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CRASH WALL DESIGN FOR MECHANICALLY STABILIZED EARTH (MSE) RETAINING WALL PHASE I: ENGINEERING ANALYSIS AND SIMULATION

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16. Abstract

Vehicular traffic may exist on either the high (fill) side of the Mechanically Stabilized Earth (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. Hence, 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 wall panels. It may prove practical to implement such a design in order to reduce costly repair to the MSE wall structure.

In this project, the research team reviewed, modeled, and analyzed a typical crash wall design to determine its effectiveness using Test Level 4 impact conditions of the crash testing guidelines (*Manual for Assessing Safety Hardware*). Three MSE wall finite element models have been developed: (1) a typical section of an MSE wall excluding the crash wall to observe damage of the panels impacted directly, (2) an MSE wall with a crash wall to quantify reduction in damage of the panels, and (3) an MSE wall with a crash wall and anchors to provide positive interaction between the wall panels and the crash wall. Based on these three simulations, a 0.2 m (8 inch) thick crash wall is considered adequately designed to reduce damage to the MSE wall.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS (CONTINUED)

Page

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

Page

LIST OF TABLES

Page

1. INTRODUCTION

1.1. RESEARCH PROBLEM STATEMENT

Vehicular traffic may exist on either the high (fill) side of the Mechanically Stabilized Earth (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 wall panels. It may prove practical to implement such a design in order to reduce costly repair to the MSE wall structure.

1.2. RESEARCH OBJECTIVE

The overall objective of this study is to analyze wall panels and a crash wall design to protect an MSE wall from vehicular impact. It is intended to provide improved crashworthiness and reduce structural damage to the MSE wall system. In this phase of the project, the research team will review, model, and analyze the proposed crash wall design to determine its expected performance under Test Level 4 (TL-4) impact conditions of the crash testing guidelines, *Manual for Assessing Safety Hardware* (*MASH*) *(1)*.

1.3. RESEARCH APPROACH

The research plan for accomplishing the project objective consisted of five tasks divides into two distinct phases outlined below.

PHASE I

Task 1 – Perform Engineering Analysis and Design

The researchers will review the design provided by Pennsylvania Department of Transportation (PennDOT) and other information from the supporting states. Texas Transportation Institute (TTI) researchers will work closely with the supporting states to select the appropriate design parameters used to design the crash wall. As part of this task, TTI researchers will perform engineering calculations on the crash wall attached to the MSE wall. A crash wall is designed with respect to American Association of State Highway and Transportation Officials (AASHTO) *Load Resistance Factor Design* (*LRFD*) Test Level 4 requirements *(2)*.

Task 2 – Perform Computer Simulations

The finite element code, LS-DYNA *(3)*, is used to evaluate the performance of the proposed crash wall design resulting from Task 1 or the design provided by PennDOT. The simulation task consists of the following subtasks:

1- Build a typical model of an MSE wall structure with the following entities:
    a. Soil (backfill and overburden).
    b. Soil reinforcement (steel strips).
    c. Wall panels and support pad including their reinforcement.
    d. Reinforced crash wall.
2- Incorporate Single Unit Truck model to simulate *MASH* Test Level 4.
3- Perform impact simulations of the MSE wall and the proposed crash wall design.

Task 3 – Submit Research Report

A report detailing the engineering analysis, design, modeling, and simulation work performed under Tasks 1 and 2 will be provided. The report will include a plan for designing a crash wall for either TL-4 or TL-5 impacts with 36000V (80,000 lb) trucks and for performing crash tests of the wall.

PHASE II

Task 4 – Full-Scale Crash Test

Upon the conclusion of Phase I, the pool fund member states will outline the work plan of Phase II of the project. Possible follow-up work may include full scale crash testing using 10000S test vehicle per *MASH* TL-4 and/or engineering design, numerical simulation, and full scale crash testing of a crash wall for TL-5 impacts with an 36000V (80,000 lb) truck. This project addresses the Phase I effort.

Task 5 – Submit Final Report

The research team will provide a final report documenting the entire research effort.

1.4. REPORT SCOPE

This report documents the research efforts, finding, and recommendations of this project. The report includes details of the engineering analyses and finite element modeling and analyses.

2. STATE OF THE PRACTICE

2.1. BACKGROUND

MSE walls typically consist of backfill soil reinforced with either steel strips, steel bar mat, or polymeric materials. The reinforcement is attached to the retaining wall (panels) to provide stability of the MSE structure (Figure 2.1). On top of the retaining wall and the backfill soil, a barrier-moment slab subsystem is installed to protect the errant vehicular impact. Figure 2.2 *(4)* and Figure 2.3 *(5)* show two photos as examples of a MSE wall in the highway.

Figure 2.1 Barriers on top of a MSE wall *(6)*

In 2009, TTI conducted six bogie tests and one full-scale crash test using a *MASH* TL-3 pickup truck against the barrier placed on MSE wall as shown in Figure 2.4 *(6, 7)*. The purpose of that research was to develop design guidelines for MSE walls subject to vehicular impact. Design guidelines for MSE walls were developed using reinforcement pullout tests, full-scale impacts of barrier systems mounted on an MSE test wall, and numerical modeling.

Figure 2.2 MSE wall in Long Beach, CA *(4)*

Figure 2.3 MSE wall in Carmel, IN *(5)*

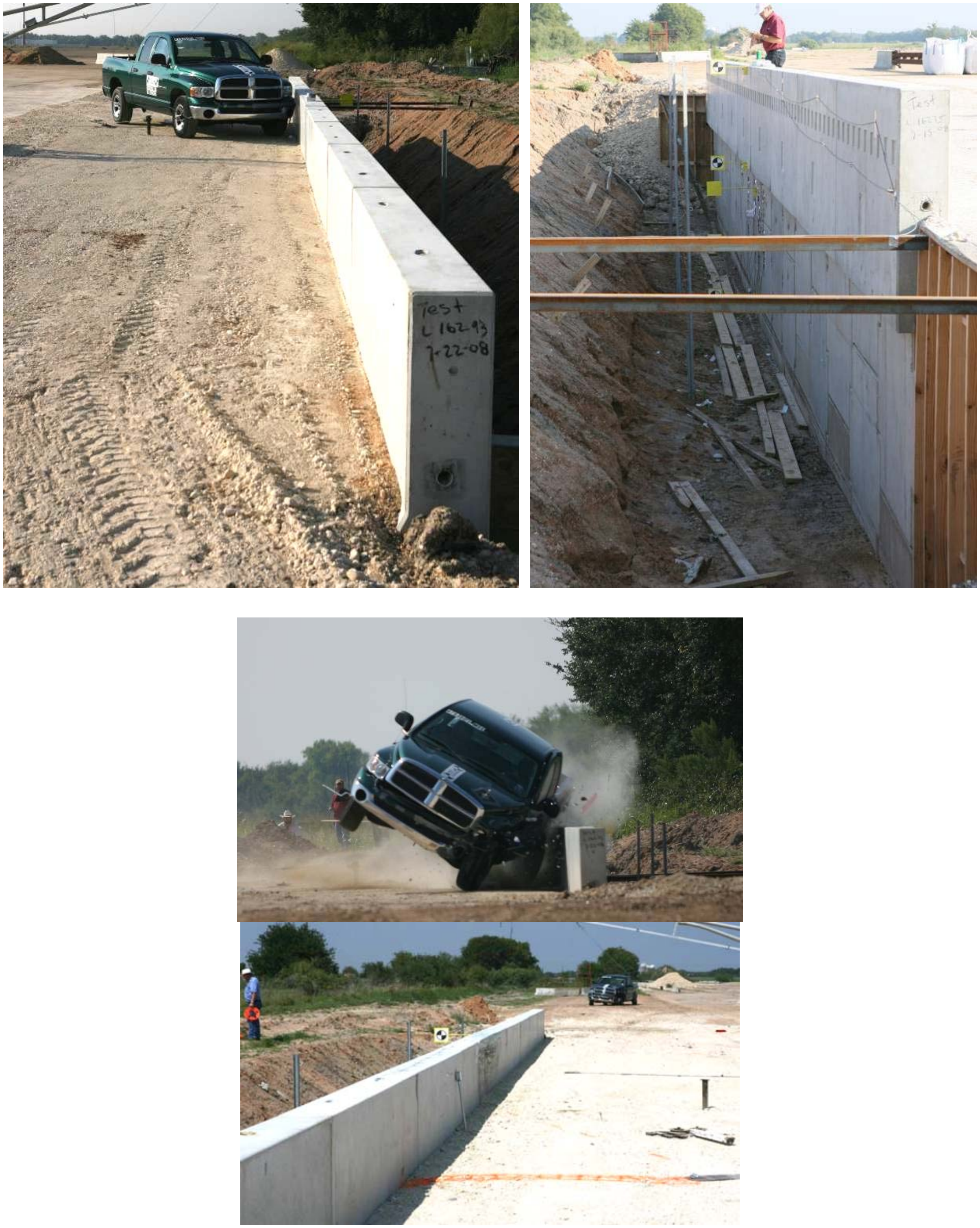


Figure 2.4 Full-scale crash test on the barrier placed on MSE wall (TTI 475350) ***(7)***

Few other crash test studies were conducted using vehicular impact on the barrier atop of the MSE wall not on the panels of the MSE wall. Currently there is no guideline on how to protect the MSE wall panels from heavy vehicle impacts. A crash wall constructed of reinforced concrete can be cast against the MSE wall panels with steel anchors embedded between the crash wall and the MSE panels. It may prove practical to implement such a design in order to prevent the complexity and the costs involved in repairing the actual MSE wall structure.

2.2. SYSTEM DESCRIPTION

For this study, an MSE wall design from Juniata County, Pennsylvania, was used as the typical system (Juniata County S.R. 0022 Section A09) *(8)*. The drawing for the crash wall is referenced in Pennsylvania Department of Transportation (PennDOT) Precast Concrete Wall Panels drawing *(9)*. Figure 2.5 shows an example drawing of an MSE wall with a single face concrete barrier for protection against vehicular impact. Appendices A and B present other details of these drawings.

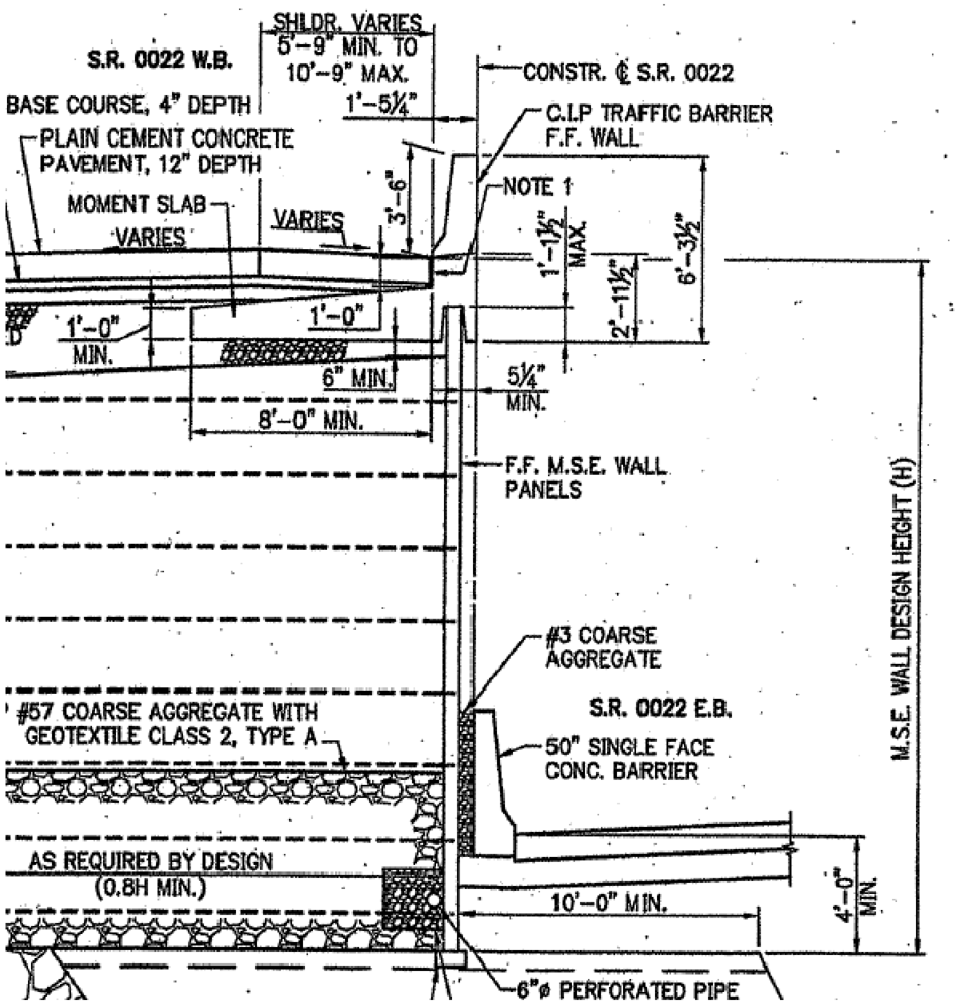


Figure 2.5 MSE wall section of Juniata County drawing *(8)*

2.3. MSE WALL DESIGN

AASHTO LRFD specification *(2)* is used to calculate the static load on the wall reinforcing strips due to earth pressure as reference for steady state condition. In this study, the unfactored static load due to earth pressure is determined to compare them with the finite element analysis result.

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

$$T = \sigma_h \times A_t \tag{2-1}$$

where σ_h: Horizontal stress due to the soil, $\sigma_h = K_r \times \sigma_v$
K_r: Lateral earth pressure coefficient (Figure 2.6)
A_t: Tributary area of the reinforcement (Figure 2.7)

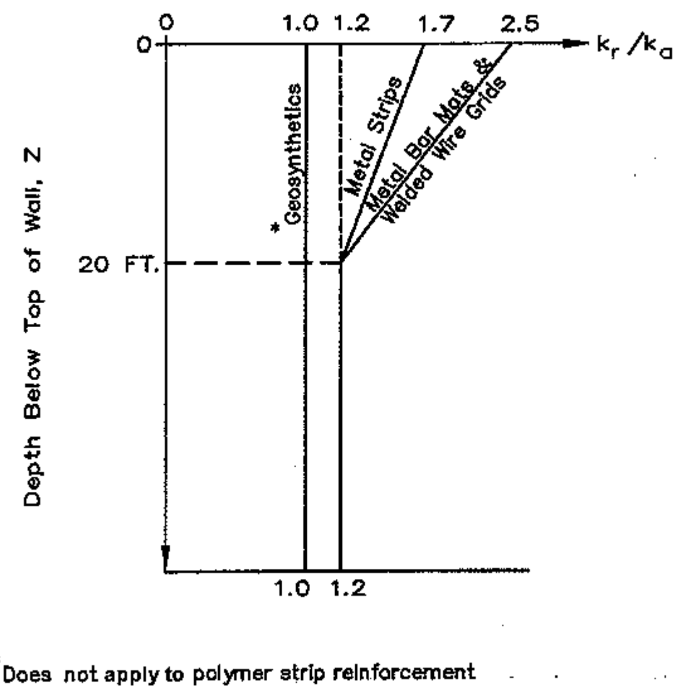


Figure 2.6 Variation of the coefficient of lateral stress ratio with depth (AASHTO LRFD Figure 11.10.6.2.1-3) *(2)*

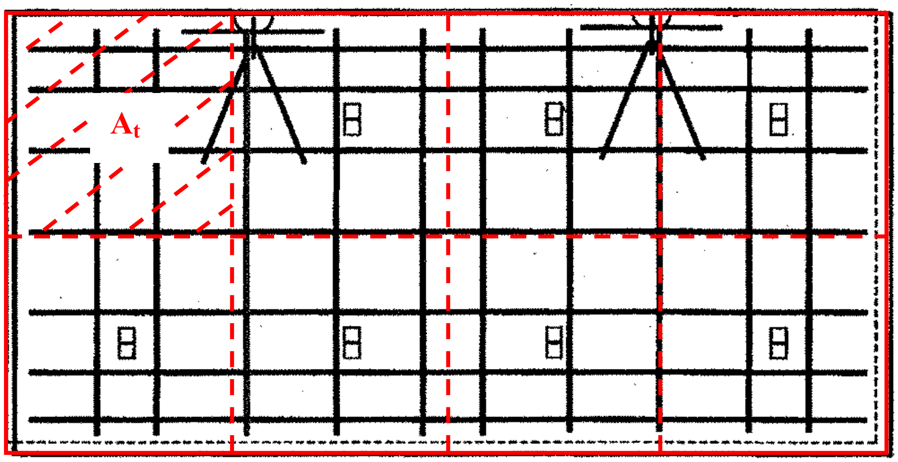


Figure 2.7 Tributary area of the wall reinforcement, A_t

Table 2.1 presents a summary of the static load per steel wall reinforcement. Figure 2.8 shows the detail of strip locations used in calculation. Appendix C presents a detailed calculation of the unfactored load (*T*).

Table 2.1 Static Load on the MSE Wall.

Strip Layer No.	Depth (ft)	Unfactored T (kips)
1	3.96	1.21
2	6.17	1.822
3	8.63	2.718
4	11.09	3.348
5	13.54	3.913
6	16	4.415
7	18.46	4.852

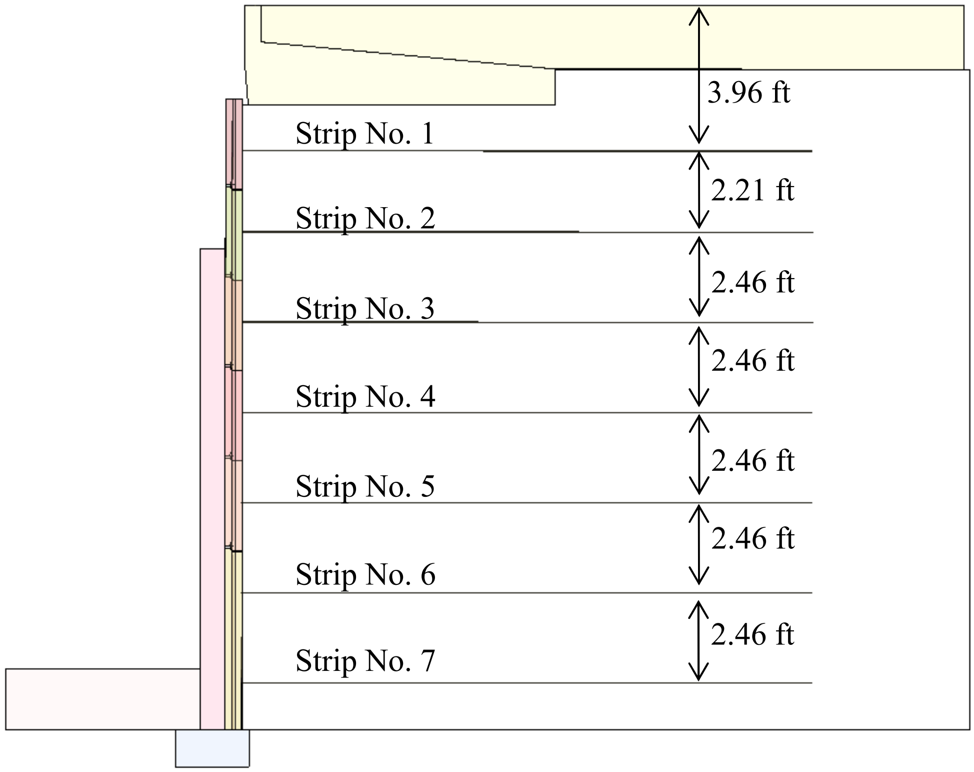


Figure 2.8 Side view of MSE wall used in calculation

2.4. CRASH WALL DESIGN

A crash wall was designed to minimize the damage to an MSE wall system upon impact by an errant vehicle. The research team performed finite element analyses on a 2.44 m (8 ft) tall × 6.1 m (20 ft) long × 0.2 m (8 in.) thick crash wall to be cast in front of an MSE wall panels. For these analyses, a 333.6 kN (75 kips) load was distributed over a 1.22 m (4 ft) long length by 3.05 m (12 in.) wide and approximately 0.91 m (3 ft) above grade. This loading was selected to represent the TL-4 impact loading from the *MASH* Single Unit Truck (SUT). This loading was applied at the end of a wall segment or joint.

Based on the analyses results, the research team determined that No. 5 vertical bars spaced at 152.4 mm (6 in.) on centers are needed approximately 1.83 m (6 ft) from the ends or at a joint (2 layers needed). Vertical steel in the barrier can be No. 5's spaced vertically on 3.05 m (12 in.) on center in the mid-span area of the wall (away from the ends or joint). Transverse reinforcement will be No. 4's spaced at 3.05 m (12 in.) on centers for the two layers of reinforcement in the wall. Figures 2.9 and 2.10 present the detailed drawings of a crash wall. Moreover, the representative crash wall design from the PennDOT drawing was reviewed as shown in Figure 2.11.

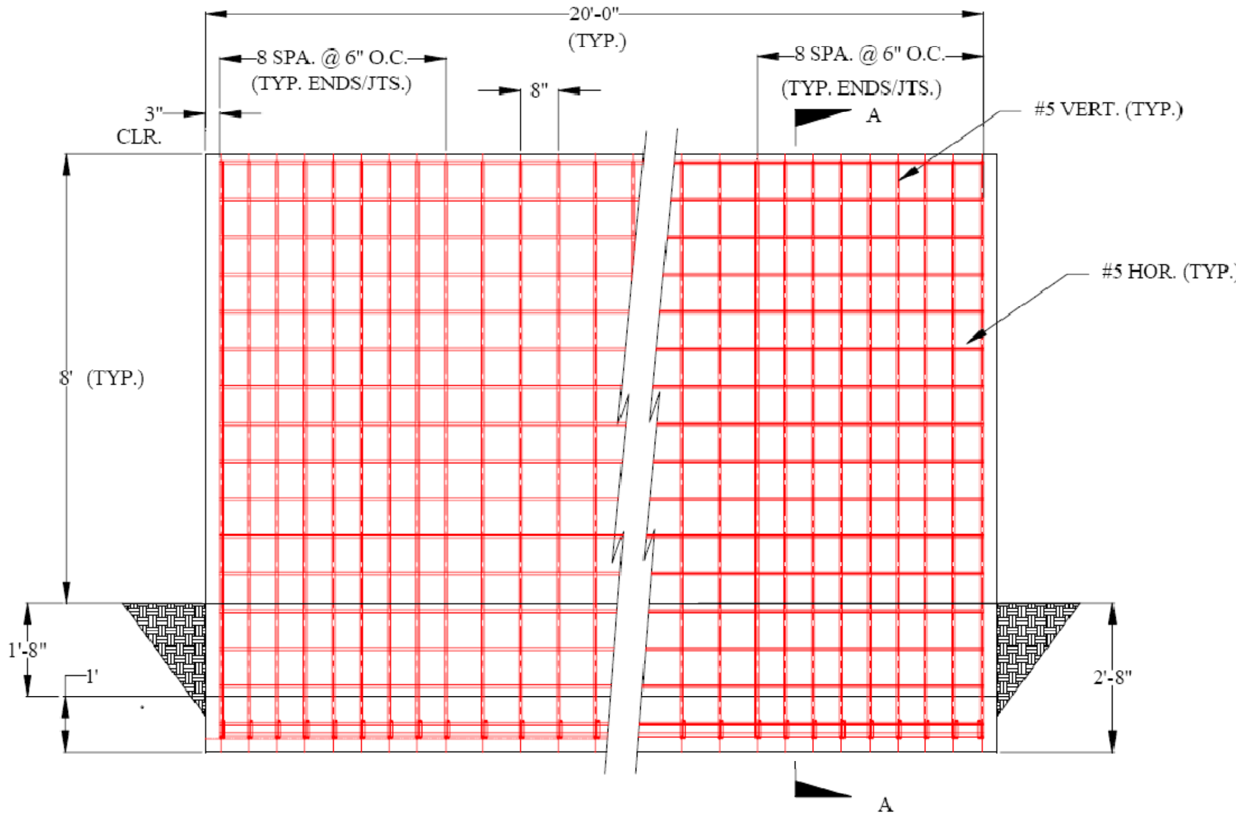


Figure 2.9 Detail front view drawing of a crash wall (designed by TTI)

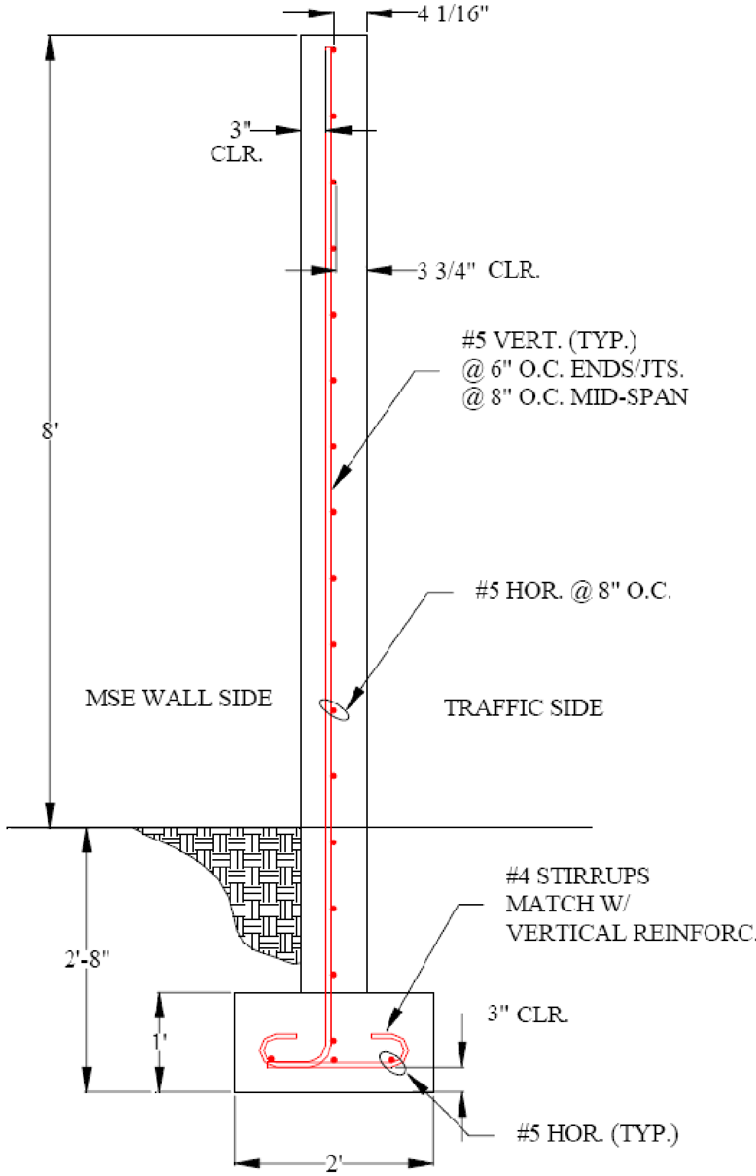


Figure 2.10 Detail cross section view drawing of a crash wall (designed by TTI)

Another crash wall design presented herein is provided by PennDOT *(9)*. This crash wall is 0.2 m (8 in.) thick placed in front of the MSE wall panels. The cast-in-place crash wall is connected to the precast wall panels by anchors. The crash wall is embedded into the ground 0.5 m (20 in.). The reinforcing bars in the crash wall consist of longitudinal No. 6 bars at 304.8 mm (12 in.) and vertical No. 4 bars at 304.8 mm (12 in.) as shown in Figure 2.11.

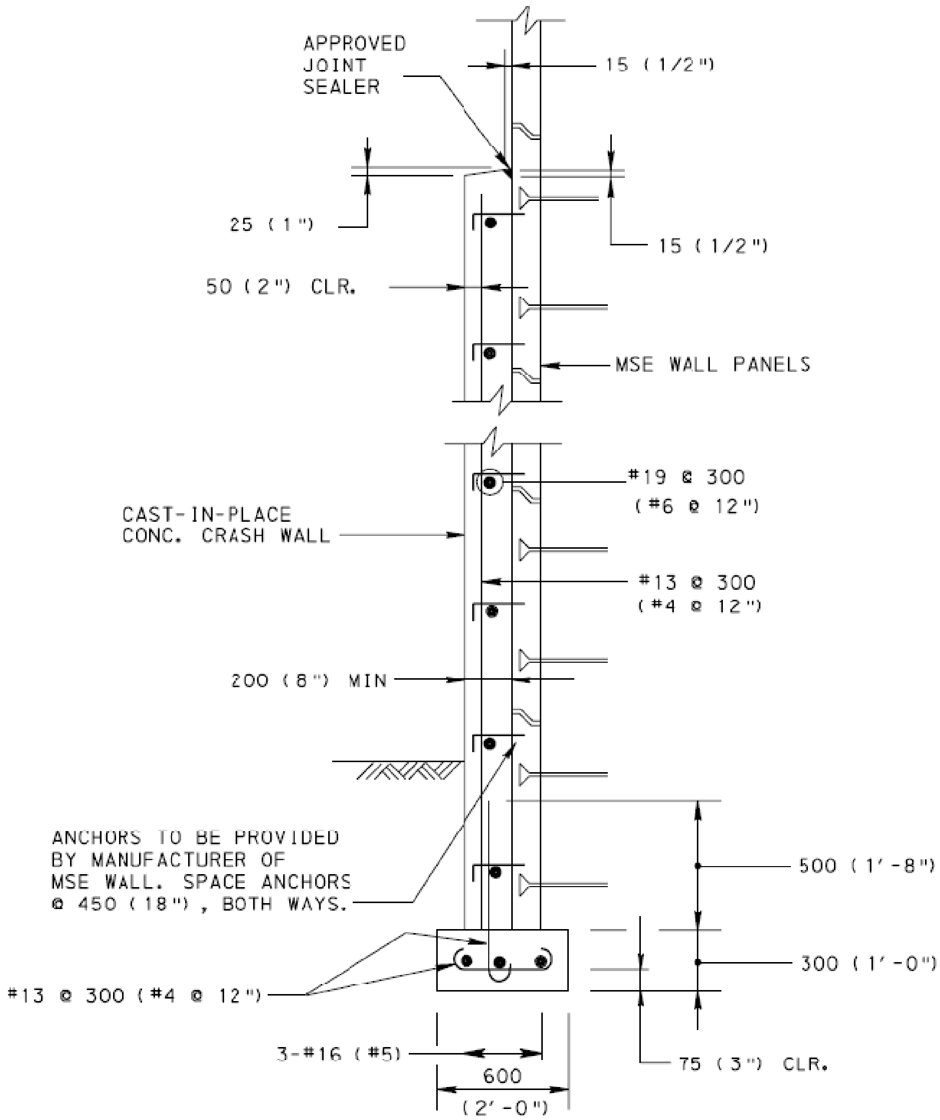


Figure 2.11 Typical crash wall section from PennDOT drawing *(9)*

3. FINITE ELEMENT PROCESS

The finite element model of the MSE wall with a crash wall was developed to evaluate the structural response of the crash wall during vehicular impact. The analyses were performed using the commercially available finite element software LS-DYNA *(3)*. The methodology used to model the MSE wall and the crash wall (PennDOT design) and to simulate their performance under *MASH* TL-4 impact consisted of the following steps:

1. Construct finite element model of the MSE wall and the crash wall.
2. Initialize the model of the MSE wall and the crash wall to account for gravitational loading.
3. Modify SUT to reflect *MASH* TL-4 and verify the performance of SUT
4. Simulate *MASH* TL-4 impact against the wall panels.
5. Analyze results and verify the performance of the MSE wall.
6. Simulate the impact against the crash wall placed in front of MSE wall.
7. Analyze results and verify the performance of the crash wall.
8. Identify any further investigation needed.

Figure 3.1 presents the flowchart for the finite element model of the crash wall on the MSE wall for *MASH* TL-4 impact conditions. Chapters 3 and 4 present the details of these steps.

3.1. GEOMETRY AND MESHING

The finite element representation of the MSE wall considers the following major components:

1. Precast concrete panels with reinforcement.
2. Concrete leveling pad.
3. Precast concrete barrier and cast-in-place moment slab.
4. Back fill soil and front soil.
5. Reinforcement in the soil to the wall panels.
6. Crash wall.

MSE wall model was a length of 15.1 m (49.5 ft) long and 5.2 m (17.11 ft) tall as shown in Figure 3.2. The barrier and moment slab were placed on the top of the MSE wall. Since the impact happens at the bottom part of the panels in this study, the interaction of the coping of the barrier and panels was not represented in this analysis. The barrier and moment slab were modeled as a one component.

The MSE wall components including soil, wall panels, and a pedestal were modeled using solid elements, as were the concrete barrier and moment slab. Beam elements with six degrees of freedom at each end were used to model the rebar of the wall panels, the crash wall, and the pedestal. The steel strip reinforcements for the MSE wall were modeled using shell elements 4 mm (0.16 in.) thick by 50.8 mm (2 in.) wide by 4.76 m (15.6 ft) long.

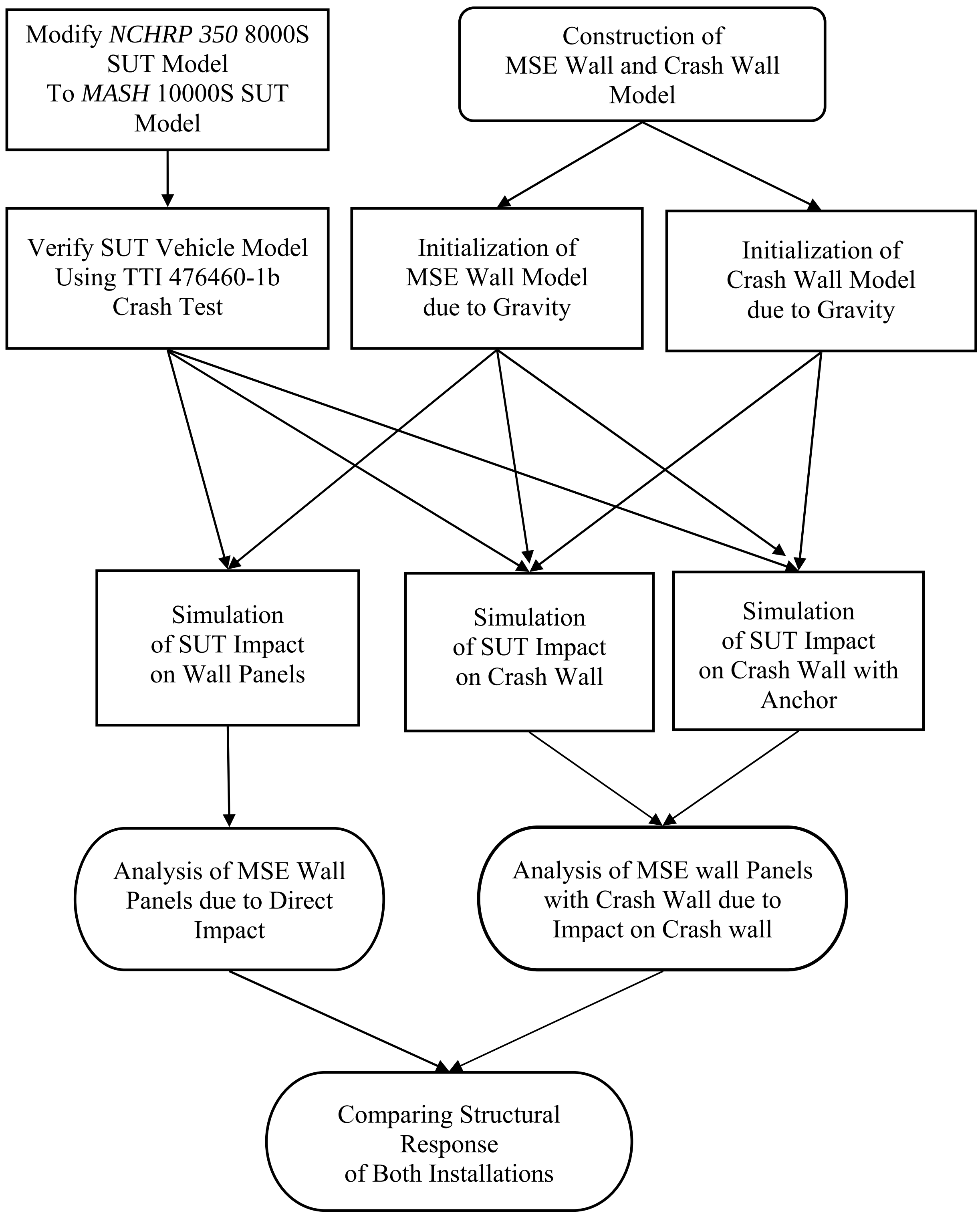


Figure 3.1 Flowchart of modeling and simulation processes.

The elements of the inner wall panels are meshed using element characteristic size of about 40 mm (1.57 in.) at the impact location to capture the wall deformation with improved accuracy. The outer elements of the wall panels are meshed rather coarsely to reduce computational costs of the simulation since these panels are outside the impact region.

The soil elements behind the area of impact were meshed finely using element size of 152.4 mm (6 in.) in order to better represent the transferred load from the vehicle impact. The rest of the soil continuum is variably meshed up to element size of about 254 mm (10 in.) at the top backside of the soil. Figure 3.3 shows the element mesh scheme used in the MSE wall.

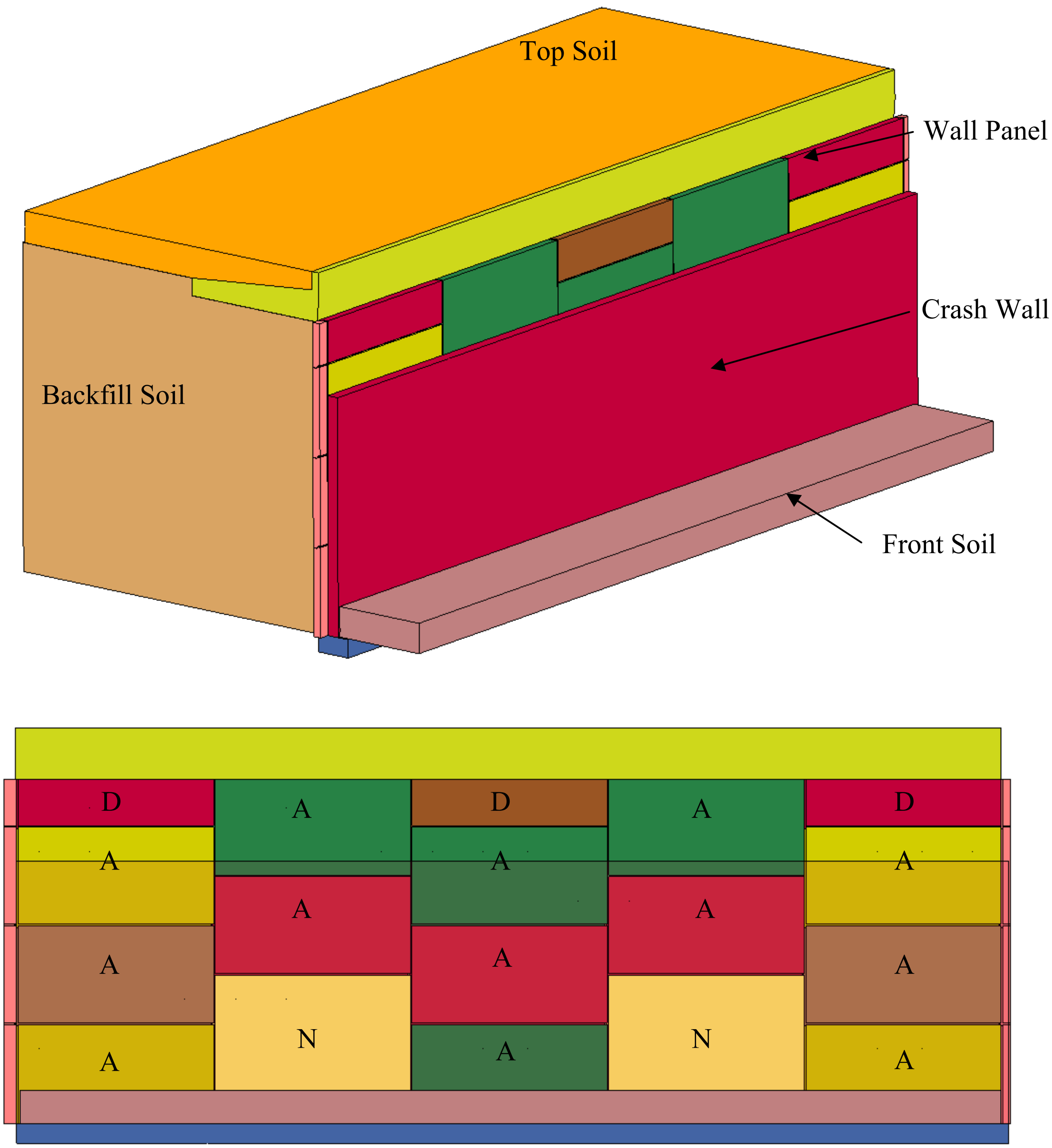


Figure 3.2 Overall view of MSE wall model

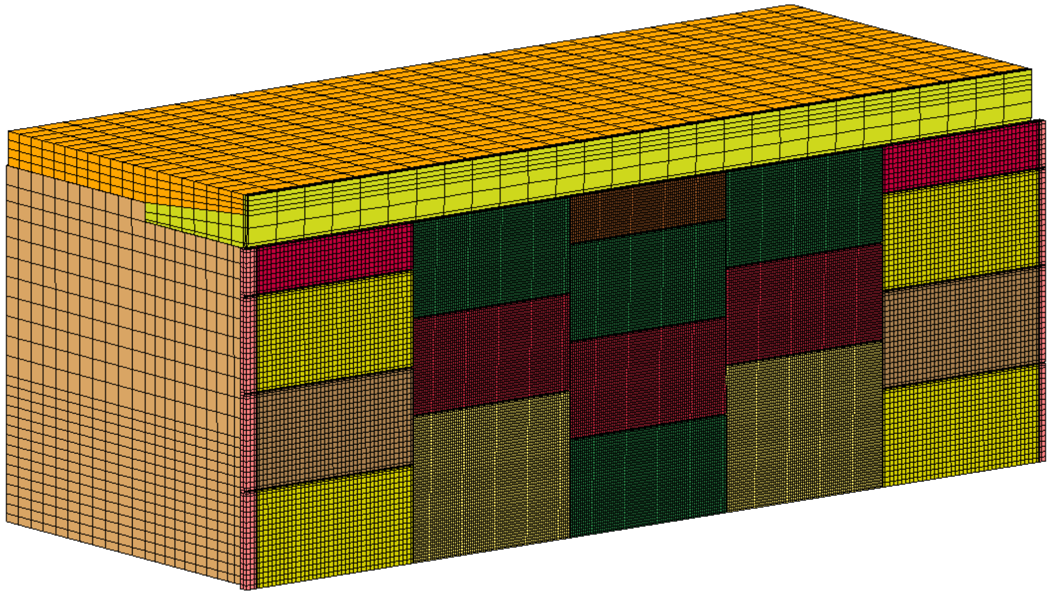


Figure 3.3 Element mesh scheme of the MSE wall model

Three types of panels were selected to build the model from PennDOT drawing *(9)*. All three panels have same width and thickness of 2.98 m (9 ft-9 1/4 in.) and 140 mm (5 1/2 in.), respectively. The height of panels varied from 0.73 m (2 ft-4 3/4 in.) to 2.23 m (7 ft-3 3/4 in.). The three kinds of panels shape, "A," "D," and "N," were used using an alphabetical indicator as shown in Figure 3.2. Figure 3.4 through Figure 3.6 show the panel details and models.

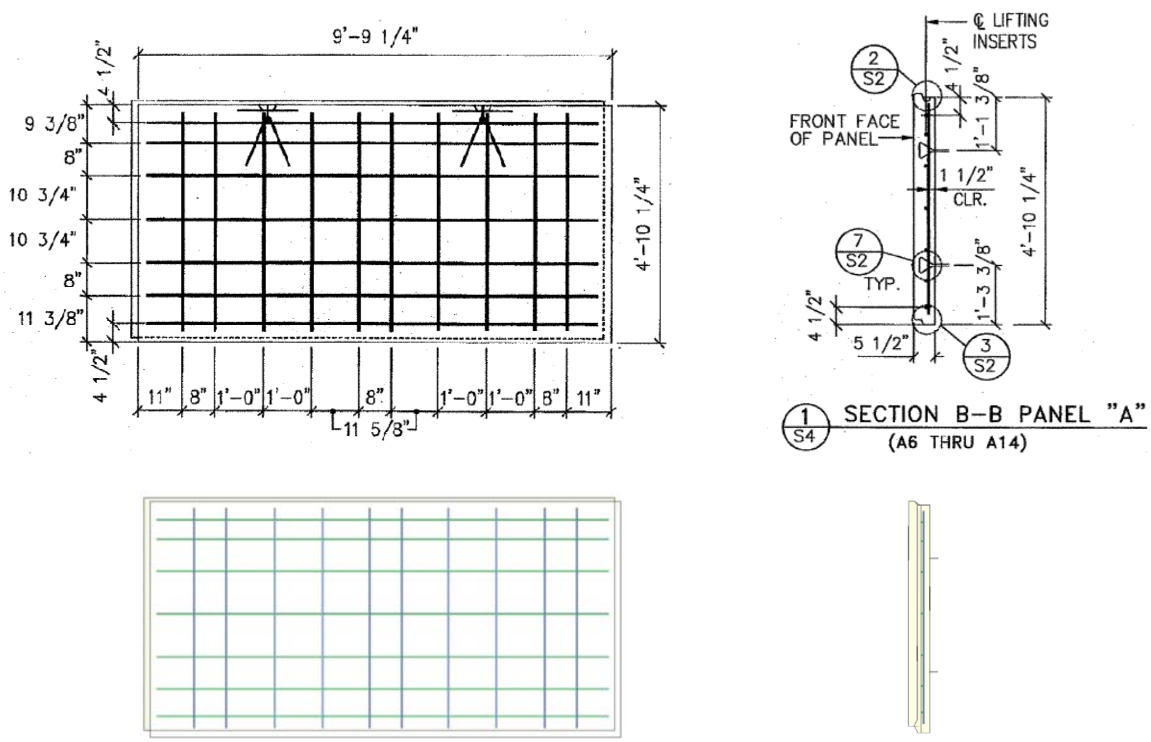


Figure 3.4 Panel "A" details and model

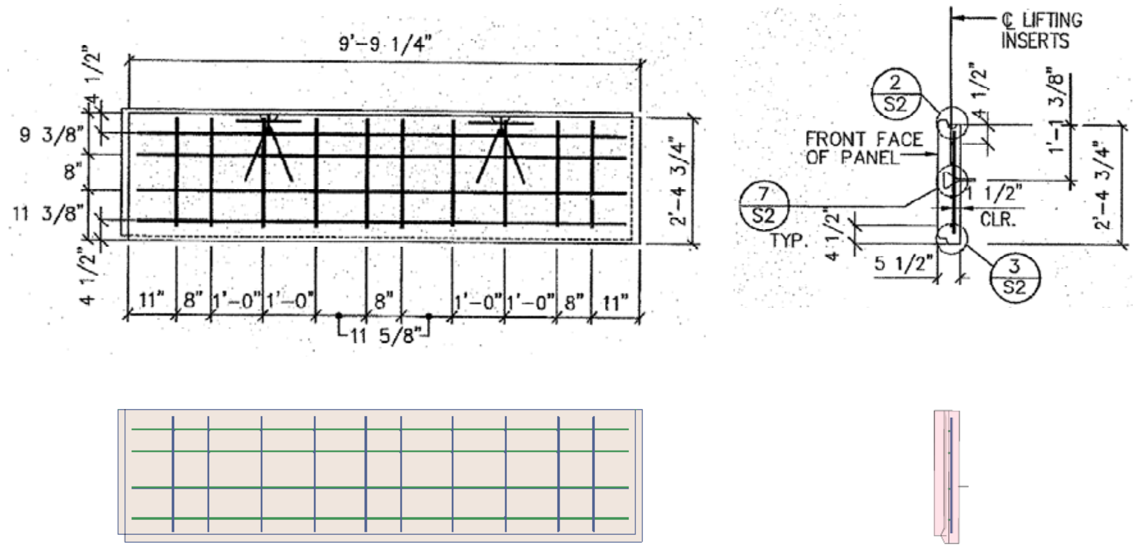


Figure 3.5 Panel "D" details and model

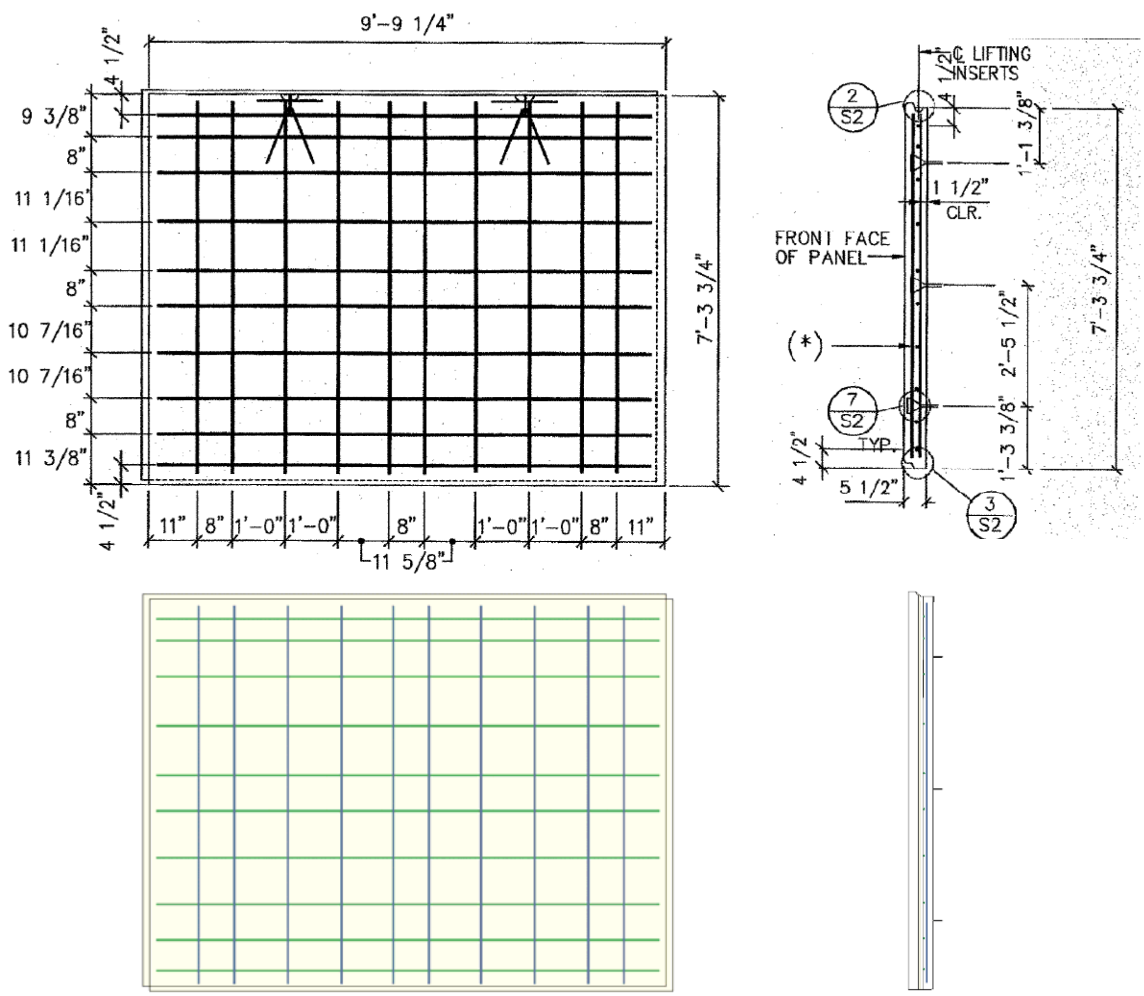


Figure 3.6 Panel "N" details and model

To account for realistic interaction between wall panels, the detail joint between panels in both vertical and horizontal direction was explicitly modeled as shown in Figure 3.7 and Figure 3.8. In the horizontal joint, bearing pads between wall panels is assumed to be the part of the panel as shown in the circle in Figure 3.8.

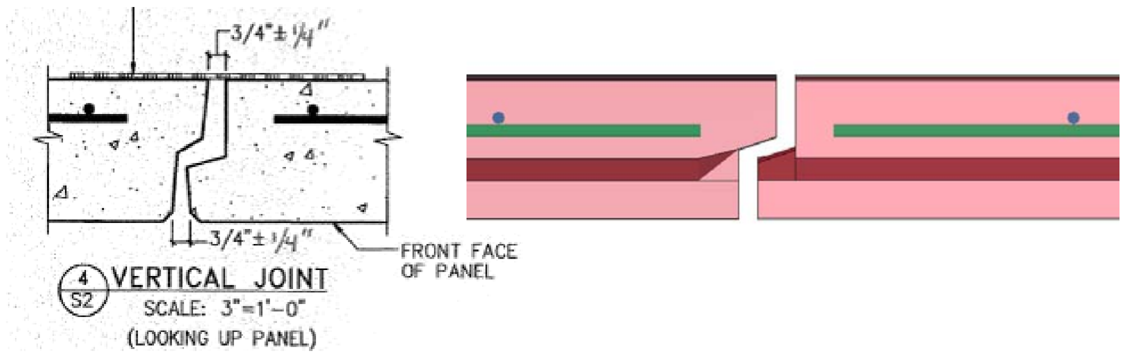


Figure 3.7 Vertical joint details and model

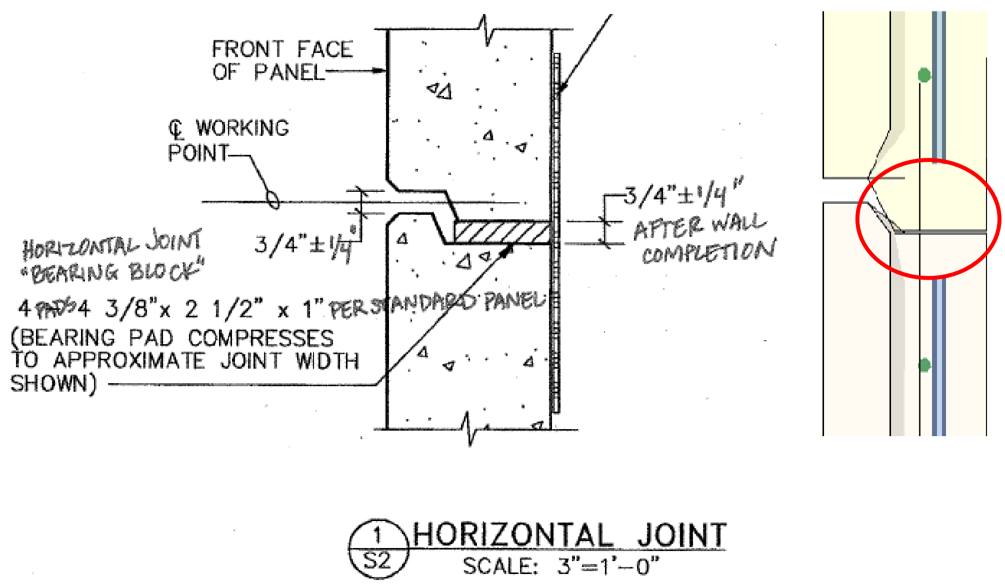


Figure 3.8 Horizontal joint details and model

The 15.1 m (49.5 ft) long crash wall was placed on the wall panels. The crash wall was used with the thickness and height of 203.2 mm (8 in.) and 4 m (13.1 ft), respectively. The details of rebars were modeled based on the PennDOT drawing as shown in Figure 3.9.

Figure 3.9 shows the embedded anchors between the wall panels and the crash wall. Since the details of such anchor were not available to research team, they were estimated based on scaling of other dimensioned entities on the PennDOT drawing. Based on that, the anchor size and length estimated to be 50.8 mm (2 in.) thick and 225 mm (8.85 in.) long. The anchor spacing was 450 mm (18 in.) on both ways.

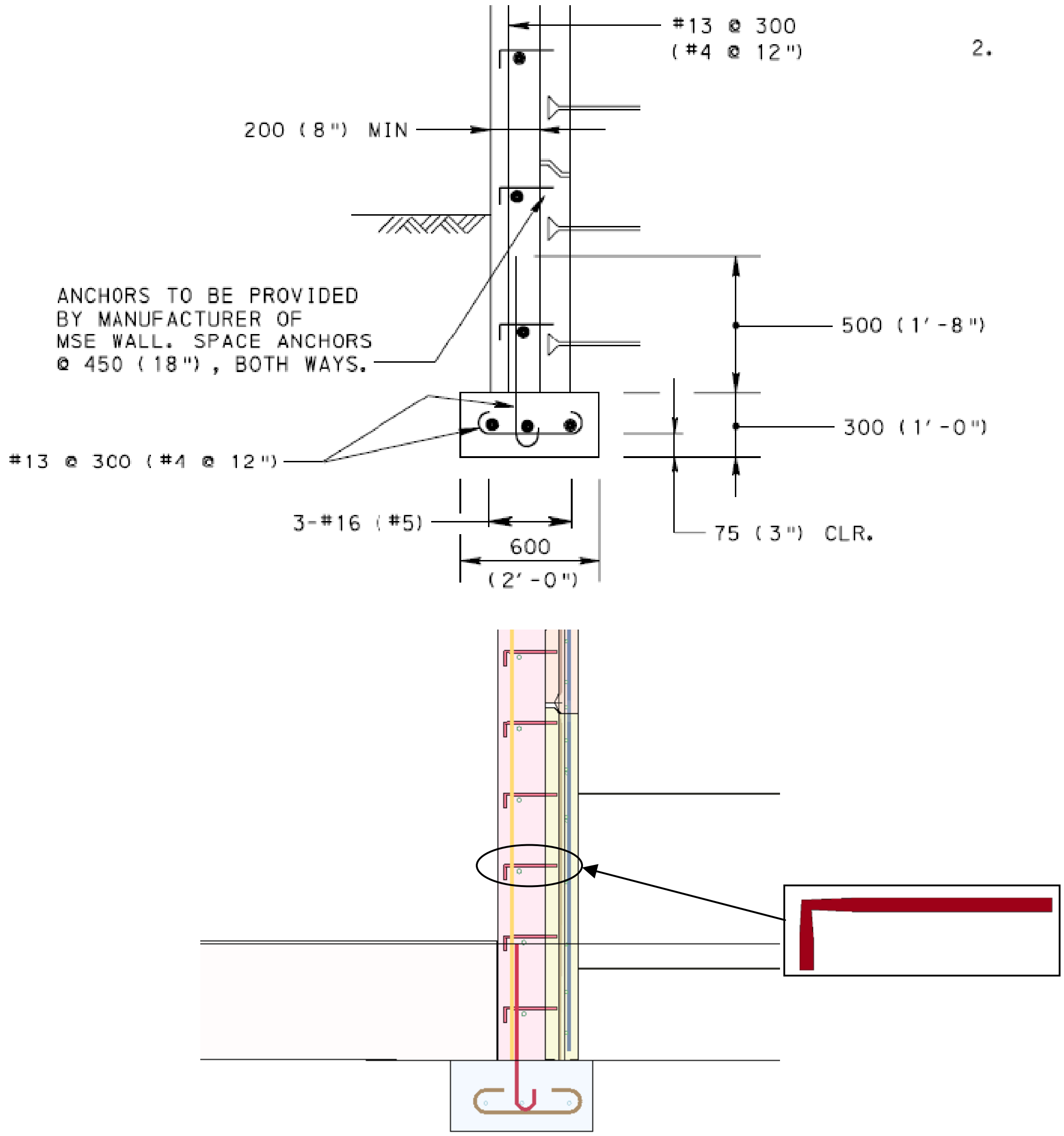


Figure 3.9 Crash wall details and model

The vehicle impact point against the wall panels was located on the second panel from the left shown in Figure 3.10. The distance from the end of the wall panel from the left was to be 5.35 m (17.55 ft). This point was chosen to maximize the severity of impact by making the impact point closer to the joint.

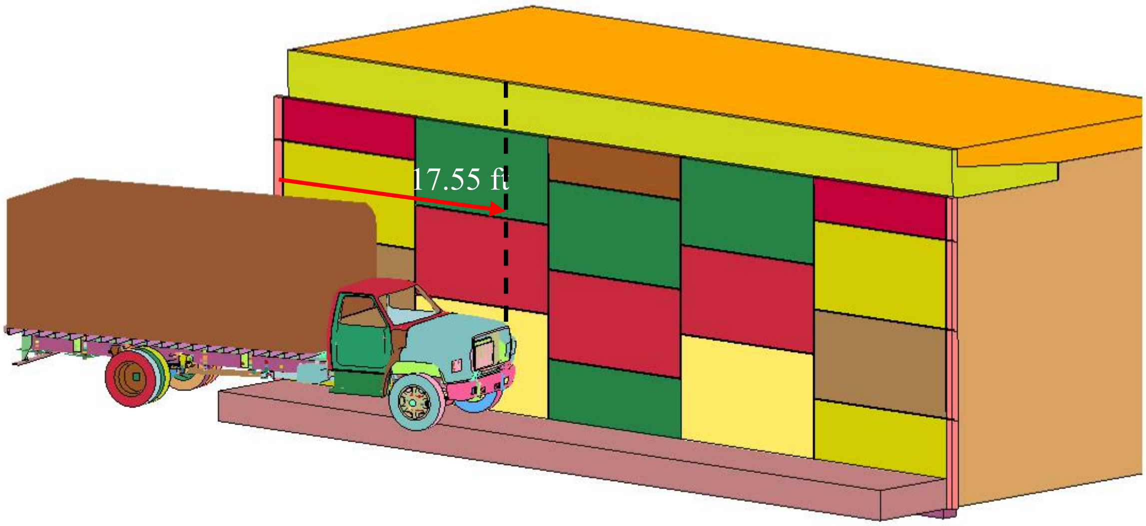


Figure 3.10 Vehicle impact point on the wall panel

3.2. COMPONENTS INTERACTIONS AND BOUNDARY CONDITION

Capturing interaction between solid and beam or shell elements is rather complex using matching nodes. The requirement of matching nodes to merge the reinforcing steel inside the concrete continuum would dictate 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 *(10)*. To mitigate this problem, a different coupling scheme was utilized between solid and beam or shell elements.

The steel reinforcements are coupled (rather than merged) to the surrounding concrete to prevent the poor quality elements otherwise required as mentioned above. This was achieved using the CONSTRAINED_LAGRANGE_IN_SOLID feature in LS-DYNA. The use of this coupling permits the concrete mesh to be constructed without consideration of the location of steel reinforcement. The steel reinforcements are treated as a slave material that is coupled with a master material comprised of the moment slab and barrier concrete. The slave parts (i.e., steel rebar) can be placed anywhere inside the master continuum part without any special mesh accommodation. The wall reinforcements are coupled to the backfill soil in a same manner. The anchors coupled to both the crash wall and the wall panels.

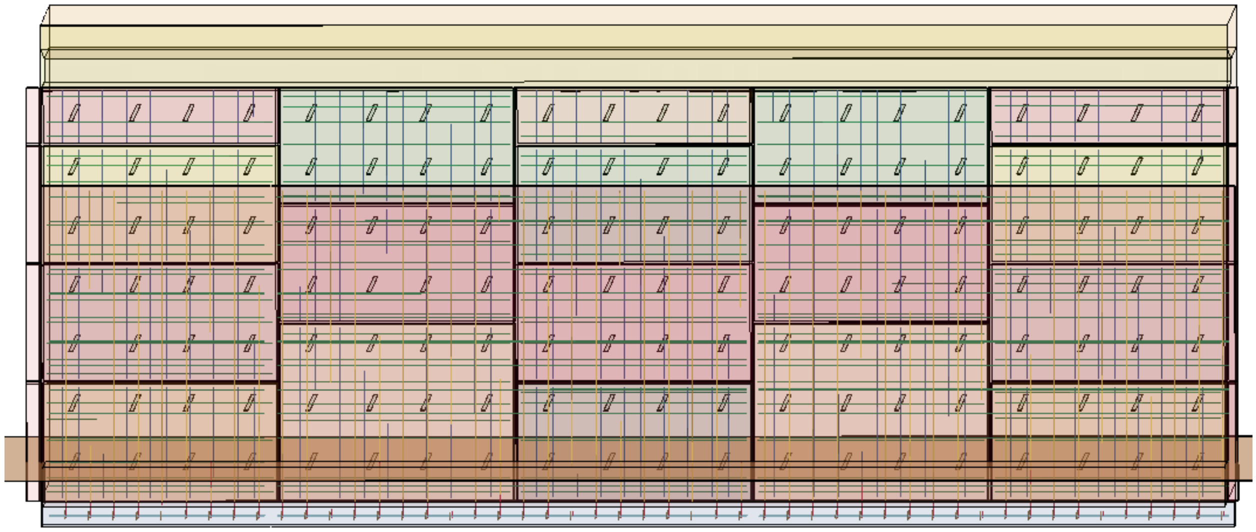


Figure 3.11 Placement of solid, beam, and shell elements

The interaction between the soil and concrete was modeled using contacts to capture the interface forces generated between the concrete structure and the MSE wall. The contact friction was based on the estimated backfill soil internal friction angle. The soil friction angle, ϕ was 35 degrees and then the contact friction angle was calculated to be 0.7 (tan ϕ). This method allows modeling soil-structure interaction without considering cohesion, which is accurate for backfill.

During initialization due to gravity, the front elements of wall reinforcing strip developed the bending stress. Therefore, dummy sliding shells were added to enable the strip to slide as shown in Figure 3.12. Figure 3.13 shows the comparison of gravitation analysis without and with sliding mechanism in this initialization step. Figure 3.13 shows clearly the significant reduction in artificial bending by incorporating the sliding mechanism in the model. The dummy sliding shells were removed and then a tied contact definition was defined to account for the connection between the panels and the wall reinforcing strips. Directional translational constraints were applied on the boundary surfaces to account for boundary conditions of the structures.

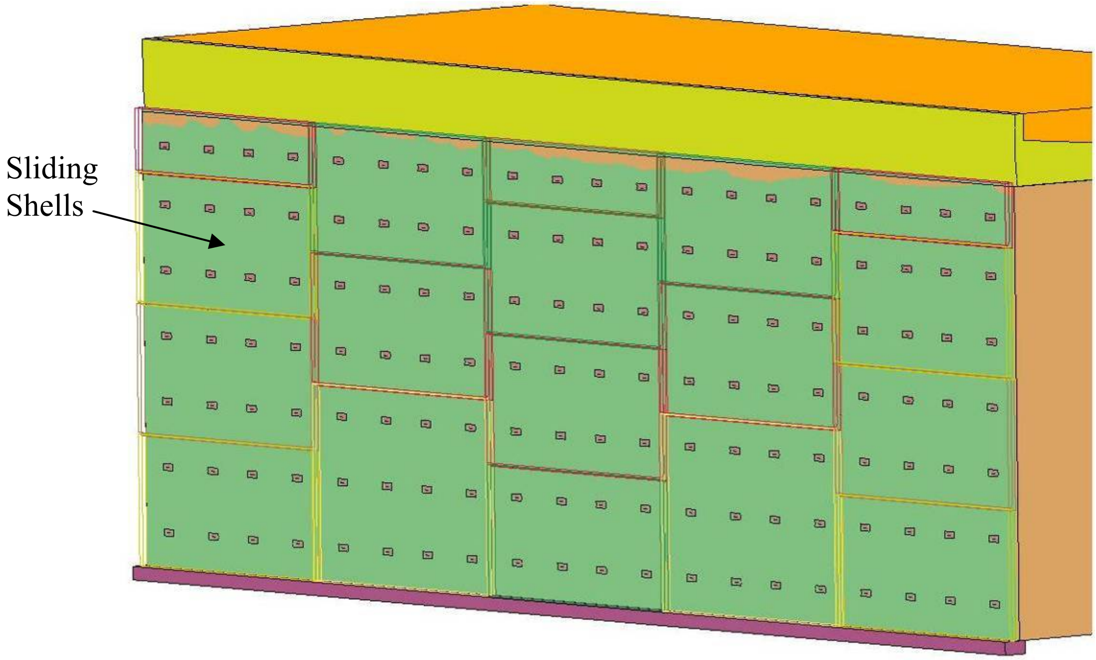
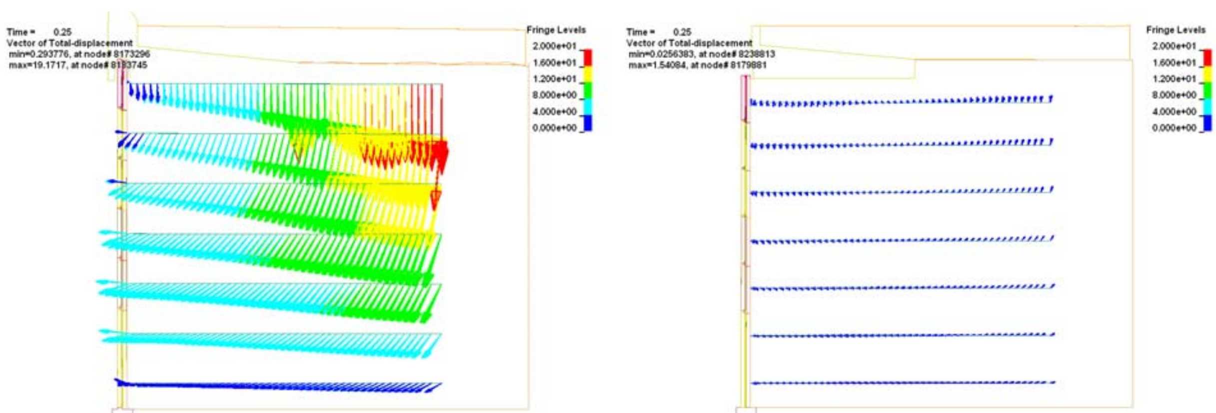


Figure 3.12 Sliding system to account for gravitational loading on the strip



(a) without sliding system **(b) with sliding system**

Figure 3.13 Displacement of the strip on two systems at the gravitational step

3.3. MATERIAL MODELS AND PARAMETERS

3.3.1 Concrete and Steel Material

The outside wall panels, a barrier, a moment slab, and a leveling pad were modeled using elastic material (MAT Type 1). The parameters of the elastic model are density, elastic modulus, and Poisson's ratio. The center wall panels subjected to direct impact was modeled using a non-linear response concrete material model definition. In LS-DYNA 971, it is designated as material MAT Type 159, CSCM Concrete *(11)*. This is a more sophisticated but computationally expensive method to explicitly model concrete. In this model, a brittle material like concrete will lose (at a given rate) its ability to carry load when a specified damage/failure is reached. This is very useful because it provides a more accurate representation of the failure mechanism of the concrete components and better prediction of the impact load transfer. The parameters of MAT Type 159 can be assigned using two additional concrete properties, the confined compressive strength of concrete *f'c* and the maximum aggregate size of 25.4 mm (1 in.).

All steel rebar and steel strips were modeled using a piecewise linear plasticity material model (MAT Type 24) that is representative of an elastic-plastic stress-strain relationship of the material. Steel rebar exhibits rate effects and yields in a ductile manner until it breaks at an ultimate strain greater than approximately 20 percents. Before yield, the material is assumed to be linearly elastic. After yielding, the steel can undergo plastic deformation and strain hardening. Table 3.1 shows detail material properties of concrete and steel models.

Table 3.1 Material Properties of Concrete and Steel Model.

	E (MPa)	ν	ρ (Tonne/mm^2)	f'_c (MPa)	Yield Stress (MPa)
Elastic Concrete	2.485E+4	0.17	2.328E-9	NA	NA
Damage Concrete	2.485E+4	0.17	2.328E-9	27.58	NA
Wall Strip (A572 Gr. 65)	2.1E+5	0.3	7.85E-9	NA	448.175
Rebar Steel	2.1E+5	0.3	7.85E-9	NA	413.7

* E is the young's modulus, ν is Poisson's ratio, ρ is the mass density, and f'_c is the compressive strength.

3.3.2 Soil Material

The soil elements were modeled using the two-invariant geological cap material model (MAT type 25). The advantage of the cap model over other models such as the Drucker-Prager formulation is the ability to model plastic compaction. In these models all purely volumetric response is elastic until the stress point hits the cap surface. Therefore, plastic volumetric strain (compaction) is generated at a rate controlled by the hardening law. Thus, in addition to controlling the amount of dilatency, the introduction of the cap surface adds another experimentally observed response characteristic of geological materials into the model *(12, 13).*

The cap model is defined in terms of the first stress invariant $I_1 = trace(\sigma)$ $= \sigma_{11} + \sigma_{22} + \sigma_{33}$ and the second deviatoric stress invariant $J_2 = 1/2\ S_{ij}S_{ij} = 1/2\ (S_{11}^2 + S_{22}^2 + S_{33}^2)$, where σ is the stress tensor and $S_{ij} = \sigma_i + \sigma_j$ is the deviatoric stress tensor. The yield surface of the cap model consists of three regions (Figure 3.14): a failure envelope f_1 (σ), an elliptical cap f_2

(σ, κ), and a tension cutoff region *f_3 (σ)*, where κ is the hardening parameter. The functional forms of the three surfaces are *(12, 13)*:

1. Failure envelope region: $f_1(\sigma) = \sqrt{J_{2D}} - F_e(I_1) = 0$, for $T \le I_1 < L(\kappa)$ (3-1)
2. Cap region: $f_2(\sigma,\kappa) = \sqrt{J_{2D}} - F_c\left(I_1,\kappa\right) = 0$, for $L(\kappa) \le I_1 < X(\kappa)$ (3-2)
3. Tension cutoff region: $f_3(\sigma) = T - I_1 = 0$, for $I_1 = T$ (3-3)

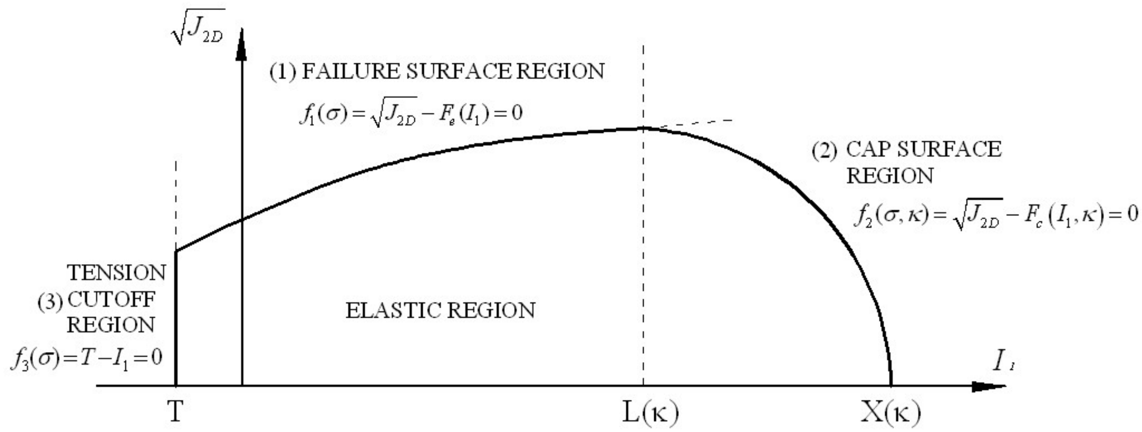


Figure 3.14 Cap soil model general yield surface *(12)*

In the failure envelop region, *F_e (I_1)* can be expressed as:

$$F_e(I_1) = \alpha - \gamma e^{-\beta I_1} + \theta I_1 \tag{3-4}$$

where the yield surface was determined by the parameters α, θ, γ and β, which are usually evaluated by fitting a curve through failure data taken from a set of triaxial compression tests.

In Eq. (3-2), *F_c (I_1, κ)* can be expressed as;

$$F_c\left(I_1,\kappa\right) = \frac{1}{R}\sqrt{\left[X(\kappa) - L(\kappa)\right]^2 - \left[I_1 - L(\kappa)\right]^2} \tag{3-5}$$

$$X(\kappa) = \kappa + RF_e(\kappa) \tag{3-6}$$

$$L(\kappa) = \begin{cases} \kappa & if\, \kappa > 0 \\ 0 & if\, \kappa \le 0 \end{cases} \tag{3-7}$$

where X(κ) is the intersection of the cap surface with the I_1 axis and the hardening parameter κ is related to the plastic volume change ε_v^p through the hardening law:

$$\varepsilon_v^p = W\left\{1 - \exp\left[-D(X(\kappa) - X_0\right]\right\} \tag{3-8}$$

where the values of parameters W and D are found from hydro static compression test data. The value of R is the ratio of major to minor axes of the quarter ellipse defining the cap surface.

Table 3.2 shows the parameters used in the numerical simulation. Using these parameters, the cap yield surface can be defined as shown in Figure 3.15.

To understand the failure behavior of the cap soil material, the various soil properties were collected as presented in Table 3.2. Two different cap models, the McCormick Ranch Sand *(14)* and the elasto-plastic soil parameters given in NCHRP Report 556 *(15)* were compared to the cap model used in this study.

The cap models for each case were plotted as shown in Figure 3.15. In the failure envelope $f_1(\sigma)$ and tension cutoff region $f_3(\sigma)$, the three soil models show good agreement, but in the elliptical cap $f_2(\sigma,\kappa)$, the soil material used in this study shows a larger cap surface area than the other soils due to the large R.

However, this difference is not an issue for this study since the cap surface is intended for very long compressive pressure. Numerical evaluation of the state of stress for this study indicated that the pressure is relatively smaller than L(κ).

Table 3.2 Comparison of Three Cap Soil Models.

		This Study	McCormick Ranch Sand *(14)*	NCHRP 556 *(15)*
Elasticity	K (MPa)	22.219	459.676	52.19
	G (MPa)	7.407	275.792	24.087
Plasticity	α (MPa)	4.154	0.00186	0.01
	β (MPa^{-1})	0.0647	0.09718	0
	γ (MPa)	4.055	0.00117	0
	θ (radian)	0	0.02	0.2925
Hardening Law	W	0.08266	0.064	0.023
	D (MPa^{-1})	0.239	0.00725	0.87
	R	28	2.5	4
	X_0 (MPa)	−2.819	1.20658	0.01593
Tension Cut	T (MPa)	0	−2.06843	0

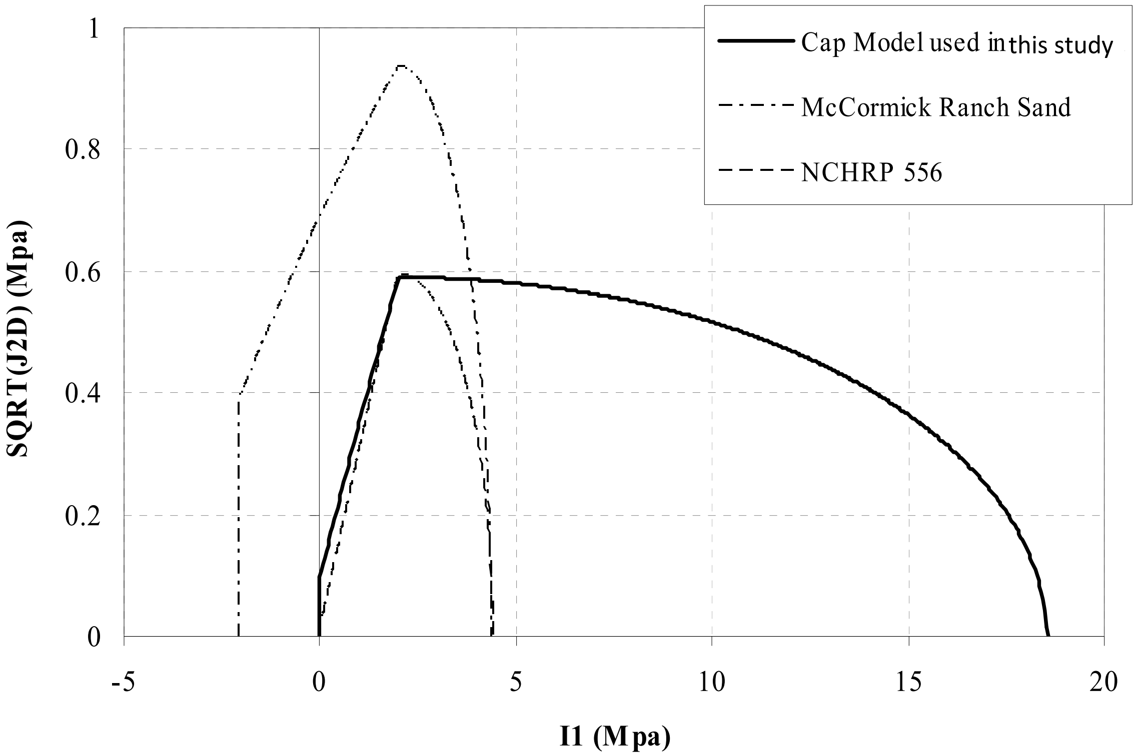


Figure 3.15 Comparison of cap models

3.4. INITIALIZATION OF THE MODEL FOR GRAVITATIONAL LOADING

The MSE wall and barrier model had to be initialized first to account for gravitational loading. Gravity loading affects soil pressure on the wall panels and 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. Figure 3.16 shows the gravitational loading and damping profiles.

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 (80,895 slug), which corresponds to a weight of 11,576.7 kN (2,602.5 kips). The total vertical reaction of the finite element model was 11,241 kN (2,527 kips) at the end of the initialization process, which is less than 3% different from the calculated total weight. This is a reasonable agreement between the calculated weight and the total vertical reaction from the finite element analysis as shown in Figure 3.17.

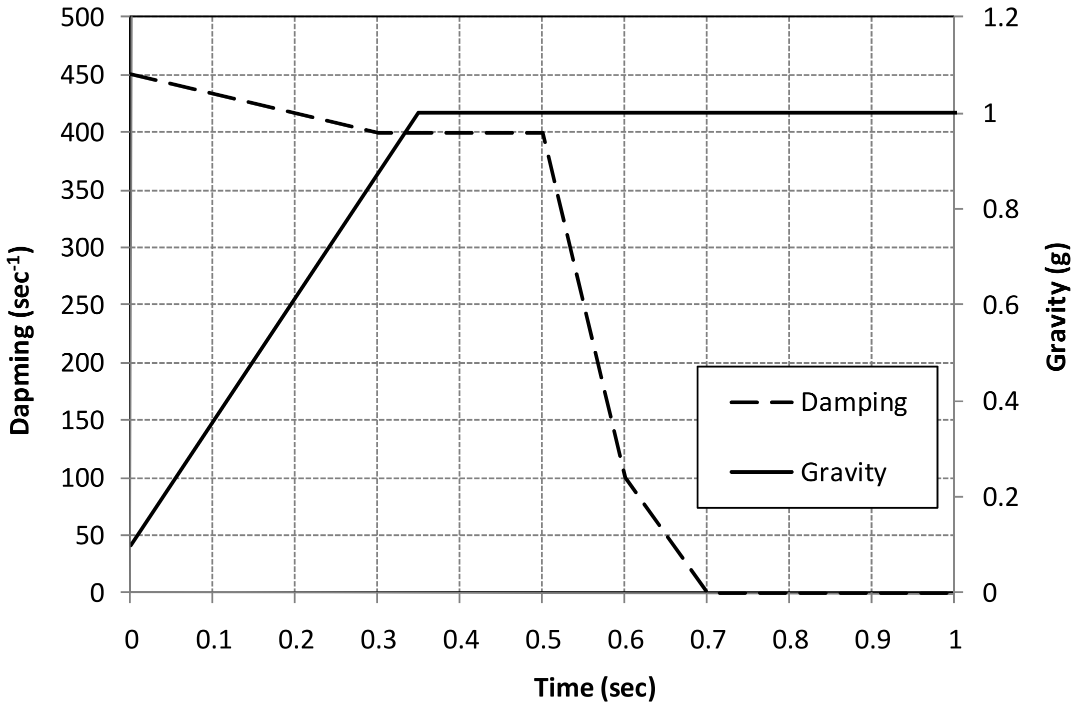


Figure 3.16 Initialization for gravitational and damping profile of the model

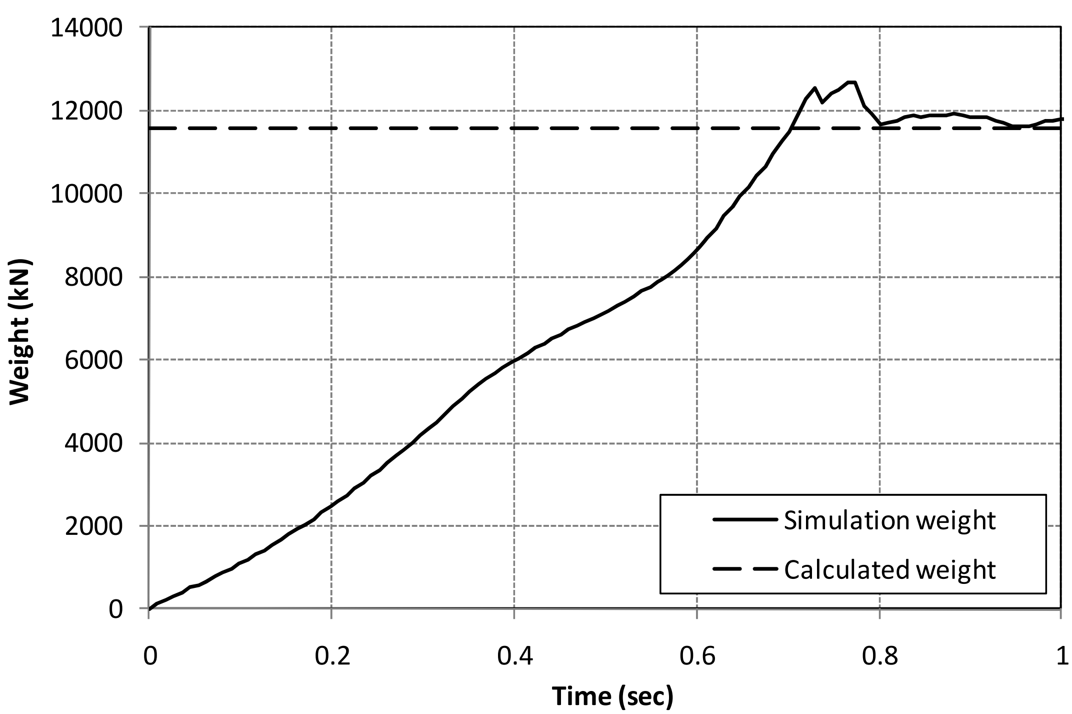


Figure 3.17 Comparison of simulation weight and calculated static weight

Once the gravitational initialization is completed, the vertical stress distribution in the backfill soil is stabilized and is shown in Figure 3.18. The load in the wall strips from simulation is compared to the unfactored load as shown in Table 3.3. The differences from calculation using *AASHTO LRFD* and simulation are less than 15% except the first layer. Since the Eq. (2-1) does not account for different materials than soil (i.e., concrete of the moment slab), the loading pattern of the first strip is not accurately captured by this formula. Moreover, at such small loads, a small variation would results in large percentage difference.

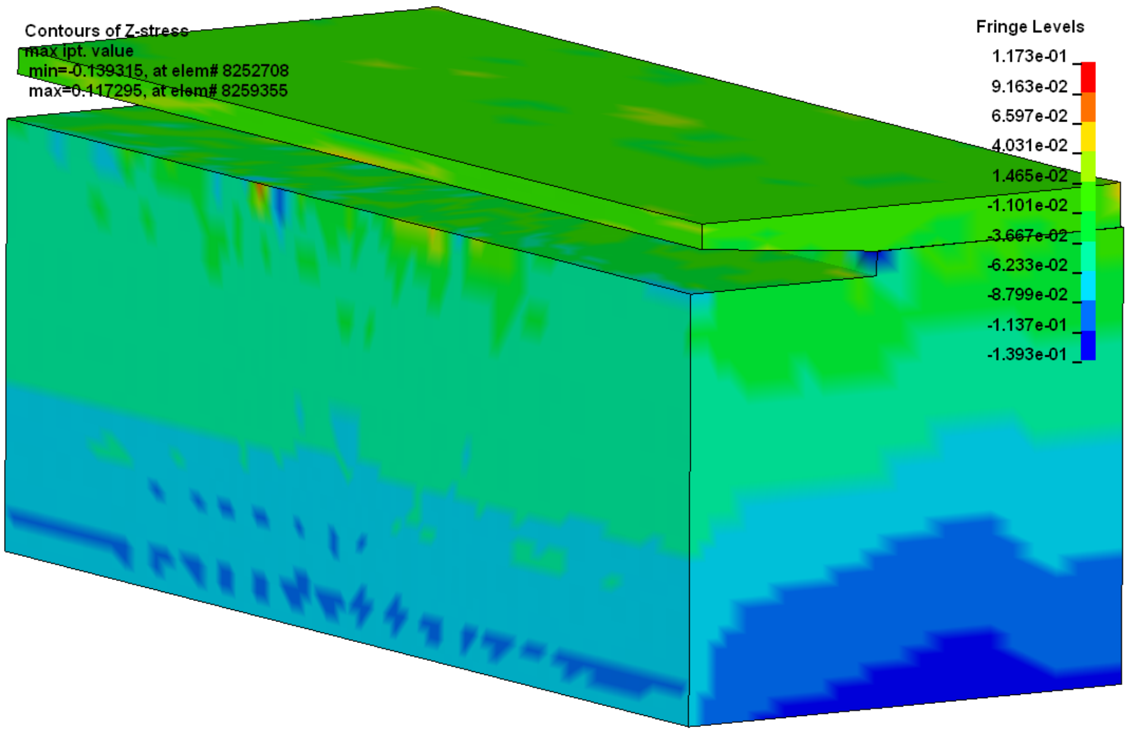


Figure 3.18 Vertical stress on the soil due to the gravitational loading

Table 3.3 Comparison of Static Load on the MSE Wall.

Rein. Layer No.	Depth (ft)	Unfactored T (*AASHTO LRFD*) (kips)	Load in the strip from simulation (kips)	Difference (%)
1	3.96	1.21	1.7	28.8
2	6.17	1.822	1.82	0.1
3	8.63	2.718	2.5	8.7
4	11.09	3.348	3.2	4.6
5	13.54	3.913	3.9	0.3
6	16	4.415	4.8	8.0
7	18.46	4.852	5.5	11.8

3.5. SINGLE UNIT TRUCK VEHICLE MODEL

The single unit truck (SUT) vehicle model was developed by the National Crash Analysis Center (NCAC) *(16)*. The Ford F800 Series Truck meets the *NCHRP Report 350 (17)* criteria of the 8000S test vehicle specification. *NCHRP Report 350* is replaced by *MASH*, which has new test vehicles. Thus, the SUT model needs to reflect the *MASH* 10000S test vehicle specification. For the TL-4 in *MASH (1)*, the mass of the SUT increased from 8,000 kg (17,637 lb) to 10,000 kg (22,000 lb) and the impact speed increased from 80.47 km/h (50 mph) to 90.12 km/h (56 mph). The ballast height of *MASH* TL-4 SUT is changed to 1.25 m (63 in.) from 1.7 m (67 in.) in *NCHRP Report 350*. Table 3.4 shows the comparison of TL-4 SUT vehicle specification per both guidelines.

The 8000S vehicle model was modified to reflect *MASH* 10000S test vehicle specification and calibrated using crash test results of TTI Project 476460-1b *(18)*. Major changes include:

1. U-bolts connecting the front axle to the suspension were modified to calibrate their failure mechanism. Moreover, null shell elements were added around the beam elements to capture the interaction of the U-bolt and the front axle as shown in Figure 3.19.

2. Two 50.8 mm (2 in.) thick wood panels were added between the bed rail and the frame of the truck as shown in Figure 3.20.

3. Lateral constraint brackets (shear plate) were added to restrain lateral displacement of the bed relative to the frame rail as shown in Figure 3.20.

4. The Z-shaped steel cross members on the bottom of the truck box were modified to be I-shaped cross members. This is representative of TTI 476460-1b test vehicle. Figure 3.20 shows these changes.

5. TTI Test 476460-1b had concrete ballast that was smaller in volume than the original SUT model ballast. Therefore, the ballast of the vehicle model was updated to reflect that as shown in Figure 3.21. In order to adjust the CG height of ballast to be 1.25 m (63 in.) above ground, two 50.8 mm (2 in.) thick wood supports were added beneath the ballast.

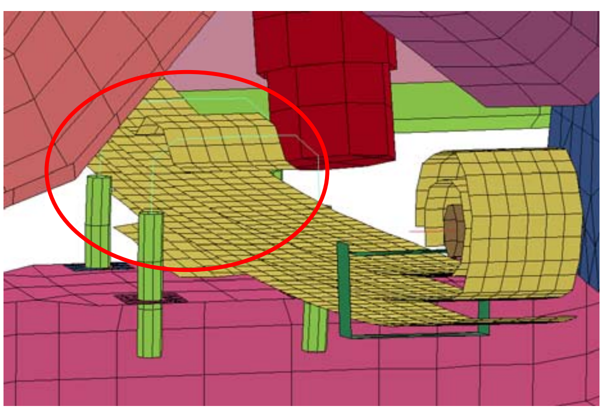
6. The number of contacts (25 contacts) was reduced to a total of 10 contacts to improve stability of the model.

After modification, the specification of the test vehicle and the vehicle model are compared as presented in Table 3.4. Although the wheelbase and overall length show some differences, the total mass and CG correlates well with the test vehicle specification.

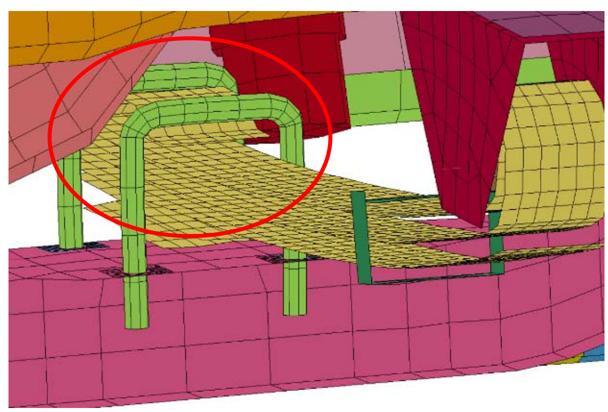
Table 3.4 Specification of TL-4 Single Unit Vehicle.

	NCHRP 350 TL-4-12 *(17)*	*MASH* TL-4-12 *(1)*	Test 476460-1b *(18)*	Modified Single Unit Vehicle Model
Property				
Vehicle	8000S	10000S	Ford 10000S	N/A
Speed, mph (km/h)	50 (80.0)	56 (90.0)	57.4 (92.4)	57.4 (92.4)
Angle, degrees	15	15	14.4	14.4
Mass, lb (kg)				
Curb	12,000 ± 1,000 (5,450 ± 450)	13,200 ± 2,200 (6,000 ± 1,000)	12,200 (5,534)	12,617 (5,753)
Ballast	As Needed	As Needed	9,890 (4,486)	9,577 (4,292)
Test Inertial	17,640 ± 440 (8,000 ± 200)	22,046 ± 660 (10,000 ± 300)	22,090 (10,020)	22,194 (10,045)
Dimension, inch (mm)				
Wheelbase (max)	210 (5350)	240 (6,100)	188 (4,775)	208 (5,287)
Overall Length (max)	343 (8700)	394 (10,000)	304 (7,721)	337.2 (8,565)
Trailer Overhang	N/A	N/A	80.5 (2,045)	88.15 (2,239)
Cargo Bed Height (Above Ground)	51 ± 2 (1,300 ± 50)	51 ± 2 (1,300 ± 50)	N/A	48.2 (1,224)
Center of Mass Location, inch (mm)				
Ballast (Above Ground)	67 ± 2 (1,700 ± 50)	63 ± 2 (1,600 ± 50)	63 (1,600)	61.7 (1,567)
Test Inertial (Above Ground)	49 ± 2 (1,250 ± 50)	N/A	50.8 (1,290)	50.7 (1,287)

(a) Front U-bolt of S10000 Vehicle for TTI Test 476460-1b *(18)*

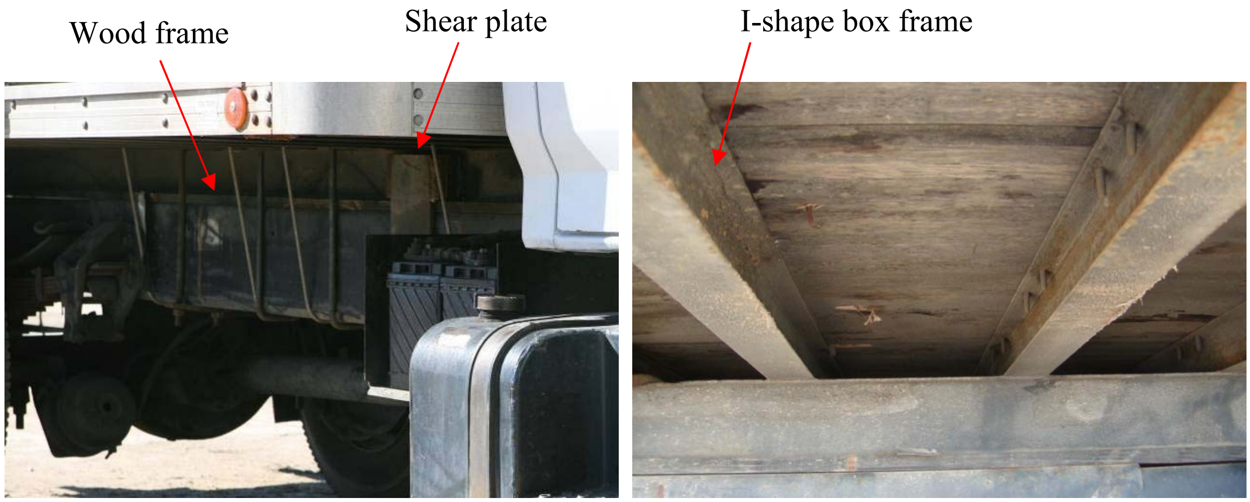


(b) Original

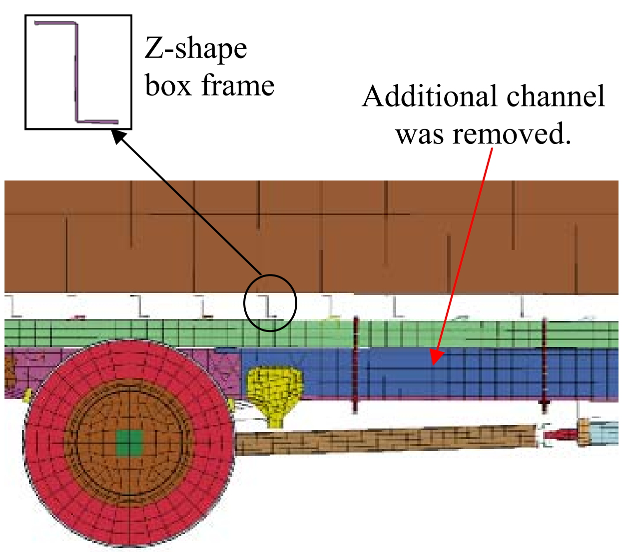


(c) Modified

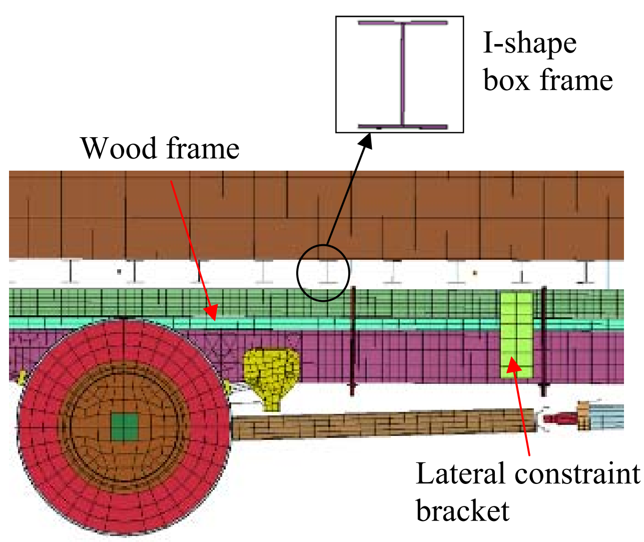
Figure 3.19 Modification to the front axle U-bolt of the SUT model



(a) 10000S vehicle for TTI Test 476460-1b *(18)*



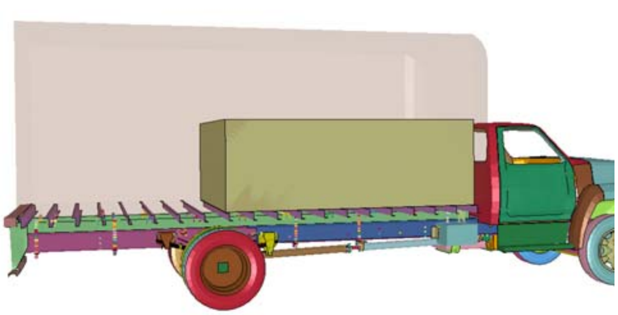
(b) Original



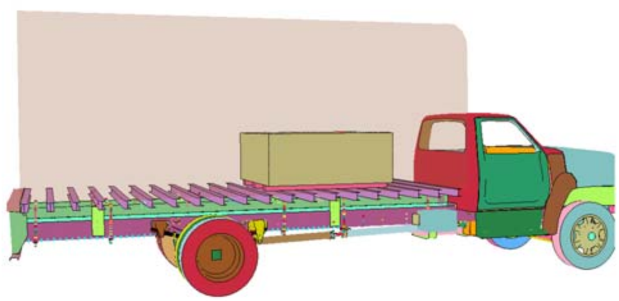
(c) Modified

Figure 3.20 Modification to the chassis of the SUT model

(a) 10000S test vehicle of TTI Test 476460-1b *(18)*



(b) Original



(c) Modified

Figure 3.21 Modification to ballast of the SUT model

3.6. VALIDATION OF SUT MODEL

The validity of the modified SUT model was investigated by performing a full-scale vehicle impact simulation and comparing the results to a previously conducted crash test.

The crash test used for this investigation was conducted at TTI using *MASH* TL-4 impact conditions *(18)*. A 0.81 m (32 in.) New Jersey Safety (N.J.) Shape bridge rail was used in this test. Figure 3.22 shows the initial bridge rail set-up with the 1999 Ford F-800 SUT. The test vehicle was traveling at an impact speed of 92.4 km/h (57.4 mph), impacted the safety shape bridge rail 6.1 m (20 ft) from the upstream end at an impact angle of 14.4 degrees.

3.6.1 Vehicle Impact Simulation

To validate the modified 10000S vehicle model, an impact simulation was performed similar to the full-scale crash test as shown in Figure 3.22. The vehicle model impacted the N.J. bridge rail at a speed of 92.4 km/h (57.4 mph) and an angle of 14.4 degrees. The vehicle in the simulation rolled on the top and over the bridge rail matched closely with the crash test results.

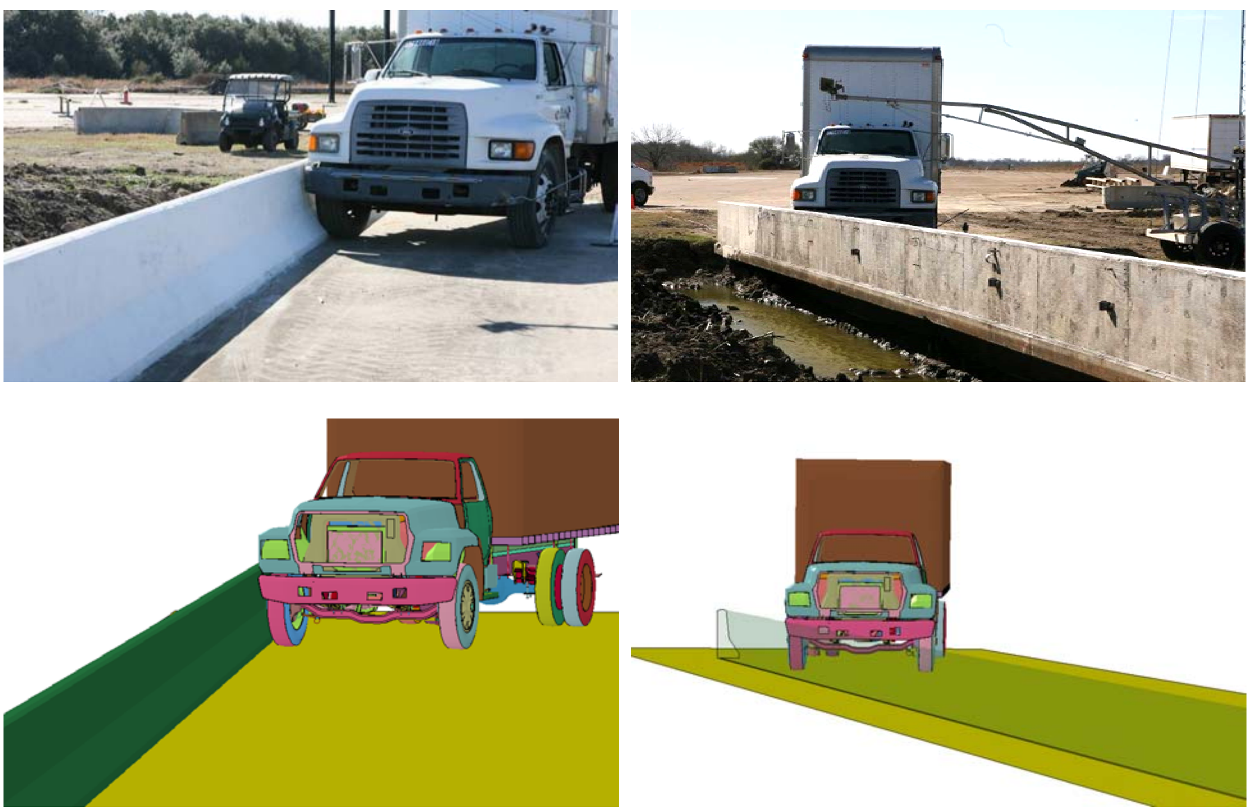


Figure 3.22 Initial set-up of TTI test 476460-1b *(18)* and simulation

In the TTI Test 476460-1b, two accelerometers were installed near the vehicle CG and in the rear axle of the vehicle to measure longitudinal, lateral, and vertical acceleration as shown in Figure 3.23. A solid-state angular rate transducer was installed in the cabin of vehicle to measure roll, pitch, and yaw angles as shown in Figure 3.24.

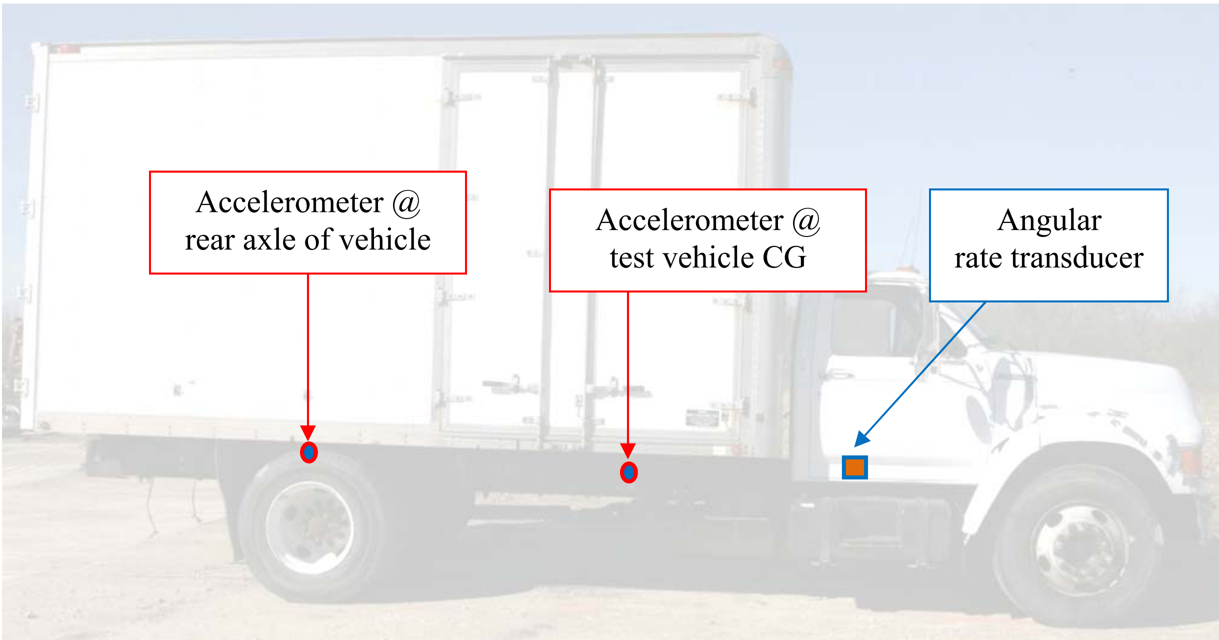


Figure 3.23 Location of accelerometers and angular rate transducer in TTI Test 476460-1b

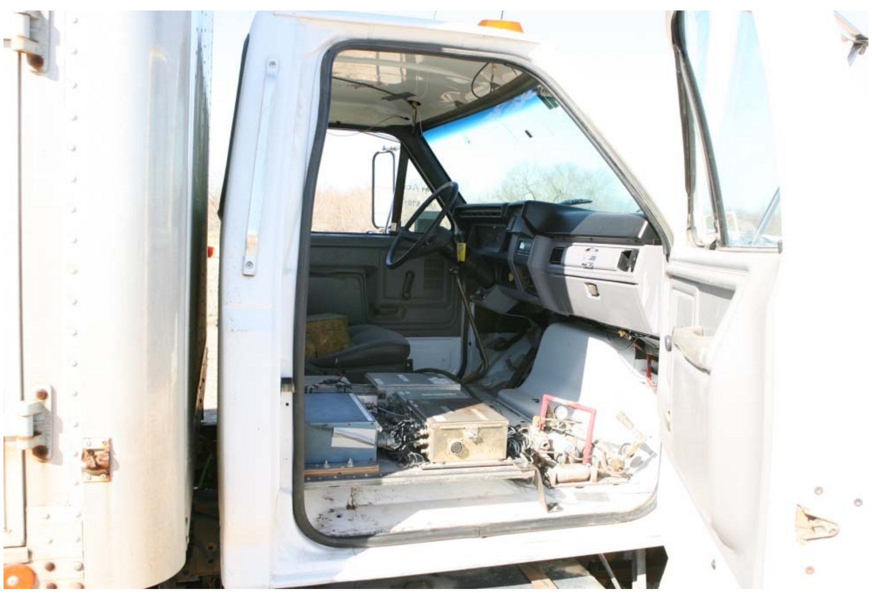


Figure 3.24 Installation of angular rate transducer in the cabin *(18)*

The accelerometer data were calibrated using the Society of Automotive Engineers (SAE) J211 class 180 Hz provided by WinDigit. This program, WinDigit, converts the analog data from each transducer into engineering units. SAE J211 follows *MASH* Appendix C for filtering acceptable data. The Test Risk Assessment Program (TRAP) uses the data from WinDigit to analyze the acceleration and angular displacement data. Figure 3.25 shows the summary of acceleration and angular displacement data from TRAP.

```
General Information
    Test Agency:   Texas Transportation Institute
    Test Number:   476460-1b
    Test Date:     02-19-08
    Test Article:  Safety Shape Bridge Rail

Test Vehicle
    Description:          1999 Ford F800 Box Van
    Test Inertial Mass:       22090 kg
    Gross Static Mass:        22090 kg

Impact Conditions
    Speed: 56.0   km/hr
    Angle:  14.4   degrees

Occupant Risk Factors
    Impact Velocity (m/s)       at 0.2230 seconds on right side of interior
        x-direction     2.5
        y-direction     4.2

    THIV (km/hr):       16.3    at 0.2147  seconds on right side of interior
    THIV (m/s):         4.5

    Ridedown Accelerations (g's)
        x-direction     -2.8    (0.2271 -  0.2371 seconds)
        y-direction     -4.5    (0.2488 -  0.2588 seconds)

    PHD (g's):          4.6     (0.2487 -  0.2587 seconds)

    ASI:                2.97    (0.3502 -  0.4002 seconds)

Max. 50msec Moving Avg. Accelerations (g's)
    x-direction         -2.2    (0.0625 -  0.1125 seconds)
    y-direction         -4.1    (0.1659 -  0.2159 seconds)
    z-direction         29.7    (0.3502 -  0.4002 seconds)

Max Roll, Pitch, and Yaw Angles (degrees)
    Roll                40.5    (0.7974 seconds)
    Pitch               7.8     (0.1519 seconds)
    Yaw                 -17.4   (0.6113 seconds)
```

(a) at test vehicle CG

```
General Information
    Test Agency:   Texas Transportation Institute
    Test Number:   476460-1b
    Test Date:     02-19-08
    Test Article:  Safety Shape Bridge Rail

Test Vehicle
    Description:          1999 Ford F800 Box Van
    Test Inertial Mass:       22090 kg
    Gross Static Mass:        22090 kg

Impact Conditions
    Speed: 92.4   km/hr
    Angle:  14.4   degrees

Occupant Risk Factors
    Impact Velocity (m/s)       at 0.2877 seconds on right side of interior
        x-direction     2.3
        y-direction     5.2

    THIV (km/hr):       18.7    at 0.2742  seconds on right side of interior
    THIV (m/s):         5.2

    Ridedown Accelerations (g's)
        x-direction     -2.2    (0.3940 -  0.4040 seconds)
        y-direction     4.3     (0.3345 -  0.3445 seconds)

    PHD (g's):          4.4     (0.3346 -  0.3446 seconds)

    ASI:                0.73    (0.2169 -  0.2669 seconds)

Max. 50msec Moving Avg. Accelerations (g's)
    x-direction         -2.0    (0.0619 -  0.1119 seconds)
    y-direction         -6.4    (0.2175 -  0.2675 seconds)
    z-direction         -3.8    (0.2045 -  0.2545 seconds)

Max Roll, Pitch, and Yaw Angles (degrees)
    Roll                40.5    (0.7974 seconds)
    Pitch               7.8     (0.1519 seconds)
    Yaw                 -17.4   (0.6113 seconds)
```

(b) at rear axle

Figure 3.25 Summary of signal data from TRAP (TTI Test 476460-1b)

Two different filtering methods were used to analyze the acceleration data, which are SAE 60 Hz and 50 milli-second (msec) average. Figure 3.26 shows the longitudinal, lateral, and vertical acceleration using SAE 60 Hz and 50 msec average from the acceleration installed at two different locations. Figure 3.27 shows the angular displacements, roll, pitch, and yaw angles installed in the cabin.

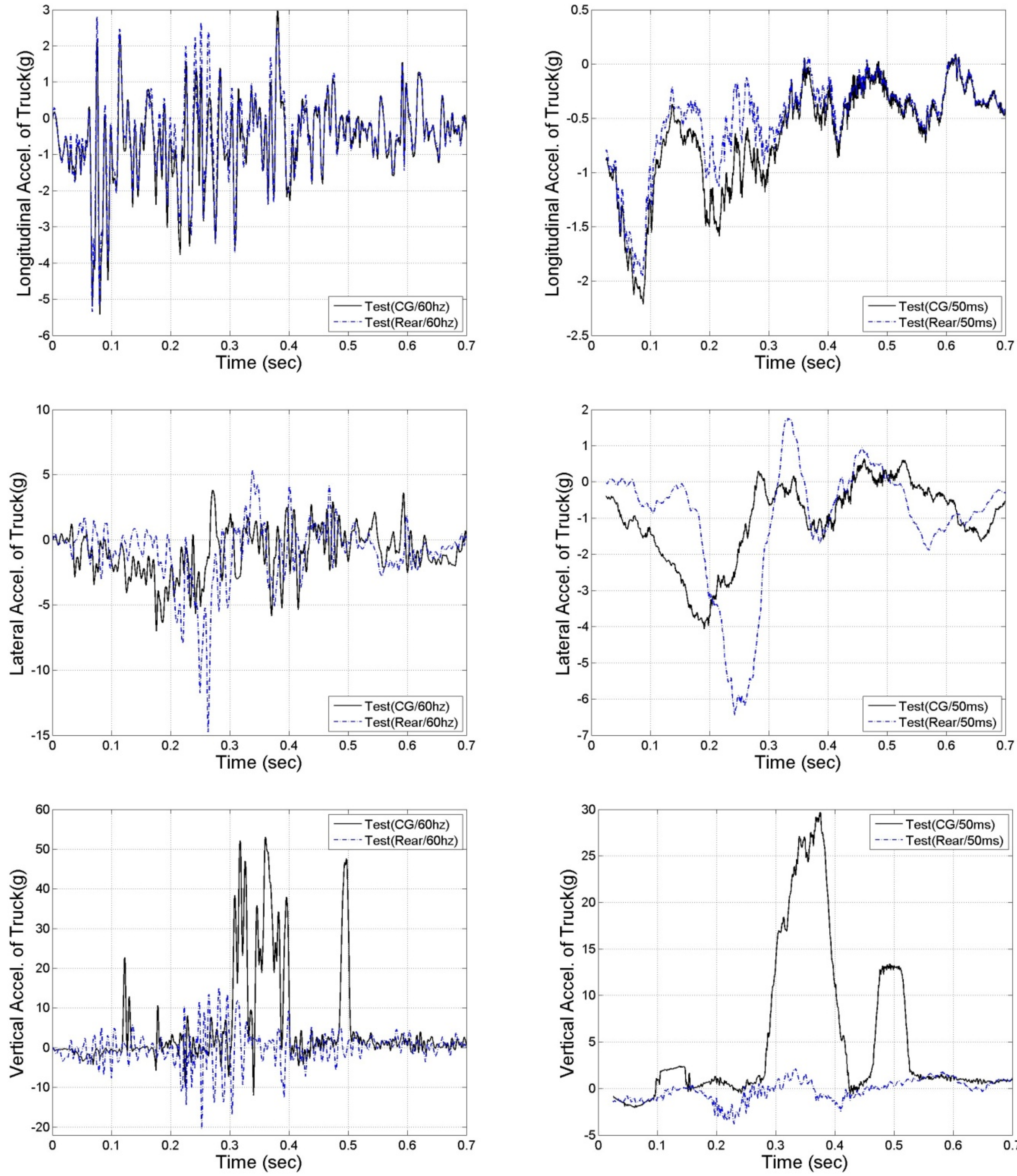


Figure 3.26 Longitudinal, lateral, and vertical acceleration from two acceleration installed at the vehicle CG and the real axle of vehicle

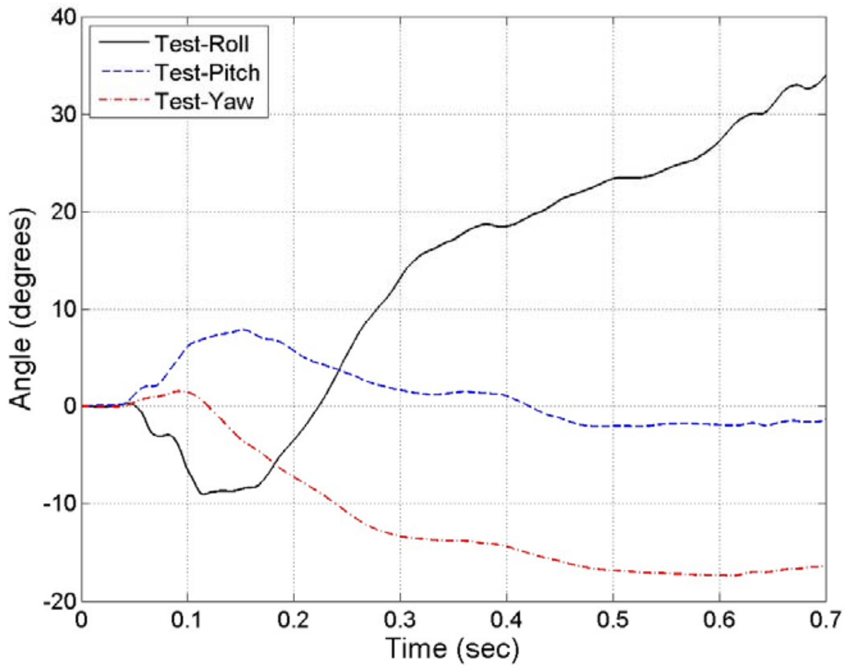


Figure 3.27 Angular displacement (TTI Test 476460-1b)

Since the vehicle model has a longer wheelbase and overhang of a truck, the longitudinal CG of the test vehicle and the vehicle model are different. In order to compare with test vehicle accelerometer data, two accelerometers were used at two locations of CG as shown in Figure 3.28. The two more accelerations were used at the rear axle of the truck and in the cabin.

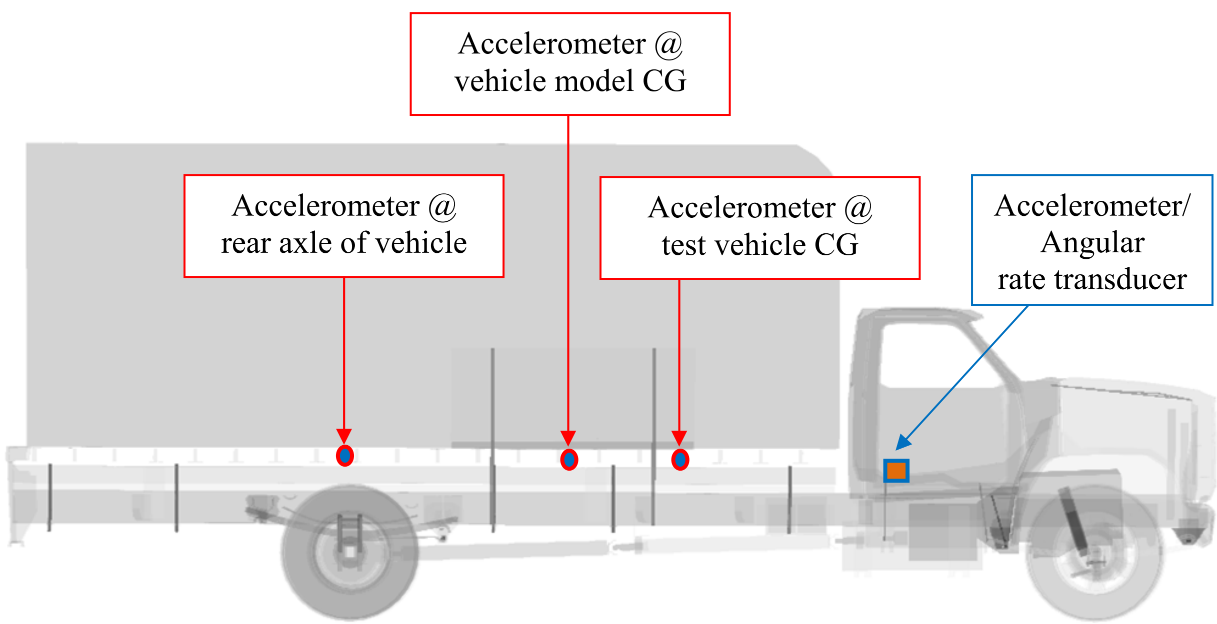


Figure 3.28 Location of accelerometers in the vehicle model

The vehicle in the crash test ended up rolling on top of the bridge rail. The simulation captured that dynamics from the beginning of rolling until 0.7 sec. This is believed to be enough time for vehicular interaction with a vertical wall like the crash wall. Figures 3.29 and 3.30 present a detailed comparison of the simulation and test results. Overall, the simulation correlates reasonably well with the results of the crash test after the modification on the vehicle model.

Table 3.5 Event Time-Sequence Comparison of the Test and Simulation.

Incident	Crash test	Model Simulation
The right front bumper impacted the bridge rail. Right front tire began to climb the face of the bridge rail and lost contact with the ground surface	0.000 sec	0.000 sec
Front axle began to shift	0.044 sec	0.05 sec
Vehicle began to redirect	0.1 sec	0.08 sec
Left front tire lost contact with the ground surface	0.166 sec	0.125 sec
Right rear outer tire made contact with the toe of bridge rail	0.223 sec	0.225 sec
Left rear tires became airborne	0.252 sec	0.23 sec
Right rear edge of the box van went over the top of the bridge rail	0.263 sec	0.26 sec
Vehicle became parallel with the bridge rail	0.4 sec (79.6 km/h)	0.4 (87.23 km/h)
Vehicle exited the view of the overhead camera	0.779 sec	N/A

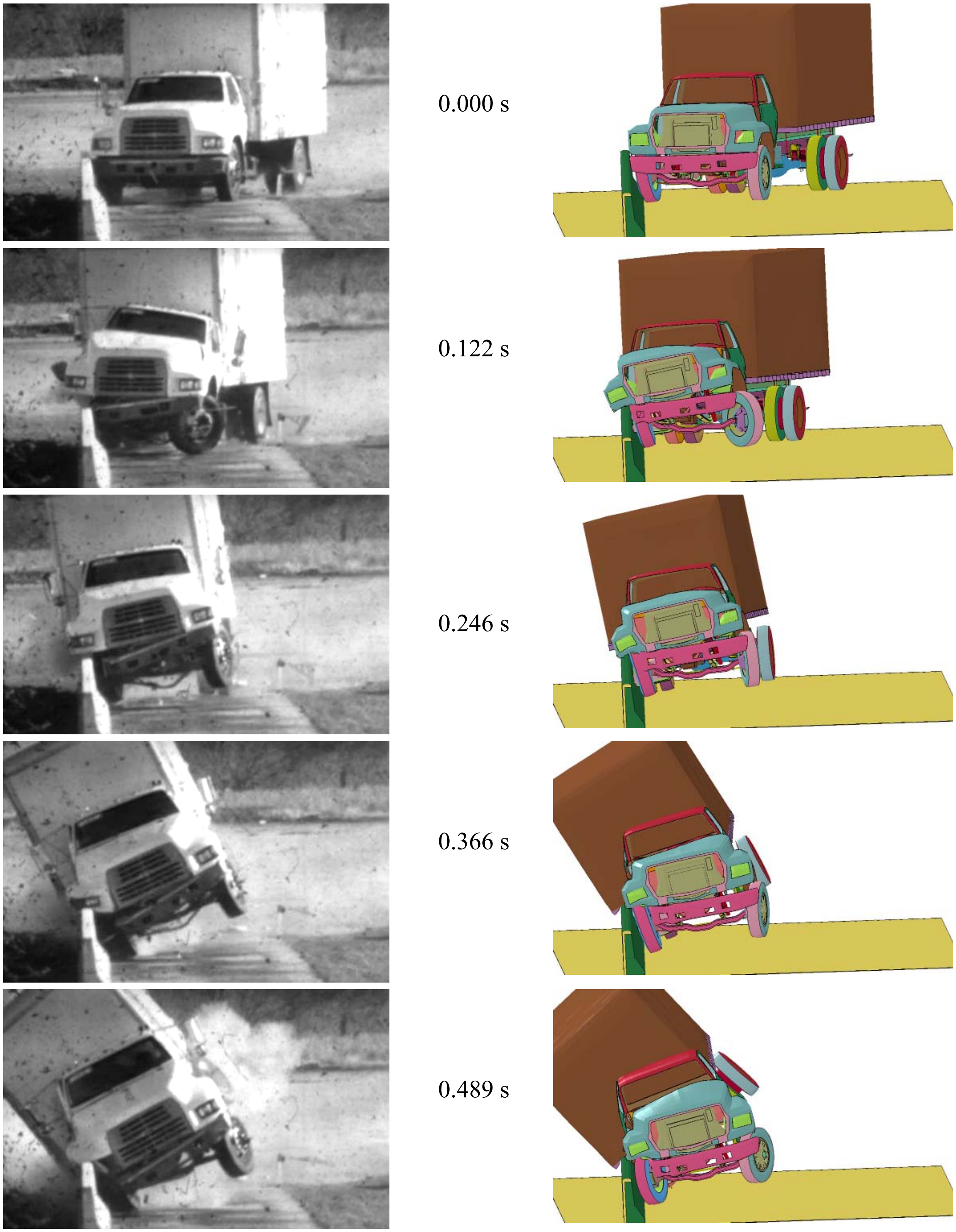


Figure 3.29 Comparison front view sequential photographs for test and simulation

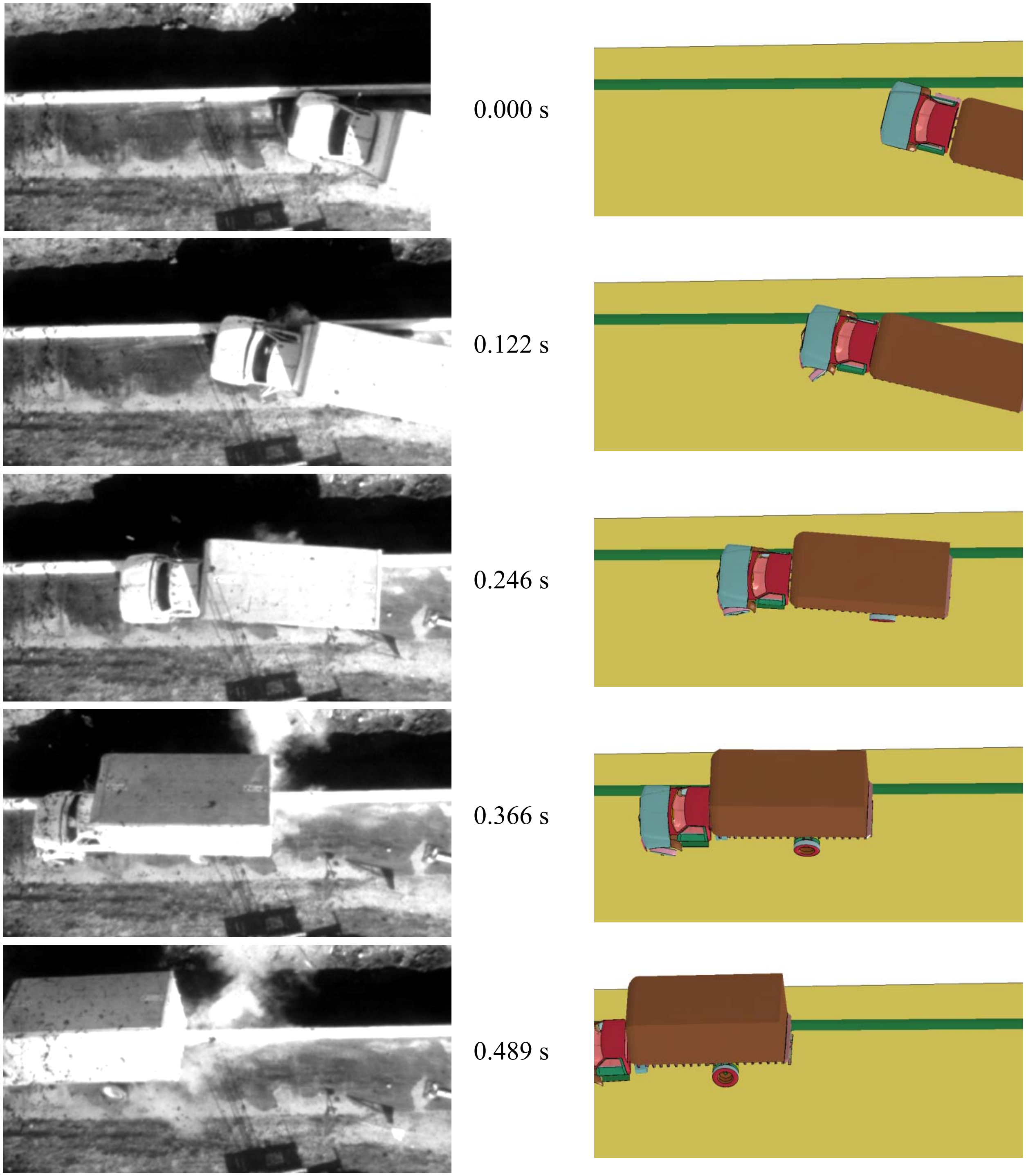


Figure 3.30 Comparison top view sequential photographs for test and simulation

The summary comparison of test and simulation data from TRAP is presented in Figure 3.31. The data in the test were recorded until 1.73 sec, however, the running time was 0.8 sec in the simulation. The data from the test were trimmed for comparison purpose herein. In the longitudinal direction, the occupant impact velocity in the test and the simulation was 2.5 m/sec (8.2 ft/sec) at 0.223 sec and 1.1 m/sec (3.61 ft/sec), respectively. The highest 10 msec occupant ridedown longitudinal acceleration in the test and the simulation was −2.8g from 0.227 to 0.237 sec and −4.2g from 0.377 to 0.387 sec, respectively. The maximum 50 msec average longitudinal acceleration in the test and the simulation was −2.2g between 0.063 and 0.113 sec and −1.6g between 0.121 and 0.171 sec, respectively.

In the lateral direction, the occupant impact velocity in the test and the simulation was 4.2 m/sec (13.8 ft/sec) at 0.223 sec and 4.3 m/sec (14.1 ft/sec), respectively. The highest 10 msec occupant ridedown lateral acceleration in the test and the simulation was −4.5g from 0.249 to 0.259 sec and 5.1g from 0.327 to 0.337 sec, respectively. The maximum 50 msec average lateral acceleration in the test and the simulation was −4.1g between 0.166 and 0.216 sec and −4.2g between 0.163 and 0.213 sec, respectively. Theoretical Head Impact Velocity (THIV) in the test and the simulation was 16.3 km/h or 4.5 m/sec at 0.215 sec and 16.3 km/h or 4.5 m/sec at 0.244 sec, respectively. Post-Impact Head Decelerations (PHD) in the test and the simulation was 4.6g between 0.249 and 0.259 sec and 5.2g between 0.327 and 0.337 sec, respectively. Acceleration Severity Index (ASI) in the test and the simulation was 2.97 between 0.35 and 0.4 sec and 0.53 between 0.285 and 0.335 sec, respectively.

General Information
Test Agency: Texas Transportation Institute
Test Number: 476460-1b
Test Date: 02-19-08
Test Article: Safety Shape Bridge Rail

Test Vehicle
Description: 1999 Ford F800 Box Van
Test Inertial Mass: 22090 kg
Gross Static Mass: 22090 kg

Impact Conditions
Speed: 92.4 km/hr
Angle: 14.4 degrees

Occupant Risk Factors
Impact Velocity (m/s) at 0.2230 seconds on right side of interior
x-direction 2.5
y-direction 4.2

THIV (km/hr): 16.3 at 0.2147 seconds on right side of interior
THIV (m/s): 4.5

Ridedown Accelerations (g's)
x-direction -2.8 (0.2271 - 0.2371 seconds)
y-direction -4.5 (0.2488 - 0.2588 seconds)

PHD (g's): 4.6 (0.2487 - 0.2587 seconds)

ASI: 2.97 (0.3502 - 0.4002 seconds)

Max. 50msec Moving Avg. Accelerations (g's)
x-direction -2.2 (0.0625 - 0.1125 seconds)
y-direction -4.1 (0.1659 - 0.2159 seconds)
z-direction 29.7 (0.3502 - 0.4002 seconds)

Max Roll, Pitch, and Yaw Angles (degrees)
Roll 40.5 (0.7974 seconds)
Pitch 7.8 (0.1519 seconds)
Yaw -17.4 (0.6113 seconds)

General Information
Test Agency: Texas Transportation Institute
Test Number:
Test Date:
Test Article: SUT against 32 in. tall N.J. barrier

Test Vehicle
Description: 10000S
Test Inertial Mass: 22194 kg
Gross Static Mass: 22194 kg

Impact Conditions
Speed: 92.4 km/hr
Angle: 14.4 degrees

Occupant Risk Factors
Impact Velocity (m/s) at 0.2404 seconds on right side of interior
x-direction 1.1
y-direction 4.3

THIV (km/hr): 16.3 at 0.2438 seconds on right side of interior
THIV (m/s): 4.5

Ridedown Accelerations (g's)
x-direction -4.2 (0.3773 - 0.3873 seconds)
y-direction 5.1 (0.3273 - 0.3373 seconds)

PHD (g's): 5.2 (0.3273 - 0.3373 seconds)

ASI: 0.53 (0.2846 - 0.3346 seconds)

Max. 50msec Moving Avg. Accelerations (g's)
x-direction -1.6 (0.1211 - 0.1711 seconds)
y-direction -4.2 (0.1632 - 0.2132 seconds)
z-direction -5.3 (0.2846 - 0.3346 seconds)

Max Roll, Pitch, and Yaw Angles (degrees)
Roll 32.7 (0.7993 seconds)
Pitch 5.1 (0.6476 seconds)
Yaw 19.1 (0.6478 seconds)

(a) TTI test 476460-1b **(b) Simulation**

Figure 3.31 Summary comparison of signal data from TRAP

There are two ways to calculate the impact force in simulation. One is from the contact definition between the barrier and the vehicle and the other is calculated using the accelerometer data of vehicle CG. The impact force was calculated from contact definition between the barrier and the vehicle as shown in Figure 3.32. Two processes, a SAE 60 Hz digital filter and a 50 msec average are used to diminish the signal noise using the TRAP. The peak impact force using SAE 60 Hz was calculated to be 332.5 kN (74.75 kips) at 0.23 sec. The peak 50 msec average impact force was calculated to be 181.9 kN (40.9 kips) at 0.11 sec and 270.45 kN (60.8 kips) at 0.23 sec.

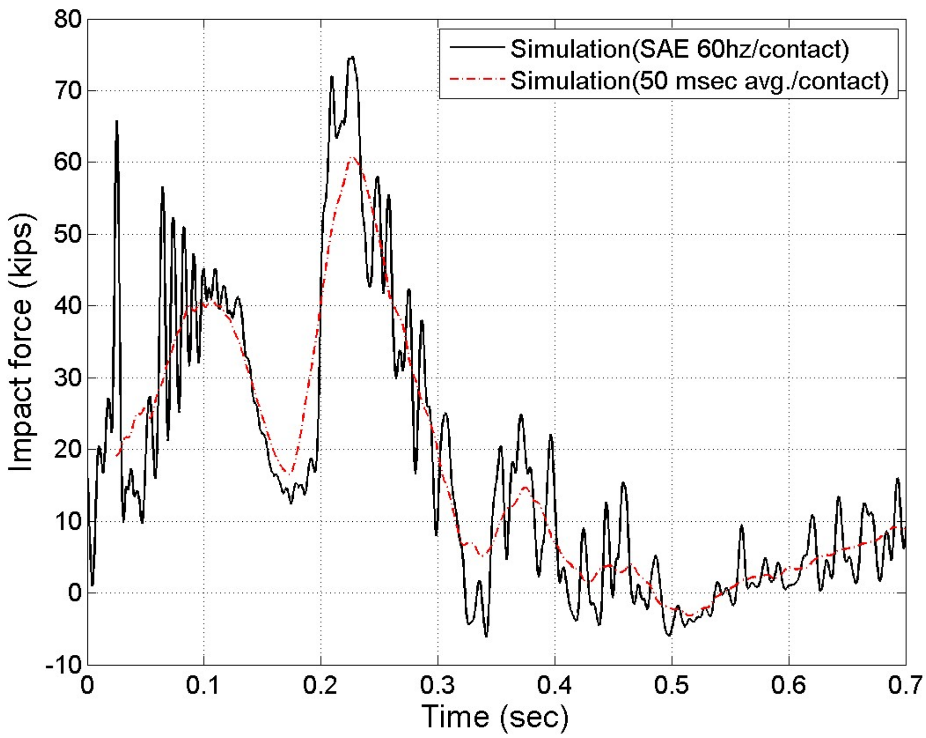


Figure 3.32 Impact force from contact definition

In order to compute the impact force from the vehicle accelerometer, Eq. (3-9) was used.

$$F_i(\mathrm{t}) = F_x(\mathrm{t})\sin\phi(\mathrm{t}) - F_y(\mathrm{t})\cos\phi(\mathrm{t}) = m(\overrightarrow{a_x}(\mathrm{t})\sin\phi(\mathrm{t}) - \overrightarrow{a_y}(\mathrm{t})\cos\phi(\mathrm{t})) \qquad (3\text{-}9)$$

where $F_i(t)$ is the impact force; $\phi\,(t)$ is the vehicular yaw angle with respect to the barrier; $F_x(\mathrm{t}) = m\overrightarrow{a_x}(\mathrm{t})$ is the longitudinal component of truck impact force; $F_y(\mathrm{t}) = m\overrightarrow{a_y}(\mathrm{t})$ is the horizontal component of truck impact force; and *m* is the mass of truck. The coordinate systems for the truck and barrier are schematically shown in Figure 3.33. This above formula assumes the vehicle as a single rigid body for the purpose of calculating the impact force.

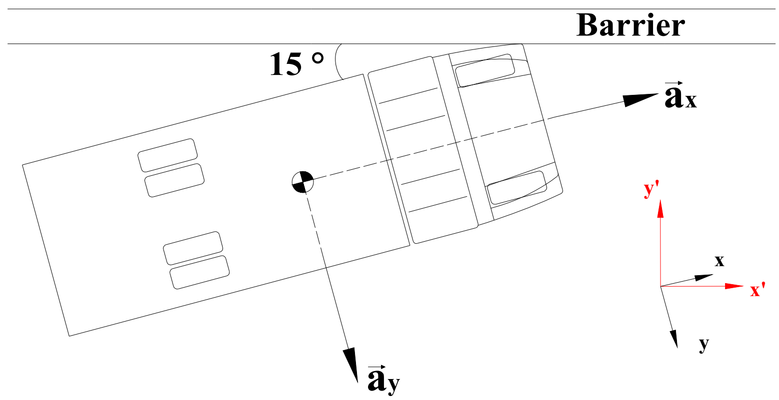


Figure 3.33 Coordinate system for vehicle and barrier

In the simulation, two accelerations were used at the test vehicle CG and model vehicle CG due to the different vehicle specification as mentioned above. As shown in Figure 3.34, the angular displacement shows the same magnitude but has time delay. Therefore, the accelerometer placed on the test vehicle CG was selected to analyze the data.

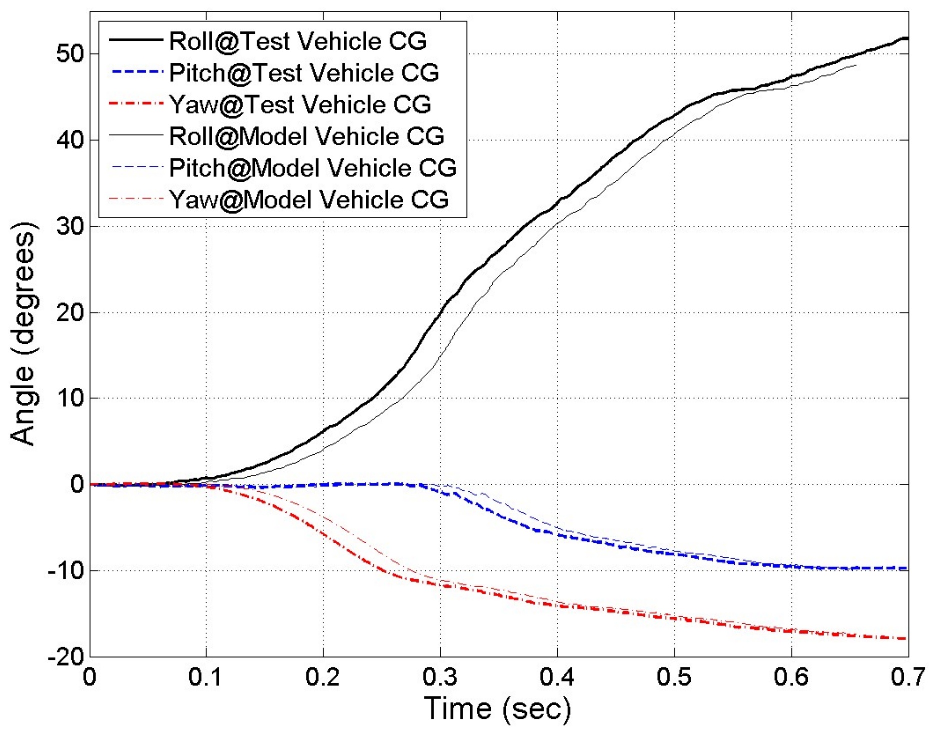
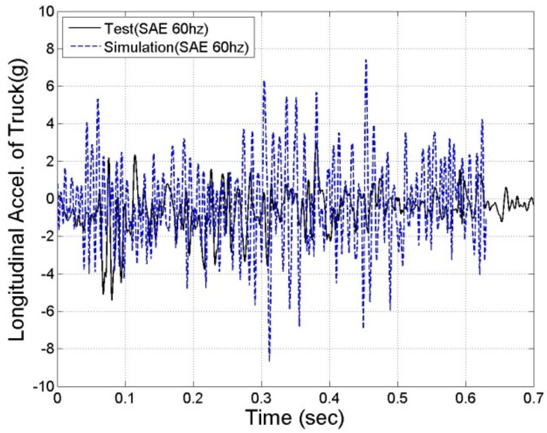


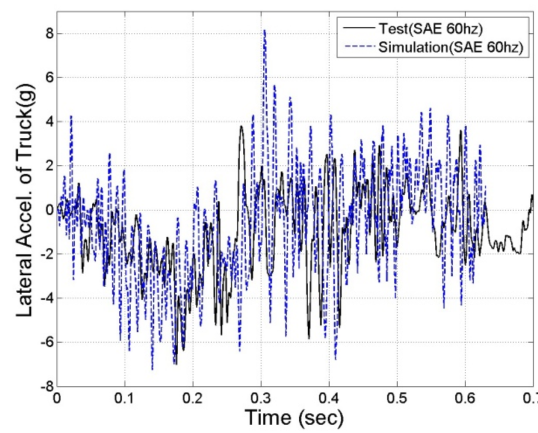
Figure 3.34 Comparison of angular displacement of different CG location

Data obtained from the accelerometer were analyzed and the results are presented in Figure 3.35 and Figure 3.36 using SAE 60 Hz digital filter and a 50 msec average, respectively. Figure 3.35 shows the longitudinal and lateral accelerations ([a] and [b]) using the SAE 60 Hz digital filter and the yaw angle with respect to the barrier (c). Using Eq. (3-9), the resultant impact force was computed as a function of time as shown in Figure 3.35(d).

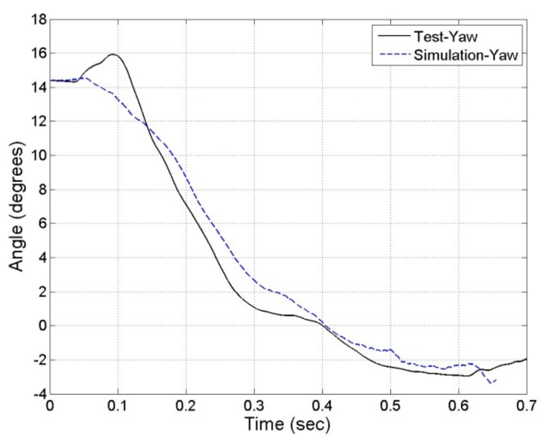
Figure 3.36 shows the longitudinal and lateral accelerations ([a] and [b]) using 50 msec average. Using Eq. (3-9), the resultant impact force using 50 msec average was computed as a function of time to be 373.3 kN (83.9 kips) at 0.19 sec in the test and 400.7 kN (90.1 kips) at 0.165 sec in the simulation. Figure 3.3 shows the vertical acceleration.



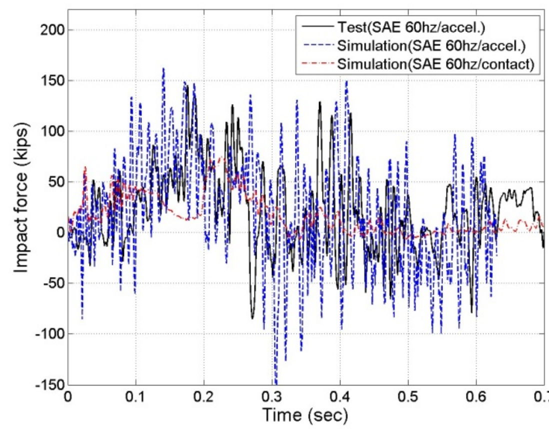
(a) Longitudinal deceleration



(b) Lateral acceleration

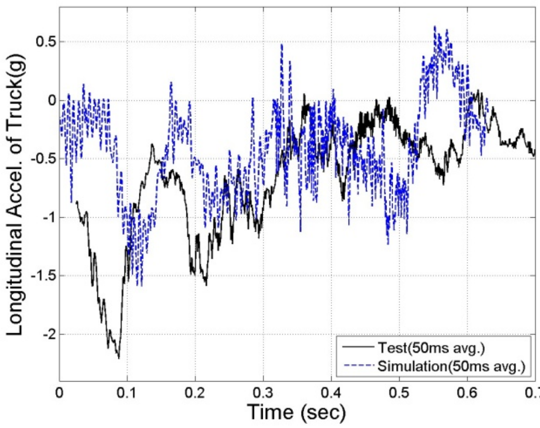


(c) Yaw angle with respect to the barrier

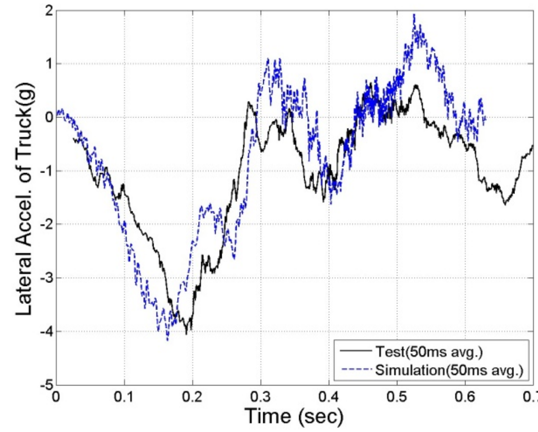


(d) Impact force

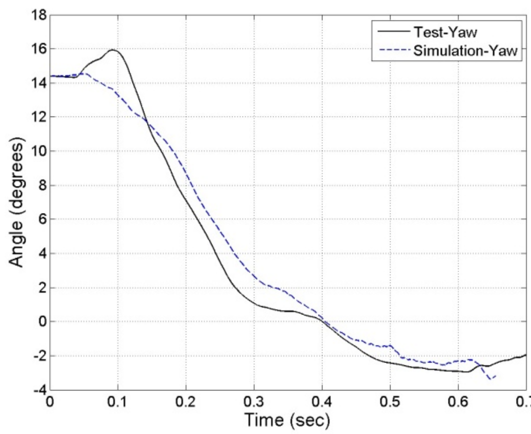
Figure 3.35 Comparison of accelerometer data and impact force (filtered by SAE 60 hz)



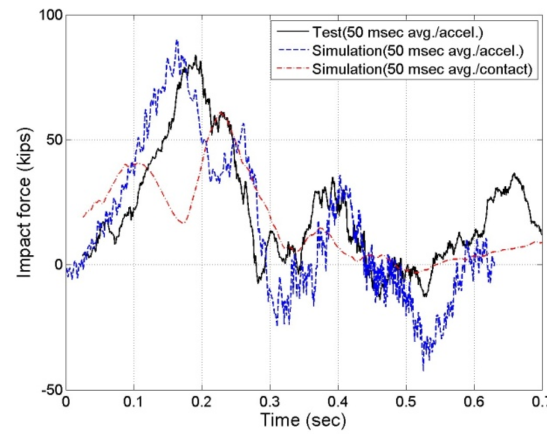
(a) Longitudinal deceleration



(b) Lateral acceleration



(c) Yaw angle with respect to the barrier



(d) Impact force

Figure 3.36 Comparison of accelerometer data and impact force (using 50 msec avg.)

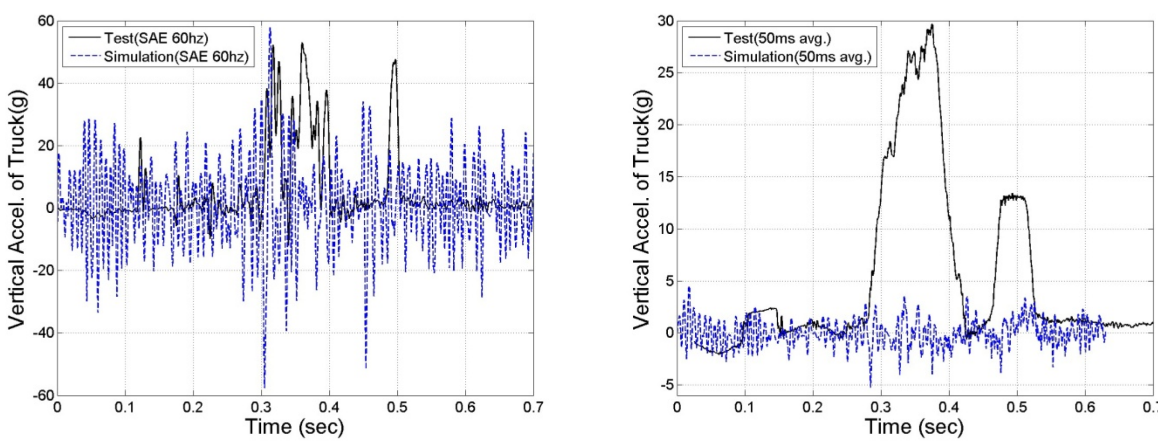


Figure 3.37 Comparison of vertical accelerometer data

The vehicle yaw, pitch, and roll angles of both test and simulation were calculated using TRAP as shown in Figure 3.38. 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 31.6 degrees, compared to 29.3 degrees of the vehicle model at 0.65 sec. The peak pitch angles in test and simulation were 7.7 degrees at 0.152 sec and 2.67 degrees at 0.13 sec, respectively. The minimum pitch angles are −1.69 degrees at 0.65 sec in the test and −8.8 degrees at 0.65 sec. The minimum yaw angles in test and simulation were −17.4 and −17.8 degrees at 0.65 sec, respectively.

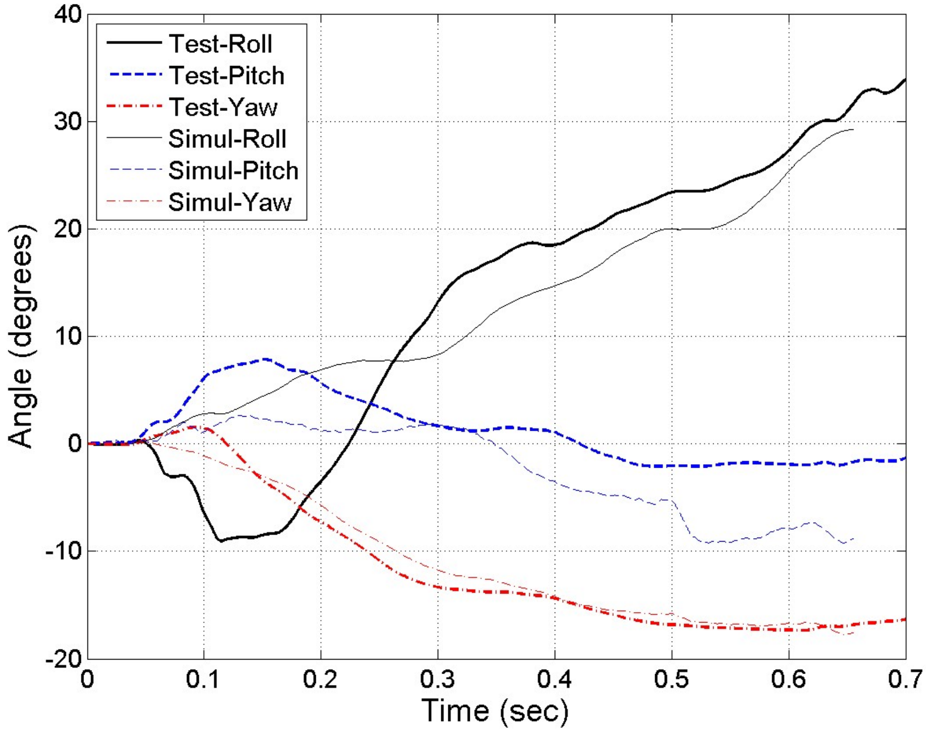


Figure 3.38 Vehicle angular displacement comparison of simulation and test

3.6.2 Quantitative Validation

Ray et al. *(19)* recently developed the Roadside Safety Verification and Validation (RSVVP) program that can calculate comparison metrics between simulation and crash test signals that are helpful in quantitatively validating a roadside hardware model. These metrics are mathematical measures of the agreement between two curves. These procedures were used in this study to help assess the validity of the modified SUT model.

Energy balance curves produced by LS-DYNA were analyzed as a measure of the numerical stability of the simulation and are shown in Figure 3.39. Table 3.6 shows that the results obtained from the simulation passed the criteria recommended by Ray et al. *(3)*.

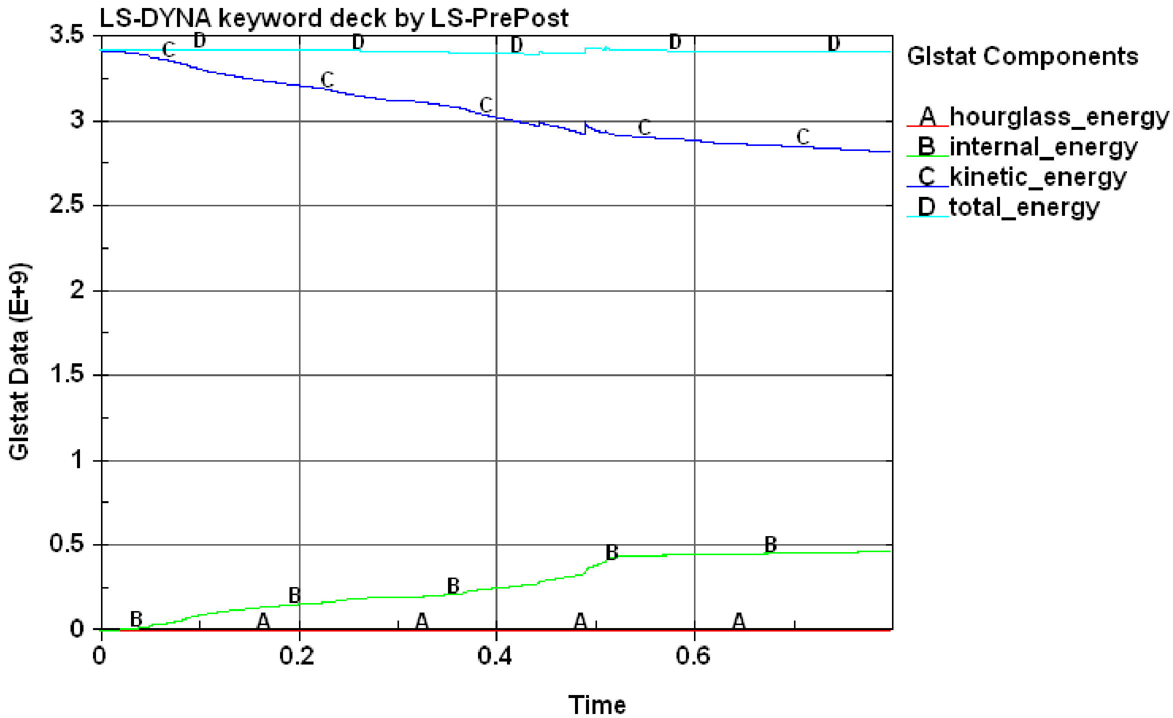


Figure 3.39 Energy balance curve for the simulation

Table 3.6 Analysis Solution Validation.

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10% from the beginning of the run to the end of the run.	1.02	Y
Hourglass Energy of the analysis solution at the end of the run is less than 5% of the total initial energy at the beginning of the run.	0.02	Y
The part/material with the highest amount of hourglass energy at any time during the run is less than 5% of the total initial energy at the beginning of the run.	0.03	Y
Mass added to the total model is less than 5% of the total model mass at the beginning of the run.	0	Y
The part/material with the most mass added had less than 10% of its initial mass added.	0	Y
The moving parts/materials in the model have less than 5% of mass added to the initial moving mass of the model.	0	Y
There are no shooting nodes in the solution?	No	Y
There are no solid elements with negative volumes?	No	Y

The Sprauge-Geer MPC metrics and Analysis-of-Variance (ANOVA) metrics were computed for the three acceleration channels and three angular rate channels obtained from the TTI test 476460-1b and the simulation using the RSVVP computer program. According to the procedure, if one or more channels do not directly satisfy the criteria, a multi-channel weighting option may be used. As shown in Table 3.7, time history comparison metrics between the crash test and simulation satisfied the criteria for the multiple channel weighting option.

Table 3.7 Time History Evaluation Table.

Compare Test 476460-1b (Filter Type: SAE60) and Simulation (Filter Type: SAE60, source: TRAP)							
Sprauge-Geer Metrics	**M ≤40**	**P ≤40**	**Pass?**	***Anova Metrics***	**Mean Residual ≤0.05**	**Std. Deviation ≤0.35**	**Pass?**
X acceleration	76.2	46.2	N	X acceleration/Peak	0.02	0.46	N
Y acceleration	23.3	39.6	Y	Y acceleration/Peak	0.03	0.40	N
Z acceleration	5.5	51.6	N	Z acceleration/Peak	−0.10	0.36	N
Roll rate	26	34.3	Y	Roll rate	−0.44	0.29	N
Pitch rate	5.1	2.4	Y	Pitch rate	0.03	0.06	Y
Yaw rate	15.6	11.9	Y	Yaw rate	0.02	0.2	Y
Multiple Channels							
Weighting factor: Area 1	12.6	29.3	Y		−0.04	0.26	Y

Some of the single channel discrepancies have to do with the fact that the SUT cabin initially rolled away from the barrier then reversed roll direction toward the barrier. However, in the simulation, the SUT cabin rolled toward the barrier early on.

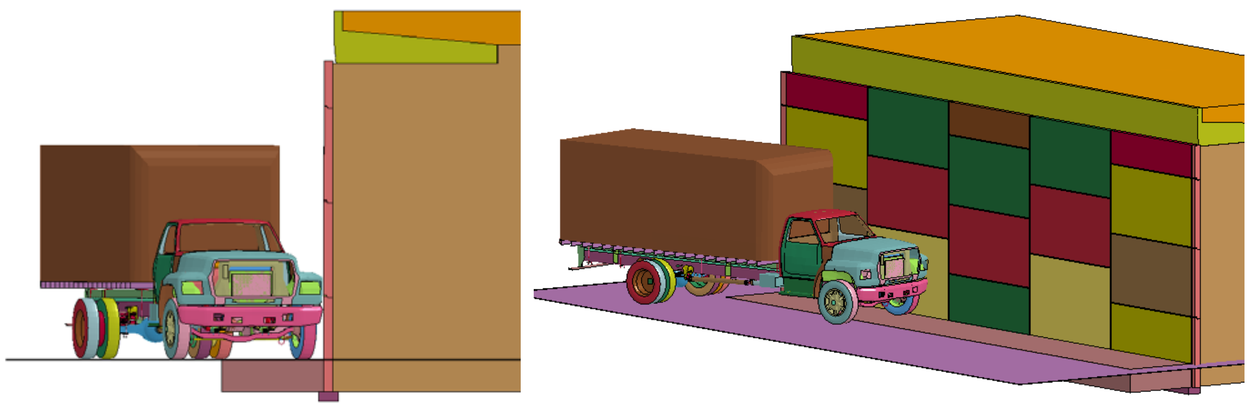
Ray et al. *(3)* also recommend developing a phenomena importance ranking table (PIRT), similar to the evaluation tables in *NCHRP Report 350* and *MASH*, as another means of comparing the test and simulation. The relative difference between the simulation and test results presented in PIRT should not exceed 20 percent or 5 degrees in the angles or 2 m/s in the velocity as shown in Table 3.8. Roll, pitch, yaw angles, occupant impact velocities, and vehicle trajectory obtained from the simulation closely match the test results. The results satisfy the criteria except one, lateral ORA. Since the data used in comparison using RSVVP are the data filtered by SAE 60, the occupant risk accelerations have some difference between the two data. However, the acceleration time history using 50 msec average as shown in Figure 3.36 shows good agreement.

Table 3.8 Roadside Safety Phenomena Importance Ranking Table (PIRT).

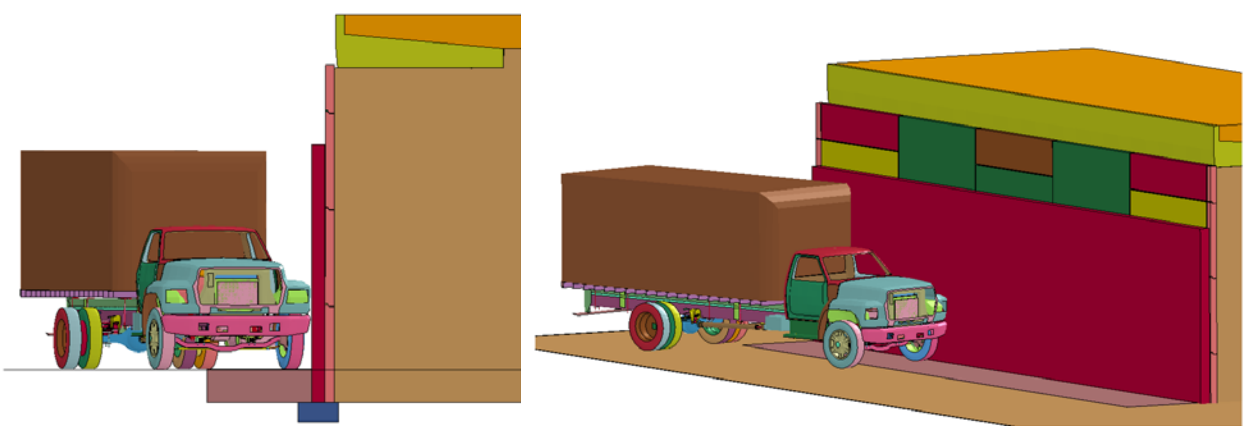
Evaluation Criteria	TTI Test	Simulation	Relative Difference	Pass?
F2: Maximum Roll (deg.)	31.6	29.3	< 20% or 5°	Y
F3: Maximum Pitch (deg.)	2.7	7.7	< 20% or 5°	Y
F4: Maximum Yaw (deg.)	−17.4	−17.8	< 20% or 5°	Y
L1: Occupant impact velocities				
Longitudinal OIV (m/s)	2.5	1.1	< 20% or 2 m/s	Y
Lateral OIV (m/s)	4.2	4.3		Y
THIV (m/s)	4.5	4.3		Y
L2: Occupant accelerations:				
Longitudinal ORA	−2.8	−4.2	< 20% or 4g’s	Y
Lateral ORA	−4.5	5.1		N
PHD	4.6	5.2		Y
ASI	2.97	0.53		Y
M3: Exit velocity at loss of contact (km/h)	79.6	87.2	< 20%	Y

4. FINITE ELEMENT ANALYSES RESULTS

Once the initialization process was completed, the vehicle was added to the model for the full-scale impact simulation. Three finite element models of the MSE wall were developed in this study. The first model has a typical section of an MSE wall as shown in Figure 4.1(a). This model would be used to quantify damage profile of the wall panels during a direct vehicular impact as a reference case. The next two models incorporate the same MSE wall model in addition to a crash wall model to quantify damage profile of the wall panels due to a vehicular impact on the crash wall as shown in Figure 4.1(b). Two different methods were used to represent the interaction between the wall panels and a crash wall. Contact definition is used in one model; embedded anchors are used for the other model.



(a) FE Model of a typical MSE wall

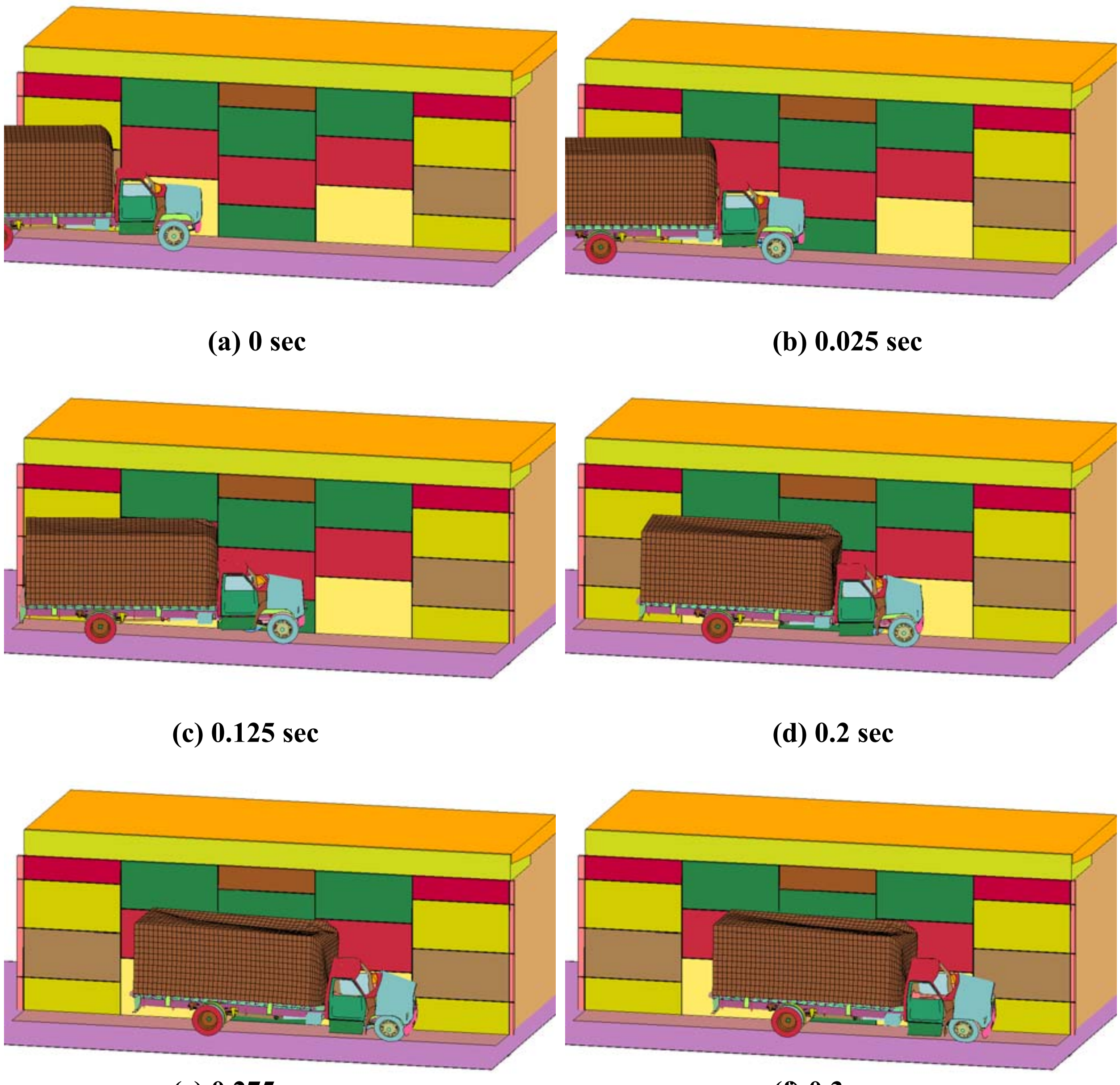


(b) FE Model of an MSE wall with a crash wall

Figure 4.1 Set-up of MSE wall models

4.1. A TYPICAL MSE WALL MODEL

The finite element model of a typical MSE wall is developed to quantify damage profile of the wall panels during a direct vehicular impact as a reference case. Figure 4.2 shows the sequential images of the overall impact event between the vehicle and the MSE wall. There are three component impact points at 0.025 sec by the front left bumper, at 0.12 sec by the front left side of truck box, and at 0.27 sec by the rear left side of truck box. After 0.2 sec, the vehicle began to travel parallel with the MSE wall panels. After 0.35 sec, no more interactions between the crash wall and the vehicle were observed.



(a) 0 sec

(b) 0.025 sec

(c) 0.125 sec

(d) 0.2 sec

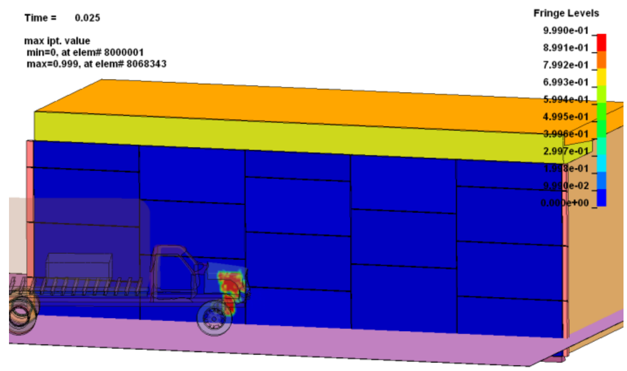
(e) 0.275 sec

(f) 0.3 sec

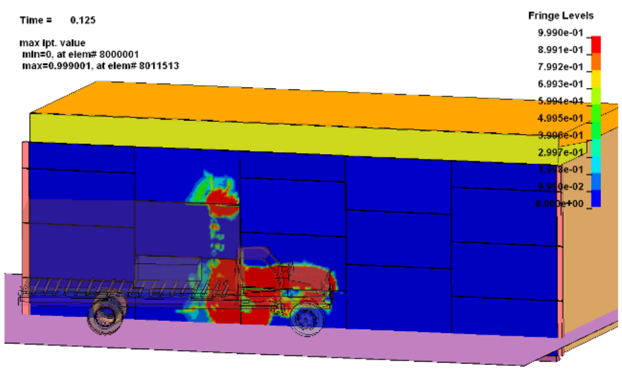
Figure 4.2 Sequential images of SUT impacting a typical MSE wall (case 1)

Figure 4.3 shows the images of the damage profile on the wall panels. The fringes shown in Figure 4.3 depict the damage profile of the panel elements on a scale from 0 to 1 where the value 0 indicates no damage and the value 1 indicates total damage (i.e., the element is not capable of carrying load). A total of nine panels show severe damage profile due this impact.

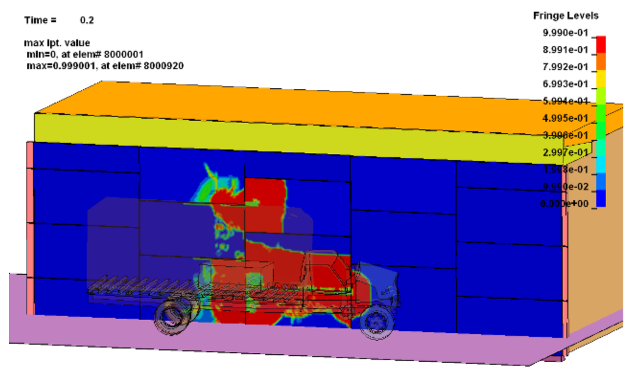
(a) 0 sec



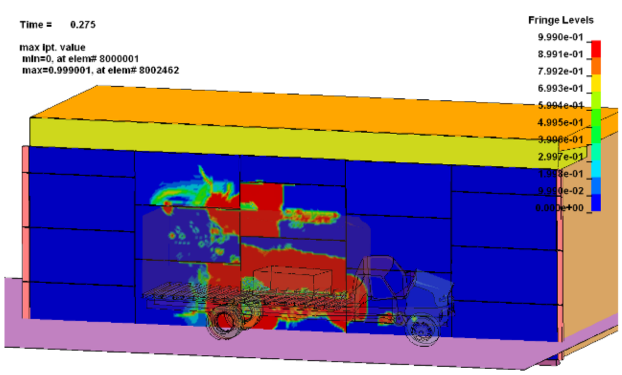
(b) 0.025 sec



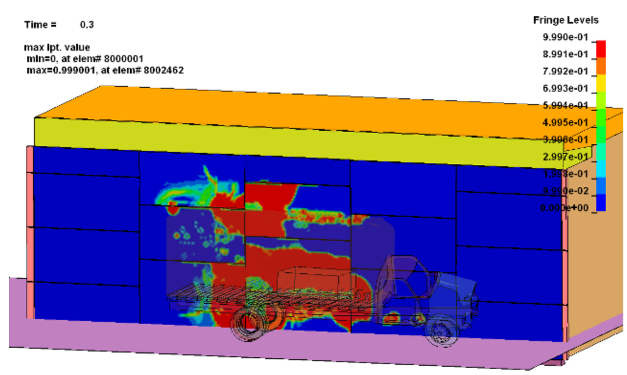
(c) 0.125 sec



(d) 0.2 sec



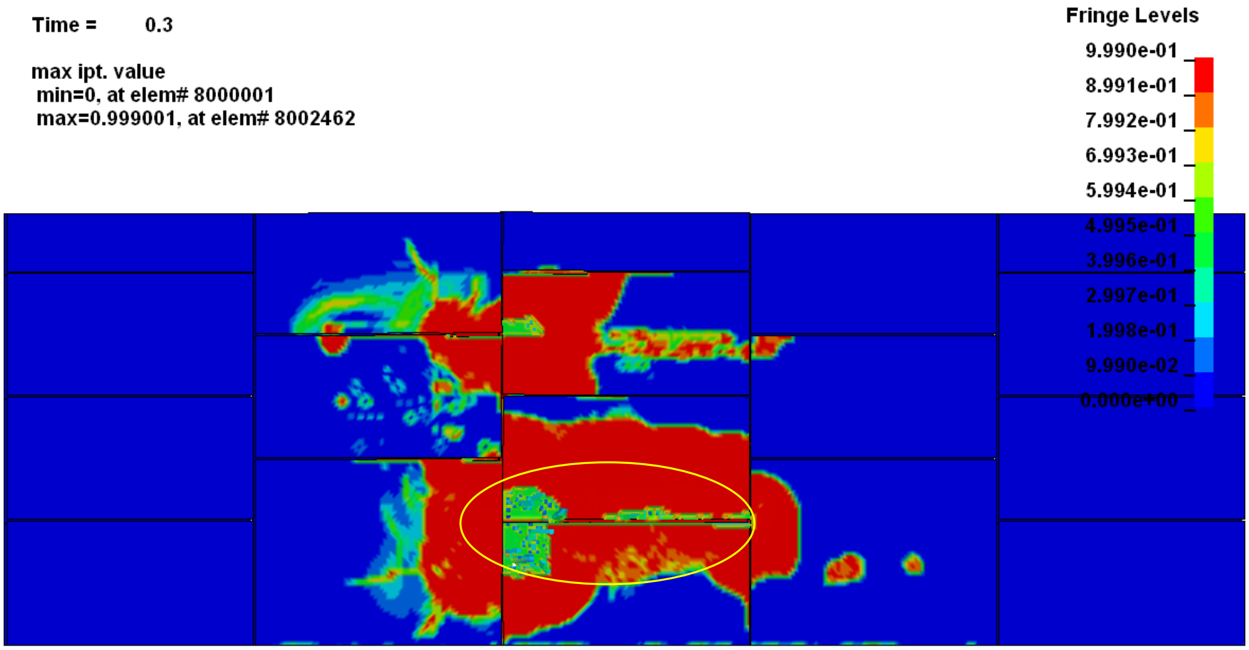
(e) 0.275 sec



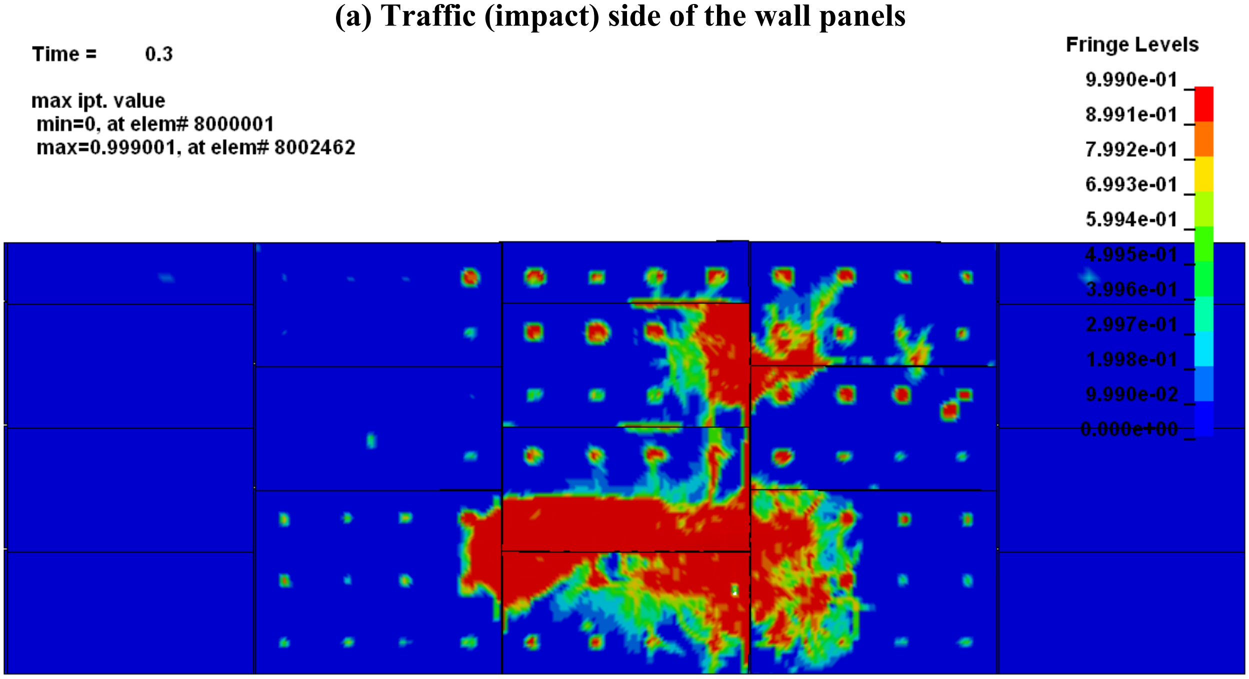
(f) 0.3 sec

Figure 4.3 Damage profile on MSE wall panel during an impact (case 1)

Since the eroding concrete material was used for the MSE wall panels, some elements of the wall panels were removed in the severely damaged areas (circled in Figure 4.4[a]). Since the steel strips are tied with the wall panels, the damage profile around the steel strips connectors location were also observed on the backfill side of the wall panels as shown in Figure 4.4(b).



(a) Traffic (impact) side of the wall panels



(b) Backfill side of the wall panels

Figure 4.4 Damage profile of the wall panels (case 1)

The impact force was obtained from the contact definition between the panels and the vehicle as shown in Figure 4.5. The peak forces for each component impact point were 326 kN (73.3 kips) by the front left bumper at 0.025 sec, 584 kN (131.3 kips) by the front left side of truck box at 0.12 sec, and 596.9 kN (134.2 kips) by the rear left side of truck box at 0.27 sec.

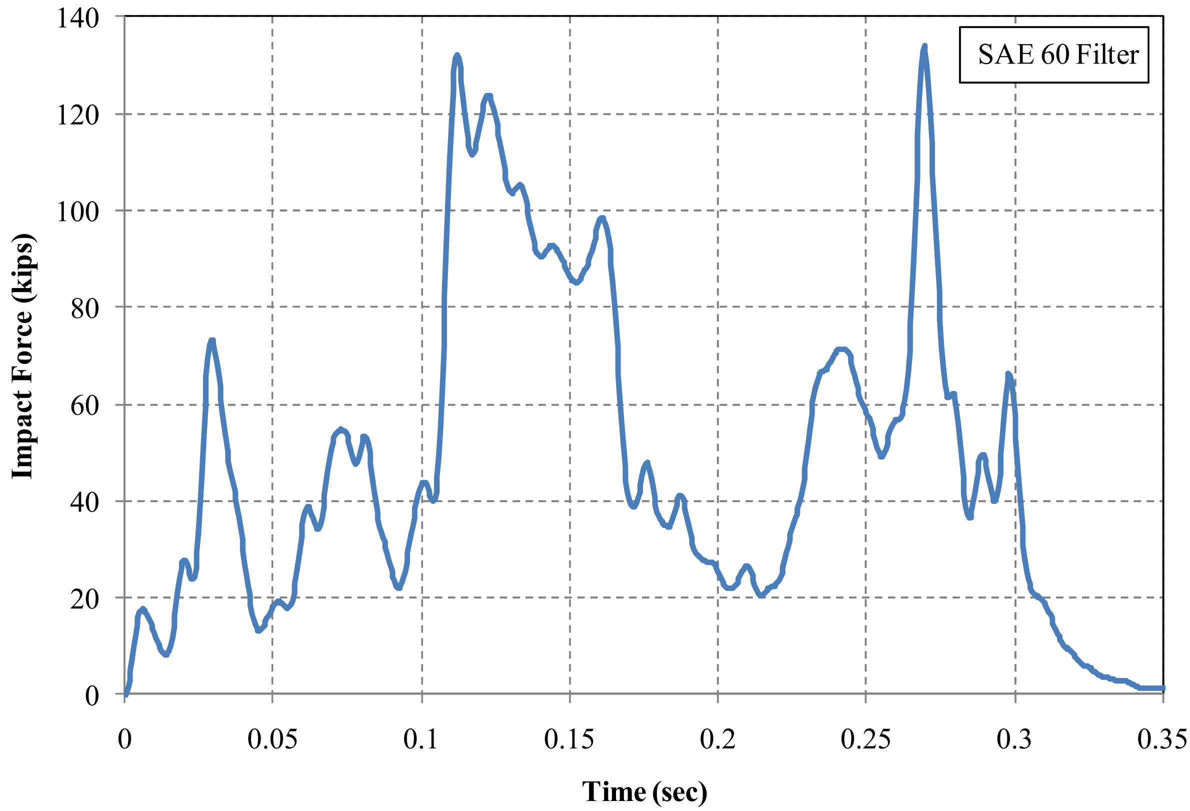
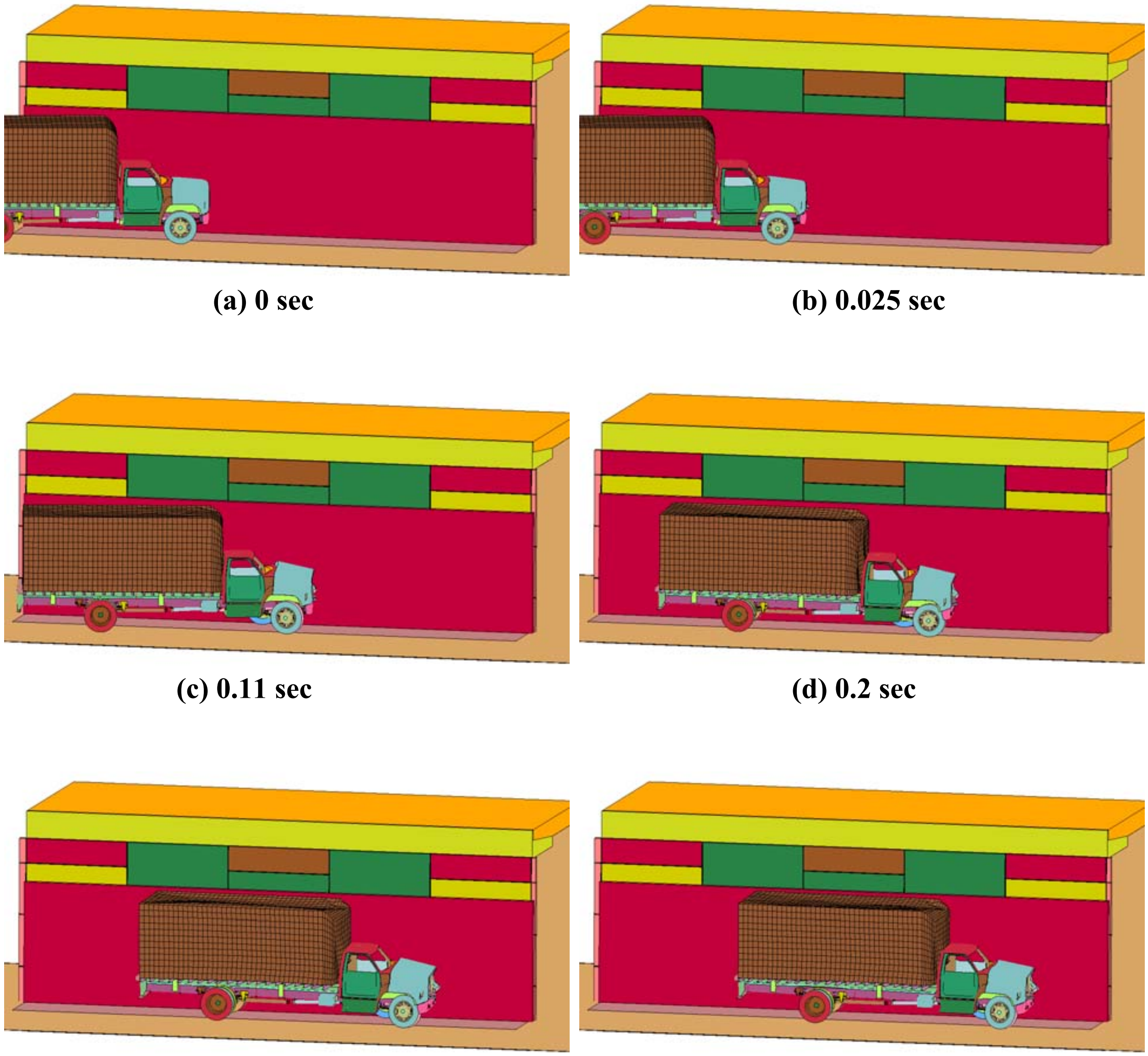


Figure 4.5 Impact force from the contact definition (case 1)

4.2. A MSE WALL MODEL INCLUDING A CRASH WALL

The crash wall is placed in the front of the wall panels to protect the panels from being damaged by vehicular impact in the model. The 15.09 m (49.5 ft) long × 4 m (13.1 ft) tall × 203.2 mm (8 in.) thick crash wall was incorporated as shown in Figure 4.6. In this case, the interaction between the crash wall and the wall panels was represented using a contact definition. Figure 4.6 shows the sequential images of the overall impact event between the vehicle and the crash wall. Similar to previous case, there are three component impact points at 0.025 sec by the cab bumper, at 0.11 sec by the front side of truck box, and at 0.24 sec by the rear side of truck box. After 0.2 sec, the vehicle began to travel parallel with the MSE wall panels. After 0.35 sec, no more interactions between the crash wall and the vehicle were observed.



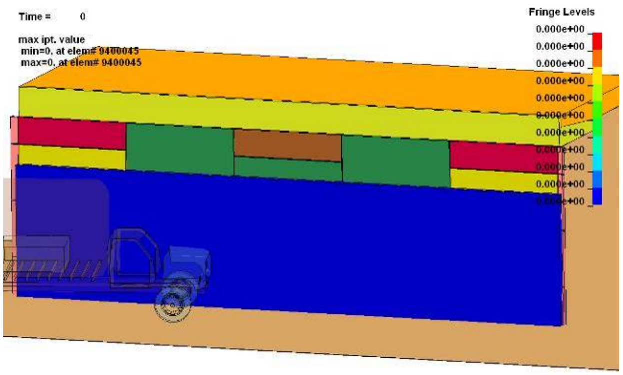
(a) 0 sec **(b) 0.025 sec**

(c) 0.11 sec **(d) 0.2 sec**

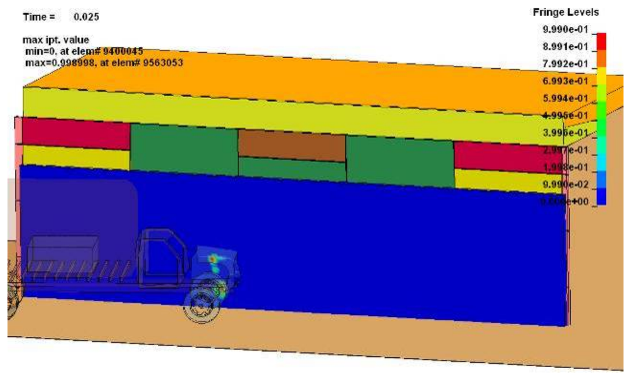
(e) 0.24 sec **(f) 0.3 sec**

Figure 4.6 Sequential images of SUT impacting a crash wall (case 2)

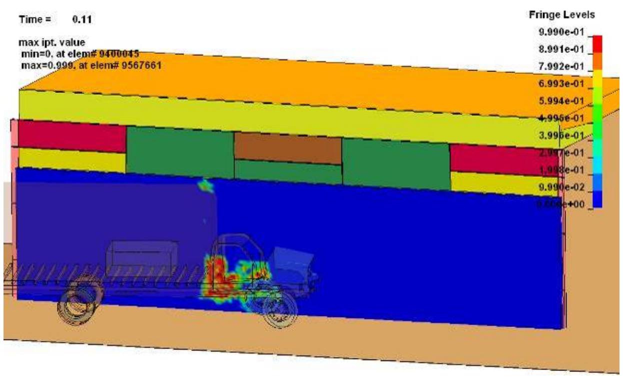
Figure 4.7 shows the images of the damage profile on the wall panels. The damage fringes depict the damage of the panel elements on a scale from 0 to 1 where the value 0 indicates no damage and the value 1 indicates total damage (i.e., the element is not capable of carrying load). The crash wall exhibited a damage profile around key component impact areas but no elements were eroded as observed in the case of direct impact on wall panels. Overall, the crash wall exhibited less area of damage than the wall panels in the direct impact case.



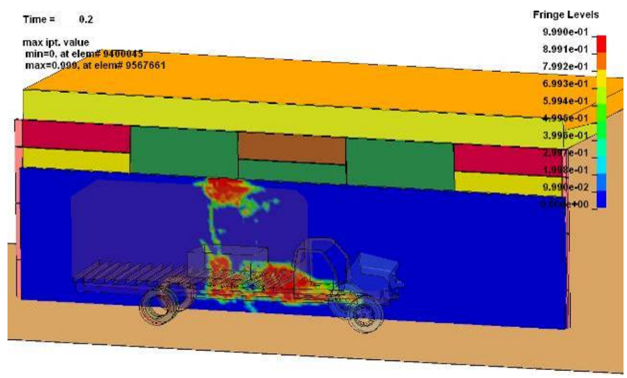
(a) 0 sec



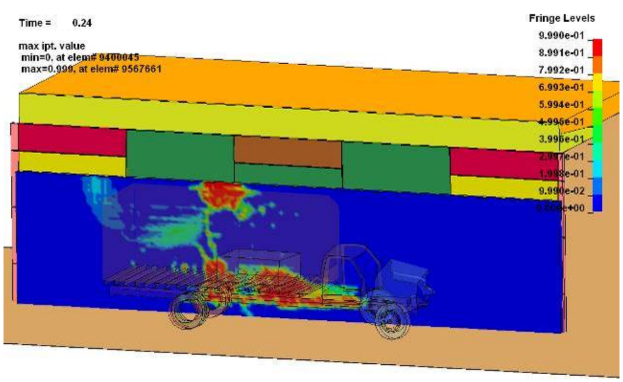
(b) 0.025 sec



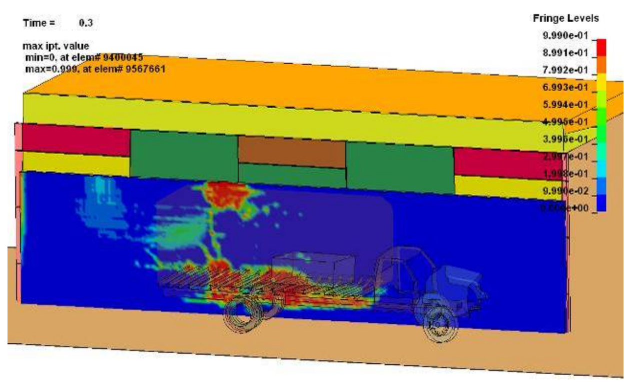
(c) 0.11 sec



(d) 0.2 sec



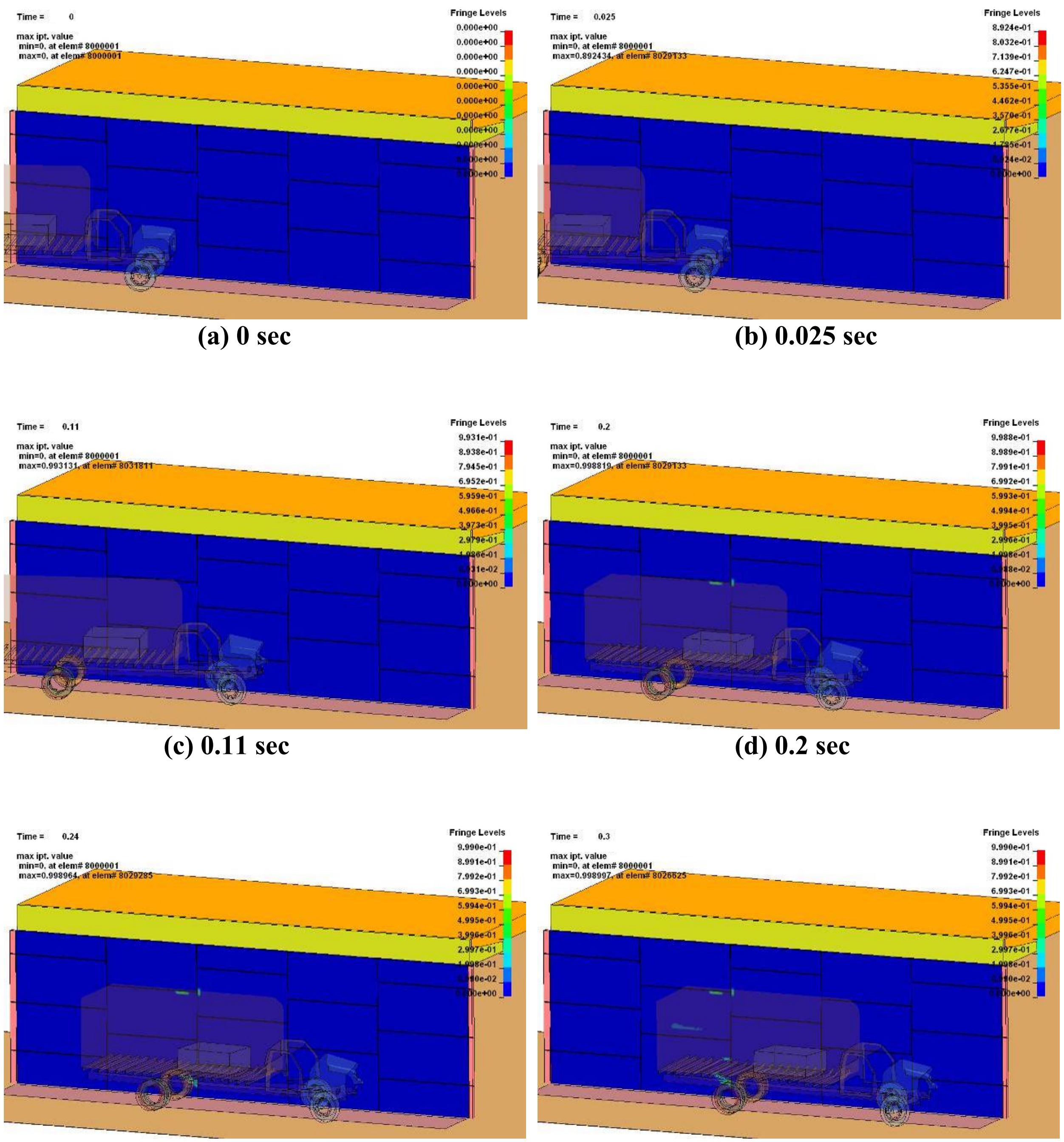
(e) 0.24 sec



(f) 0.3 sec

Figure 4.7 Damage profile on crash wall during an impact (case 2)

Moreover, the damage profile on the wall panels themselves was significantly reduced to very minimal as shown in Figure 4.8.



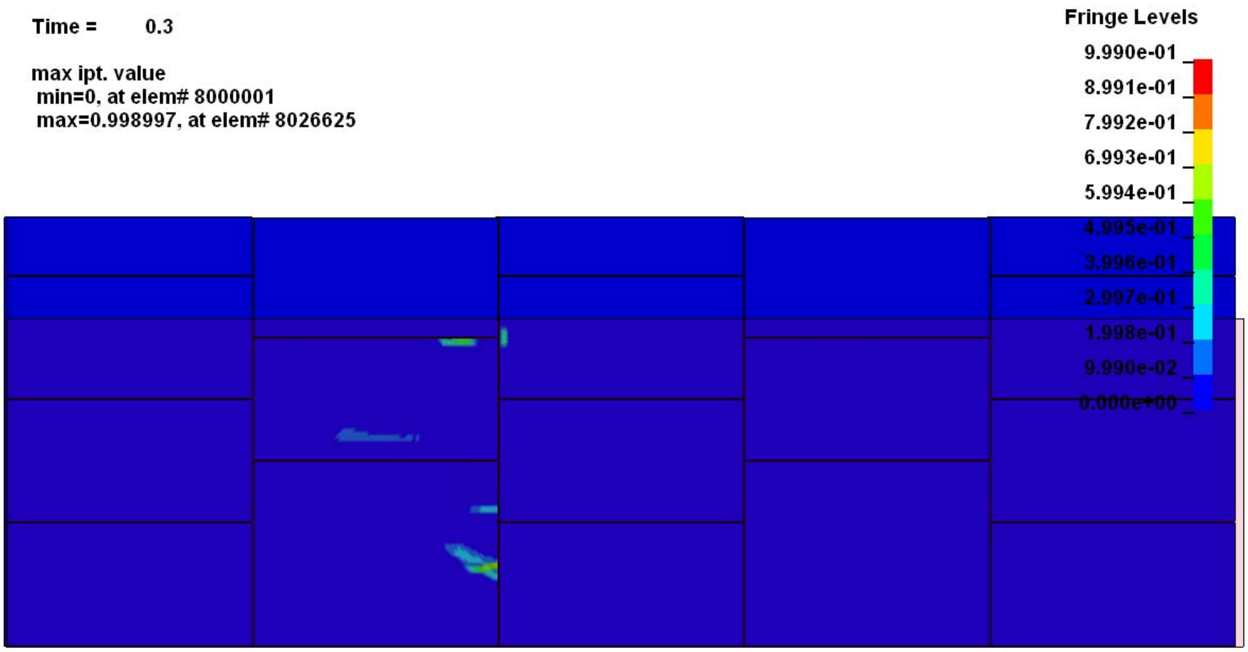
(a) 0 sec **(b) 0.025 sec**

(c) 0.11 sec **(d) 0.2 sec**

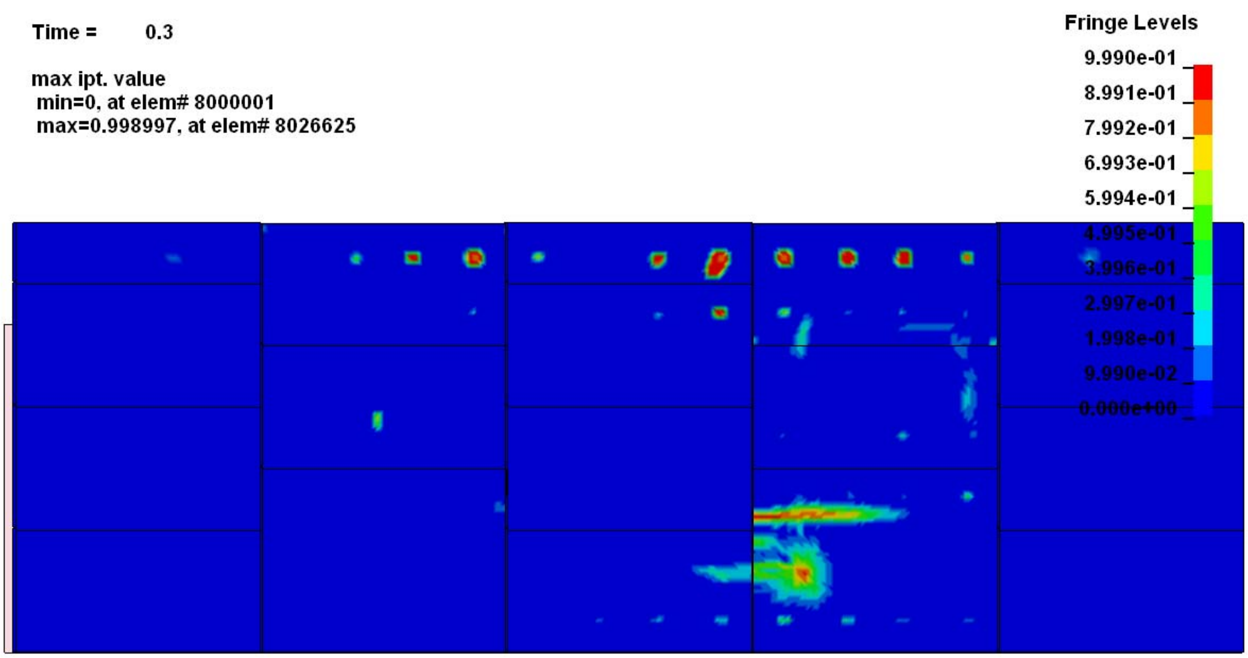
(e) 0.24 sec **(f) 0.3 sec**

Figure 4.8 Damage profile on MSE wall panel during an impact (case 2)

Figure 4.9 shows the damage profiles of the traffic side and backfill side of the wall panels at 0.3 sec. A total of three panels shows some minor damage profile in traffic side of the wall panels. Damages in backfill side of the wall panels were observed at the location of the steel wall strip connectors to the panels.



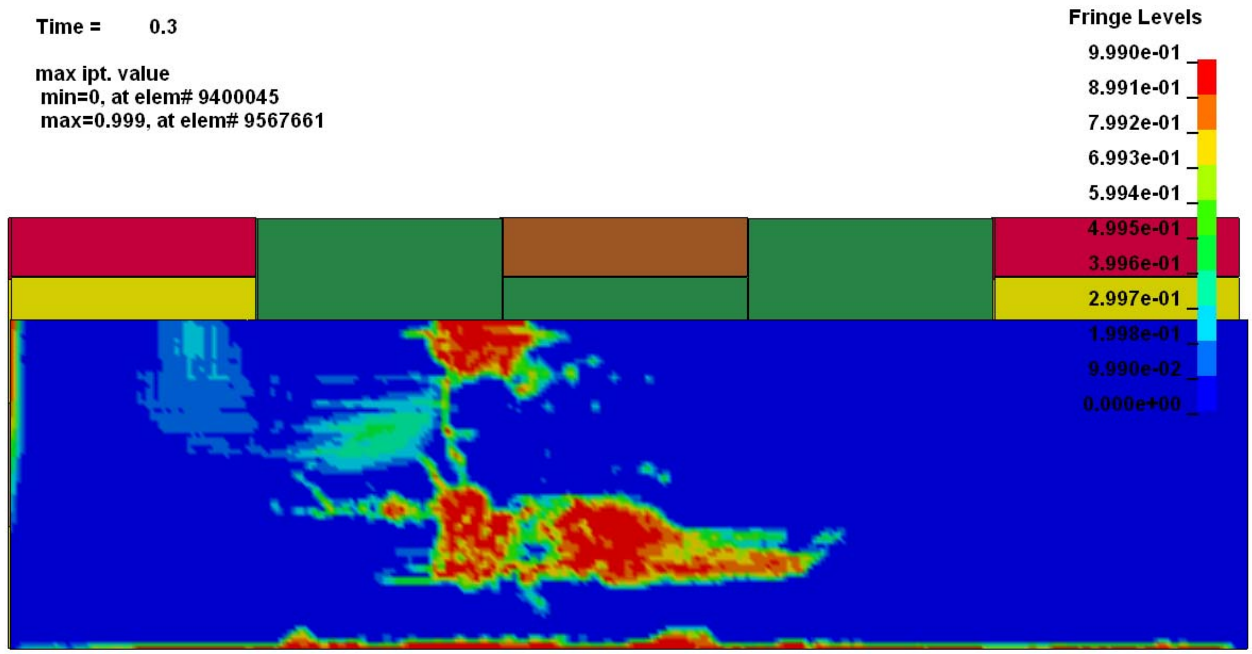
(a) Traffic (impact) side of the wall panels



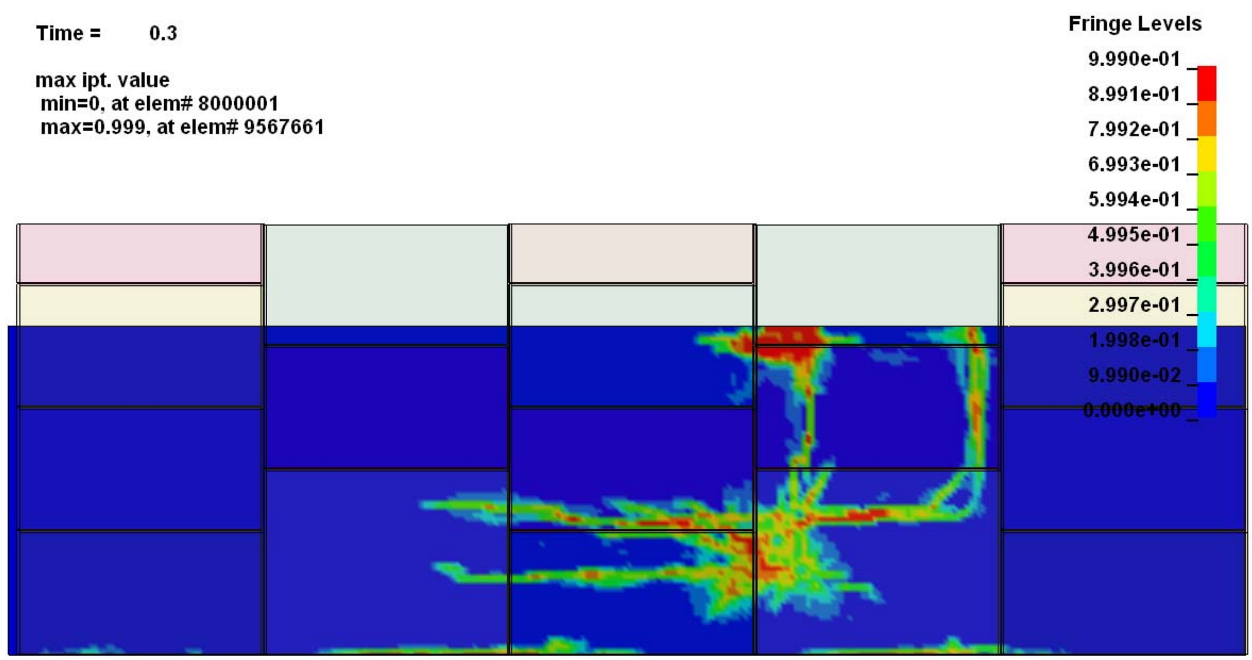
(b) Backfill side of the wall panels

Figure 4.9 Damage profile of the wall panels (case 2)

Figure 4.10 shows the damage profile of the traffic side and backfill side of the crash wall at 0.3 sec. The crash wall damage profile became smaller as it propagates to the back side of the crash wall as shown in Figure 4.10 (a) and (b).



(a) Traffic (impact) side of the crash wall



(b) Back side of the crash wall

Figure 4.10 Damage profile of the crash wall (case 2)

The impact force filtered using SAE 60 was obtained from the contact definition between the panels and the vehicle as shown in Figure 4.11. The peak forces for each component impact point were 421.6 kN (94.8 kips) by the front left bumper at 0.025 sec, 574.7 kN (129.2 kips) by the front left side of truck box at 0.11 sec, and 1,476.4 kN (331.9 kips) by the rear left side of truck box at 0.24 sec.

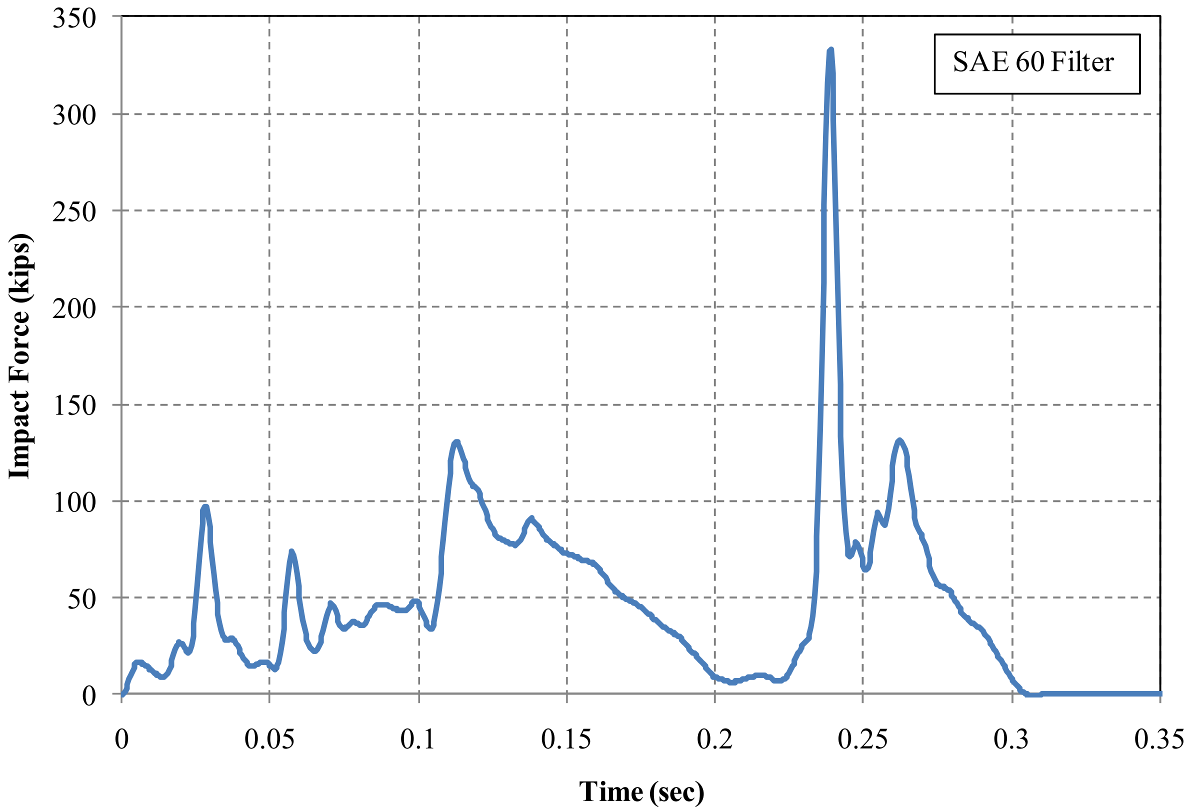
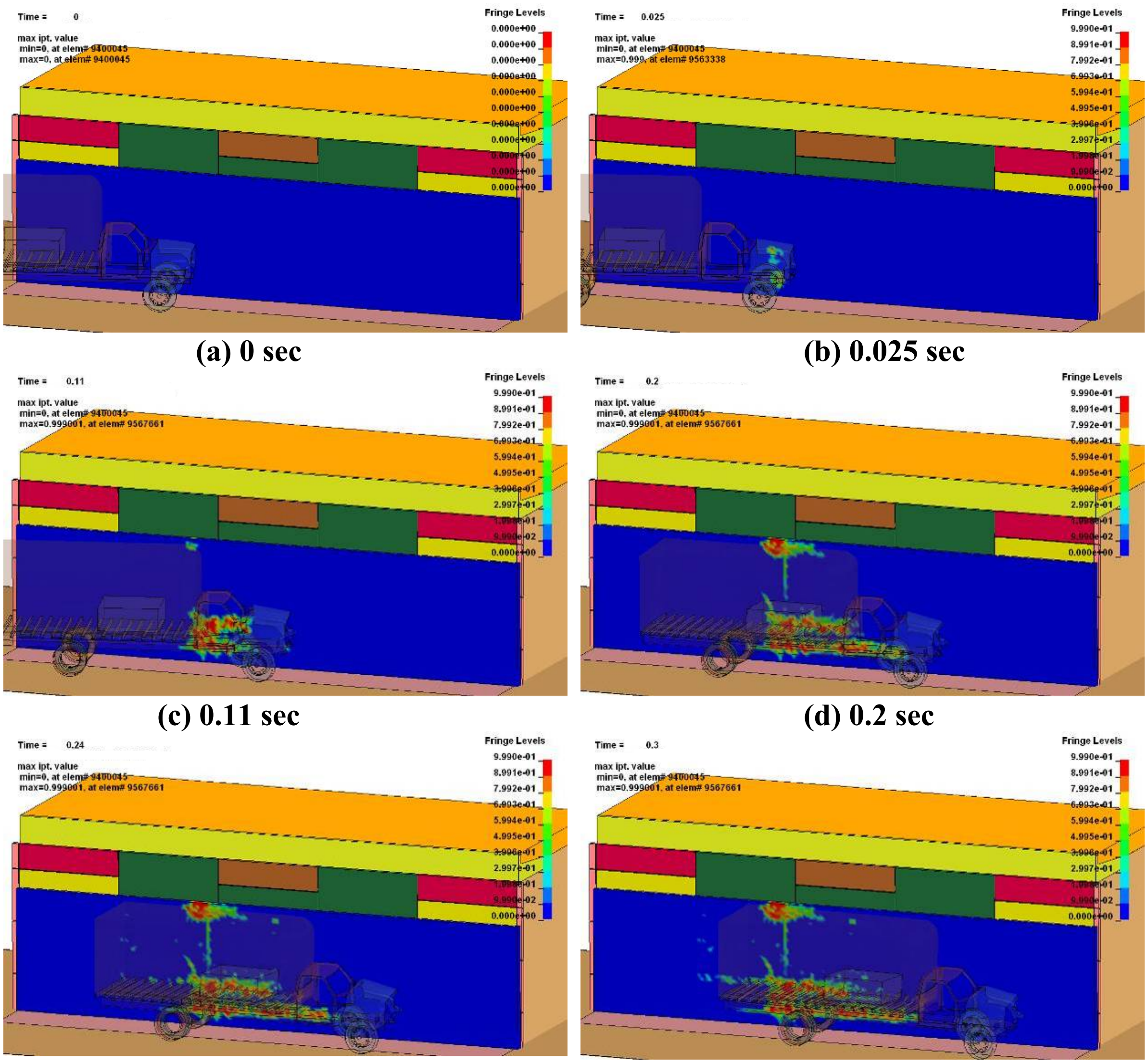


Figure 4.11 Impact force from the contact definition (case 2)

4.3. A MSE WALL MODEL INCLUDING A CRASH WALL AND ANCHORS

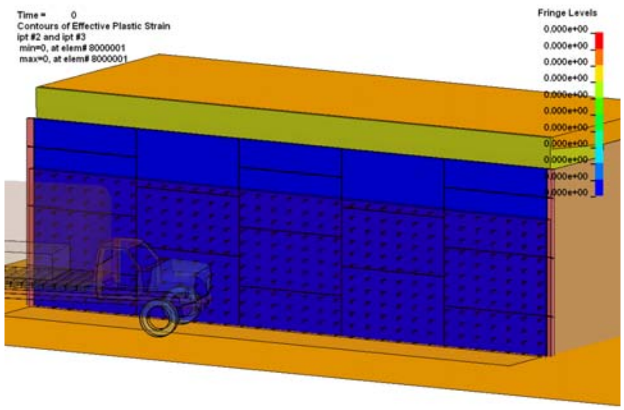
The interaction between the crash wall and the wall panels was represented using an embedded anchor. The general phenomena during an impact against the crash wall are similar to the simulation results without anchors. Similar to the previous case, there are three component impact points at 0.025 sec by the bumper, at 0.11 sec by the front left side of truck box, and 0.24 sec by the rear side of truck box. After 0.2 sec, the vehicle began to travel parallel with the MSE wall panels. After 0.35 sec, no more interactions between the crash wall and the vehicle were observed.

Figure 4.12 shows the images of the damage profile on the wall panels. The damage fringes depict the damage of the panel elements on a scale from 0 to 1 where the value 0 indicates no damage and the value 1 indicates total damage (i.e., the element is not capable of carrying load). Figure 4.13 shows the sequential images of the damages on the wall panels.

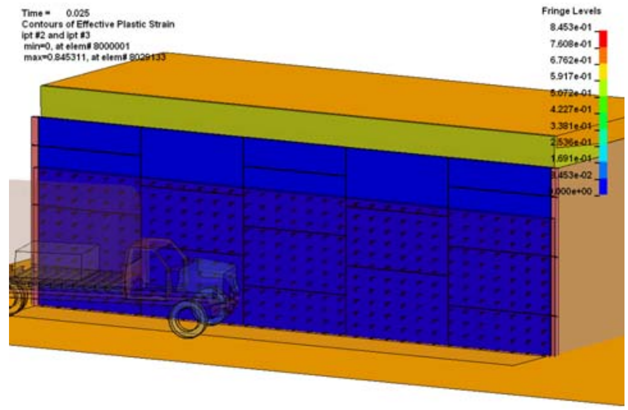


(a) 0 sec (b) 0.025 sec
(c) 0.11 sec (d) 0.2 sec
(e) 0.24 sec (f) 0.3 sec

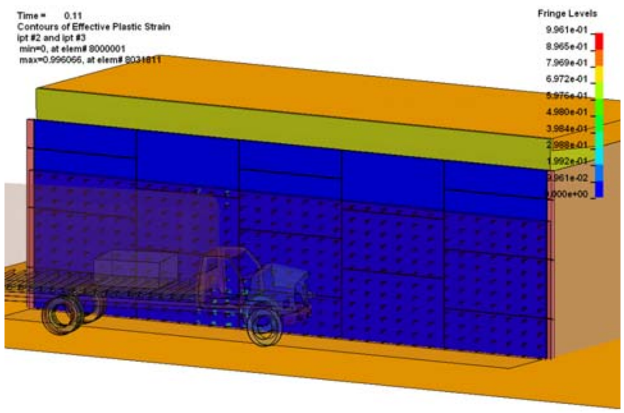
Figure 4.12 Damage profile on crash wall during an impact (case 3)



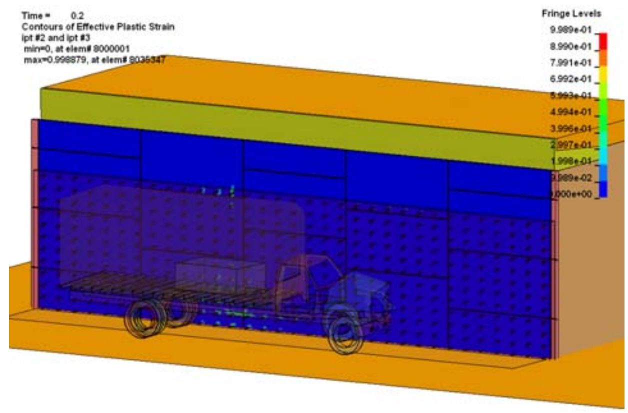
(a) 0 sec



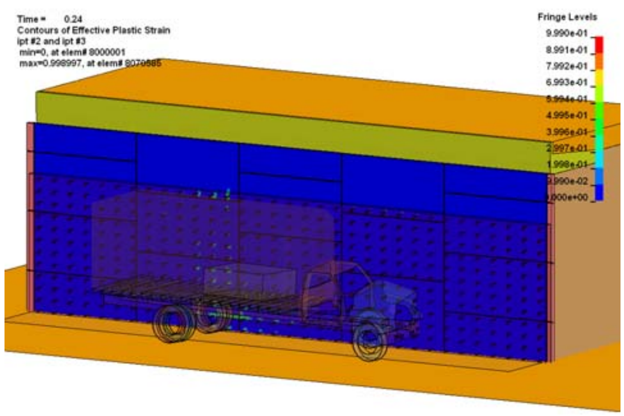
(b) 0.025 sec (first hit)



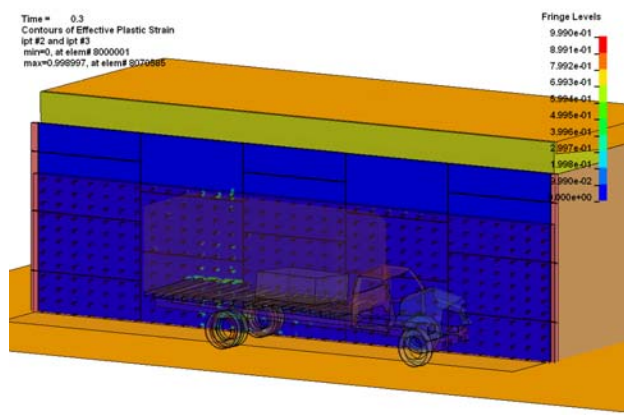
(c) 0.11 sec



(d) 0.2 sec



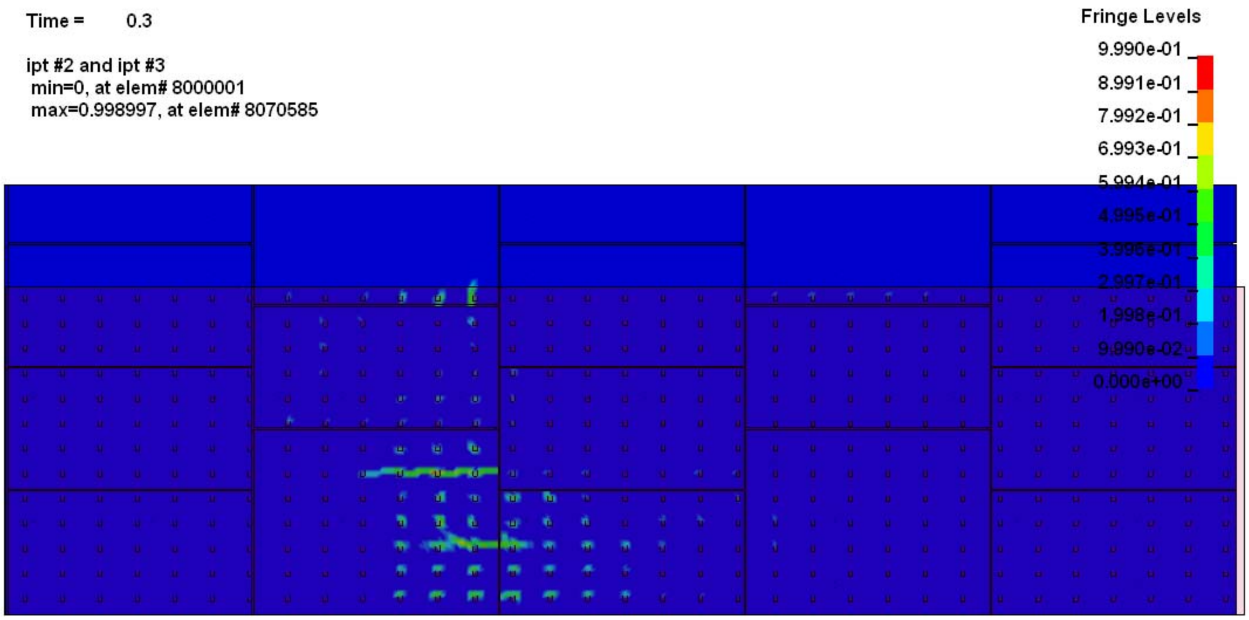
(e) 0.24 sec



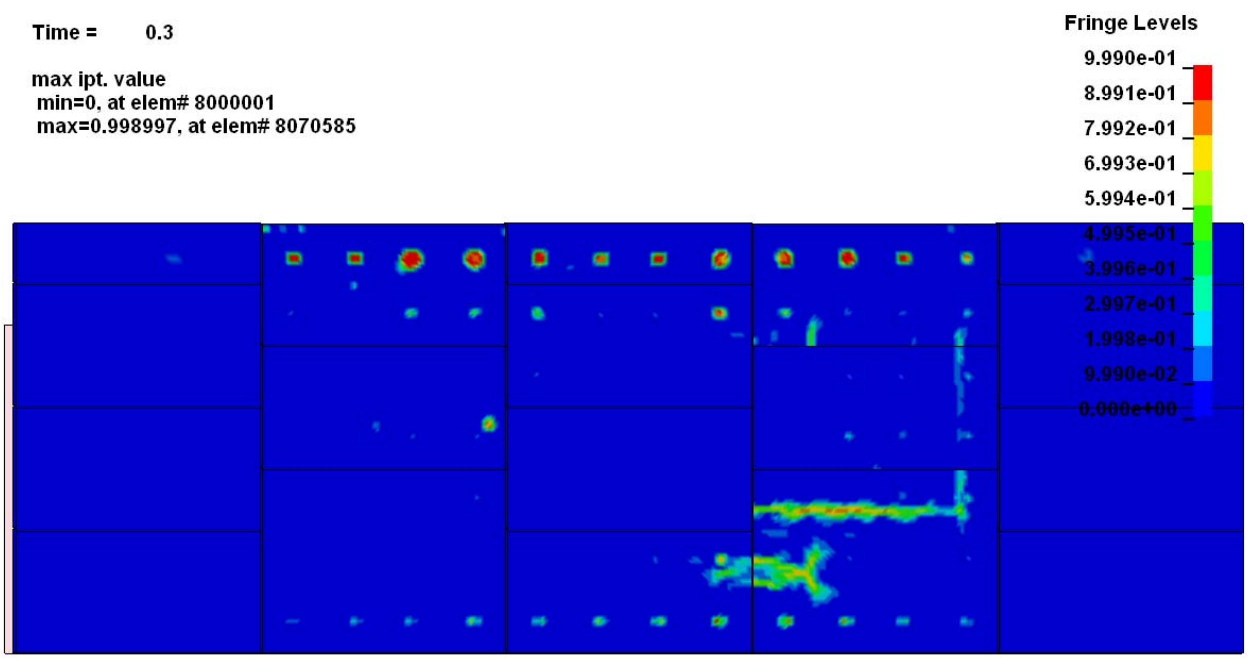
(f) 0.3 sec

Figure 4.13 Damage profile on MSE wall panel during an impact (case 3)

Figure 4.14 shows the damage profiles of the traffic side and inside of the wall panels at 0.3 sec. It is evident that the presence of the crash wall significantly reduced the damage to the wall panels.



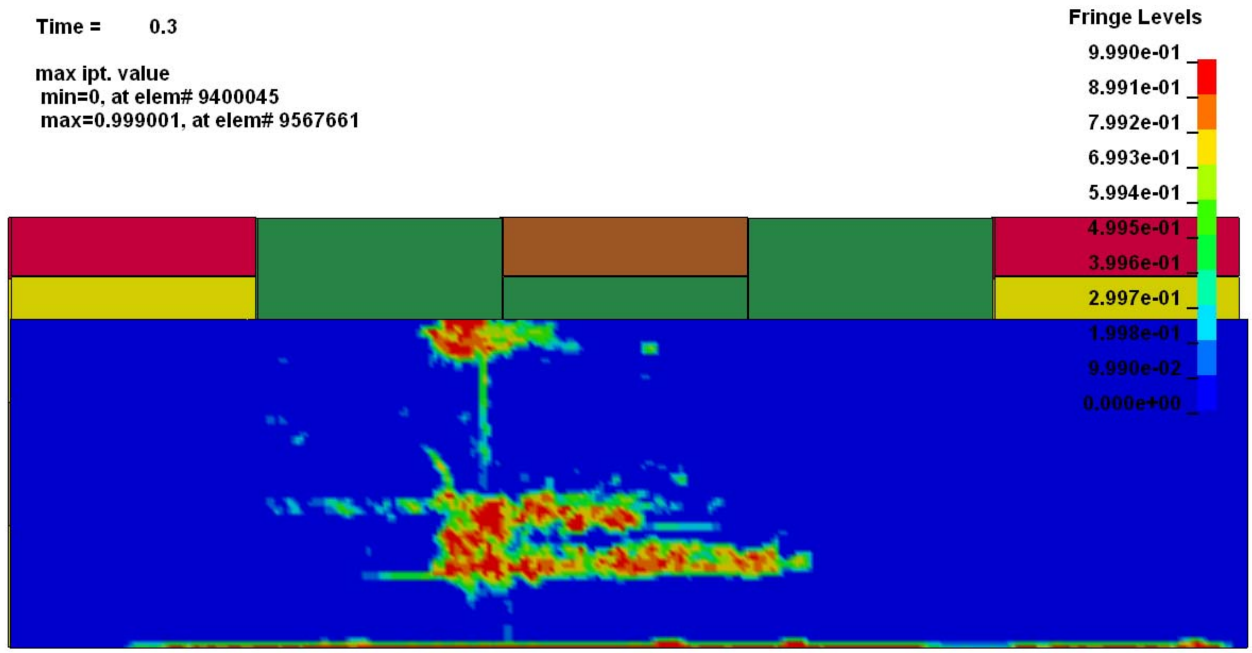
(a) Traffic (impact) side of the wall panels (red is the anchors)



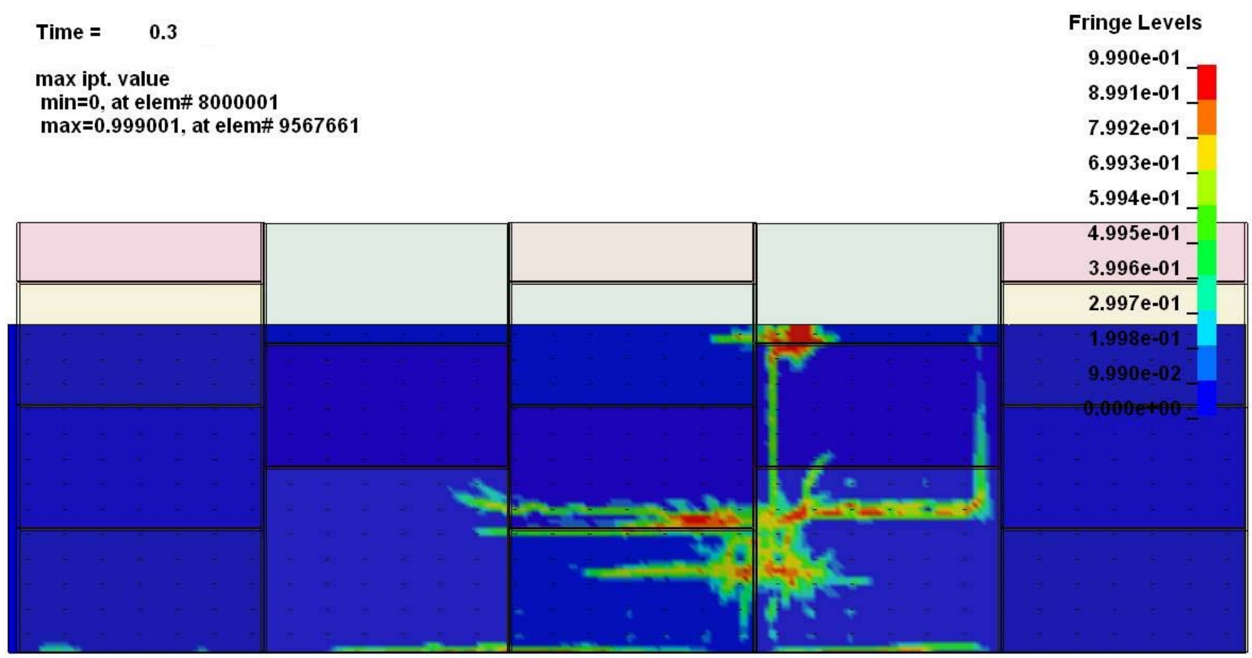
(b) Backfill side of the wall panels

Figure 4.14 Damage profile of the wall panels (case 3)

Figure 4.15 shows the damage profiles of the traffic side and the inside face of the crash wall. The damage profile is similar to the damage profile of the crash wall impact simulation without using anchors.



(a) Traffic (impact) side of the crash wall



(b) Back side of the crash wall

Figure 4.15 Damage profile of the crash wall (case 3)

The impact force was obtained from the contact definition between the panels and the SUT vehicle as shown in Figure 4.16. The maximum impact forces of three hitting moments were 448.8 kN (100.9 kips) by the bumper at 0.027 sec, 579.6 kN (130.3 kips) by the front left side of truck box at 0.11 sec, and 1,611 kN (362.2 kips) by the rear left side of truck box at 0.24 sec.

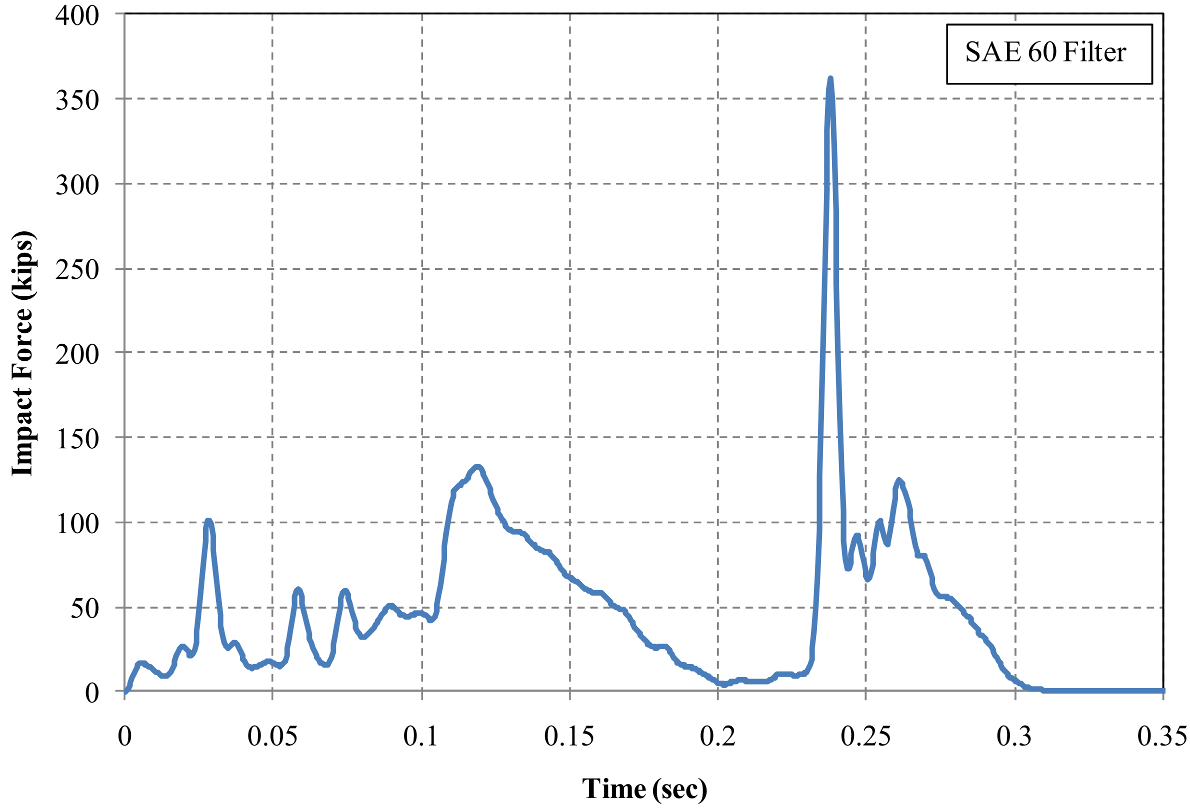


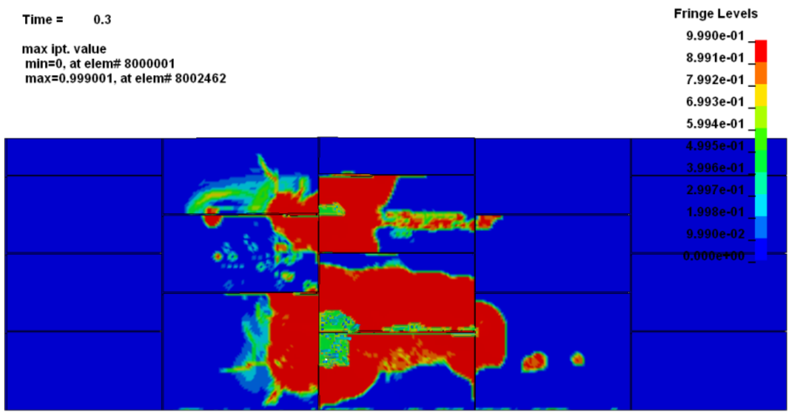
Figure 4.16 Impact force from the contact definition (case 3)

4.4. COMPARISON OF SIMULATIONS

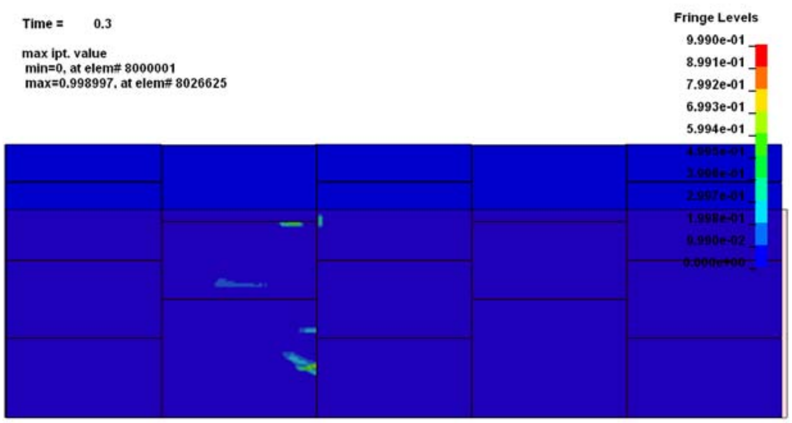
The damage profile distribution was reviewed in an impact side and back side of the wall panels and the crash wall to investigate the impact response of the wall panels for three models: (1) a typical MSE wall, (2) an MSE wall with a crash wall, and (3) an MSE wall with a crash wall and anchors.

4.4.1 Impact Side

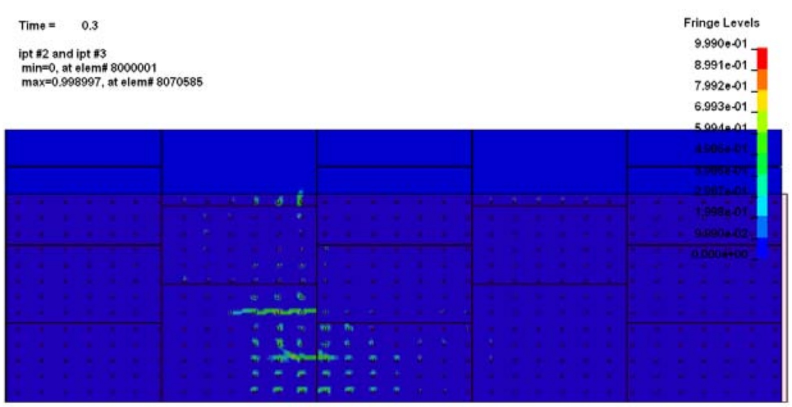
The wall panels exhibited significant damage once impacted by the 10000S vehicle as shown in Figure 4.17(a). This indicates that the panels alone cannot resist direct impact of such severity. However, a 0.2 m (8 in.) thick continuous crash wall is added in front of the panels, the panels exhibited minor damage profile as shown in Figure 4.17(b). Similarly, in the case of an MSE wall with a crash wall and anchors, the panels exhibited minor damage profile as shown in Figure 4.17(c).



(a) Case 1: A typical MSE wall



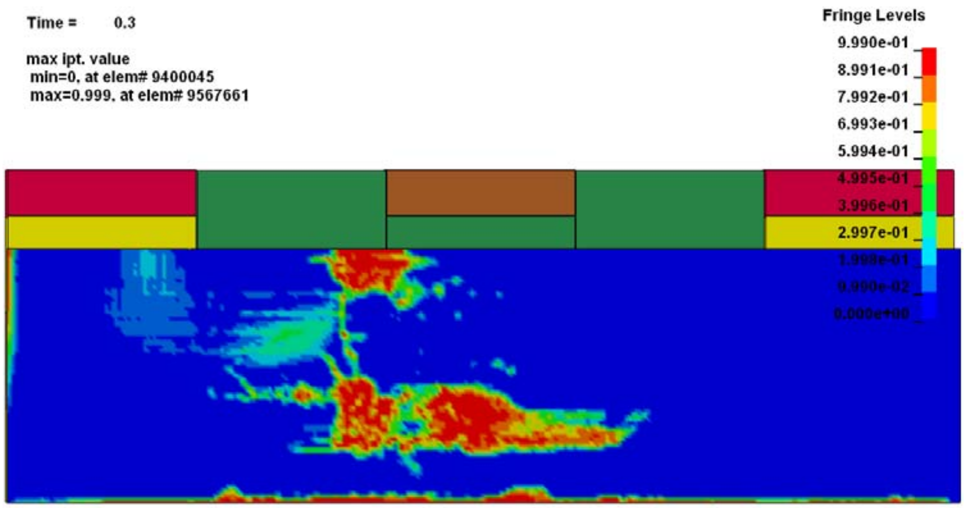
(b) Case 2: Model with the crash wall



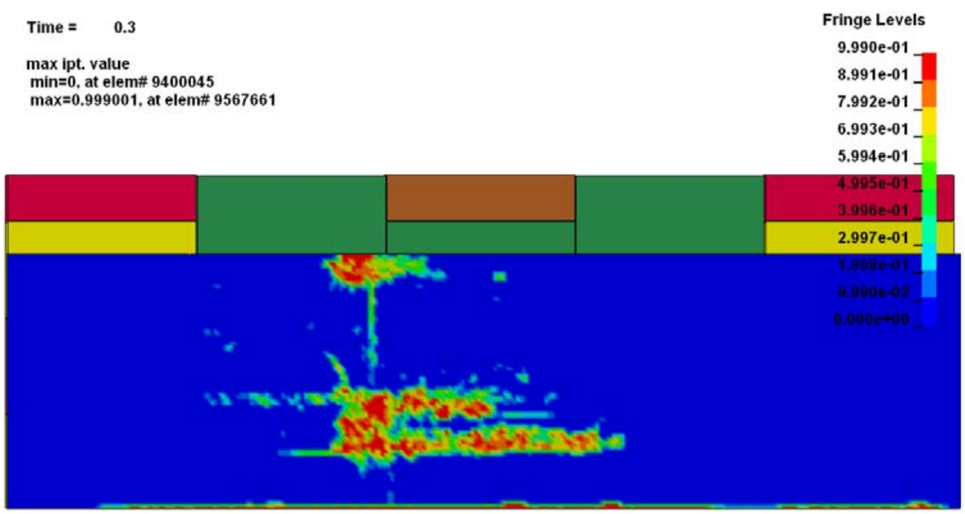
(c) Case 3: Model with the crash wall and anchors

Figure 4.17 Comparison of damage profile on the wall panels (Impact side)

The damage moved to the crash wall instead of the panels as expected. However, this damage on the crash wall is spread over a smaller surface area of the crash wall than the damaged area of the panels when impacted directly. This is observed from comparing Figure 4.18(a) with Figure 4.17(a). Moreover, adding the anchors reduced the damaged area to the crash wall as shown in Figure 4.18(b) with respect to Figure 4.18(a).



(a) Case 2: Model with the crash wall

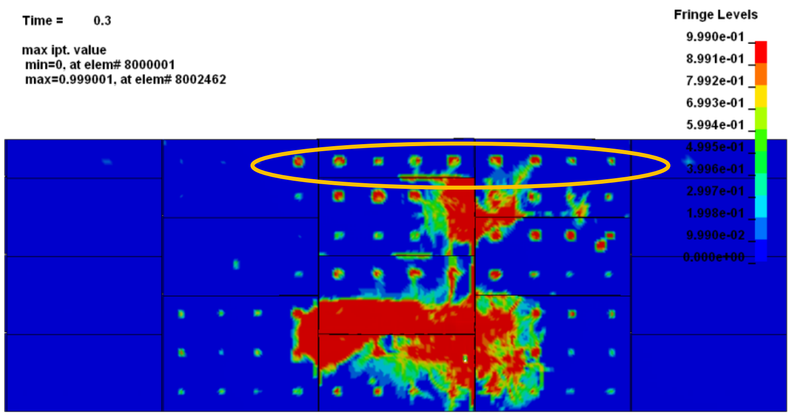


(b) Case 3: Model with the crash wall and anchors

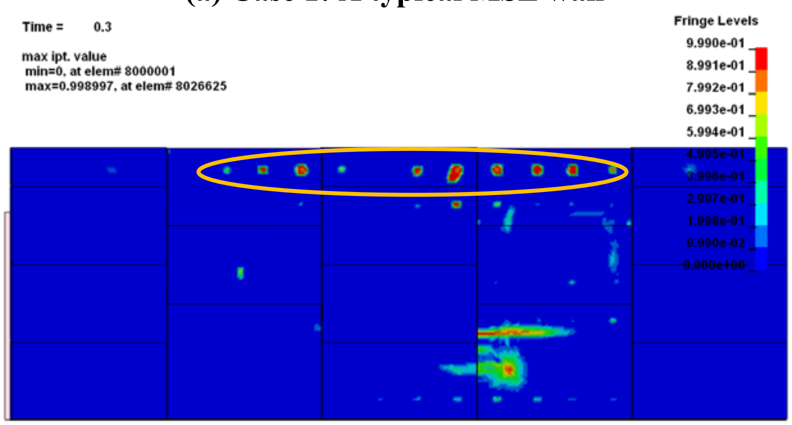
Figure 4.18 Comparison of damage profile on the crash wall (Impact side)

4.4.2 Inside of the Wall or Crash Wall

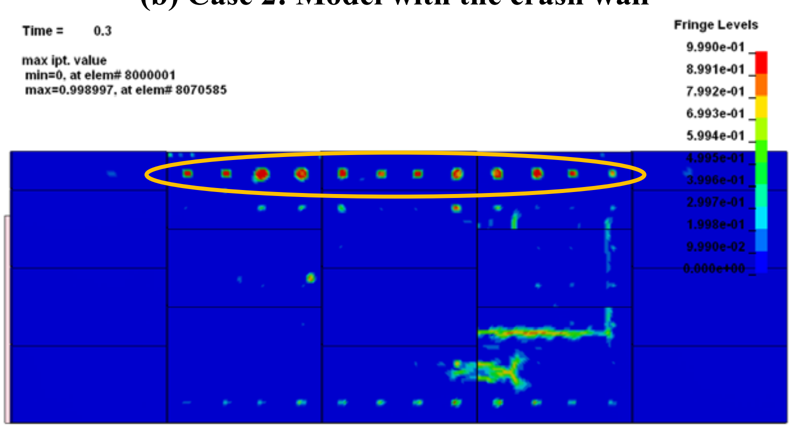
Figure 4.19(a) depicts the propagation of damage from direct impact on the MSE wall panels. Figure 4.19 shows the comparison of the damage profile on the inside (backfill interface) of the MSE wall panels. This reinforces the findings that the panels alone cannot resist direct impact of such severity. However, once a 0.2 m (8 in.) thick continuous crash wall is added in front of the panels, the panels exhibited minor damage profile as shown in Figure 4.17(b) and (c).



(a) Case 1: A typical MSE wall



(b) Case 2: Model with the crash wall



(c) Case 3: Model with the crash wall and anchors

Figure 4.19 Comparison of damage profile on the wall panel (Inside)

Since the steel strips are tied with the wall panels, the damage profile was also observed around the steel strips connectors' location (see the ellipses in Figure 4.19). The damage fringes shown in Figure 4.19 describe the relative damage for each case on a scale from 0 to 1. In order to quantify the intensity of damage profile, the vertical movement of top of the wall panels on each case was analyzed as shown in Figure 4.20. In the first case of a typical MSE wall model, the vertical displacement was 13.5 mm (0.53 in.) at 0.31 sec due to the direct impact. In the other two cases the top panel had a vertical displacement that is less than 1 mm (0.04 in.). It is believed that a larger panel displacement would result in bigger damage around the connector location. The connector attachment to the concrete panel has more flexibility than the tied behavior used in this model. Hence, these localized damage patterns might be less in physical testing.

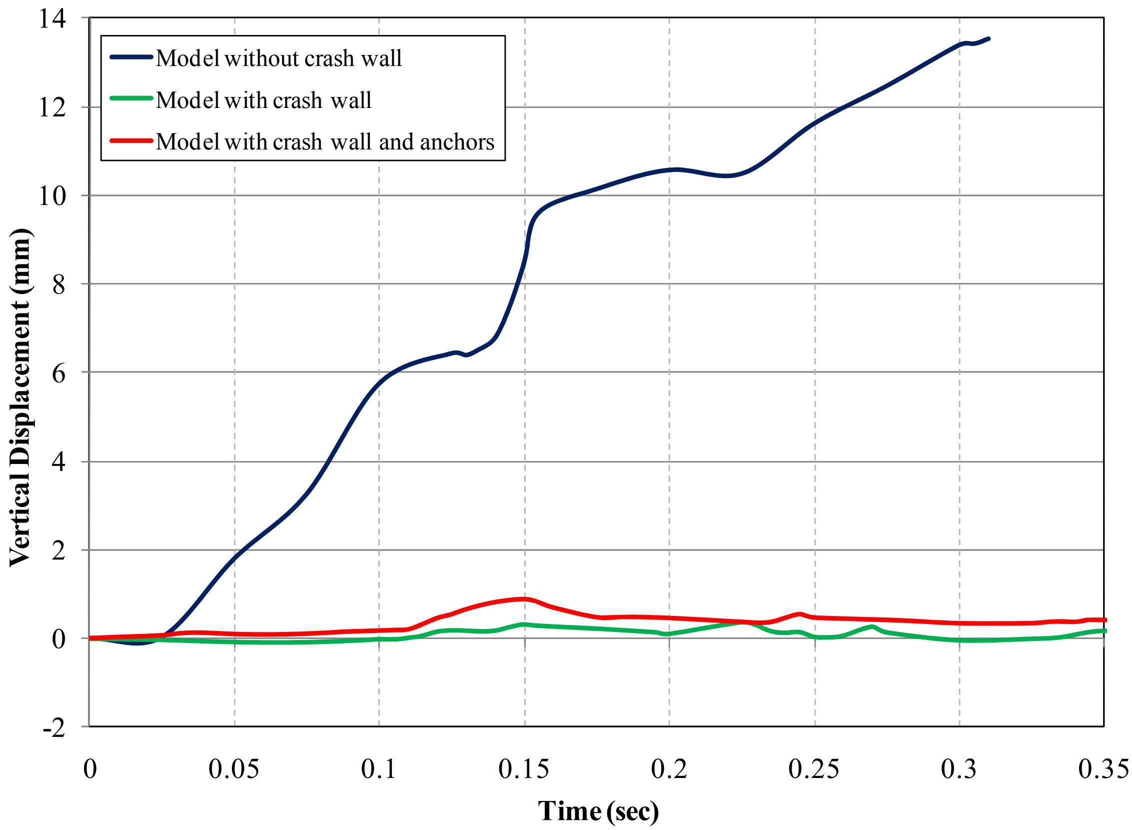
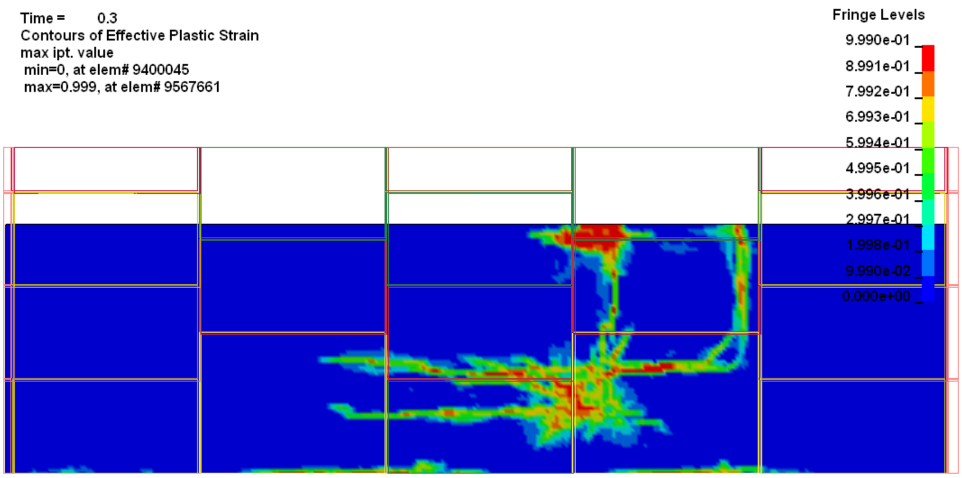
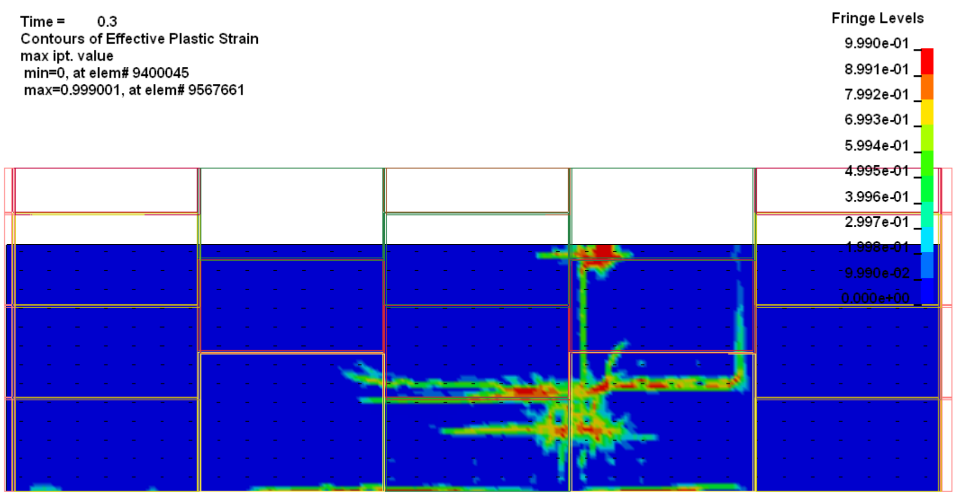


Figure 4.20 Comparison of vertical displacement on the top panel

The damage profile on the inside (panel interface) of the crash wall (Figure 4.21) exhibits less damaged area than the damage profile on impact side (see Figure 4.18). This is expected since damage will become less as we move away from the impact surface.



(a) Case 2: Model with the crash wall



(b) Case 3: Model with the crash wall and anchors

Figure 4.21 Comparison of damage profile on the crash wall (Inside)

5. SUMMARY AND CONCLUSION

This study was undertaken to evaluate the impact response of a crash wall design installed in front of MSE wall panels. A 0.2 m (8 in.) thick crash wall is shown to significantly reduce the damage to the wall panels due to the Single Unit Truck (SUT) impact.

In order to evaluate the crash wall design on the MSE wall, three MSE wall models (cases) were developed herein: (1) a typical MSE wall structure, (2) the same MSE wall with a crash wall, and (3) the same MSE wall with a crash wall that is tied with anchors to the panels. These models have explicit representation of the backfill soil, the concrete panels, the moment slab, the barrier and coping, and the crash wall for cases 2 and 3. Concrete steel reinforcement and soil steel strips were modeled as well and their connectivity to the surrounding continuum was defined. Beam elements were used to represent rebars and embedded in reinforced concrete parts (panels, barrier, moment slab, and crash wall). Shell elements were used to represent steel strips and embedded in the backfill soil. The remaining parts were modeled using solid elements.

The system was subjected to initialization loading phase to capture initial stress at the steady state condition. Namely, the initial stress in the backfill soil due to gravitational loading was determined and the initial stress in the steel strips due to active earth pressure of the wall was determined too. This phase was verified using checks on weight calculations of the system and checks on the maximum strip loads using the equation in Section 11 in *AASHTO LRFD Bridge Design Specifications (2).*

An SUT traveling at a speed of 90.12 km/h (56 mph) and an angle of 15 degrees was used to represent the impact load. These impact parameters are representative of MASH TL-4 test condition. The existing SUT vehicle model was modified to reflect *MASH* 10000S vehicle specification for TL-4 since it was developed as an NCHRP 350 8000S test vehicle. The research team validated the modified SUT (10000S) model using the results of a *MASH* TL-4 full-scale crash test performed by TTI. The simulation results with modified SUT vehicle reasonably correlates well with the test results. Moreover, the validity of the simulation was quantified by calculating comparison metrics between simulation and crash test signals.

Using this 10000S vehicle model, three impact simulations were performed using the three different MSE wall models presented earlier. The results of the analysis of the MSE wall impact showed that the wall panels exhibited considerable damage from the direct impact. This indicates that the wall panels alone cannot resist a direct impact with such severity. However, if a 0.2 m (8 in.) thick continuous crash wall is added in front of the panels, the panels exhibited less damage profile. Most of the damage was limited to the crash wall and the panels exhibited minor damage profile. Moreover, the damage is spread over smaller surface area of the crash wall than the damaged area of the panels when impacted directly. Similar behavior is observed when simulating the impact on the MSE wall with a crash wall and anchors.

When the wall panels are damaged by a direct impact, the reconstruction work for the panels is complicated because significant section of the MSE wall system might need to be rebuilt. This means it would be expensive to repair the system. Reconstruction of the crash wall is less complicated than reconstruction of the MSE wall structure because pouring concrete can be accomplished from the outside area without rebuilding the wall panels. This would result in reducing construction time on the traveling public as well a significant reduction in repair cost for the user agency.

REFERENCES

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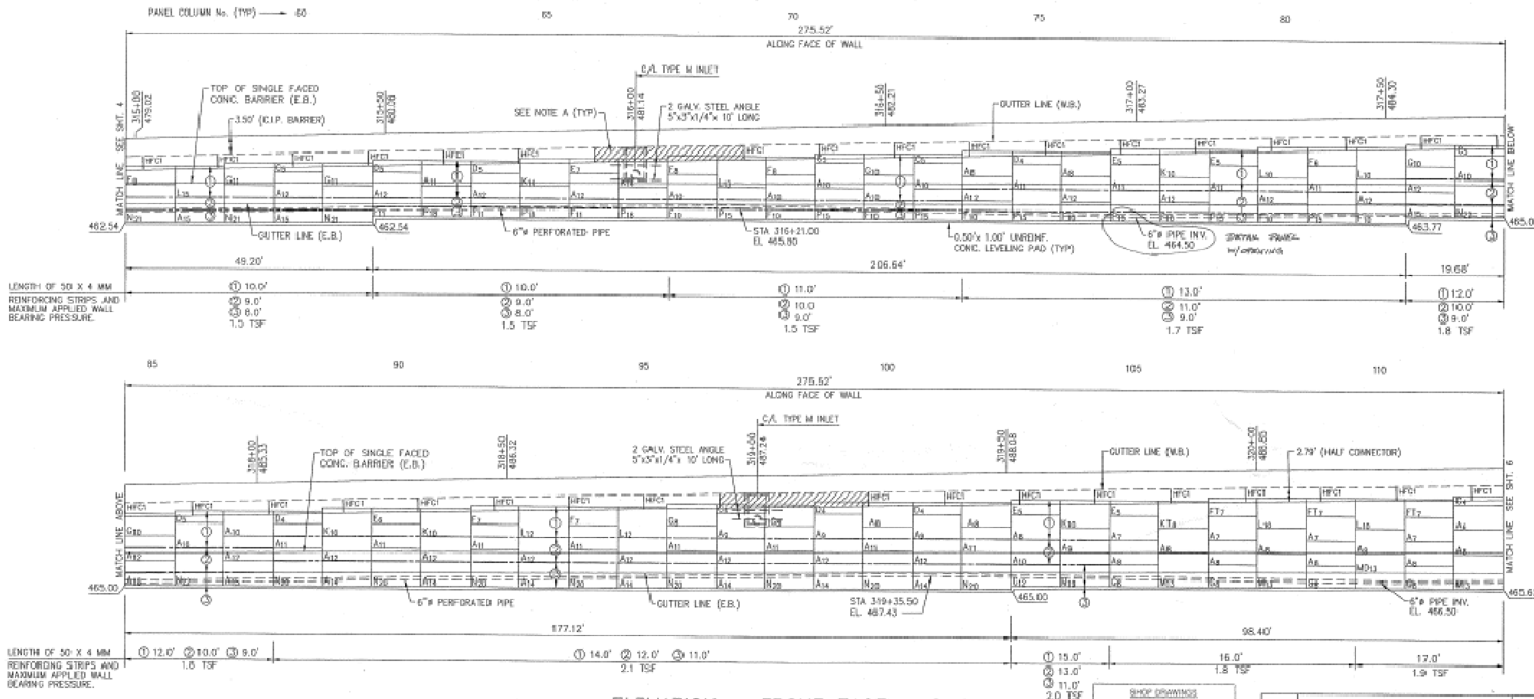
APPENDIX A: JUNIATA COUNTY DRAWING



ELEVATION - FRONT FACE - S-23871

SCALE : 1" = 10'

NOTES:

1. LENGTH OF LEVELING PAD IS BASED ON INDIVIDUAL PANEL WIDTHS. ℄ OF PANEL JOINT TO ℄ OF PANEL JOINT. USE STEP DETAIL ON SHEET 13 TO DETERMINE THE ACTUAL LEVELING PAD STEP LOCATION.
2. FOR TYPICAL SECTIONS THRU WALL, SEE SHEET 9 & 10.

NOTE A:

C.I.P. HALF CONNECTOR SECTION TO MATCH PRECAST HALF CONNECTOR SECTION. SEE SHEET 11 OF 13.

HFC1 PRECAST HALF-CONNECTOR

C.I.P. HALF-CONNECTOR

SHOP DRAWINGS

FURNISH AS SUBMITTED

X FURNISH AS NOTED

REVISE AND RESUBMIT

REJECTED

REFER TO TRANSMITTAL LETTER FOR CONDITIONS OF THIS REVIEW

ERDMAN ANTHONY CONSULTING ENGINEERS

DATE BY

MARK	DESCRIPTION	BY	Chk'd	Recm'd	DATE

REVISION

STRUCTURE 110

"I HEREBY CERTIFY THAT ALL DESIGN ASSUMPTIONS HAVE BEEN VALIDATED EITHER THROUGH CONSTRUCTION DETAILS OR NOTES ON THESE DRAWINGS, OR THROUGH THE CONTRACT PLANS AND PROVISIONS."

DATE:

PREPARED BY: THE REINFORCED EARTH COMPANY

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

JUNIATA COUNTY
S.R. 0022 SECTION A09

SEGMENT 0022 OFFSET 1250
S.R. 0022-A09 STA. 309+50.00 TO STA. 336+00.70
ALONG C/L CONSTRUCTION S.R. 0022
REINFORCED EARTH RETAINING WALLS

MSE WALL ELEVATIONS

RECOMMENDED

SHEET 5 OF 13

S-23871 P

The Reinforced Earth Company

1	10/26/04	REV. HALF CONNECTOR PRECAST UNIT LENGTH
REV.	DATE	DESCRIPTION

"REINFORCED EARTH" is the registered trademark of The Reinforced Earth Company.

DESIGNED BY: MTG

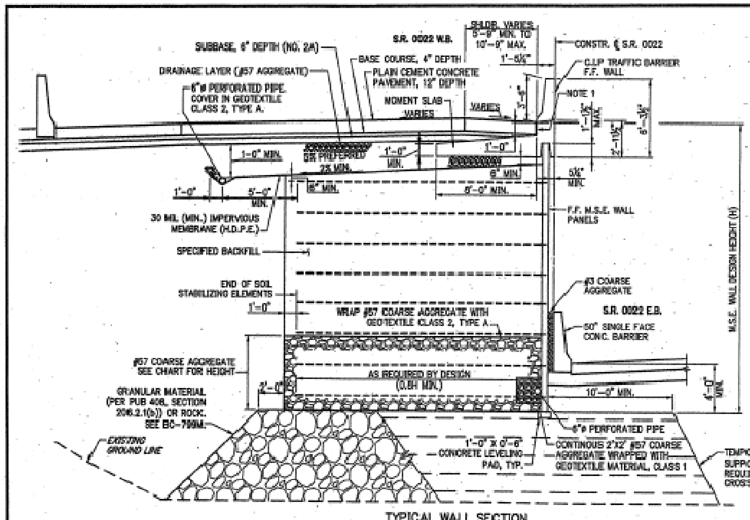
PROJECT ENGR:

CHECKED BY:

ENG. MANAGER

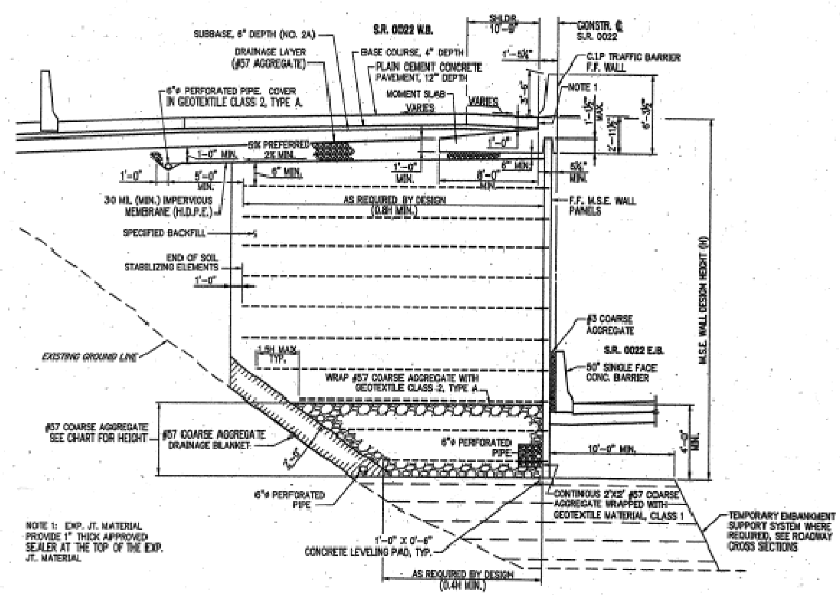
THESE DRAWINGS ARE INTENDED FOR USE ONLY AT THE SITE FOR WHICH THEY WERE PREPARED. THE REINFORCED EARTH COMPANY DISCLAIMS ANY LIABILITY FOR ANY OTHER USE.

06/18/04



TYPICAL WALL SECTION
Ⓐ STA. 309+50 TO STA. 314+40
STA. 319+70 TO STA. 324+00
STA. 325+75 TO STA. 336+70
SCALE: ¼" = 1'-0"

NO. 57 COARSE AGGREGATE CHART	
STA. 309+50 TO STA. 314+00	FULL HIGHT
STA. 314+00 TO STA. 315+50	5'-6" MIN.
STA. 315+50 TO STA. 317+50	4'-3" MIN.
STA. 317+50 TO STA. 319+50	2'-6" MIN.
STA. 319+50 TO STA. 321+00	2'-0" MIN.
STA. 321+00 TO STA. 324+00	2'-6" MIN.
STA. 324+00 TO STA. 325+50	2'-0" MIN.
STA. 325+50 TO STA. 336+70	NONE



NOTE 1: EXP. JT. MATERIAL PROVIDE 1" THICK APPROVED SEALER AT THE TOP OF THE EXP. JT. MATERIAL

TYPICAL WALL SECTION
Ⓐ STA. 324+00 TO STA. 325+75
SCALE: ¼" = 1'-0"

GRAPHIC SCALES
SCALE: ¼" = 1'-0"
2' 1' 0 4' 8'

SHOP DRAWINGS
FURNISH AS SUBMITTED
X FURNISH AS NOTED
REVISE AND RESUBMIT
REJECTED
REFER TO TRANSMITTAL LETTER FOR CONDITIONS OF THIS REVIEW.
ERDMAN ANTHONY CONSULTING ENGINEERS

Ⓐ THESE DETAILS WERE PRESENTED WITHIN THE PADOT CONTRACT DOCUMENTS FOR THIS PROJECT S-23871, S.R. 0022, SECTION A09, MIFFLIN COUNTY, PA. THESE DETAILS WERE INCLUDED IN THIS SET FOR INFORMATION AND FOR THE PURPOSE OF PROVIDING A COMPLETE DESIGN PACKAGE.

MARK	DESCRIPTION	BY	Chk'd	Recm'd	DATE
	REVISION				

STRUCTURE 110

"I HEREBY CERTIFY THAT ALL DESIGN ASSUMPTIONS HAVE BEEN VALIDATED EITHER THROUGH CONSTRUCTION DETAILS OR NOTES ON THESE DRAWINGS, OR THROUGH THE CONTRACT PLANS AND PROVISIONS."

DATE: 7/13/04

PREPARED BY: THE REINFORCED EARTH COMPANY

The Reinforced Earth Company

"REINFORCED EARTH" is the registered trademark of The Reinforced Earth Company

REV.	DATE	DESCRIPTION

DESIGNED BY: MTG
PROJECT ENGR: MTG
CHECKED BY:
ENG. MANAGER:

THESE DRAWINGS ARE INTENDED FOR USE ONLY AT THE SITE FOR WHICH THEY WERE PREPARED. THE REINFORCED EARTH COMPANY DISCLAIMS ANY LIABILITY FOR ANY OTHER USE.

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

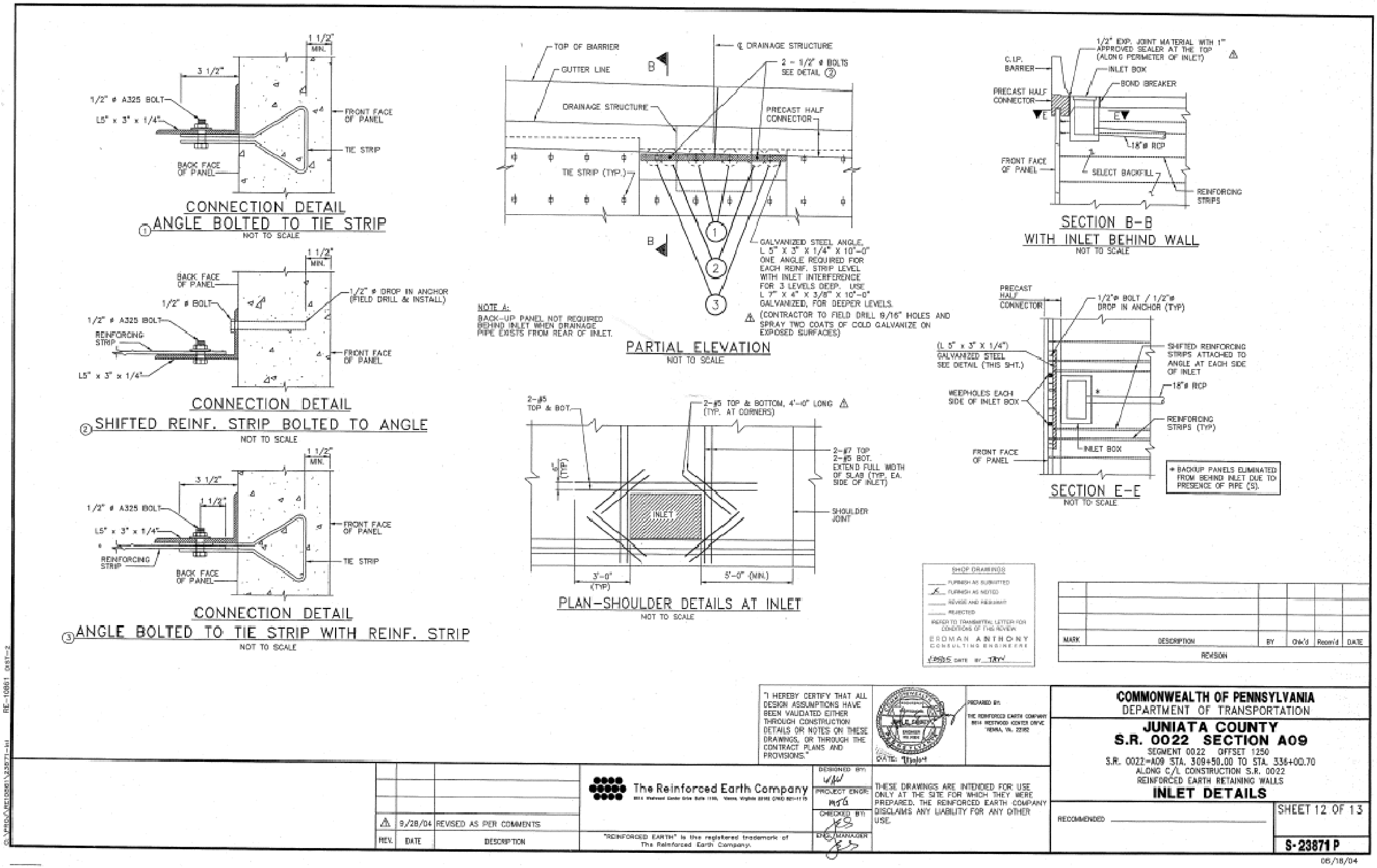
JUNIATA COUNTY
S.R. 0022 SECTION A09
SEGMENT 0022 OFFSET 1250
S.R. 0022-A09 STA. 309+50.00 TO STA. 336+00.70
ALONG C/L CONSTRUCTION S.R. 0022
REINFORCED EARTH RETAINING WALLS
TYPICAL WALL SECTION - 1

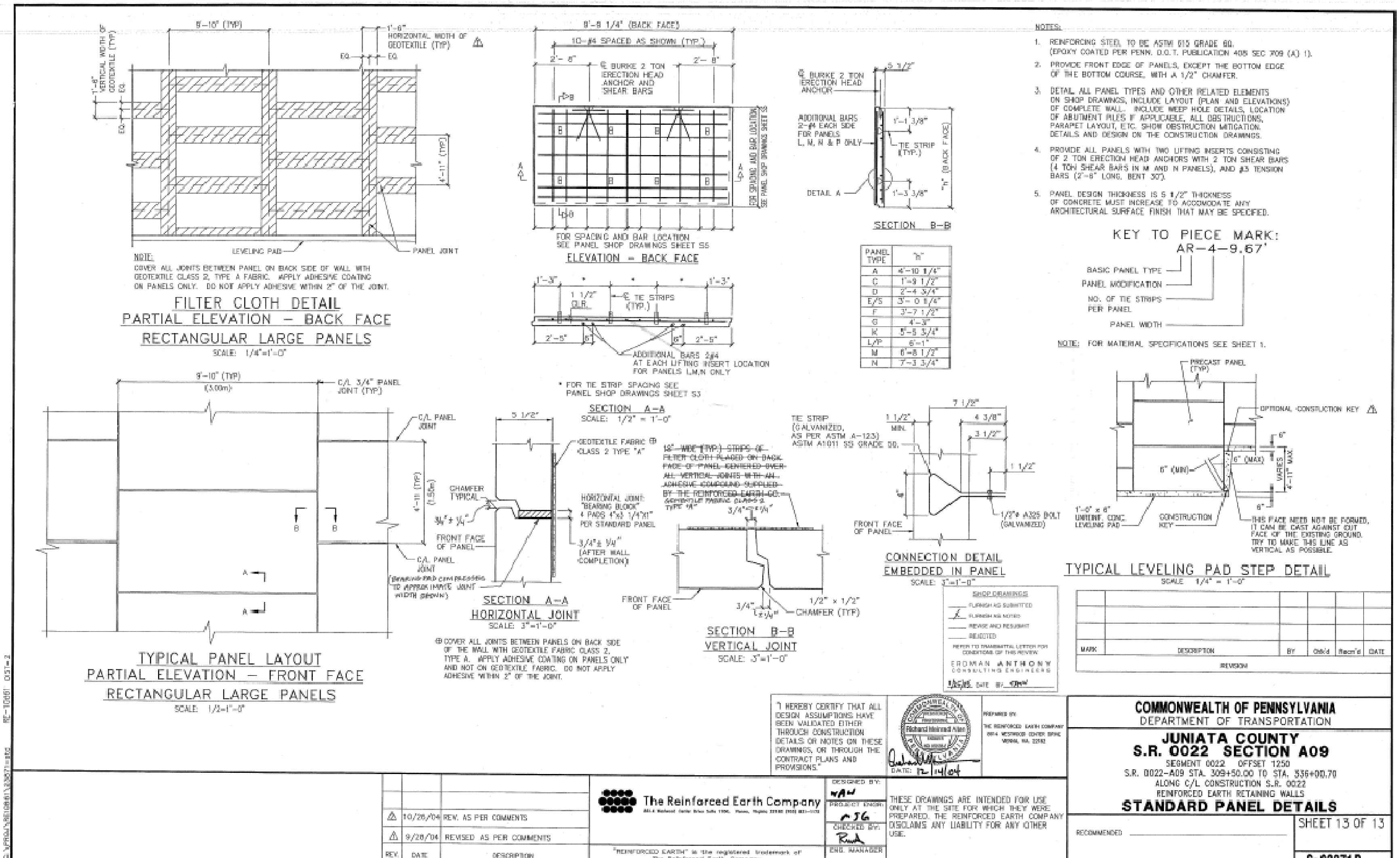
RECOMMENDED

SHEET 9 OF 13

S-23871 P

06/18/04


1 1/2" MIN.
3 1/2"
1/2" ø A325 BOLT
L5" x 3" x 1/4"
FRONT FACE OF PANEL
TIE STRIP
BACK FACE OF PANEL
CONNECTION DETAIL
① ANGLE BOLTED TO TIE STRIP
NOT TO SCALE
1 1/2" MIN.
BACK FACE OF PANEL
1/2" ø BOLT
1/2" ø DROP IN ANCHOR (FIELD DRILL & INSTALL)
1/2" ø A325 BOLT
REINFORCING STRIP
FRONT FACE OF PANEL
L5" x 3" x 1/4"
CONNECTION DETAIL
② SHIFTED REINF. STRIP BOLTED TO ANGLE
NOT TO SCALE
1 1/2" MIN.
3 1/2"
1 1/2"
1/2" ø A325 BOLT
L5" x 3" x 1/4"
REINFORCING STRIP
BACK FACE OF PANEL
FRONT FACE OF PANEL
TIE STRIP
CONNECTION DETAIL
③ ANGLE BOLTED TO TIE STRIP WITH REINF. STRIP
NOT TO SCALE
TOP OF BARRIER
GUTTER LINE
℄ DRAINAGE STRUCTURE
2 - 1/2" ø BOLTS SEE DETAIL ②
DRAINAGE STRUCTURE
PRECAST HALF CONNECTOR
TIE STRIP (TYP.)
B
B
GALVANIZED STEEL ANGLE, L 5" X 3" X 1/4" X 10'-0" ONE ANGLE REQUIRED FOR EACH REINF. STRIP LEVEL WITH INLET INTERFERENCE FOR 3 LEVELS DEEP. USE L 7" X 4" X 3/8" X 10'-0" GALVANIZED, FOR DEEPER LEVELS.
(CONTRACTOR TO FIELD DRILL 9/16" HOLES AND SPRAY TWO COATS OF COLD GALVANIZE ON EXPOSED SURFACES)
NOTE A:
BACK-UP PANEL NOT REQUIRED BEHIND INLET WHEN DRAINAGE PIPE EXISTS FROM REAR OF INLET.
PARTIAL ELEVATION
NOT TO SCALE
2-#5 TOP & BOT.
2-#5 TOP & BOTTOM, 4'-0" LONG (TYP. AT CORNERS)
2-#7 TOP 2-#5 BOT. EXTEND FULL WIDTH OF SLAB (TYP. EA. SIDE OF INLET)
SHOULDER JOINT
INLET
3'-0" (TYP)
5'-0" (MIN.)
PLAN-SHOULDER DETAILS AT INLET
NOT TO SCALE
1/2" EXP. JOINT MATERIAL WITH 1" APPROVED SEALER AT THE TOP (ALONG PERIMETER OF INLET)
C.I.P. BARRIER
INLET BOX
BOND BREAKER
PRECAST HALF CONNECTOR
E
E
18"ø RCP
FRONT FACE OF PANEL
SELECT BACKFILL
REINFORCING STRIPS
SECTION B-B
WITH INLET BEHIND WALL
NOT TO SCALE
PRECAST HALF CONNECTOR
1/2"ø BOLT / 1/2"ø DROP IN ANCHOR (TYP)
(L 5" x 3" X 1/4") GALVANIZED STEEL SEE DETAIL (THIS SHT.)
SHIFTED REINFORCING STRIPS ATTACHED TO ANGLE AT EACH SIDE OF INLET
18"ø RCP
WEEPHOLES EACH SIDE OF INLET BOX
REINFORCING STRIPS (TYP)
INLET BOX
FRONT FACE OF PANEL
* BACKUP PANELS ELIMINATED FROM BEHIND INLET DUE TO PRESENCE OF PIPE (S).
SECTION E-E
NOT TO SCALE
SHOP DRAWINGS
FURNISH AS SUBMITTED
FURNISH AS NOTED
REVISE AND RESUBMIT
REJECTED
ERDMAN ANTHONY CONSULTING ENGINEERS
MARK
DESCRIPTION
BY
Chk'd
Recm'd
DATE
REVISION
"I HEREBY CERTIFY THAT ALL DESIGN ASSUMPTIONS HAVE BEEN VALIDATED EITHER THROUGH CONSTRUCTION DETAILS OR NOTES ON THESE DRAWINGS, OR THROUGH THE CONTRACT PLANS AND PROVISIONS."
PREPARED BY:
THE REINFORCED EARTH COMPANY
COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION
JUNIATA COUNTY
S.R. 0022 SECTION A09
SEGMENT 0022 OFFSET 1250
S.R. 0022-A09 STA. 309+50.00 TO STA. 336+00.70
ALONG C/L CONSTRUCTION S.R. 0022
REINFORCED EARTH RETAINING WALLS
INLET DETAILS
The Reinforced Earth Company
DESIGNED BY
PROJECT ENGR.
CHECKED BY
ENGR. MANAGER
THESE DRAWINGS ARE INTENDED FOR USE ONLY AT THE SITE FOR WHICH THEY WERE PREPARED. THE REINFORCED EARTH COMPANY DISCLAIMS ANY LIABILITY FOR ANY OTHER USE.
RECOMMENDED
SHEET 12 OF 13
S-23871 P
06/18/04
9/28/04 REVISED AS PER COMMENTS
REV.
DATE
DESCRIPTION
"REINFORCED EARTH" is the registered trademark of The Reinforced Earth Company.



NOTES:

1. REINFORCING STEEL TO BE ASTM 615 GRADE 60. (EPOXY COATED PER PENN. D.O.T. PUBLICATION 408 SEC 709 (A) 1).
2. PROVIDE FRONT EDGE OF PANELS, EXCEPT THE BOTTOM EDGE OF THE BOTTOM COURSE, WITH A 1/2" CHAMFER.
3. DETAIL ALL PANEL TYPES AND OTHER RELATED ELEMENTS ON SHOP DRAWINGS, INCLUDE LAYOUT (PLAN AND ELEVATIONS) OF COMPLETE WALL. INCLUDE WEEP HOLE DETAILS, LOCATION OF ABUTMENT PILES IF APPLICABLE, ALL OBSTRUCTIONS, PARAPET LAYOUT, ETC. SHOW OBSTRUCTION MITIGATION DETAILS AND DESIGN ON THE CONSTRUCTION DRAWINGS.
4. PROVIDE ALL PANELS WITH TWO LIFTING INSERTS CONSISTING OF 2 TON ERECTION HEAD ANCHORS WITH 2 TON SHEAR BARS (4 TON SHEAR BARS IN M AND N PANELS), AND #3 TENSION BARS (2'-8" LONG, BENT 30°).
5. PANEL DESIGN THICKNESS IS 5 1/2" THICKNESS OF CONCRETE MUST INCREASE TO ACCOMODATE ANY ARCHITECTURAL SURFACE FINISH THAT MAY BE SPECIFIED.

KEY TO PIECE MARK: AR–4–9.67'

BASIC PANEL TYPE / PANEL MODIFICATION / NO. OF TIE STRIPS PER PANEL / PANEL WIDTH

NOTE: FOR MATERIAL SPECIFICATIONS SEE SHEET 1.

PANEL TYPE	"h"
A	4'-10 1/4"
C	1'-9 1/2"
D	2'-4 3/4"
E/S	3'-0 1/4"
F	3'-7 1/2"
G	4'-3"
K	5'-5 3/4"
L/P	6'-1"
M	6'-8 1/2"
N	7'-3 3/4"

"I HEREBY CERTIFY THAT ALL DESIGN ASSUMPTIONS HAVE BEEN VALIDATED EITHER THROUGH CONSTRUCTION DETAILS OR NOTES ON THESE DRAWINGS, OR THROUGH THE CONTRACT PLANS AND PROVISIONS."

DATE: 12/14/04

REV.	DATE	DESCRIPTION
⚠	10/28/04	REV. AS PER COMMENTS
⚠	9/28/04	REVISED AS PER COMMENTS

The Reinforced Earth Company

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COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

JUNIATA COUNTY
S.R. 0022 SECTION A09

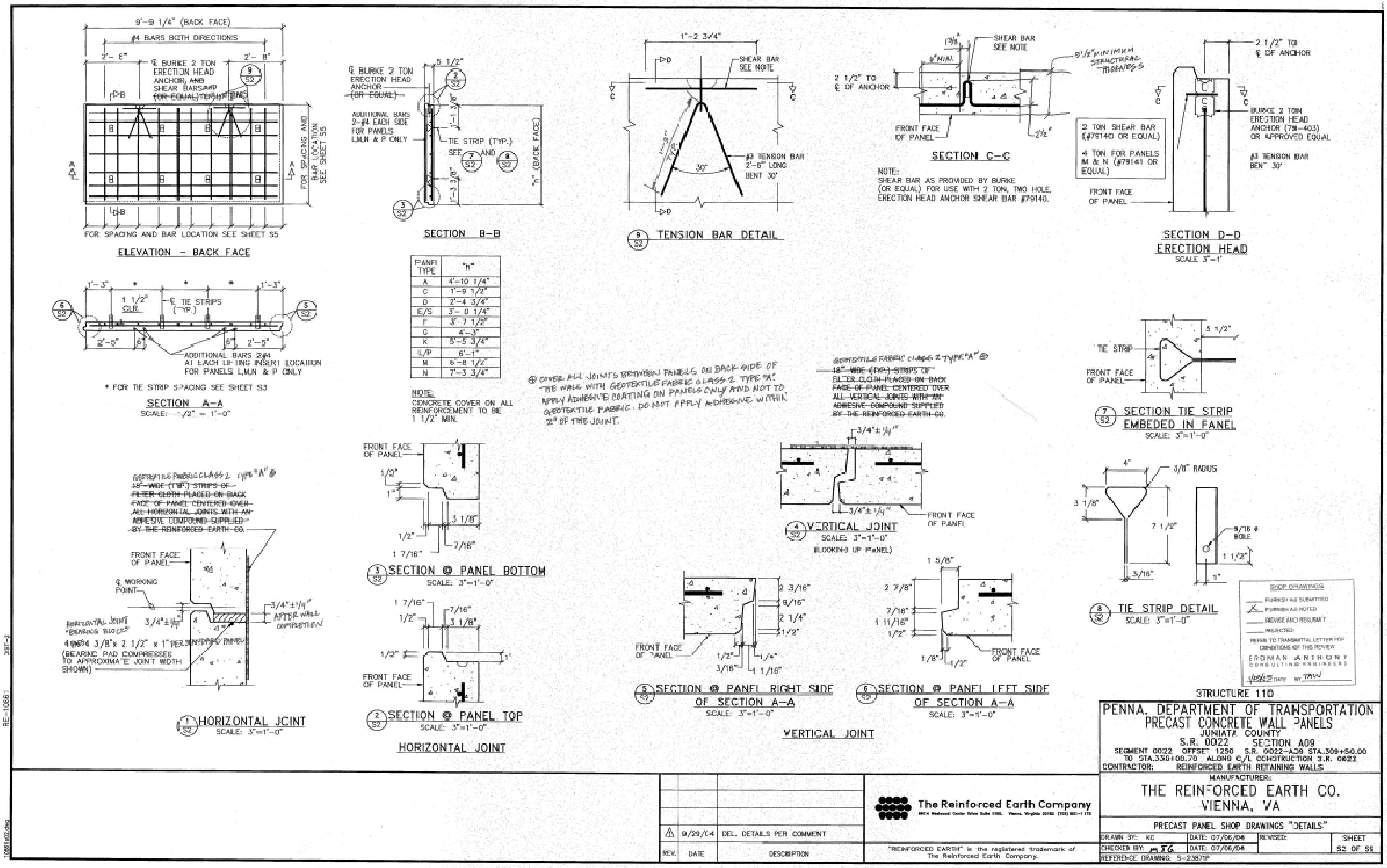
SEGMENT 0022 OFFSET 1250
S.R. 0022–A09 STA. 309+50.00 TO STA. 336+00.70
ALONG C/L CONSTRUCTION S.R. 0022
REINFORCED EARTH RETAINING WALLS

STANDARD PANEL DETAILS

SHEET 13 OF 13

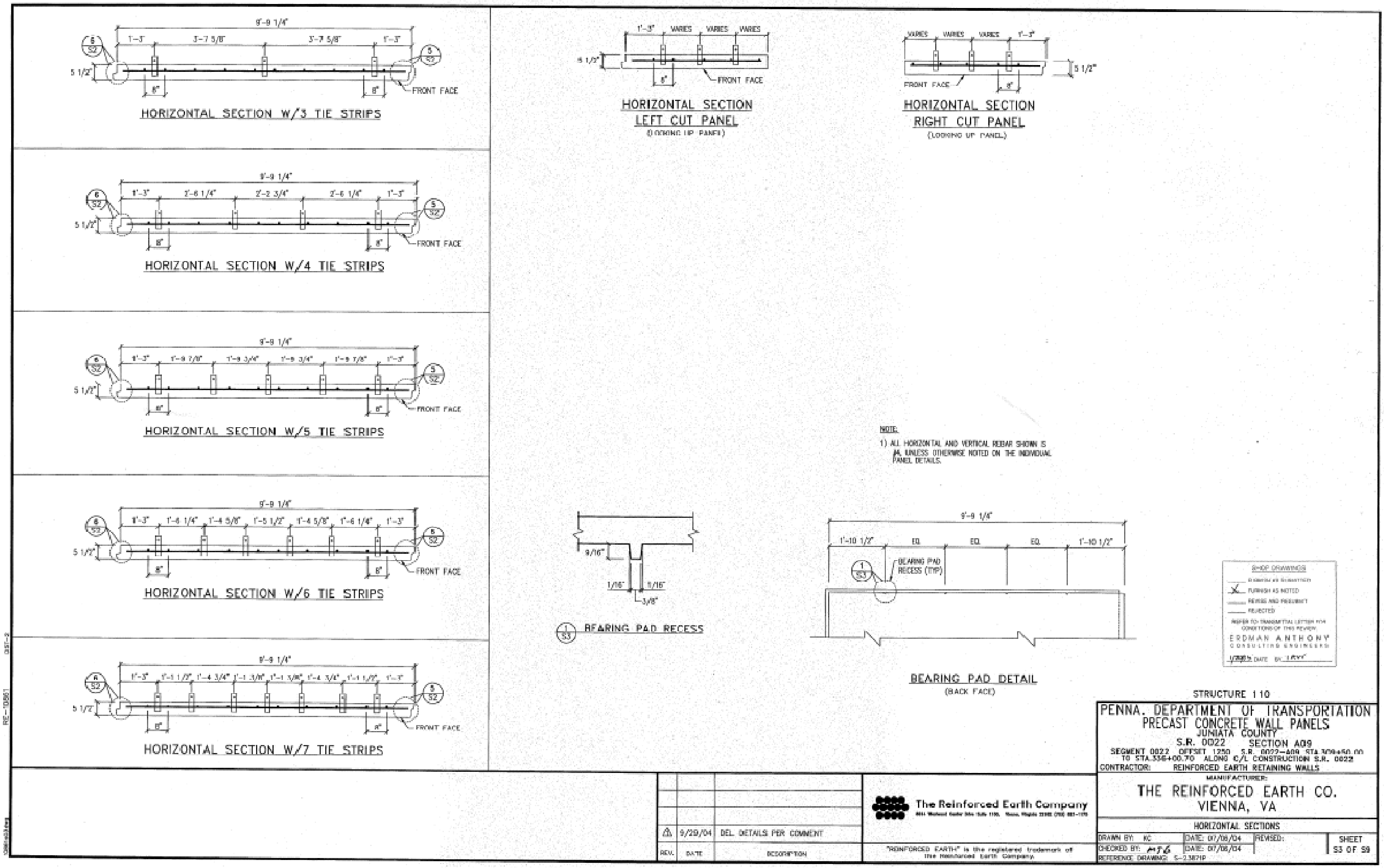
S-23871P

06/18/04

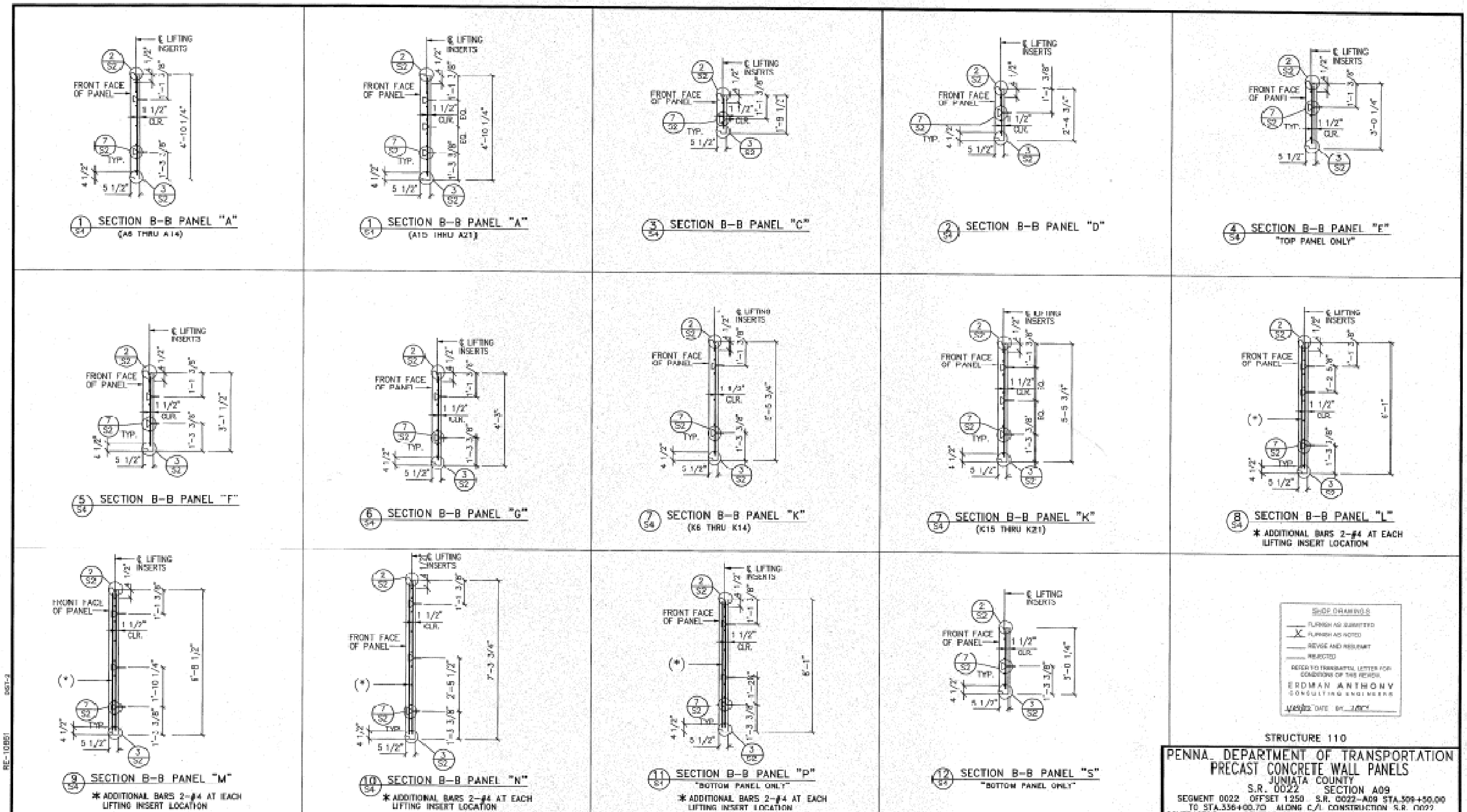


PANEL TYPE	"h"
A	4'-10 1/4"
C	1'-9 1/2"
D	2'-4 3/4"
E/S	3'- 0 1/4"
F	3'-7 1/2"
G	4'-3"
K	5'-5 3/4"
L/P	6'-1"
M	6'-8 1/2"
N	7'-3 3/4"

NOTE:
CONCRETE COVER ON ALL REINFORCEMENT TO BE 1 1/2" MIN.



HORIZONTAL SECTION W/3 TIE STRIPS
HORIZONTAL SECTION W/4 TIE STRIPS
HORIZONTAL SECTION W/5 TIE STRIPS
HORIZONTAL SECTION W/6 TIE STRIPS
HORIZONTAL SECTION W/7 TIE STRIPS
9'-9 1/4"
5 1/2"
FRONT FACE
HORIZONTAL SECTION LEFT CUT PANEL
HORIZONTAL SECTION RIGHT CUT PANEL
(LOOKING UP PANEL)
NOTE:
1) ALL HORIZONTAL AND VERTICAL REBAR SHOWN IS #4 UNLESS OTHERWISE NOTED ON THE INDIVIDUAL PANEL DETAILS.
BEARING PAD RECESS
BEARING PAD DETAIL
(BACK FACE)
BEARING PAD RECESS (TYP)
SHOP DRAWINGS
FURNISH AS NOTED
REJECTED
ERDMAN ANTHONY
CONSULTING ENGINEERS
STRUCTURE 110
PENNA. DEPARTMENT OF TRANSPORTATION
PRECAST CONCRETE WALL PANELS
JUNIATA COUNTY
S.R. 0022 SECTION A09
CONTRACTOR: REINFORCED EARTH RETAINING WALLS
MANUFACTURER:
THE REINFORCED EARTH CO.
VIENNA, VA
HORIZONTAL SECTIONS
DRAWN BY: KC DATE: 07/08/04
CHECKED BY: DATE: 07/08/04
SHEET S3 OF S9
9/29/04 DEL. DETAILS PER COMMENT
REV. DATE DESCRIPTION
The Reinforced Earth Company
"REINFORCED EARTH" is the registered trademark of the Reinforced Earth Company.



SHOP DRAWINGS
FURNISH AS SUBMITTED
X FURNISH AS NOTED
REVISE AND RESUBMIT
REJECTED
REFER TO TRANSMITTAL LETTER FOR CONDITIONS OF THIS REVIEW
ERDMAN ANTHONY CONSULTING ENGINEERS

STRUCTURE 110

PENNA. DEPARTMENT OF TRANSPORTATION
PRECAST CONCRETE WALL PANELS
JUNIATA COUNTY
S.R. 0022 SECTION A09
SEGMENT 0022 OFFSET 1250 S.R. 0022-A09 STA.309+50.00 TO STA.336+00.70 ALONG C/L CONSTRUCTION S.R. 0022
CONTRACTOR: REINFORCED EARTH RETAINING WALLS

MANUFACTURER:
THE REINFORCED EARTH CO.
VIENNA, VA

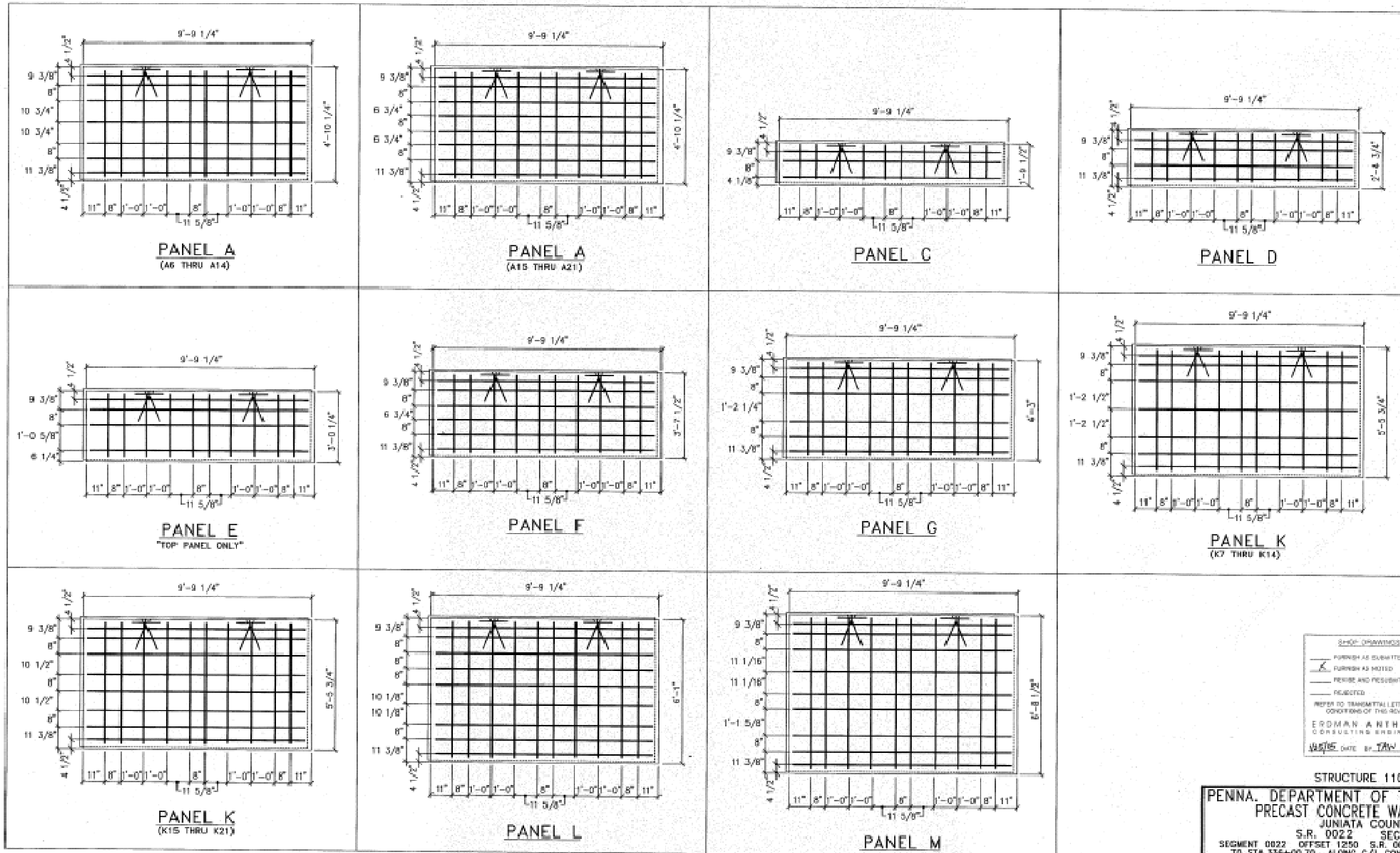
VERTICAL SECTIONS

DRAWN BY: KC	DATE: 07/06/04	REVISED:	SHEET S4 OF S9
CHECKED BY: MTG	DATE: 07/06/04		
REFERENCE DRAWING: S-25871P			

REV.	DATE	DESCRIPTION

The Reinforced Earth Company

"REINFORCED EARTH" is the registered trademark of The Reinforced Earth Company.



SHOP DRAWINGS
FURNISH AS SUBMITTED
X FURNISH AS NOTED
REVISE AND RESUBMIT
REJECTED
REFER TO TRANSMITTAL LETTER FOR CONDITIONS OF THIS REVIEW.
ERDMAN ANTHONY
CONSULTING ENGINEERS
DATE BY TAW

STRUCTURE 110

PENNA. DEPARTMENT OF TRANSPORTATION
PRECAST CONCRETE WALL PANELS
JUNIATA COUNTY
S.R. 0022 SECTION A09
SEGMENT 0022 OFFSET 1250 S.R. 0022-A09 STA.309+50.00 TO STA.336+00.70 ALONG C/L CONSTRUCTION S.R. 0022
CONTRACTOR: REINFORCED EARTH RETAINING WALLS
MANUFACTURER:
THE REINFORCED EARTH CO.
VIENNA, VA

STANDARD PANEL REINFORCEMENT

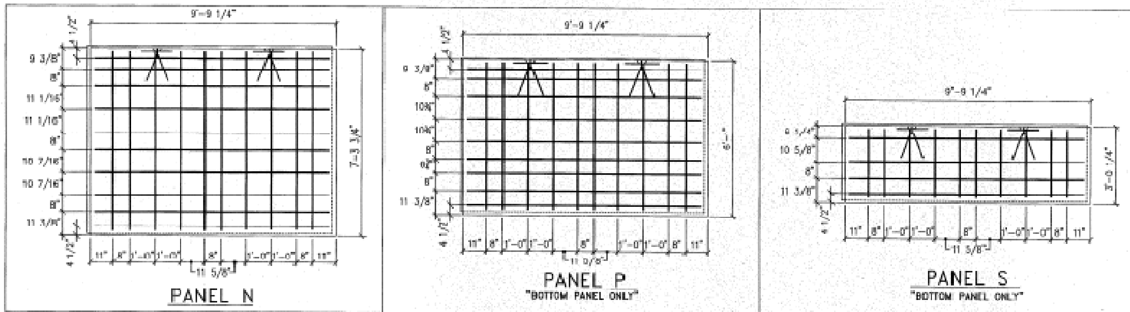
DRAWN BY: KC	DATE: 07/06/04	REVISED:	SHEET
CHECKED BY: MJG	DATE: 07/06/04		55 OF 57
REFERENCE DRAWING: S-23871P			

REV.	DATE	DESCRIPTION

The Reinforced Earth Company

"REINFORCED EARTH" is the registered trademark of The Reinforced Earth Company.

RE-10861



STRUCTURE 110

PENNA. DEPARTMENT OF TRANSPORTATION
PRECAST CONCRETE WALL PANELS
JUNIATA COUNTY
S.R. 0022 SECTION A09
SEGMENT 0022 OFFSET 1250 S.R. 0022-A09 STA.309+50.00
TO STA.336+00.70 ALONG C/L CONSTRUCTION S.R. 0022
CONTRACTOR: REINFORCED EARTH RETAINING WALLS
MANUFACTURER:
THE REINFORCED EARTH CO.
VIENNA, VA

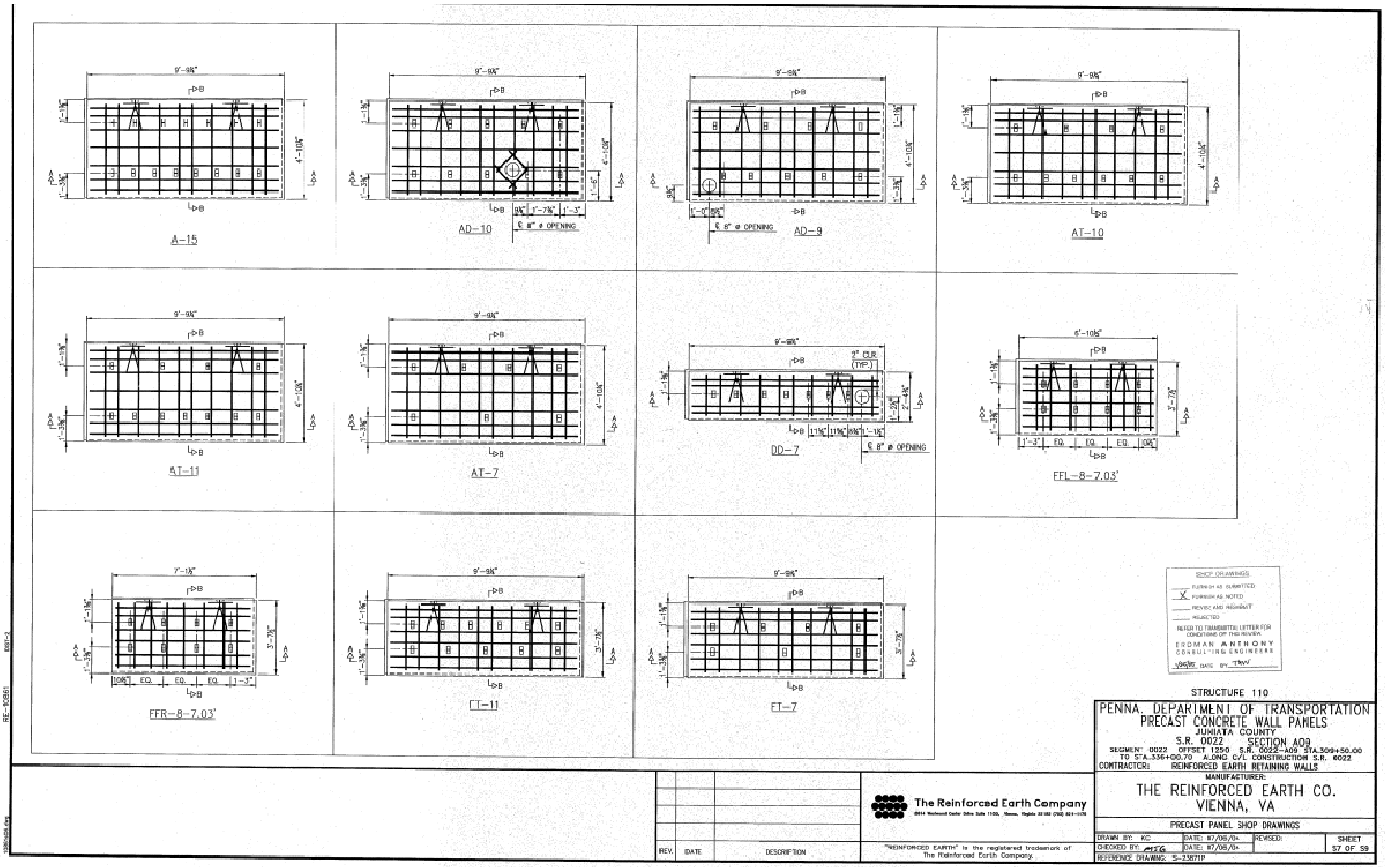
The Reinforced Earth Company

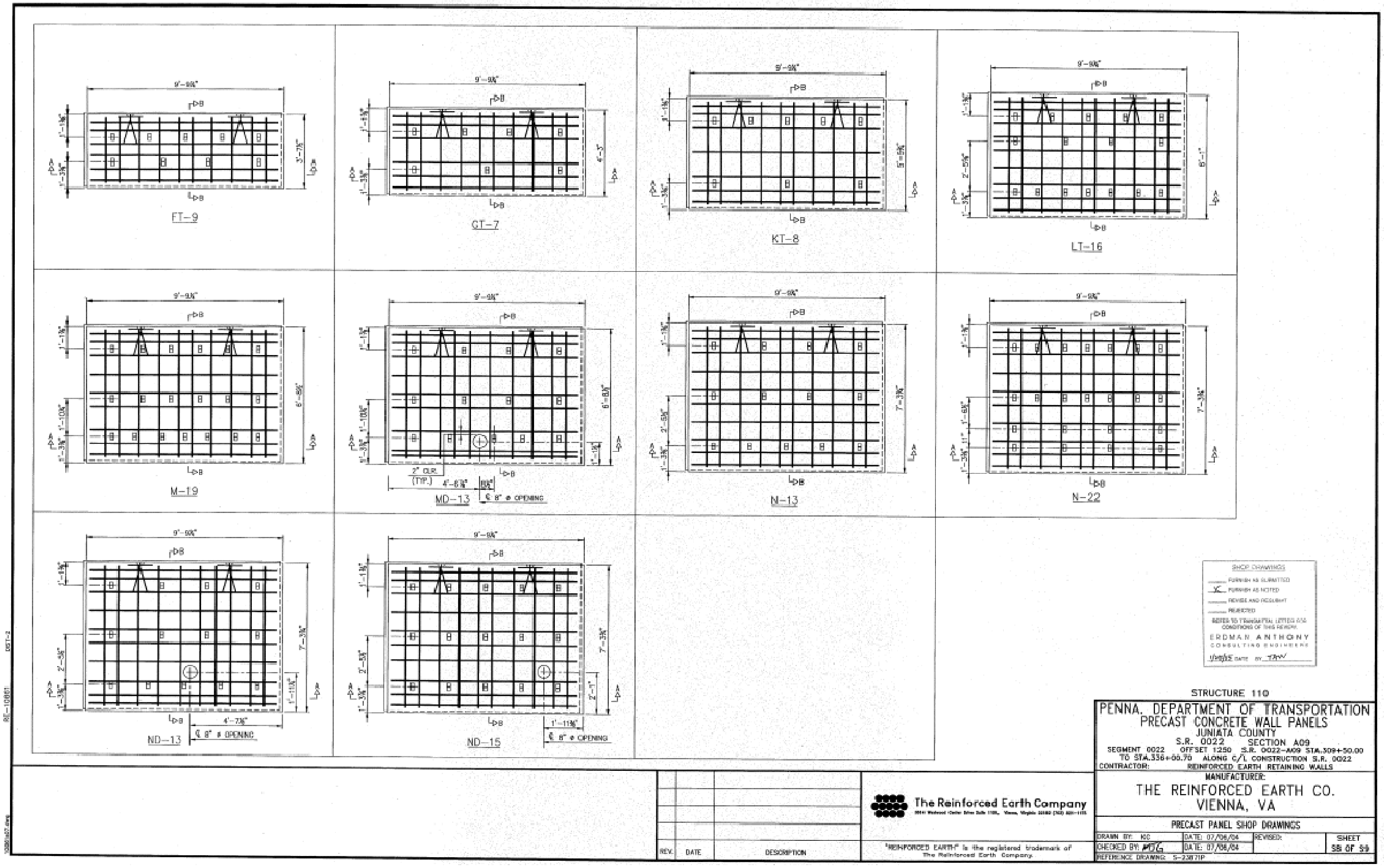
"REINFORCED EARTH" is the registered trademark of The Reinforced Earth Company.

STANDARD PANEL REINFORCEMENT

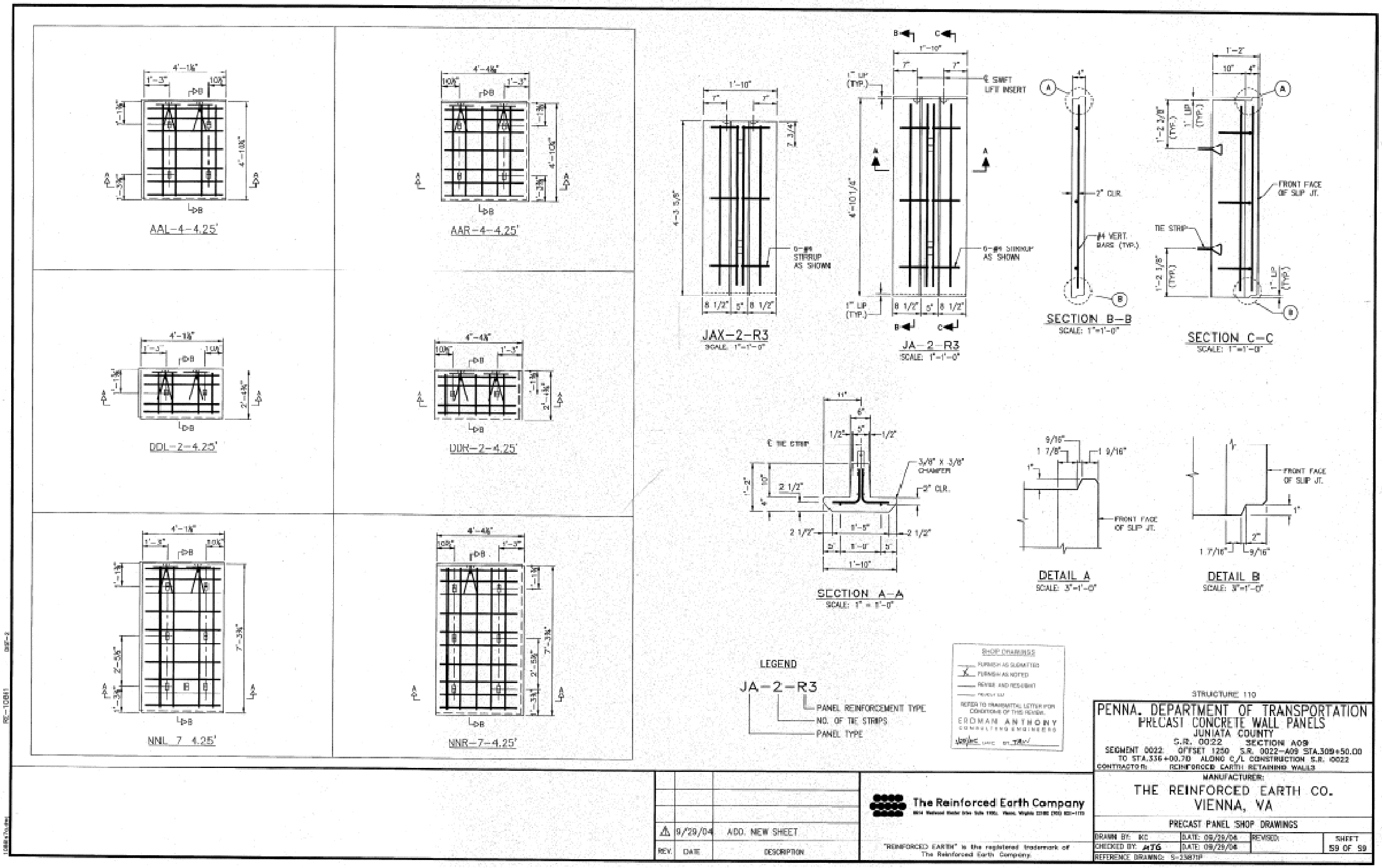
DRAWN BY: KC	DATE: 07/06/04	REVISED:	SHEET 56 OF 59
CHECKED BY: MTB	DATE: 07/06/04		
REFERENCE DRAWING: S-23871P			

REV.	DATE	DESCRIPTION

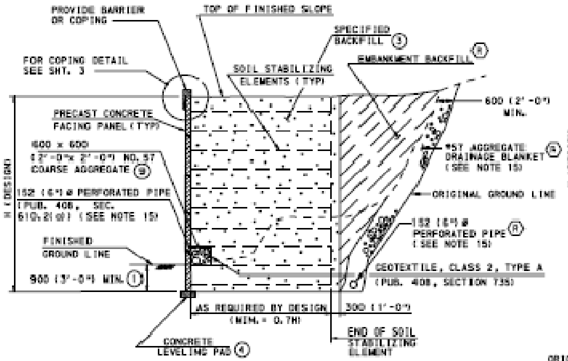

A-15
AD-10
AD-9
AT-10
AT-11
AT-7
DD-7
FFL-8-7.03'
FFR-8-7.03'
FT-11
FT-7
STRUCTURE 110
PENNA. DEPARTMENT OF TRANSPORTATION
PRECAST CONCRETE WALL PANELS
JUNIATA COUNTY
S.R. 0022 SECTION A09
SEGMENT 0022 OFFSET 1250 S.R. 0022-A09 STA.309+50.00
TO STA.336+00.70 ALONG C/L CONSTRUCTION S.R. 0022
CONTRACTOR: REINFORCED EARTH RETAINING WALLS
MANUFACTURER:
THE REINFORCED EARTH CO.
VIENNA, VA
PRECAST PANEL SHOP DRAWINGS
DRAWN BY: KC
DATE: 07/06/04
CHECKED BY:
DATE: 07/06/04
REVISED:
SHEET
57 OF 59
The Reinforced Earth Company
"REINFORCED EARTH" is the registered trademark of The Reinforced Earth Company.
REV.
DATE
DESCRIPTION
ERDMAN ANTHONY
CONSULTING ENGINEERS



FT-9
GT-7
KT-8
LT-16
M-19
MD-13
N-13
N-22
ND-13
ND-15
℄ 8" ⌀ OPENING
SHOP DRAWINGS
FURNISH AS NOTED
ERDMAN ANTHONY
CONSULTING ENGINEERS
STRUCTURE 110
PENNA. DEPARTMENT OF TRANSPORTATION
PRECAST CONCRETE WALL PANELS
JUNIATA COUNTY
S.R. 0022 SECTION A09
SEGMENT 0022 OFFSET 1250 S.R. 0022-A09 STA.309+50.00
TO STA.336+00.70 ALONG C/L CONSTRUCTION S.R. 0022
CONTRACTOR: REINFORCED EARTH RETAINING WALLS
MANUFACTURER:
THE REINFORCED EARTH CO.
VIENNA, VA
PRECAST PANEL SHOP DRAWINGS
DRAWN BY: KC
DATE: 07/06/04
CHECKED BY:
DATE: 07/06/04
REVISED:
SHEET
58 OF 59
REFERENCE DRAWING: S-23871P
The Reinforced Earth Company
"REINFORCED EARTH" is the registered trademark of The Reinforced Earth Company.
REV.
DATE
DESCRIPTION

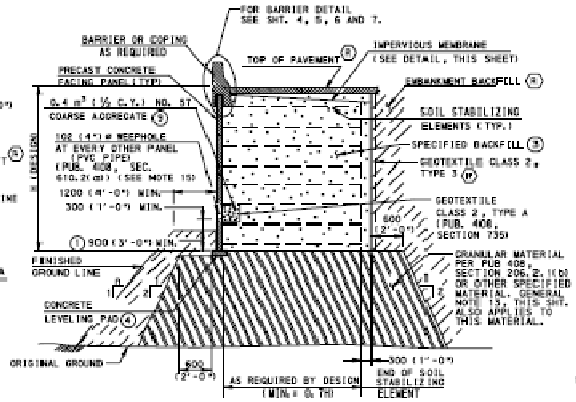

AAL-4-4.25'
AAR-4-4.25'
DDL-2-4.25'
DDR-2-4.25'
NNL-7-4.25'
NNR-7-4.25'
JAX-2-R3
SCALE: 1"=1'-0"
JA-2-R3
SCALE: 1"=1'-0"
SECTION B-B
SCALE: 1"=1'-0"
SECTION C-C
SCALE: 1"=1'-0"
SECTION A-A
SCALE: 1" = 1'-0"
DETAIL A
SCALE: 3"=1'-0"
DETAIL B
SCALE: 3"=1'-0"
LEGEND
JA-2-R3
PANEL REINFORCEMENT TYPE
NO. OF TIE STRIPS
PANEL TYPE
STRUCTURE 110
PENNA. DEPARTMENT OF TRANSPORTATION
PRECAST CONCRETE WALL PANELS
JUNIATA COUNTY
S.R. 0022 SECTION A09
SEGMENT 0022 OFFSET 1250 S.R. 0022-A09 STA.309+50.00
TO STA.336+00.70 ALONG C/L CONSTRUCTION S.R. 0022
CONTRACTOR: REINFORCED EARTH RETAINING WALLS
MANUFACTURER:
THE REINFORCED EARTH CO.
VIENNA, VA
PRECAST PANEL SHOP DRAWINGS
DRAWN BY: KC
DATE: 09/29/04
CHECKED BY: ATG
DATE: 09/29/04
REVISED:
SHEET 59 OF 59
REFERENCE DRAWING: S-23870P
The Reinforced Earth Company
"REINFORCED EARTH" is the registered trademark of The Reinforced Earth Company.
9/29/04
ADD. NEW SHEET
REV.
DATE
DESCRIPTION

APPENDIX B: PENNDOT PRECAST CONCRETE WALL PANELS



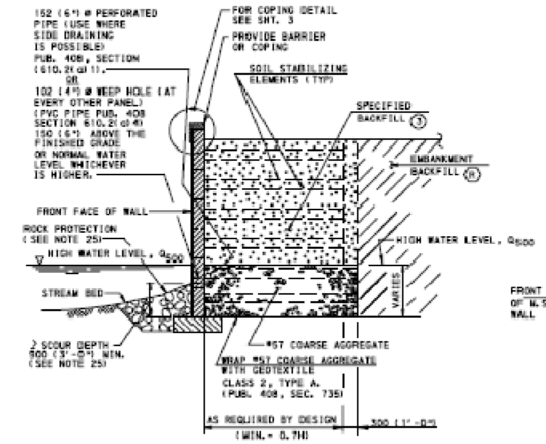
TYPICAL CUT SECTION

DETAIL TO BE USED WHERE SIDE DRAINAGE IS POSSIBLE



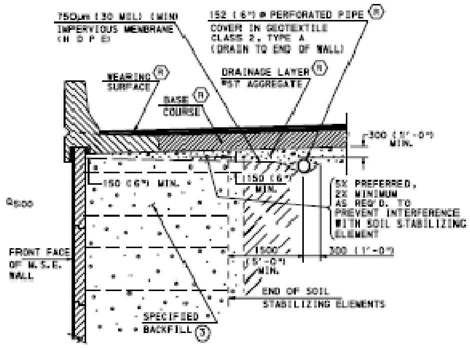
TYPICAL FILL SECTION

DETAIL TO BE USED WHERE WEEPHOLES ARE POSSIBLE
n = SLOPE AS PER CONTRACT PLAN



TYPICAL SECTION AT STREAM

DETAIL TO BE USED WHERE HIGH WATER LEVEL IN FRONT OF THE WALL IS ANTICIPATED, AND THE STREAM VELOCITY, V, IS LESS THAN 0.61 MPS (2.0 fps)



IMPERVIOUS MEMBRANE DETAIL

NOTE: PROVIDE IMPERVIOUS MEMBRANE WHEN SPECIFIED.

GENERAL NOTES:

1. ALL DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE NOTED. U.S. CUSTOMARY UNITS IN ( ) PARENTHESES.
2. USE THIS STANDARD FOR THE PREPARATION OF CONSTRUCTION PLANS IN CONJUNCTION WITH THE DEPARTMENT'S DESIGN MANUAL, PART 4, SECTION 11.9, SPECIAL PROVISIONS AND PUB. 408 SPECIFICATIONS.
3. THIS STANDARD IS INTENDED TO BE USED AS A GUIDE FOR DETAILING THE PREFABRICATED WALLS. FOR UNUSUAL COMBINATIONS OF SHARP SKEW AND/OR VERTICAL AND HORIZONTAL CURVATURE, THIS STANDARD MUST BE USED WITH CAUTION SINCE THESE CONDITIONS MAY REQUIRE SPECIAL DESIGN CONSIDERATIONS.
4. DESIGN COMPUTATIONS ARE NOT REQUIRED FOR THE C.I.P. AND PRECAST BARRIER AND C.I.P. SLAB CONFIGURATIONS SHOWN ON THIS STANDARD. WHERE CONDITIONS AND/OR DETAILS DIFFER FROM THE STANDARD, COMPLETE DESIGN COMPUTATIONS MUST BE SUBMITTED TO THE DEPARTMENT. SUCH SPECIAL DESIGN FOR BARRIER MUST PROVIDE ULTIMATE STRENGTH EQUAL TO THE DESIGN PROVIDED IN THIS STANDARD.
5. PROVIDE MATERIALS AND WORKMANSHIP IN ACCORDANCE WITH PUBLICATION 408, AND CONTRACT SPECIAL PROVISIONS.
6. DESIGN SPECIFICATIONS:
   * ALL EXCEPT TRAFFIC AND SIDEWALK BARRIER: CURRENT AASHTO LRFD BRIDGE DESIGN SPECIFICATIONS AND COMMENTARY AS AMENDED BY DESIGN MANUAL PART 4, VOLUME 1, PUB. 15M.
   * TRAFFIC AND SIDEWALK BARRIER: DESIGN DIVISION OF AASHTO STANDARD SPECIFICATIONS FOR HIGHWAY BRIDGES, 1992 (INCLUDING LATEST IMPLEMENTED REVISIONS) AND AS AMENDED BY DESIGN MANUAL PART 4, PUB. 15.
7. CHAMFER EXPOSED CONCRETE EDGES 20mm x 20mm (¾"x¾"), EXCEPT AS NOTED OTHERWISE.
8. FOR CONCRETE STRENGTH FOR PANELS, REFER TO SPECIAL PROVISIONS.
9. USE CLASS A CEMENT CONCRETE, f'c = 21MPa (3.0 ksi), FOR FOOTINGS, LEVELING PADS, STEP DETAILS AND CRASH WALLS.
10. USE CLASS AA, f'c = 24MPa (3.5 ksi), CEMENT CONCRETE FOR CURBS, BARRIERS, CONCRETE LEVELING FILLS, MOMENT SLABS, BACKWALLS AND COPINGS.
11. USE GRADE 420 (60) STEEL DEFORMED REINFORCEMENT BARS AS SET FORTH IN PUBLICATION 408. PROVIDE 50 mm (2") CONCRETE COVER ON REINFORCEMENT BARS EXCEPT AS NOTED. PROVIDE MINIMUM LAP LENGTH AND EMBEDMENT LENGTH IN ACCORDANCE WITH BC-736M.
12. PROVIDE EPOXY COATED REINFORCEMENT STEEL FOR COPINGS, BARRIERS AND SHOULDER SLABS, AND BACKWALLS. PROVIDE EPOXY COATED REINFORCEMENT STEEL FOR PANELS AS INDICATED.
13. THE DIFFERENCE BETWEEN SPECIFIED BACKFILL AND EMBANKMENT BACKFILL ELEVATIONS IS NOT TO BE MORE THAN 600 mm (2'-0") AT ANY TIME DURING BACKFILLING.
14. WHERE STYROFOAM IS INDICATED, USE STYROFOAM ASTM C 578, TYPE 1, EXCEPT LIMIT THE WATER ABSORPTION TO 2% BY VOLUME.
15. PROVIDE DRAINAGE DETAILS SUCH AS 102 mm (4") ⌀ WEEPHOLES OR 152 mm (6") ⌀ PERFORATED PIPE UNDERDRAIN AND/OR #57 DRAINAGE BLANKETS BASED UPON THE FIELD CONDITIONS. FOR WALL INSTALLATION AT STREAM CROSSINGS PROVIDE ADEQUATE DRAINAGE SO THE DIFFERENCE BETWEEN STREAMBED AND SATURATED BACKFILLS IS NOT GREATER THAN WHAT IS CONSIDERED IN THE DESIGN, BUT NOT GREATER THAN 900 mm (3'-0") DURING DRAWDOWN CONDITIONS.
16. PROVIDE SHOP DRAWINGS AS PER PUB. 408.
17. FOR PREFABRICATED WALLS ALONG RAILROADS, REFER TO DM-4 FOR CRASH WALL REQUIREMENTS AND THE TYPICAL DETAIL ON SHEET 3.
18. GALVANIZE ALL SOIL STABILIZING ELEMENTS AND HARDWARE AS SPECIFIED.
19. REMOVE UNSUITABLE OR UNSTABLE FOUNDATION MATERIAL BELOW THE TOP OF LEVELING PAD AND REPLACE WITH SELECT GRANULAR MATERIAL. PRIOR TO WALL CONSTRUCTION, COMPACT THE FOUNDATION AREA WITH A SMOOTH VIBRATORY ROLLER ACCORDING TO PUB. 408.
20. BACKFILL MATERIALS (DESIGN PROPERTIES):
    EMBANKMENT BACKFILL ϕ = 30°
    SPECIFIED BACKFILL ϕ = 34°
    #57 COARSE AGGREGATE USE ϕ = 34°
    WEIGHT OF SOIL = 1900 kg PER M^3 (120 LBS. PER CUBIC FOOT) OR AS SPECIFIED ON DESIGN DRAWINGS
21. THE M.S.E. WALL DESIGNER/SUPPLIER MUST CERTIFY ALL ASSUMPTIONS MADE IN THE DESIGN. PLACE THE FOLLOWING NOTE NEAR THE P.E. SEAL ON THE FIRST SHEET OF THE DRAWINGS: "ALL DESIGN ASSUMPTIONS ARE VALIDATED THROUGH NOTES OR DETAILS ON THESE DRAWINGS"
22. SOME OF THE TECHNICAL DETAILS WERE PROVIDED BY REINFORCED EARTH COMPANY AND RETAINED EARTH (FOSTER GEOTECHNICAL) COMPANY. FOR PROPRIETARY RIGHTS CONTACT APPROPRIATE PROPRIETOR.
23. DO NOT CUT REINFORCEMENT STRIPS OR MESH. BEND OR SKEW ONLY AS SHOWN IN DETAIL OR NOTES ON SHEETS 2, 10 & 11.
24. DURING THE SPECIFIED BACKFILL PLACEMENT, KEEP THE BACKFILL AT OR JUST ABOVE THE REINFORCEMENT CONNECTION TO PANEL, PRIOR TO MAKING THE CONNECTION. REMOVE AND REPLACE ANY FACE PANEL THAT DOES NOT MEET CONSTRUCTION TOLERANCE, SPECIFIED IN THE SPECIAL PROVISIONS.
25. PROVIDE ROCK PROTECTION AS REQUIRED BY SCOUR CALCULATIONS.
26. FOR LEGEND OF SYMBOLS, SEE SHEET 2.
27. PUNCTURING IMPERVIOUS MEMBRANE IS TO BE AVOIDED. FORMWORK SUPPORTS UTILIZING STAKES DRIVEN THROUGH IMPERVIOUS MEMBRANE ARE PROHIBITED. IMPERVIOUS MEMBRANE'S INTEGRITY MUST NOT BE COMPROMISED.

NOTE: EITHER ALL METRIC OR ALL ENGLISH VALUES MUST BE USED ON PLANS. METRIC AND ENGLISH VALUES SHOWN MAY NOT BE MIXED.

INDEX OF SHEETS

SHEET NO.	SHEET TITLE
1	DETAILS AND GENERAL NOTES
2	ABUTMENT
3	CRASH WALL AND MISCELLANEOUS WALL DETAILS
4	C.I.P. TRAFFIC BARRIER
5	PRECAST TRAFFIC BARRIER
6	MOMENT SLAB AND BARRIER JOINT
7	SIDEWALK AND ALTERNATE BARRIER AND GUIDE RAIL TRANSITION
8	DRAINAGE INSTALLATIONS
9	SHOULDER RELIEF JOINT AND INLET INSTALLATION
10	REINFORCED EARTH WALL PANELS
11	REINFORCED EARTH WALL PANELS
12	FOSTER GEOTECHNICAL RETAINED EARTH WALL PANELS

BC-735M	WALL CONSTR. & EXP. JOINTS DETAILS
BC-736M	REINFORCEMENT BAR FABRICATION DETAILS
BC-739M	BRIDGE BARRIER TO GUIDE RAIL TRANSITION
BC-752M	CONCRETE DECK SLAB DETAILS
BC-767M	NEOPRENE STRIP SEAL DAM
BC-788M	TYP. WATERPROOFING AND EXPANSION DETAILS
RC-11M	CLASSIFICATION OF EARTHWORK FOR STRUCTURES
RC-12M	BACKFILL AT STRUCTURES
RC-20M	CEMENT CONCRETE PAVEMENT JOINTS

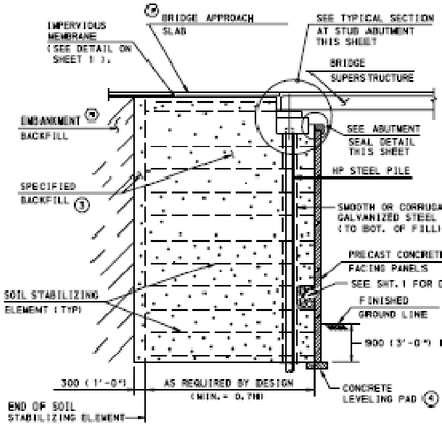
REFERENCE DRAWINGS

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION
BUREAU OF DESIGN

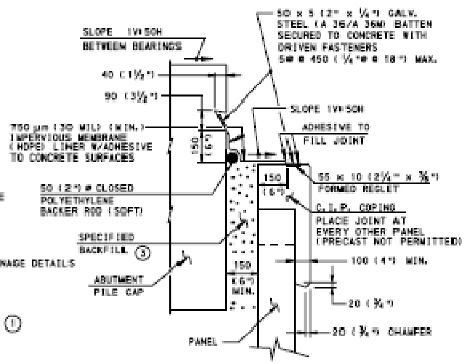
STANDARD
MECHANICALLY STABILIZED EARTH
RETAINING WALLS
DETAILS AND GENERAL NOTES

RECOMMENDED JULY 24, 2006	RECOMMENDED JUL. 24, 2006	RECOMMENDED JUL. 24, 2006	SHEET 1 OF 13
CHIEF BRIDGE ENGINEER	DIR., BUREAU OF DESIGN	CHIEF ENG., HWY. ADMIN.	BC-799M

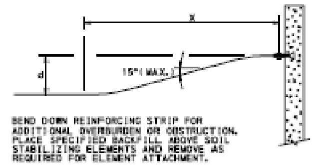
B-4



BRIDGE ABUTMENT



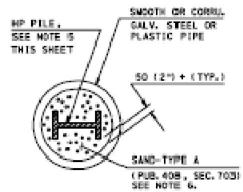
ABUTMENT SEAL DETAIL



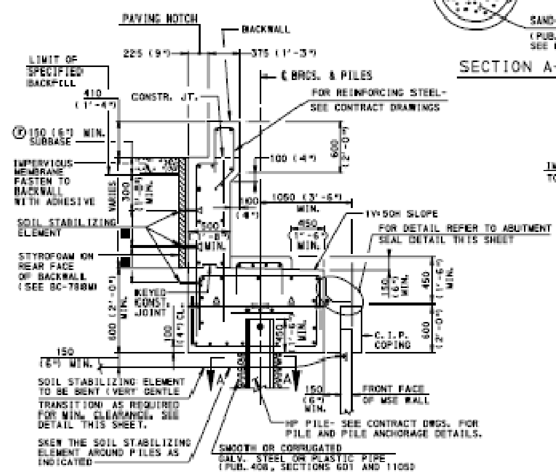
REINFORCING STRIP OR MESH BEND DETAIL

METRIC UNITS	
ADDITIONAL DEPTH (d) OF R.S. REQUIRED (mm)	REQUIRED MINIMUM DISTANCE (X) TO ACHIEVE SMOOTH BEND (mm)
75	675
150	975
225	1200
300	1500
375	1800

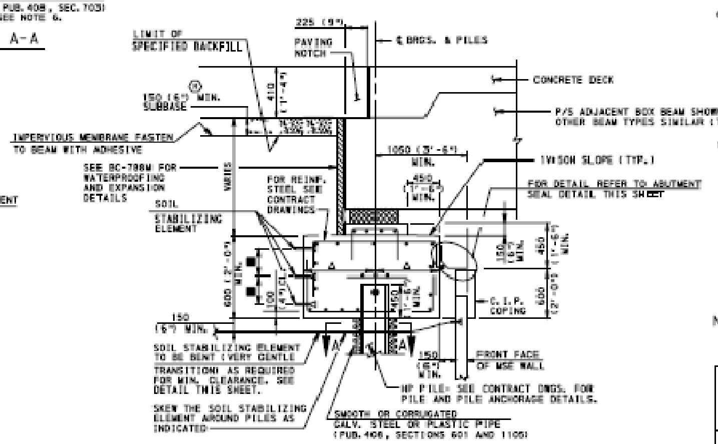
U.S. CUSTOMARY UNITS	
ADDITIONAL DEPTH (d) OF R.S. REQUIRED	REQUIRED MINIMUM DISTANCE (X) TO ACHIEVE SMOOTH BEND
3"	2'-3"
6"	3'-3"
9"	4'-0"
12"	5'-0"
15"	6'-0"



SECTION A-A



TYPICAL SECTION AT STUB ABUTMENT WITH BACKWALL



TYPICAL SECTION AT STUB ABUTMENT WITHOUT BACKWALL

■ SOIL STABILIZING ELEMENTS TO BE DESIGNED AND DETAILED (NUMBER, SIZE AND SPACING) BY THE M.S.E. WALL COMPANY FOR FORCES INDICATED ON THE CONTRACT DRAWINGS. MINIMUM AND MAXIMUM HORIZONTAL FORCES (KN/M; K/FT.) DUE TO EARTH PRESSURE, LIVE LOAD SURCHARGE, AND FORCES AT BRIDGE BEARINGS TO BE PROVIDED BY THE DESIGNER AND INDICATED ON THE CONTRACT DRAWINGS.

Δ 1/2 OF PILE CAP DESIGN WIDTH

LEGEND

① OR PREVAILING FROST DEPTH OR AS REQUIRED BY DESIGN AND SLOPE STABILITY ANALYSIS.

② AS REQUIRED BY DESIGN. (EXCLUSIVE OF ANY AESTHETIC DETAILS.)

③ REFER TO SPECIAL PROVISIONS FOR GRANULAR FILL MATERIALS.

④ 300 mm (12") WIDE x 150 mm (6") THICK (MIN.) UNREINFORCED CONCRETE, EXCEPT FOR CRASHWALL CONDITION.

⑤ MIN. SHOWN OR PANEL THICKNESS + 265 mm (10 1/2").

⑥ MIN. SHOWN OR PANEL THICKNESS + 40 mm (1 1/2").

⑦ MIN. SHOWN OR PANEL THICKNESS + 80 mm (3").

⑧ MIN. SHOWN OR PANEL THICKNESS + 100 mm (4").

⑨ MODIFY FIELD DIMENSIONS TO SUIT SOIL STABILIZING ELEMENT LAYOUT.

Ⓡ ROADWAY ITEM

H D P E = HIGH DENSITY POLYETHELENE
C.I.P. = CAST IN PLACE
M.S.E. = MECHANICALLY STABILIZED EARTH
C.C.N.S. = CLOSED CELL NEOPRENE SPONGE
SCGS = SMOOTH OR CORRUGATED GALVANIZED STEEL PIPE
R.S. = REINFORCING STRIP

PILE INSTALLATION SEQUENCE NOTES

1. DRIVE ALL PILES PRIOR TO MSE WALL INSTALLATION. PREDRILL AS INDICATED.
2. PLACE OVER EACH PILE, A SMOOTH WALL OR CORRUGATED GALVANIZED STEEL (SCGS) OR PLASTIC PIPE OF SUFFICIENT THICKNESS OR AS SPECIFIED, TO PREVENT BUCKLING OR DISTORTION DURING THE PLACEMENT AND COMPACTION OF THE BACKFILL.
3. PLACE SPACERS BETWEEN THE PILE AND THE SCGS PIPE TO PREVENT THE SCGS PIPE FROM COMING INTO CONTACT WITH THE PILE DURING BACKFILLING OF THE WALL.
4. EXTEND SCGS PIPE FROM THE BOTTOM OF THE MSE WALL BACKFILL TO THE BOTTOM OF THE BRIDGE STUB ABUTMENT FOOTER.
5. SEAL THE TOP OF THE SCGS PIPE UNTIL PIPE IS FILLED WITH AGGREGATE.
6. FILL THE SCGS PIPE LOOSELY WITH FINE AGGREGATE, SAND - TYPE A (PUBLICATION 408, SECTION 703). AT THE CONTRACTOR'S OPTION, PLACE FINE AGGREGATE BEFORE OR AFTER THE MSE WALL CONSTRUCTION IS COMPLETED.

M.S.E. WALL ABUTMENT NOTES

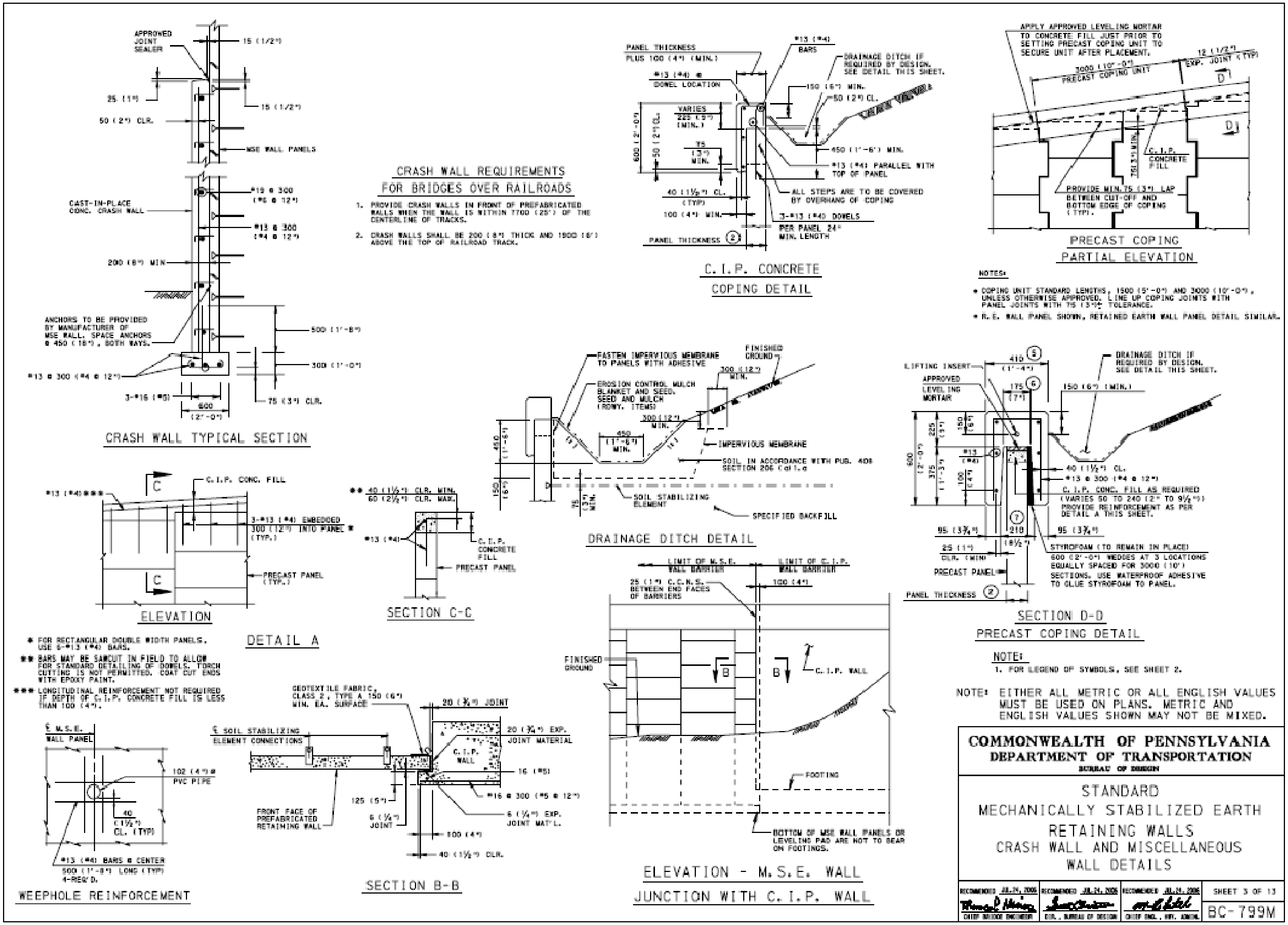
1. ALL M.S.E. WALL PLANS AND SHOP DRAWINGS MUST SHOW PILE LOCATION AND ARRANGEMENT OF M.S.E. WALL SOIL REINFORCEMENT ELEMENTS TO AVOID INTERFERENCE WITH PILES. CUTTING SOIL REINFORCING ELEMENTS TO AVOID INTERFERENCE WITH PILES IS NOT PERMITTED.

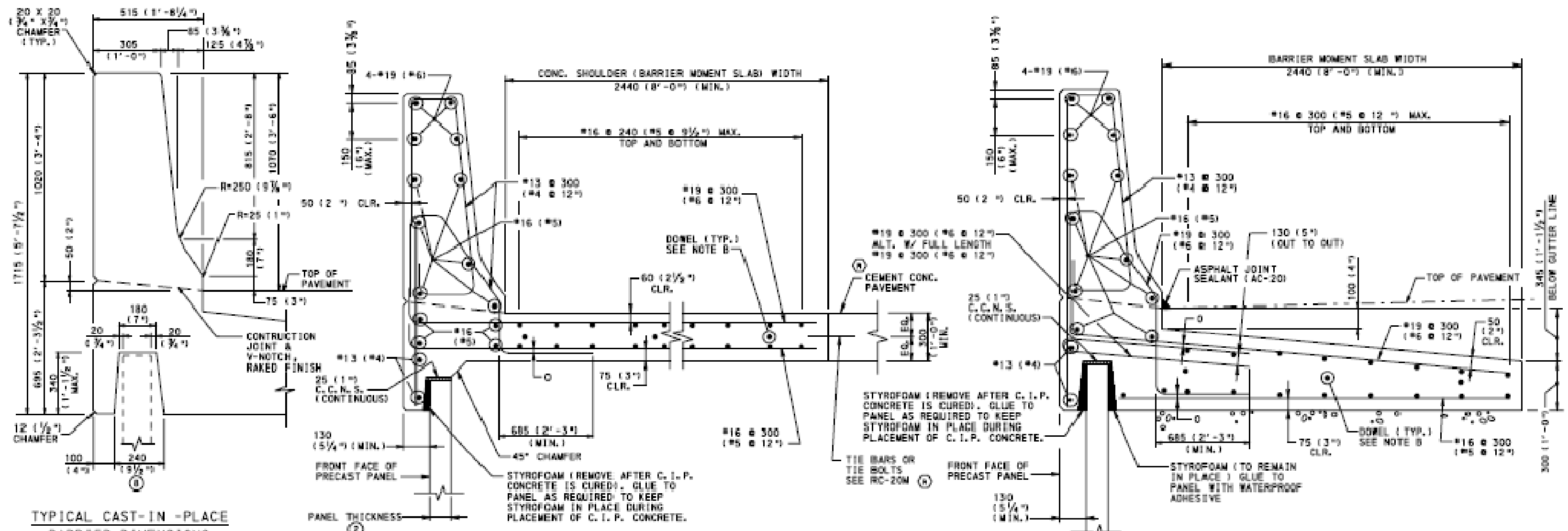
NOTE: EITHER ALL METRIC OR ALL ENGLISH VALUES MUST BE USED ON PLANS. METRIC AND ENGLISH VALUES SHOWN MAY NOT BE MIXED.

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION
BUREAU OF DESIGN

STANDARD
MECHANICALLY STABILIZED EARTH
RETAINING WALLS
ABUTMENT

RECOMMENDED JUL.24, 2006	RECOMMENDED JUL.24, 2006	RECOMMENDED JUL.24, 2006	SHEET 2 OF 13
CHIEF BRIDGE ENGINEER	DIR., BUREAU OF DESIGN	CHIEF ENGL., HWY. ADMIN.	BC-799M


CRASH WALL TYPICAL SECTION
APPROVED JOINT SEALER
15 (1/2")
25 (1")
50 (2") CLR.
MSE WALL PANELS
CAST-IN-PLACE CONC. CRASH WALL
#19 @ 300 (#6 @ 12")
#13 @ 300 (#4 @ 12")
200 (8") MIN
ANCHORS TO BE PROVIDED BY MANUFACTURER OF MSE WALL. SPACE ANCHORS @ 450 (18"), BOTH WAYS.
500 (1'-8")
300 (1'-0")
#13 @ 300 (#4 @ 12")
3-#16 (#5)
75 (3") CLR.
600 (2'-0")
CRASH WALL REQUIREMENTS FOR BRIDGES OVER RAILROADS
1. PROVIDE CRASH WALLS IN FRONT OF PREFABRICATED WALLS WHEN THE WALL IS WITHIN 7700 (25') OF THE CENTERLINE OF TRACKS.
2. CRASH WALLS SHALL BE 200 (8") THICK AND 1900 (6') ABOVE THE TOP OF RAILROAD TRACK.
C.I.P. CONCRETE COPING DETAIL
PANEL THICKNESS PLUS 100 (4") (MIN.)
#13 (#4) @ DOWEL LOCATION
#13 (#4) BARS
DRAINAGE DITCH IF REQUIRED BY DESIGN. SEE DETAIL THIS SHEET.
150 (6") MIN.
50 (2") CL.
450 (1'-6") MIN.
#13 (#4) PARALLEL WITH TOP OF PANEL
ALL STEPS ARE TO BE COVERED BY OVERHANG OF COPING
3-#13 (#4) DOWELS PER PANEL 24" MIN. LENGTH
VARIES 225 (9") (MIN.)
75 (3") MIN.
600 (2'-0")
50 (2") CL.
40 (1½") CL. (TYP)
100 (4") MIN.
PANEL THICKNESS (2)
PRECAST COPING PARTIAL ELEVATION
APPLY APPROVED LEVELING MORTAR TO CONCRETE FILL JUST PRIOR TO SETTING PRECAST COPING UNIT TO SECURE UNIT AFTER PLACEMENT.
3000 (10'-0") PRECAST COPING UNIT
12 (1/2") EXP. JOINT (TYP)
C.I.P. CONCRETE FILL
PROVIDE MIN. 75 (3") LAP BETWEEN CUT-OFF AND BOTTOM EDGE OF COPING (TYP).
NOTES:
* COPING UNIT STANDARD LENGTHS, 1500 (5'-0") AND 3000 (10'-0"), UNLESS OTHERWISE APPROVED. LINE UP COPING JOINTS WITH PANEL JOINTS WITH 75 (3")± TOLERANCE.
* R.E. WALL PANEL SHOWN, RETAINED EARTH WALL PANEL DETAIL SIMILAR.
DRAINAGE DITCH DETAIL
FASTEN IMPERVIOUS MEMBRANE TO PANELS WITH ADHESIVE
FINISHED GROUND
EROSION CONTROL MULCH BLANKET AND SEED. SEED AND MULCH (RDWY. ITEMS)
300 (12") MIN.
450 (1'-6") MIN.
IMPERVIOUS MEMBRANE
SOIL IN ACCORDANCE WITH PUB. 408 SECTION 206 (a)1.a
SOIL STABILIZING ELEMENT
SPECIFIED BACKFILL
SECTION D-D PRECAST COPING DETAIL
LIFTING INSERT
APPROVED LEVELING MORTAR
410 (1'-4") (5)
175 (7") (6)
150 (6") (MIN.)
DRAINAGE DITCH IF REQUIRED BY DESIGN. SEE DETAIL THIS SHEET.
40 (1½") CL.
#13 @ 300 (#4 @ 12")
C.I.P. CONC. FILL AS REQUIRED (VARIES 50 TO 240 (2" TO 9½")) PROVIDE REINFORCEMENT AS PER DETAIL A THIS SHEET.
95 (3¾")
210 (8½") (7)
25 (1") CLR. (MIN)
PRECAST PANEL
PANEL THICKNESS (2)
STYROFOAM (TO REMAIN IN PLACE) 600 (2'-0") WEDGES AT 3 LOCATIONS EQUALLY SPACED FOR 3000 (10') SECTIONS. USE WATERPROOF ADHESIVE TO GLUE STYROFOAM TO PANEL.
NOTE:
1. FOR LEGEND OF SYMBOLS, SEE SHEET 2.
NOTE: EITHER ALL METRIC OR ALL ENGLISH VALUES MUST BE USED ON PLANS. METRIC AND ENGLISH VALUES SHOWN MAY NOT BE MIXED.
ELEVATION
DETAIL A
#13 (#4)***
C.I.P. CONC. FILL
3-#13 (#4) EMBEDDED 300 (12") INTO PANEL * (TYP.)
PRECAST PANEL (TYP.)
SECTION C-C
** 40 (1½") CLR. MIN. 60 (2½") CLR. MAX.
#13 (#4)
C.I.P. CONCRETE FILL
PRECAST PANEL
* FOR RECTANGULAR DOUBLE WIDTH PANELS, USE 6-#13 (#4) BARS.
** BARS MAY BE SAWCUT IN FIELD TO ALLOW FOR STANDARD DETAILING OF DOWELS. TORCH CUTTING IS NOT PERMITTED. COAT CUT ENDS WITH EPOXY PAINT.
*** LONGITUDINAL REINFORCEMENT NOT REQUIRED IF DEPTH OF C.I.P. CONCRETE FILL IS LESS THAN 100 (4").
WEEPHOLE REINFORCEMENT
℄ M.S.E. WALL PANEL
102 (4") ø PVC PIPE
40 (1½") CL. (TYP)
#13 (#4) BARS @ CENTER 500 (1'-8") LONG (TYP) 4-REQ'D.
SECTION B-B
GEOTEXTILE FABRIC, CLASS 2, TYPE A 150 (6") MIN. EA. SURFACE
℄ SOIL STABILIZING ELEMENT CONNECTIONS
20 (¾") JOINT
20 (¾") EXP. JOINT MATERIAL
C.I.P. WALL
16 (#5)
#16 @ 300 (#5 @ 12")
FRONT FACE OF PREFABRICATED RETAINING WALL
125 (5")
6 (¼") JOINT
6 (¼") EXP. JOINT MAT'L.
100 (4")
40 (1½") CLR.
ELEVATION - M.S.E. WALL JUNCTION WITH C.I.P. WALL
LIMIT OF M.S.E. WALL BARRIER
LIMIT OF C.I.P. WALL BARRIER
25 (1") C.C.N.S. BETWEEN END FACES OF BARRIERS
100 (4")
FINISHED GROUND
C.I.P. WALL
FOOTING
BOTTOM OF MSE WALL PANELS OR LEVELING PAD ARE NOT TO BEAR ON FOOTINGS.
COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION
BUREAU OF DESIGN
STANDARD
MECHANICALLY STABILIZED EARTH
RETAINING WALLS
CRASH WALL AND MISCELLANEOUS
WALL DETAILS
RECOMMENDED JUL.24, 2006
RECOMMENDED JUL.24, 2006
RECOMMENDED JUL.24, 2006
CHIEF BRIDGE ENGINEER
DIR., BUREAU OF DESIGN
CHIEF ENGL., HWY. ADMIN.
SHEET 3 OF 13
BC-799M



TYPICAL CAST-IN-PLACE BARRIER DIMENSIONS

TYPICAL C.I.P. BARRIER WITH CEMENT CONCRETE SHOULDER

SEE SHEET 6 FOR PLAN OF C.I.P. MOMENT SLAB

TYPICAL C.I.P. BARRIER WITH BITUMINOUS CONCRETE SHOULDER

SEE SHEET 6 FOR PLAN OF C.I.P. MOMENT SLAB

TRAFFIC BARRIER AND MOMENT SLAB NOTES:

1. PLACE EXPANSION JOINT IN BARRIER WITH PAVEMENT JOINT, EXCEPT NOT TO FALL WITHIN 1830 (6'-0") OF CENTERLINE OF LIGHT POLE OR 600 (2'-0") OF CENTERLINE OF JUNCTION BOX. SEE SHEET 9 FOR INLET INSTALLATION DETAILS.
2. FOR BRIDGE BARRIER TO GUIDE RAIL TRANSITION, SEE SHT. 7.

NOTE:
1. FOR LEGEND OF SYMBOLS, SEE SHEET 2.

NOTE: EITHER ALL METRIC OR ALL ENGLISH VALUES MUST BE USED ON PLANS. METRIC AND ENGLISH VALUES SHOWN MAY NOT BE MIXED.

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION
BUREAU OF DESIGN

STANDARD
MECHANICALLY STABILIZED EARTH
RETAINING WALLS
C.I.P. TRAFFIC BARRIER

RECOMMENDED JUL. 24, 2006	RECOMMENDED JUL. 24, 2006	RECOMMENDED JUL. 24, 2006	SHEET 4 OF 13
CHIEF BRIDGE ENGINEER	DIR., BUREAU OF DESIGN	CHIEF ENG., HWY. ADMIN.	BC-799M

APPENDIX C: DESIGN OF MSE WALL

INPUT

Wall								
Wall height,	H =	19.763	ft	1/2 H=	9.881	ft		
Reinforcing fill length,	L =	15.500	ft	Length of slab =	4.500	ft		
	B =	15.844	ft	D_{60}=	6.800	mm	C_u =	90.667
Soil unit weight,	γ_{soil} =	0.125	kcf	D_{10}=	0.075	mm	log C_u =	1.957
Traffic surcharge,	q =	0.25	ksf					
Reinforcement fill, ϕ =		34 degrees	->	0.593	radians			
(LRFD 11.10.6.2)			->	tanϕ =	0.675	->	Ka =	0.283
Retained fill, ϕ =		30 degrees	->	0.524	radians			
			->	tanϕ_f =	0.577	->	Kaf =	0.333
Static load =		10 kips						
Panel								
First strip location =		3.957	ft	Strip width =	1.969	in. =	0.164	ft
Location of slab bottom =		2.705	ft	Strip thickness =	4	mm =	0.013	ft
First Vertical spacing of strips, S		2.213	ft	Horizontal spacing of strip=	2.443	ft		
Second Vertical spacing of strips		2.458	ft					
Panel width =		9.771	ft	Steel Reinforcement Strength f_y =			60	ksi
Panel height =		4.771	ft	density of strip per panel =		8		
Panel thickness =		0.344	ft					

1.1 Load Factor, γ (LRFD 11.5.5)

1. Typical application

1.a. Bearing Resistance

γ_{EV} = 1.35 γ_{EH} = 1.5

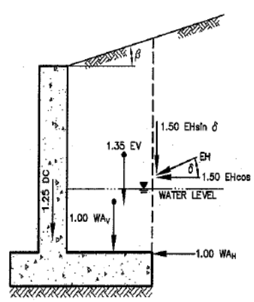


Figure C11.5.5-1 Typical Application of Load Factors for Bearing Resistance.

1.b. Sliding and Eccentricity

γ_{EV} = 1 γ_{EH} = 1.5

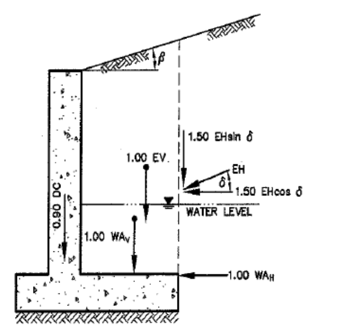


Figure C11.5.5-2 Typical Application of Load Factors for Sliding and Eccentricity.

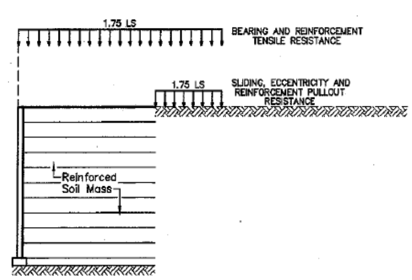
2. Live Load Surcharge on MSE wall

2.a. Bearing and reinforcement tensile resistnace

γ_{LS} = 1.75

2.b. Sliding, eccentricity and reinforcement pullout resistance

γ_{LS} = 1.75



(LRFD Figure C11.5.5-3(b))

1.2Resistance Factor, ϕ (LRFD Table 11.5.6-1)

Mechanically Stabilized Earth Walls		
Pullout resistance of tensile reinforcement,	Static loading = 0.9	
	Combined static and impact loading =	1
Tensile Resistance of strip reinforcement,	Static loading = 0.75	
	Combined static and impact loading =	1

2. Internal Stability

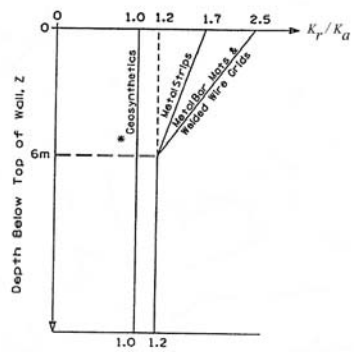
2.1 Static Load

2.1.1 Compute Kr (LRFD Figure 11.10.6.2.1-3)

γ_{EH}Kr = 1.7 × Ka = 1.7 × 0.28 = 0.48 at 0 ft

γ_{EH}Kr = 1.2 × Ka = 1.2 × 0.28 = 0.34 under 20 ft

Use interpolation at other depth



*Does not include polymer strip reinforcement

2.1.2 Fisrt strip at h1= 3.96 ft

h1 = 3.96 ft

kr = 0.453

1. Vertical stress

1) Reinforced Soil

σ_{V1} = γ_{soil} × H

σ_{V1} = 0.125 (kcf) × 3.957 (ft) = 0.495 kips/ft^2

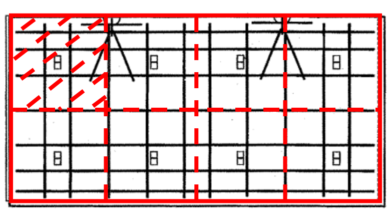
γ_{EV} × σ_{V1} = 1.35 × 0.495 = 0.668 kips/ft^2

2) Traffic surcharge

σ_{V2} = 0.25 ksf

γ_{EV} × σ_{V2} = 1.75 × 0.25 = 0.438 kips/ft^2

a) ignoring tracffic surcharge	b) including tracffic surcharge
$\sum\sigma_v$ = 0.495 kips/ft^2	$\sum\sigma_v$ = 0.745 kips/ft^2
$\sum\gamma_{EV}\sigma_v$ = 0.668 kips/ft^2	$\sum\gamma_{EV}\sigma_v$ = 1.105 kips/ft^2



2. Horizontal stress, $\sigma_H = \gamma_P(\sigma_v k_r + \Delta\sigma_H)$ (LRFD Eq. 11.10.6.2.1-1)

a) ignoring tracffic surcharge

σ_h= $\sigma_v\, k_r$ = 0.495 ksf × 0.453 = 0.224 ksf

$\gamma_{EV}\sigma_h$ = $\gamma_{EV}\,\sigma_v\, k_r$ = 0.668 ksf × 0.453 = 0.302 ksf

A_t per strip = 9.771 (ft) × 2.213 (ft) / 4 = 5.405 ft^2

Tmax = $\sigma_H\, S_v$ = 0.224 ksf × 5.405 ft^2 = **1.21** kips per strip

γ_{EV} Tmax = $\gamma_{EV}\,\sigma_H\, S_v$ = 0.302 ksf × 5.405 ft^2 = **1.63** kips per strip

b) including tracffic surcharge

$\sigma_h =$ $\sigma_v\, k_r =$ 0.745 ksf × 0.453 = 0.337 ksf

$\gamma_{EV}\sigma_h =$ $\gamma_{EV}\, \sigma_v\, k_r =$ 1.105 ksf × 0.453 = 0.500 ksf

Tmax = $\sigma_H\, S_v =$ 0.337 ksf × 5.405 $ft^2 =$ **1.82** kips per strip

γ_{EV} Tmax = $\gamma_{EV}\, \sigma_H\, S_v =$ 0.500 ksf × 5.405 $ft^2 =$ **2.70** kips per strip

2.1.3 Second strip at h2= 6.17 ft

h2 = 6.170 ft

Kr = 0.437

1. Vertical stress

1) Reinforced Soil

$\sigma_{V1} =$ γ_{soil} × H

$\sigma_{V1} =$ 0.125 (kcf) × 6.170 (ft) =

γ_{EV} × $\sigma_{V1} =$ 1.35 × /ft²

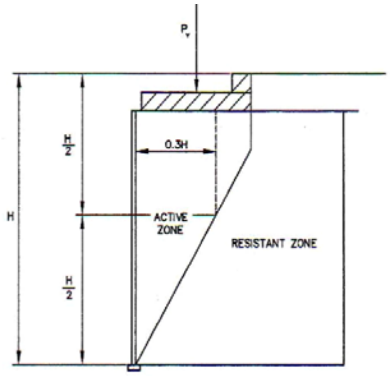


Figure 11.10.10.1-2 Location of Maximum Tensile Force Line in Case of Large Surcharge Slabs (Inextensible Reinforcements).

2) Traffic surcharge

$\sigma_{V2} =$ 0.25 ksf

γ_{EV} × $\sigma_{V2} =$ 1.75 × 0.25 = 0.438 kips/ft²

a) ignoring tracffic surcharge

$\sum\sigma_v =$ 0.771 kips/ft²

$\sum\gamma_{EV}\sigma_v =$ 1.041 kips/ft²

b) including tracffic surcharge

$\sum\sigma_v =$ 1.021 kips/ft²

$\sum\gamma_{EV}\sigma_v =$ 1.479 kips/ft²

2. Horizontal stress, $\sigma_H = \gamma_P(\sigma_v k_r + \Delta\sigma_H)$ (LRFD Eq. 11.10.6.2.1-1)

$\sigma_h =$ $\sigma_v\, k_r =$ 0.771 ksf × 0.437 = 0.337 ksf

$\gamma_{EV}\sigma_h =$ $\gamma_{EV}\, \sigma_v\, k_r =$ 1.041 ksf × 0.437 = 0.455 ksf

A_t per strip = 9.771 (ft) × 2.213 (ft) / 4 = 5.405 ft²

depth for A_t at the second layer = $S_v =$ 2.213 ft

Tmax = $\sigma_H\, S_v =$ 0.337 ksf × 5.405 $ft^2 =$ **1.822** kips per strip

γ_{EV} Tmax = $\gamma_{EV}\, \sigma_H\, S_v =$ 0.455 ksf × 5.405 $ft^2 =$ **2.459** kips per strip

2.1.4 Third strip at h3= 8.63 ft

h3 = 8.628 ft

Kr = 0.420

1. Vertical stress

1) Reinforced Soil

$\sigma_{V1} =$ γ_{soil} × H

$\sigma_{V1} =$ 0.125 (kcf) × 8.628 (ft) = 1.079 kips/ft²

γ_{EV} × $\sigma_{V1} =$ 1.35 × 1.079 = 1.456 kips/ft²

2) Traffic surcharge

σ_{V2} = 0.25 ksf

$\gamma_{EV} \times \sigma_{V2}$ = 1.75 × 0.25 = 0.438 kips/ft^2

a) ignoring tracffic surcharge			b) including tracffic surcharge		
$\sum\sigma_v$ =	1.079	kips/ft^2	$\sum\sigma_v$ =	1.329	kips/ft^2
$\sum\gamma_{EV}\sigma_v$ =	1.456	kips/ft^2	$\sum\gamma_{EV}\sigma_v$ =	1.894	kips/ft^2

2. Horizontal stress, $\sigma_H = \gamma_P(\sigma_v k_r + \Delta\sigma_H)$ (LRFD Eq. 11.10.6.2.1-1)

σ_h= $\sigma_v\, k_r$ = 1.079 ksf × 0.420 = 0.453 ksf

$\gamma_{EV}\sigma_h$ = $\gamma_{EV}\,\sigma_v\, k_r$ = 1.456 ksf × 0.420 = 0.611 ksf

A_t per strip = 9.771 (ft) × 2.458 (ft) / 4 = 6.005 ft^2

depth for A_t at the second layer = S_v = 2.458 ft

Tmax = $\sigma_H\, S_v$ = 0.453 ksf × 6.005 ft^2 = **2.718** kips per strip

γ_{EV} Tmax = $\gamma_{EV}\,\sigma_H\, S_v$ = 0.611 ksf × 6.005 ft^2 = **3.669** kips per strip

2.1.5 Forth strip at h4= 11.09 ft

h4 = 11.087 ft

Kr = 0.402

1. Vertical stress

1) Reinforced Soil

σ_{V1} = γ_{soil} × H

σ_{V1} = 0.125 (kcf) × 11.087 (ft) = 1.386 kips/ft^2

$\gamma_{EV} \times \sigma_{V1}$ = 1.35 × 1.386 = 1.871 kips/ft^2

2) Traffic surcharge

σ_{V2} = 0.25 ksf

$\gamma_{EV} \times \sigma_{V2}$ = 1.75 × 0.25 = 0.438 kips/ft^2

a) ignoring tracffic surcharge			b) including tracffic surcharge		
$\sum\sigma_v$ =	1.386	kips/ft^2	$\sum\sigma_v$ =	1.636	kips/ft^2
$\sum\gamma_{EV}\sigma_v$ =	1.871	kips/ft^2	$\sum\gamma_{EV}\sigma_v$ =	2.308	kips/ft^2

2. Horizontal stress, $\sigma_H = \gamma_P(\sigma_v k_r + \Delta\sigma_H)$ (LRFD Eq. 11.10.6.2.1-1)

σ_h= $\sigma_v\, k_r$ = 1.386 ksf × 0.402 = 0.557 ksf

$\gamma_{EV}\sigma_h$ = $\gamma_{EV}\,\sigma_v\, k_r$ = 1.871 ksf × 0.402 = 0.753 ksf

A_t per strip = 9.771 (ft) × 2.458 (ft) / 4 = 6.005 ft^2

depth for A_t at the second layer = S_v = 2.458 ft

Tmax = $\sigma_H\, S_v$ = 0.557 ksf × 6.005 ft^2 = **3.348** kips per strip

γ_{EV} Tmax = $\gamma_{EV}\,\sigma_H\, S_v$ = 0.753 ksf × 6.005 ft^2 = **4.519** kips per strip

2.1.6 Fifth strip at h5= 13.54 ft

h5 = 13.545 ft
Kr = 0.385

1. Vertical stress

1) Reinforced Soil

σ_{V1} = γ_{soil} × H

σ_{V1} = 0.125 (kcf) × 13.545 (ft) = 1.693 kips/ft^2

γ_{EV} × σ_{V1} = 1.35 × 1.693 = 2.286 kips/ft^2

2) Traffic surcharge

σ_{V2} = 0.25 ksf

γ_{EV} × σ_{V2} = 1.75 × 0.25 = 0.438 kips/ft^2

a) ignoring tracffic surcharge

$\sum\sigma_v$ = 1.693 kips/ft^2

$\sum\gamma_{EV}\sigma_v$ = 2.286 kips/ft^2

b) including tracffic surcharge

$\sum\sigma_v$ = 1.943 kips/ft^2

$\sum\gamma_{EV}\sigma_v$ = 2.723 kips/ft^2

2. Horizontal stress, $\sigma_H = \gamma_P(\sigma_v k_r + \Delta\sigma_H)$ (LRFD Eq. 11.10.6.2.1-1)

σ_h= σ_v k_r = 1.693 ksf × 0.385 = 0.652 ksf

$\gamma_{EV}\sigma_h$ = γ_{EV} σ_v k_r = 2.286 ksf × 0.385 = 0.880 ksf

A_t per strip = 9.771 (ft) × 2.458 (ft) / 4 = 6.005 ft^2

depth for A_t at the second layer = S_v = 2.458 ft

Tmax = σ_H S_v = 0.652 ksf × 6.005 ft^2 = **3.913** kips per strip

γ_{EV} Tmax = γ_{EV} σ_H S_v = 0.880 ksf × 6.005 ft^2 = **5.283** kips per strip

2.1.7 Sixth strip at h6= 16.00 ft

h6 = 16.003 ft
Kr = 0.368

1. Vertical stress

1) Reinforced Soil

σ_{V1} = γ_{soil} × H

σ_{V1} = 0.125 (kcf) × 16.003 (ft) = 2.000 kips/ft^2

γ_{EV} × σ_{V1} = 1.35 × 2.000 = 2.701 kips/ft^2

2) Traffic surcharge

σ_{V2} = 0.25 ksf

γ_{EV} × σ_{V2} = 1.75 × 0.25 = 0.438 kips/ft^2

a) ignoring tracffic surcharge

$\sum\sigma_v$ = 2.000 kips/ft^2

$\sum\gamma_{EV}\sigma_v$ = 2.701 kips/ft^2

b) including tracffic surcharge

$\sum\sigma_v$ = 2.250 kips/ft^2

$\sum\gamma_{EV}\sigma_v$ = 3.138 kips/ft^2

2. Horizontal stress, $\sigma_H = \gamma_P(\sigma_v k_r + \Delta\sigma_H)$ (LRFD Eq. 11.10.6.2.1-1)

a) ignoring tracffic surcharge

σ_h=	$\sigma_v\ k_r$ =	2.000 ksf ×	0.368 =	0.735 ksf
$\gamma_{EV}\sigma_h$ =	$\gamma_{EV}\ \sigma_v\ k_r$ =	2.701 ksf ×	0.368 =	0.992 ksf

A_t per strip = 9.771 (ft) × 2.458 (ft) / 4 = 6.005 ft^2

depth for A_t at the second layer = S_v = 2.458 ft

Tmax = $\sigma_H\ S_v$ = 0.735 ksf × 6.005 ft^2 = **4.415** kips per strip

γ_{EV} Tmax = $\gamma_{EV}\ \sigma_H\ S_v$ = 0.992 ksf × 6.005 ft^2 = **5.960** kips per strip

b) including tracffic surcharge

σ_h=	$\sigma_v\ k_r$ =	2.250 ksf ×	0.368 =	0.827 ksf
$\gamma_{EV}\sigma_h$ =	$\gamma_{EV}\ \sigma_v\ k_r$ =	3.138 ksf ×	0.368 =	1.153 ksf

Tmax = $\sigma_H\ S_v$ = 0.827 ksf × 6.005 ft^2 = **4.97** kips per strip

γ_{EV} Tmax = $\gamma_{EV}\ \sigma_H\ S_v$ = 1.153 ksf × 6.005 ft^2 = **6.93** kips per strip

2.1.8 Seventh strip at h7= 18.46 ft

h7 = 18.462 ft

Kr = 0.350

1. Vertical stress

1) Reinforced Soil

σ_{V1} = γ_{soil} × H

σ_{V1} = 0.125 (kcf) × 18.462 (ft) = 2.308 kips/ft^2

γ_{EV} × σ_{V1} = 1.35 × 2.308 = 3.115 kips/ft^2

2) Traffic surcharge

σ_{V2} = 0.25 ksf

γ_{EV} × σ_{V2} = 1.75 × 0.25 = 0.438 kips/ft^2

a) ignoring tracffic surcharge		b) including tracffic surcharge	
$\sum\sigma_v$ =	2.308 kips/ft^2	$\sum\sigma_v$ =	2.558 kips/ft^2
$\sum\gamma_{EV}\sigma_v$ =	3.115 kips/ft^2	$\sum\gamma_{EV}\sigma_v$ =	3.553 kips/ft^2

2. Horizontal stress, $\sigma_H = \gamma_P(\sigma_v k_r + \Delta\sigma_H)$ (LRFD Eq. 11.10.6.2.1-1)

a) ignoring tracffic surcharge

σ_h=	$\sigma_v\ k_r$ =	2.308 ksf ×	0.350 =	0.808 ksf
$\gamma_{EV}\sigma_h$ =	$\gamma_{EV}\ \sigma_v\ k_r$ =	3.115 ksf ×	0.350 =	1.091 ksf

A_t per strip = 9.771 (ft) × 2.458 (ft) / 4 = 6.005 ft^2

depth for A_t at the second layer = S_v = 2.458 ft

$Tmax = \sigma_H S_v =$ 0.808 ksf × 6.005 $ft^2 =$ **4.852** kips per strip

$\gamma_{EV} Tmax = \gamma_{EV} \sigma_H S_v =$ 1.091 ksf × 6.005 $ft^2 =$ **6.550** kips per strip

b) including tracffic surcharge

$\sigma_h =$ $\sigma_v k_r =$ 2.558 ksf × 0.350 = 0.896 ksf

$\gamma_{EV}\sigma_h =$ $\gamma_{EV} \sigma_v k_r =$ 3.553 ksf × 0.350 = 1.244 ksf

$Tmax = \sigma_H S_v =$ 0.896 ksf × 6.005 $ft^2 =$ **5.38** kips per strip

$\gamma_{EV} Tmax = \gamma_{EV} \sigma_H S_v =$ 1.244 ksf × 6.005 $ft^2 =$ **7.47** kips per strip

2.1.10 Summary

1) Pullout - ignoring traffic surcharge

Rein. Layer NO.	**Z** (ft)	**T** (kips)	**γT** (kips)
1	3.957	1.210	**1.634**
2	6.170	1.822	**2.459**
3	8.628	2.718	**3.669**
4	11.087	3.348	**4.519**
5	13.545	3.913	**5.283**
6	16.003	4.415	**5.960**
7	18.462	4.852	**6.550**