walls.

Table 4. Suggested TL5 design pressures for pull out of MSE wall reinforcing strips.

First layer		Second layer	
p_{dp-1} (kPa)	h_1 (m)	p_{dp-2} (kPa)	h_2 (m)
34.7	0.488	19.2	0.762

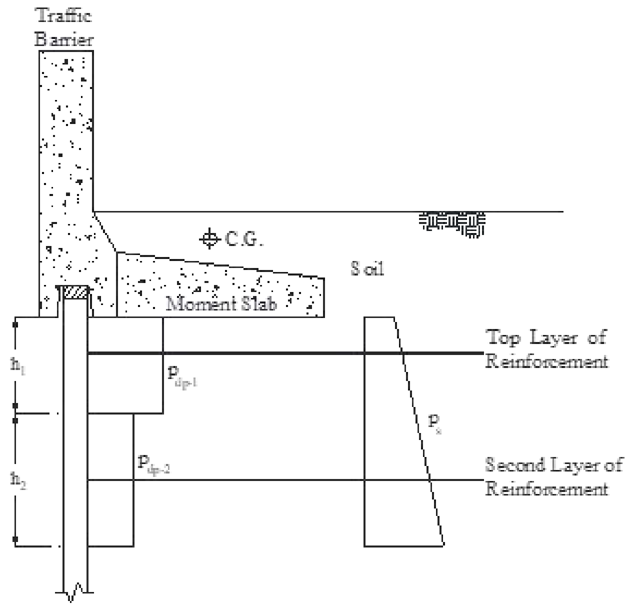


Figure 19. Pressure diagram for static and dynamic components to design MSE wall strips for TL5 impact loading.

Table 5. Suggested TL5 design line loads for pull out of MSE wall reinforcing strips.

Line load (kN/m)	
First layer, Q_{dp-1}	Second layer, Q_{dp-2}
16.9	14.6

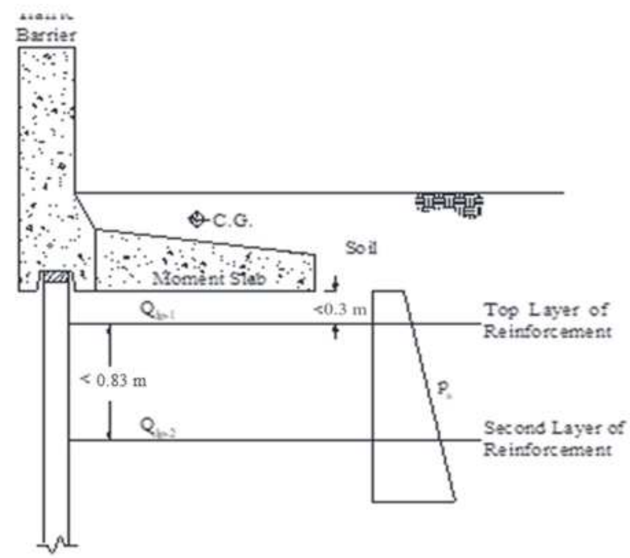


Figure 20. Line load diagram for static and dynamic components to design MSE wall strips for TL5 impact loading.

Table 6. Suggested TL5 design pressures for yielding of MSE wall reinforcing strips.

First layer		Second layer
p_{dy-1} (kPa)	h_1 (m)	p_{dy-1} (kPa)
155.6	0.488	155.6

Table 7. Suggested TL5 design pressures for yielding of MSE wall reinforcing strips.

Line load (kN/m)	
First layer, Q_{dy-1}	Second layer, Q_{dy-2}
75.9	17.7

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