HEAVY VEHICLE BARRIER DESIGN WITH STRUCTURALLY INDEPENDENT FOUNDATION

A Thesis

by

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ABSTRACT

The Texas Department of Transportation (TxDOT) *Bridge Design Manual* (*BDM*) requires that bridge columns that are placed near a roadway to be designed or shielded for impact. Many of them were built years before the *Bridge Design Manual* reflected these guidelines, leaving shielding as the only effective solution. *BDM* demands the design of the barrier to be 54 inches tall to maintain the structurally independent foundation and to meet *Manual for Assessing Safety Hardware* (MASH) Test Level 5 (TL-5) for any bridge pier within 10 feet of the roadway. A barrier design meeting these requirements is not currently available, neither a specific method to design such a barrier. Furthermore, TxDOT demands the design of a 36-inch tall structurally independent barrier to be placed as a continuation barrier from the bridge deck to the roadway and to meet MASH Test Level 4 requirements. The main objectives of this work are to (i) develop conceptual designs of structurally independent foundation with 54-inch tall single slope concrete barrier (SSCB) for MASH TL-5 and 36-inch tall SSCB for MASH TL-4, (ii) evaluate, develop and simulate full-scale finite element models (FEM) of the concepts, and (iii) select the most critical design for further evaluation.

DEDICATION

To my best friend, Kristiano:

For being my guardian angel.

To my parents, Qesko and Fatmira:

For their unconditional love and support.

To my sister and brother, Enrajda and Aleksandro:

For always being there for me.

To my partner, Karen:

For her love.

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Contributors

This work was supervised by a thesis committee consisting of Professor Stefan Hurlebaus and Assistant Professor Petros Sideris of the Department of Civil Engineering and Assistant Professor Sevan Gonezen of the Department of Mechanical Engineering.

Some work depicted in Chapter 3 was conducted in part by Nauman Sheikh and James Kovar.

All other work conducted for the thesis was completed by the student independently.

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The contents of this thesis are solely the responsibility of the author and do not necessarily represent the official views of Texas A&M Transportation Institute.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

1. INTRODUCTION

1.1 Problem Background and Significance

The area between the lanes in a divided highway and area beyond the road shoulder have been valuable features regarding the safety of the motoring public as errant vehicles may pull over and come to a stop without risking colliding with the oncoming traffic. However, this is not always the case when objects or structures are placed and constructed in these “safe” clear zones. Examples of these structures and objects are bridge piers, roadside signs, drainage structures etc. To avoid fatalities and also preserve the structures, special guidance is usually provided to design or shield them. This thesis studies one type of these fixed objects, the bridge piers.

Regarding bridge columns or piers, additional risk might exist from the possibility of a pier collapsing from a heavy-load truck impact. An impact with a single unit truck (SUT) or a trailer truck produces a significant force and might result in a catastrophic failure leading to the collapse of the entire bridge structure. Figure 1 and Figure 2 depict the impact of a tractor-trailer with a bridge pier in Dallas, Texas in 2001.

Figure 1. Collapsed Bridge in Dallas, Texas (TxDOT, 2001)

Figure 2. Impacted Bridge Pier by a Trailer-Truck in Dallas, Texas (TxDOT, 2001)

TxDOT *BDM* requires for columns or piers that are located near the roadways where the traffic annual frequency passes a specified threshold, that one of the two following options should be implemented to nurse the risk of collision with a heavy vehicle.

The first option, which is also the approach that is studied by this thesis, is to shield the pier with a barrier. In the case of the pier being placed more than 10 feet from the edge of the roadway, it should be shielded with a 42-inch tall MASH TL- 5 single slope barrier. If, however, the pier is placed within 10 feet of the edge of the roadway, the TxDOT *BDM* demands for it to be shielded with a "structurally independent, ground-mounted 54-inch tall single slope barrier (or other 54-inch tall, Test Level approved equivalent)**"** (TxDOT, 2018). The second option is to initially design and construct the column such that it will be able to sustain a heavy-load vehicle impact. This approach is studied by Sharma et al. (2012). A bridge pier capable of sustaining such an impact is shown in Figure 3.

Figure 3. Bridge Pier Contains Heavy Vehicle in Dallas, Texas (TxDOT, 2007)

This option is not practically feasible in most of the cases. Most of the bridge columns, that are now qualified to be protected by the *Bridge Design Manual*, were built several years ago and the only solution for them is Option 1. Moreover, to account for the high energy of a heavy vehicle impact (around 600-kip static load according to *BDM*), the column will have to be designed significantly larger compared to the demand for supporting the super structure of a bridge. This is not always possible, as it requires design adjustments for the entire structure to account for the spatial needs of the new column.

The annual frequency for a bridge pier or bent to be hit by a vehicle is calculated using the following formula given in *BDM Section 2.2 Vehicular Collision Force*:

$$AF_{HPB}=2(ADTT)(P_{HPB})365 \qquad (1.1)$$

Where:

$AF_{HPB} \stackrel{\text{def}}{=}$ Annual frequency for a bridge pier to be hit by a vehicle

$ADTT \stackrel{\text{def}}{=}$ Number of trucks per day in one direction

$P_{HPB} \stackrel{\text{def}}{=}$ Annual probability for a bridge pier to be hit by a heavy vehicle

Eq. (1.1) is also found in American Association of State Highway Transportation Officials (AASHTO) *LRFD Bridge Design Manual* as Equation C3.6.5.1-1. For piers and bents to be eligible for investigation, AF_{HPB} has to be greater or equal to 0.001.

According to TxDOT, currently there is no 54-inch tall single slope barrier that is mounted on a structurally independent foundation that has also been crash tested to MASH Test Level 5. Moreover, a method for designing such barriers does not exist.

AASHTO published a consequent 4th edition of the *Roadside Design Guide* including several updates on Chapter 6 about the median barriers in 2006. However, these updates only concern and mention median obstacles briefly and thus, are not of significance to this study.

Additionally, to successfully construct a MASH Test Level 4 or 5 single slope concrete barrier mounted on a structurally independent foundation requires a sizable foundation. Depending on the site conditions and limitations, several variations of such foundations can be designed with each of them having its advantages and disadvantages. For sites with limited depth, a shallow moment slab foundation is suitable but the site should also allow larger width to account for this specific design. On the other hand, a drilled shaft foundation might not require a large width, but a greater depth is needed.

Therefore, to shield columns in different site conditions, several foundation concepts are designed and tested. This thesis aims to select the most appropriate designs and evaluate them with the standards required by TxDOT.

1.2 Research Objective

This work developed several concepts of the 36-inch and 54-inch tall single slope barriers mounted on structurally independent foundations. Some of the concepts include wall type footing, shallow footing, drilled shaft footing, or other hybrid footings. TxDOT initially selected three foundations design concepts from the preliminary concepts to further develop. Simulation models using Finite Element Modeling for the selected designs were created and dynamic vehicle impacts were then performed. These simulations determined the overall permanent and dynamic deflections of the system and the impact loads on the foundation and the barrier.

The deflections are important parameters in this study, as they determine the minimum offset necessary behind the barrier where a bridge pier can be placed to avoid any damage by the impact. Based on the simulation results, the designs were updated and optimized to less conservative concepts. Finally, the results were presented to TxDOT alongside the necessary recommendations.

2. LITERATURE REVIEW

A single slope concrete barrier with structurally independent foundation meeting the requirements demanded by the TxDOT *BDM* currently does not exist. Furthermore, guidelines on the specific methodology and procedure to design such a barrier are not available. Barrier types that are currently being used as roadside safety features were thoroughly investigated before designing the preliminary concepts. Some of the barriers studied are briefly introduced in this chapter. Also, the test levels presented in MASH and how they have changed by the transition from National Cooperative Highway Research Program (NCHRP) Report 350 were studied.

2.1. Longitudinal Barriers

A longitudinal barrier is a physical structure implemented alongside a roadway with the purpose of redirecting errant vehicles, protecting the fixed object placed near the roadway by shielding it or preventing the vehicles from rolling over dangerous slopes and injuring the occupants (Jordan, 2017). These longitudinal barriers are usually placed between the traffic lanes as medians keeping the errant vehicles from driving into the opposite traffic. Other longitudinal barriers exist, such as bridge rails, transitions, terminals and guardrails (Ross et al., 1993). MASH classifies the longitudinal barriers in the following three categories:

- Flexible and semi-rigid barriers
- Rigid barriers
- Barriers transitions

Traffic barriers may also be dangerous if not used appropriately. They can be a hazard for the motoring vehicles when the implementation has not been reasonable. When designing and constructing a roadway, the use of safety barriers should be carefully considered with the purpose of limiting their use. When shielding a fixed object, the purpose of the safety features is to provide a less harming impact to the occupants than the impact caused by the collision with the fixed object itself. The same argument stands for vehicles that drive off the roadway. If the slope beyond the roadway shoulder is not steep enough to cause other than minor injuries when the vehicles leave the road, the installation of a longitudinal barrier might not be needed. The placement of such barrier might worsen the collision situation.

The *Roadway Design Manual* by TxDOT has developed a priority treatment list to consider if a roadside barrier should be installed. The treatment is in the following priority:

1. Remove the obstacle.
2. Replace the obstacle so it can be considered safe.
3. Move the obstacle out of the clear zone to reduce the possibility of a collision.
4. Treat the obstacle to reduce accident severity, i.e., use flush or yielding designs.
5. Shield the obstacle with a safety barrier (median barrier, roadside barrier, or crash cushion).
6. Delineate the obstacle if the above alternatives are not appropriate.

However, sometimes the need of a longitudinal barrier is crucial and its utilization cannot be avoided. Example features for flexible and semi-rigid barrier and rigid barrier categories are briefly presented below.

2.1.1. Flexible Barriers

This longitudinal barrier is the one of most common barrier types utilized in preventing the collision caused by vehicles driving off the roadway around the world (Nimmi et al., 2011). The flexible barrier consists of generally three or four pre-tensioned wire ropes supported by equally spaced steel posts.

There are two general configurations of the highly tensioned ropes. The first configuration features all the ropes positioned parallel to the surface of the road. The second configuration consists of the lower two ropes tangled with each other and the upper two ropes placed parallel to the surface of the road. This system exercises two mechanisms to absorb the kinetic energy of the impacting vehicle. The first mechanism is employed by the wire ropes, which upon collision, deflect and absorb the majority of the energy. They also guide the vehicle towards the posts, which provide the second mechanism. The posts break progressively, thus dissipating the remaining kinetic energy until the vehicle comes to rest.

Figure 4 shows a TL-3 system with three strands developed by Valmont Highway.

Figure 4. ArmorWire TL-3 Barrier Developed by Valmont Highway

2.1.2. Semi-Rigid Barriers

Probably the most well known roadside safety features in the world are the guardrail systems. These W-section galvanized steel beams supported by steel or timber posts have been protecting the errant motorists from colliding with hazards off the roadway for more than 50 years (Faller et al., 2004). The energy absorption mechanism for guardrails uses the versatile characteristics of the beam in bending and tension. The W beam contains and redirects the vehicle while the steel or timber posts provide lateral resistance. The main components of a guardrail system are the W-beam rail, the post (which can be steel or timber), the blocks (offer anti-snagging support), the anchorages and the terminals. The guardrails behavior falls between the flexible and the rigid barriers. This type of system contains and redirects the system without imposing high deceleration forces on the occupants.

Figure 5 shows the front view of the Midwest guardrail system design and Figure 6 shows the side view.

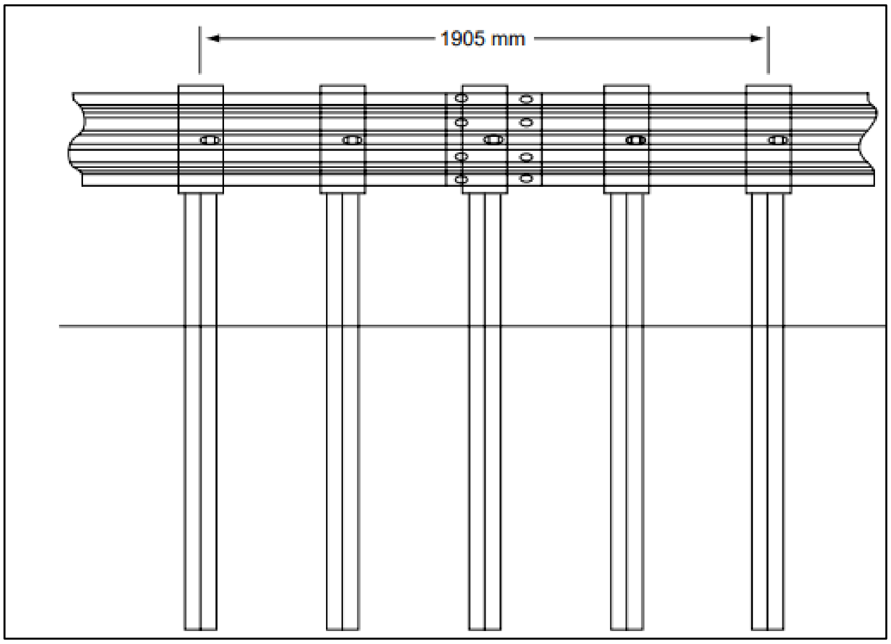


Figure 5. Front View of the Midwest Guardrail System (Faller et al., 2004)

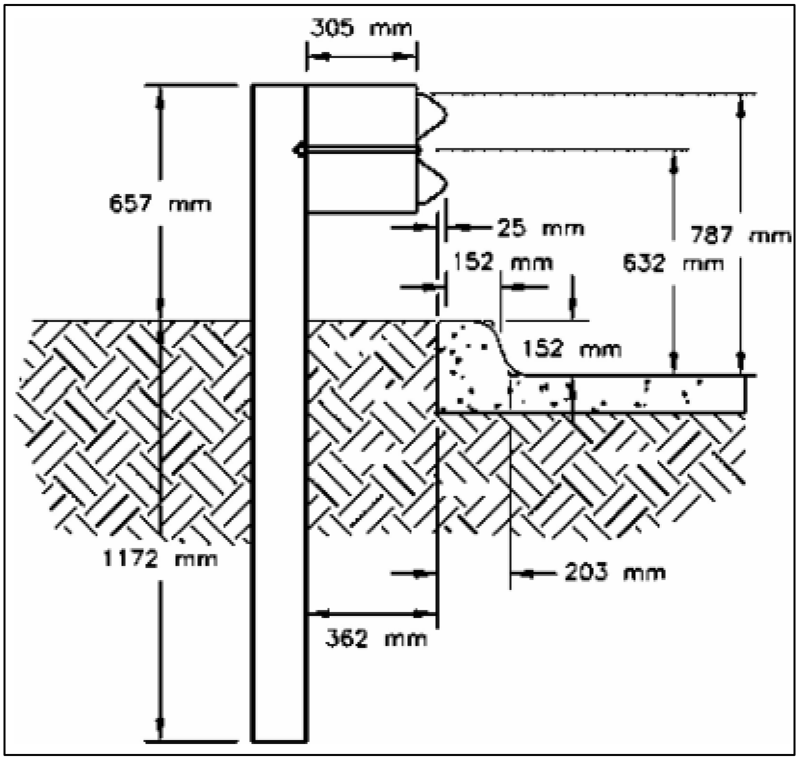


Figure 6. Side View of the Midwest Guardrail System (Faller et al., 2004)

2.1.3. Rigid Barriers

Bligh et al. (2006) mention that the rigid concrete barrier profiles were initially developed in the United States in mid-1960s for implementation in narrow medians. They were later improved to reflect the actual infrastructure and traffic conditions. The types of barriers developed in this thesis are also rigid barriers. These barriers are usually made of concrete and steel reinforcement. The rigid barriers are designed to be crashworthy. They are supposed to prevent any lateral displacement of the vehicle. The permanent deflection should be as minimal as possible to avoid the need of barrier readjustment. Their maintenance-free characteristic makes these barriers preferable for median use in areas with heavy traffic. Common profiles of the rigid barriers include constant or single slope barrier (the same profile studied in this thesis), vertical face barrier, F-shape barrier and the New Jersey safety barrier. Unlike the flexible barriers, the rigid concrete barriers yield higher deceleration rates and increase the risk of injury for the occupants upon impact. The energy absorbing mechanism comes from the shape of the barrier itself. The barrier dissipates the kinetic energy by redirecting the vehicle in a parallel direction to the travel way. Some part of the energy is also absorbed by the impacting vehicle.

A single constant slope concrete barrier similar to the profiles developed in this thesis is shown in Figure 7. This design features a constant sloped face and a flat face at the top. Also, Figure 8 shows a New Jersey barrier next to a later generation F-shape barrier profile developed by J-J Hooks. Both these profiles feature a vertical face at the base, a lower sloped section, a higher sloped section and a flat horizontal face on top.

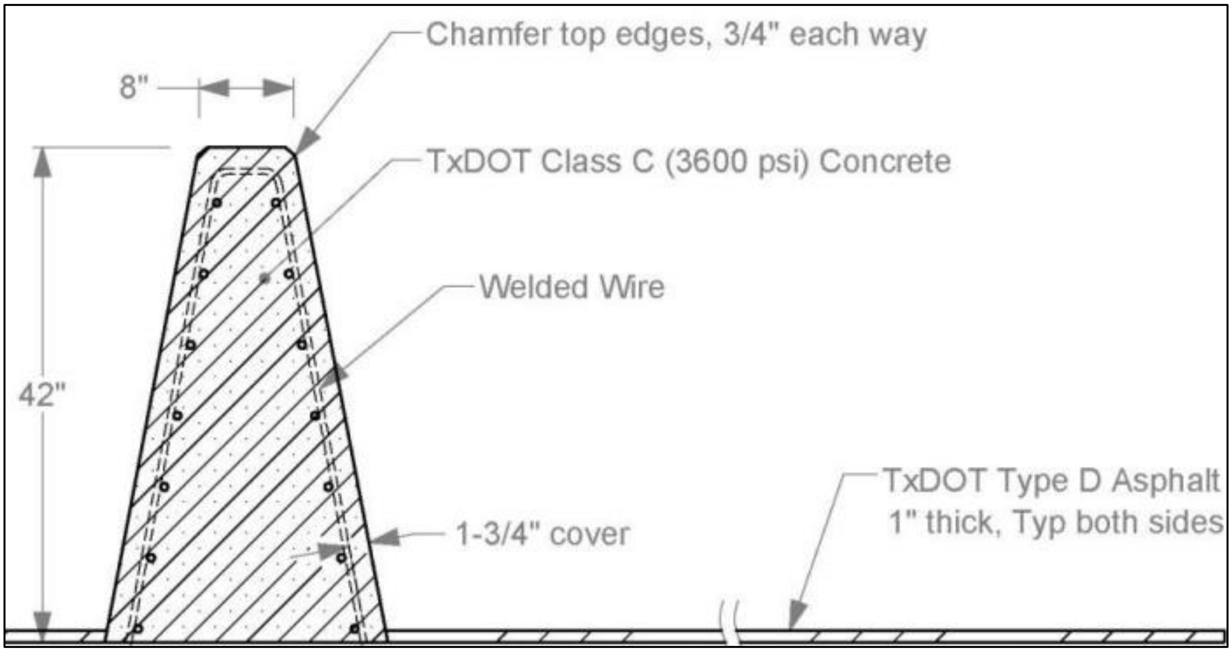


Figure 7. 42-inch Tall SSCB (Bligh et al., 2018)

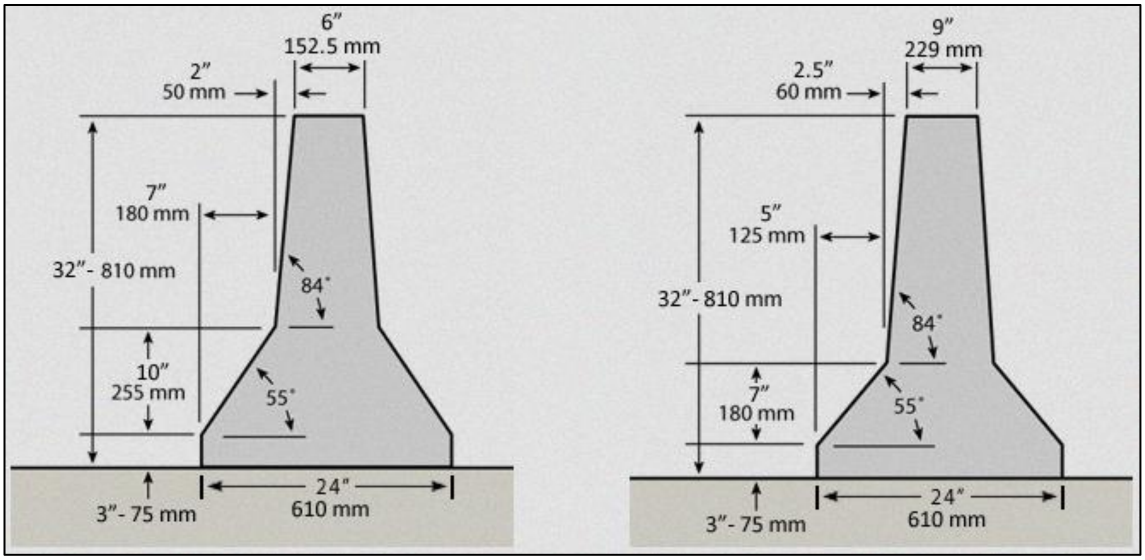


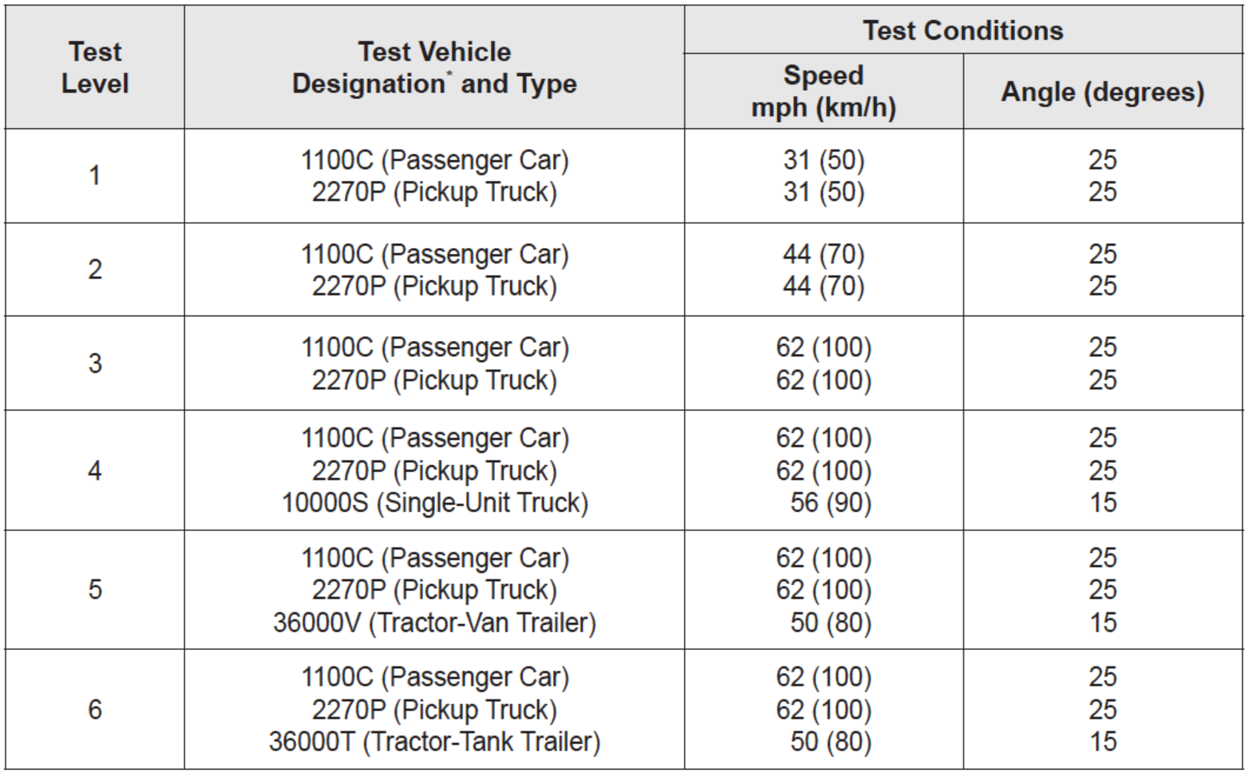
Figure 8. New Jersey Shape (left) and F-shape (right) Barriers Developed by J-J Hooks

2.2. MASH Test Levels

The longitudinal barrier is only one type of several safety features currently developed and in use. MASH safety features list includes also terminals (such as guardrails), crash cushions, support structures, work zone attenuation and other devices such as traffic gates or drainage features. All these safety features are tested on the same standard test levels as defined by MASH. The longitudinal barriers are the only safety feature to be tested to six levels while others may be evaluated to three test levels.

When MASH evolved as an updated replacement for NCHRP Report 350 in 2009, the impact severity for several tests was significantly increased. For example, for Test Level 4-12, which is also used in this thesis, the impact severity was bumped up by 56% (Sheikh et al., 2012). Also, the mass of the test vehicle enlarged from 17,640 to 22,050 pounds and the impact speed went up from 50 to 56 mph.

Figure 9 defines the conditions for each test level.



Test Level	Test Vehicle Designation* and Type	Test Conditions	
		Speed mph (km/h)	Angle (degrees)
1	1100C (Passenger Car) 2270P (Pickup Truck)	31 (50) 31 (50)	25 25
2	1100C (Passenger Car) 2270P (Pickup Truck)	44 (70) 44 (70)	25 25
3	1100C (Passenger Car) 2270P (Pickup Truck)	62 (100) 62 (100)	25 25
4	1100C (Passenger Car) 2270P (Pickup Truck) 10000S (Single-Unit Truck)	62 (100) 62 (100) 56 (90)	25 25 15
5	1100C (Passenger Car) 2270P (Pickup Truck) 36000V (Tractor-Van Trailer)	62 (100) 62 (100) 50 (80)	25 25 15
6	1100C (Passenger Car) 2270P (Pickup Truck) 36000T (Tractor-Tank Trailer)	62 (100) 62 (100) 50 (80)	25 25 15

Figure 9. MASH Test Levels (MASH, 2016)

The test level is specified by the mass of the vehicle, the impacting speed and the angle of approach. The mass of the vehicle defines indeed the type of the car. The first three levels are defined to incorporate a passenger car and a pickup truck only, while the latter three involve heavy vehicles. The lower the testing level is, the lower the impact speed is. Generally, the safety features that tested for the lower levels are installed in roadways with low volume, typically in urban areas.

On the other hand, the safety features that pass higher test levels are generally used in high-speed, high-volume rural roadways and freeways. As the brief introduction of the barrier types in the beginning of this chapter noted, different systems behave differently due to their specific energy absorbing mechanisms. This means that safety features evaluated for the same MASH test level do not perform in the same manner and give different results. Thus, they have different applications.

In this thesis, two test levels are used to evaluate the systems that are developed. The first test is MASH Test Level 4 with a single unit truck, also called MASH TL 4-12. The performance of a 36-inch tall single slope concrete barrier with structurally independent foundation is evaluated with the MASH TL 4-12 test. The second test used is MASH Test Level 5-12 with a tractor-trailer, which evaluates the performance of a 54-inch tall SSCB with structurally independent foundation.

3. RESEARCH PLAN AND PROCEDURE

In a previous study, preliminary design concepts of the single slope barriers mounted on structurally independent foundations for MASH TL-4 and TL-5 were developed. Some of these concepts were then selected to be evaluated through finite element simulations in the next step. Then, finite element models of the barriers, the foundations and the different types of soil were built. Ultimately, these models were used to perform crash simulations for both test levels. Based on the results, it was decided on the final design of the barriers and their independent foundation concept.

3.1. Preliminary Design and Selection of Initial Concepts

Several initial concepts of the 54-inch (TL-5) and the 36-inch (TL-4) tall single slope concrete barriers mounted on structurally independent foundation were developed in a preliminary study.

The goal of this research study is to eventually design and evaluate the barriers that are able to protect a bridge column adjacent to the roadway getting hit by a tractor-trailer (TL-5) and a single unit truck (TL-4). The impact of such heavy vehicles with bridge columns might cause the columns to fail and the bridge to catastrophically collapse as shown in Figure 1.

Moreover, these barrier designs must meet the crashworthy requirements specified in MASH for both cases, TL-4 and TL-5. These requirements demand that upon impact with the barrier and the foundation system, the vehicle must be contained and redirected. Also, the barrier-foundation system must meet the occupant safety regulations per respective test level. Another important aspect of the system, that determines if the barriers are feasible or not, is the permanent deflection. If the permanent deflection is large, the barrier becomes very costly as it should be aligned and put back to the initial position after every impact. All the above factors were considered to conclude with the best solutions for the stated problem.

Furthermore, the preliminary design process focused mainly on two aspects. The first aspect considered the parameters of the 54-inch and the 36-inch tall single slope concrete barriers. The second aspect considered the parameters of the structurally independent foundations.

To estimate the impact loads for a MASH Test Level 4 and MASH Test Level 5 crash, a static analysis on each foundation concept was performed. This approach accounts only for the static force resulting from the weight of the barrier-foundation system and the resistance provided by the soil. This analysis approach ignored the dynamic inertia factor and subsequently making the foundation design conservative regarding its size**.**

Data from NCHRP Project 22-20 (2) were used to estimate the static lateral impact load of 260 kips at a height of 52 inches above grade for the design of the 54-inch barrier-foundation system. NCHRP Project 22-20 (2) investigates and provides design lateral loads for MASH TL-3 through MASH TL-5 impact with a rigid concrete barrier supported by a mechanically stabilized Earth wall. Based on the same report, a static lateral load of 80 kips was selected for the design of the 36-inch barrier-foundation system. It is very important to note that the design guidelines provided by this report were estimated using finite element impact analysis.

Also, Fossier et al. (2016) mention that for any barrier taller than 43 inches, the system will sustain the maximum lateral load of the impact with a 79,300-pound tractor-trailer, which is approximately 260 kips. However, this data is useful mainly for the design of the MASH TL-5 barrier. The maximum load of 260 kips is indeed a static load and will be fully applied only to the barrier. As the barrier is deflected from inertia and the foundation moves while buried in soil, the load applied to the foundation will eventually be reduced. The effects of the soil properties are discussed in Section 3.2. If the soil is found to be expansive, there will be a high potential for damage on the foundation (Rodger et al., 1985). Soil properties play a significant role in the final selection of the systems.

The initial static load estimates guided the development of the foundation concepts, their preliminary shape and size, so that the 36-inch and 54-inch tall single slope concrete barrier-foundation systems could sustain structural independence.

The barrier-foundation system, as mentioned above, was assumed to be rigid in the preliminary analysis. To evaluate the resistance of the soil to the displacement of the barrier and the movement of the foundation system as the lateral load was applied, a modified Broms load analysis method (Broms, 1964) was used.

3.1.1. 54-inch Tall Single Slope Concrete Barrier with Structurally Independent Foundation Concepts (MASH TL-5)

Seven preliminary concepts for the barrier-foundation system of the 54-inch single slope concrete barrier mounted on a structurally independent foundation were presented and developed. For the concrete barrier, the single face barrier profile shown in Figure 10 was used. TxDOT selected three of these designs for further evaluation.

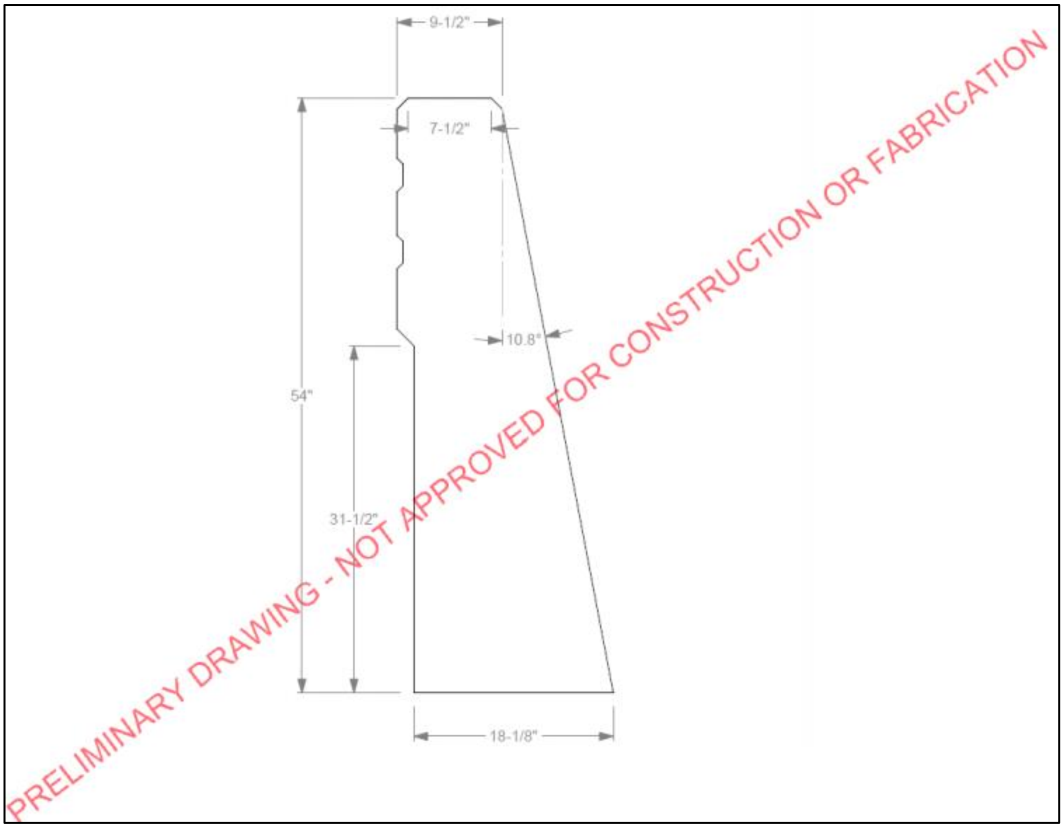


Figure 10. 54-inch Tall Single Slope Barrier Profile (TTI, 2017)

Design Concept 1 – Drilled Shaft

The first foundation preliminary design concept considered is shown in Figure 11 and it presents the utilization of a drilled shaft system as the foundation. The depth of the shafts provides a strong resistance to counter the overturning moment caused by the vehicle impact. However, some sites may not be feasible for the amount of depth needed to install the concrete piers. This system consists of reinforced concrete piers tied to the barrier. This preliminary design assumed four reinforced concrete piers per every 50 feet of barrier length. The shaft diameter was developed to be 18 inches per TxDOT standard shaft design. From the preliminary design analysis, the shaft spacing was decided to be 14 feet and the depth 10 feet. Also, a design with a shorter shaft length of 6 feet was evaluated, since the results of the preliminary concept were considered too conservative.

Design Concept 2 – Concrete Beam

The second preliminary concept developed and proposed involves a concrete beam type system, as shown in Figure 12. In this preliminary system, the concrete beam supports the single slope concrete barrier. The foundation beam width is chosen to be 24 inches and the depth is designed as 48 inches. The large proposed depth means that the system will utilize the interaction of the beam with the soil as the main resistance to the overturning moment produced by the vehicle impact. However, there are a few potential disadvantages with this concept. The increased depth yields a higher construction cost and might require geometric optimization to evaluate the efficiency of the system. Also, this design makes the soil properties vital. If the soil happens to have weak properties, the system will most likely fail to contain the vehicle. An optimized version of this design was evaluated in two different types of soil properties.

Design Concept 3 – Hybrid Shaft and Beam

The third preliminary design concept proposed and developed is a hybrid of Concept 1 (drilled shaft) and Concept 2 (concrete beam) foundation systems as shown in Figure 13. The total depth of this foundation system's shafts was 8.5 feet. It was initially thought that this hybrid concept may not have any technical disadvantages and may reduce the depth of the drilled shafts significantly compared to Concept 1 (drilled shaft). However, preliminary design analysis only resulted in a reduction of the depth by 1.5 feet. Furthermore, this concept requires a continuous beam at the base of the barrier. While this preliminary design could have been further optimized in the simulation phase, it didn't appear to have an overall advantage due to the additional cost of a continuous beam and a relatively less reduction in shaft depth than initially anticipated.

Design Concept 4 – Moment Slab

The fourth preliminary design concept developed and proposed is the moment slab foundation system as shown in Figure 14. It consists of a continuous moment slab casted underneath the single slope concrete barrier. The large footing shown signifies that the foundation will provide a great amount of resistance to the overturning moment upon vehicle impact. The advantage of this design is that it does not require special skills to construct (a fairly easy standard construction) and it demands minimal excavation for the shallow foundation. The main disadvantage is that it requires a very wide footprint to be able to resist the overturning moment from the impact of a tractor-trailer. The spatial needs in the lateral direction might limit the use of this design in certain sites. However, this design went under several optimizations and proved to be a very effective solution.

Design Concept 5 – Moment Slab with Overlay

The fifth preliminary design concept proposed and developed is the moment slab foundation from Concept 4 with the addition of 20 inches of soil and pavement overlay. This preliminary concept is shown in Figure 15. This design reduces the overall width of the moment slab.

Design Concept 6 – Moment Slab with Concrete Beam

The sixth preliminary design concept was proposed by TxDOT and is shown in Figure 16. The design consists of a moment slab foundation with an offset concrete beam on the traffic side of the barrier. This concept uses the concrete beam to provide additional counter moment to resist the overturning of the barrier due to the load created by the vehicle impact. This design reduces the width of the moment slab in Concept 4, but increases the depth at the location of the concrete beam.

Design Concept 7 – Moment Slab with Concrete Beam and Overlay

This preliminary design concept is shown in Figure 17. It consists of the same moment slab with offset concrete beam as in Concept 6 with a soil/asphalt overlay. The overlay provides a counter moment to the rotation of the barrier due to impact, thus allowing the reduction in the width of the moment slab.

Selected Concepts for FEM Analysis

TxDOT selected three concepts from the seven presented for further evaluation. The selected preliminary concepts were Concept 1 (drilled shaft), Concept 2 (concrete beam) and Concept 4 (moment slab).

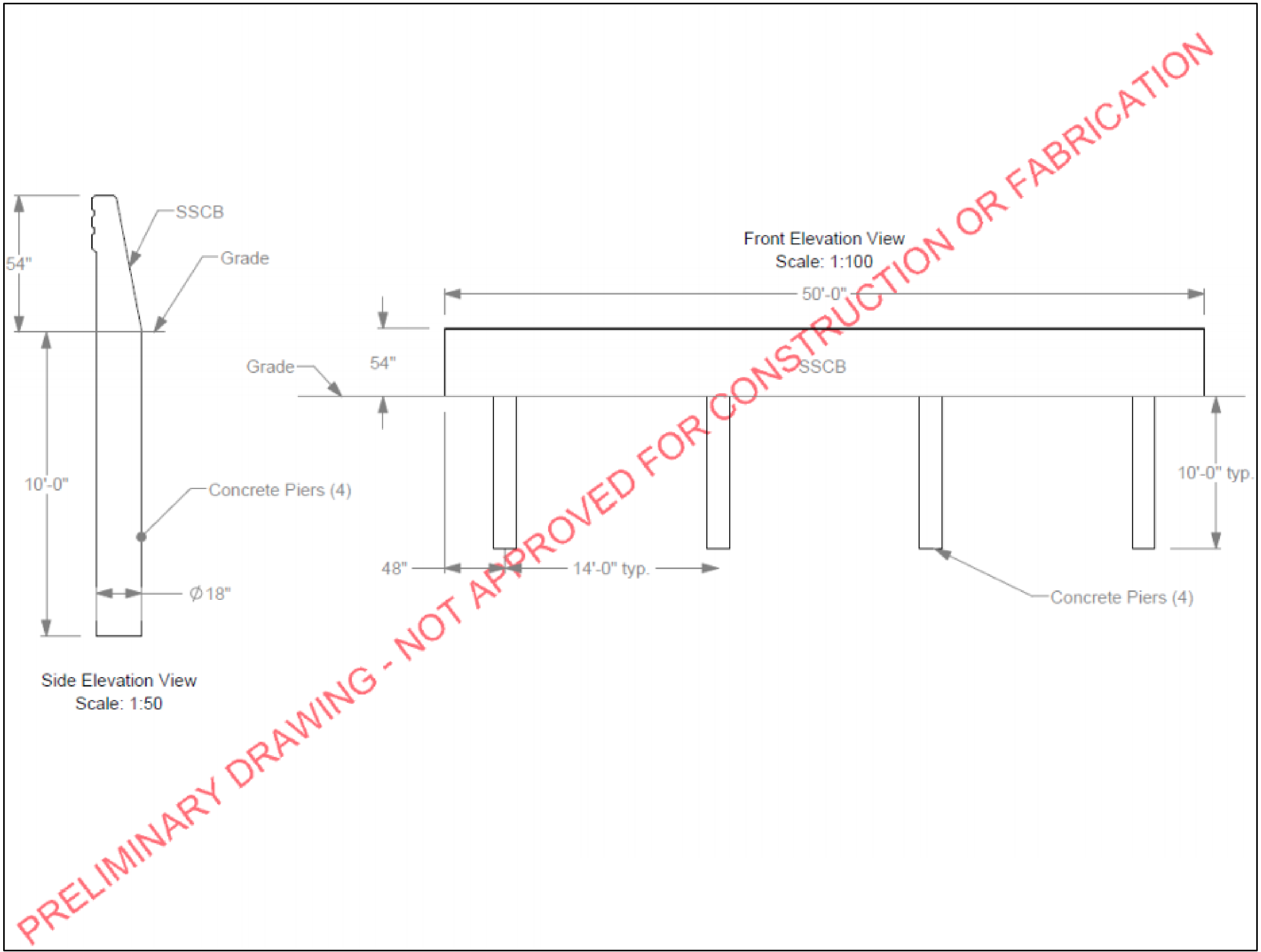


Figure 11. Design Concept 1 – Drilled Shaft Design (TTI, 2017)

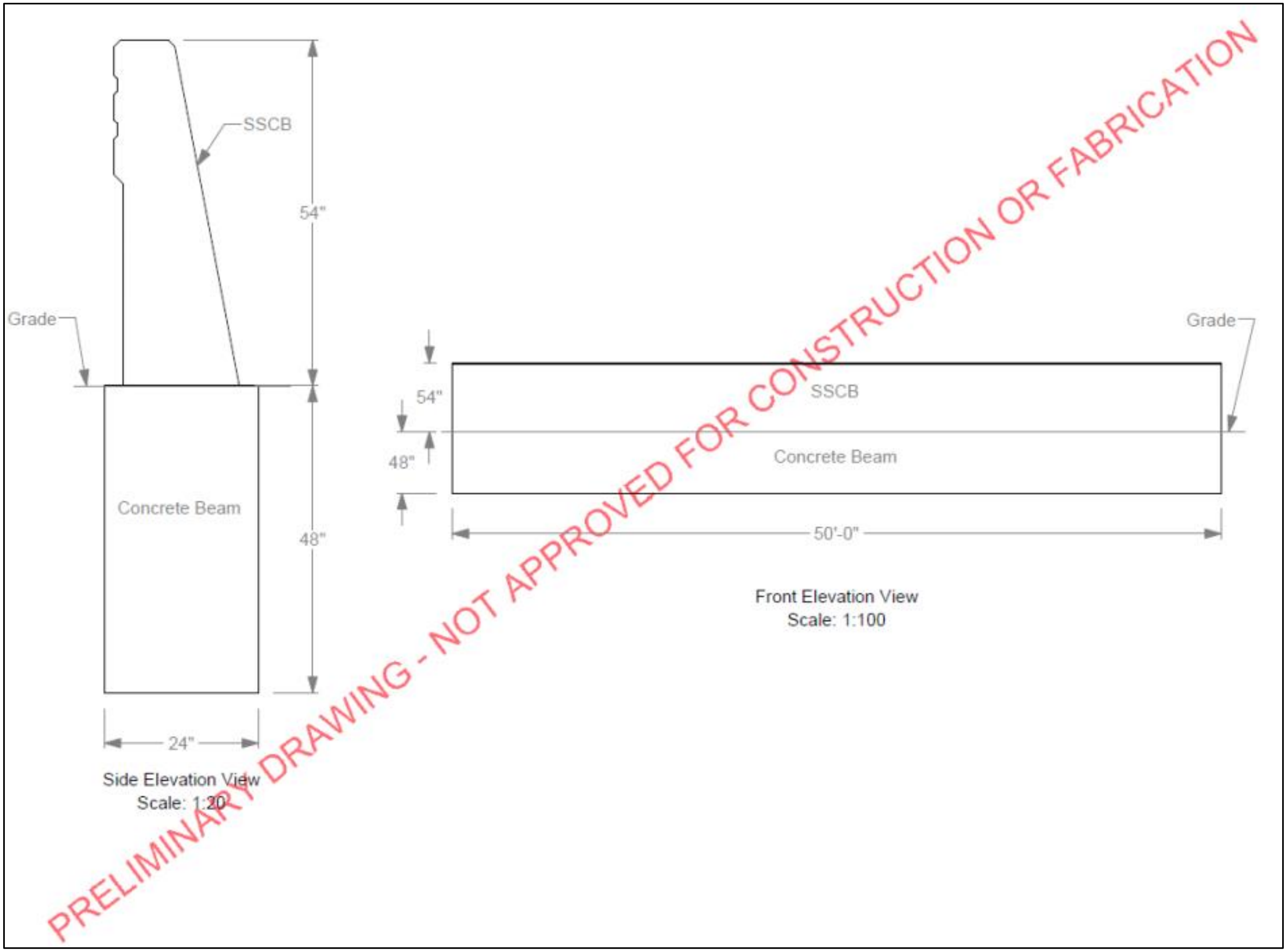


Figure 12. Design Concept 2 – Concrete Beam Design (TTI, 2017)

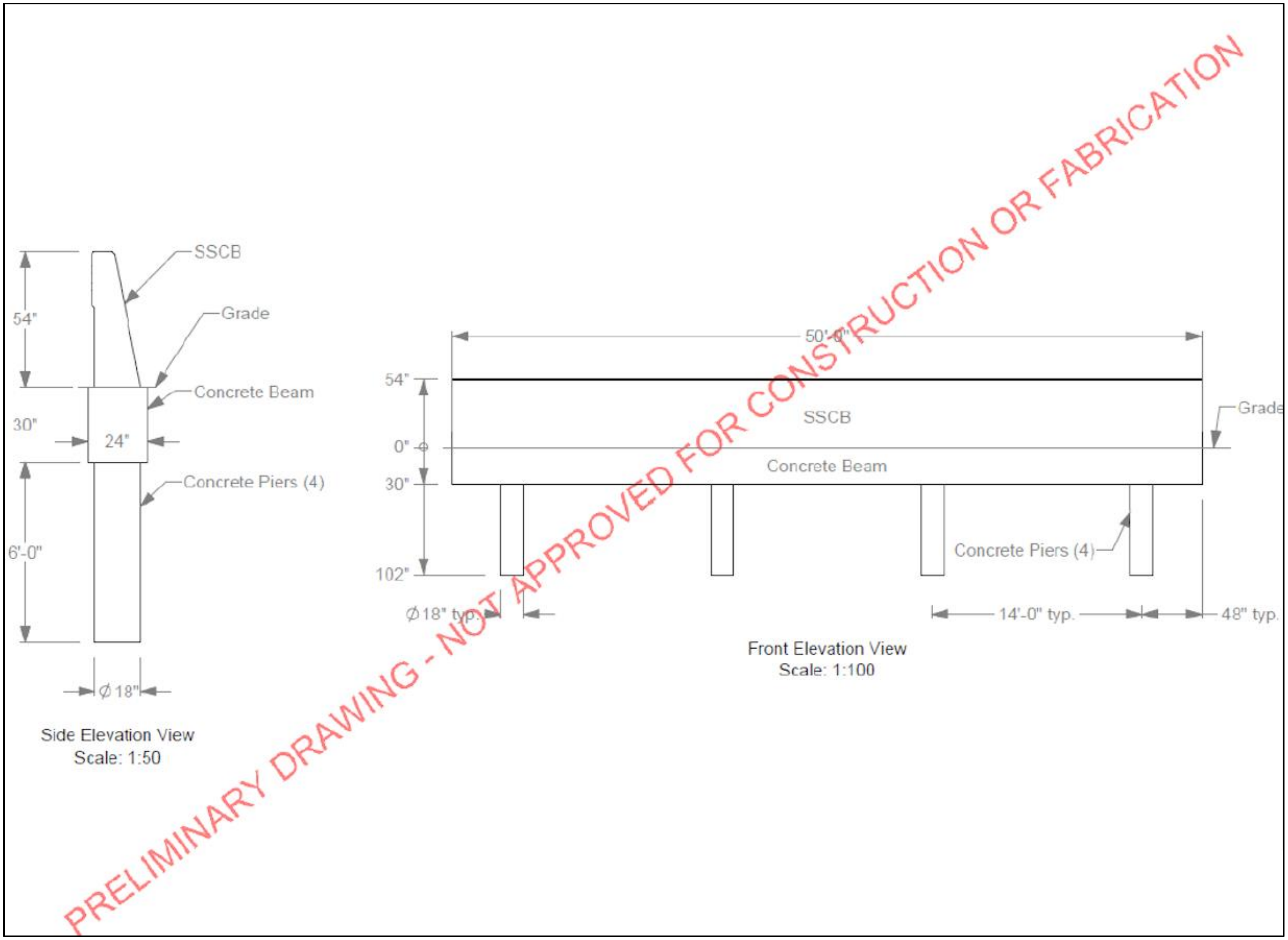


Figure 13. Design Concept 3 – Hybrid of Drilled Shaft and Concrete Beam Foundations (TTI, 2017)

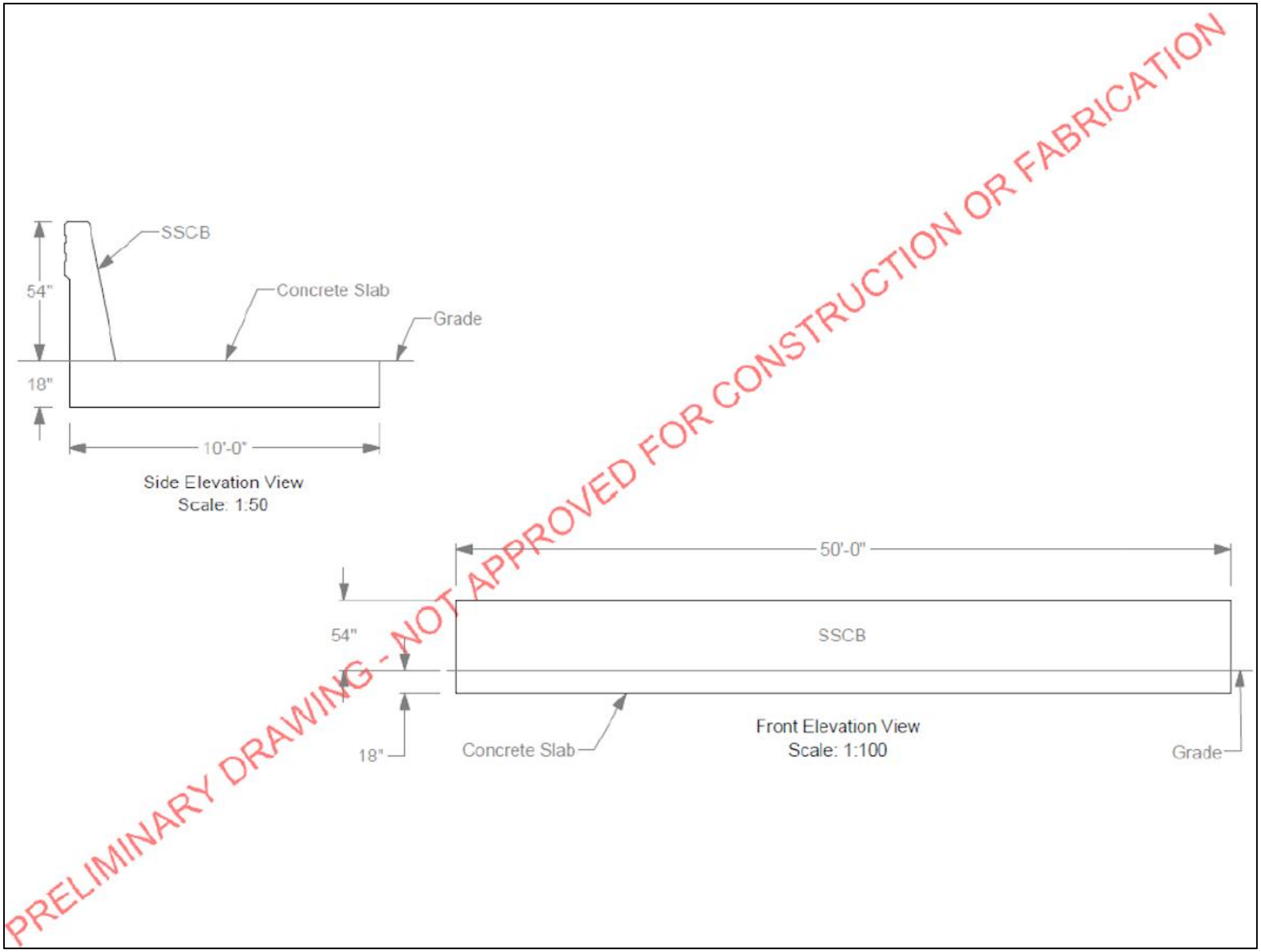


Figure 14. Design Concept 4 – Moment Slab Design (TTI, 2017)

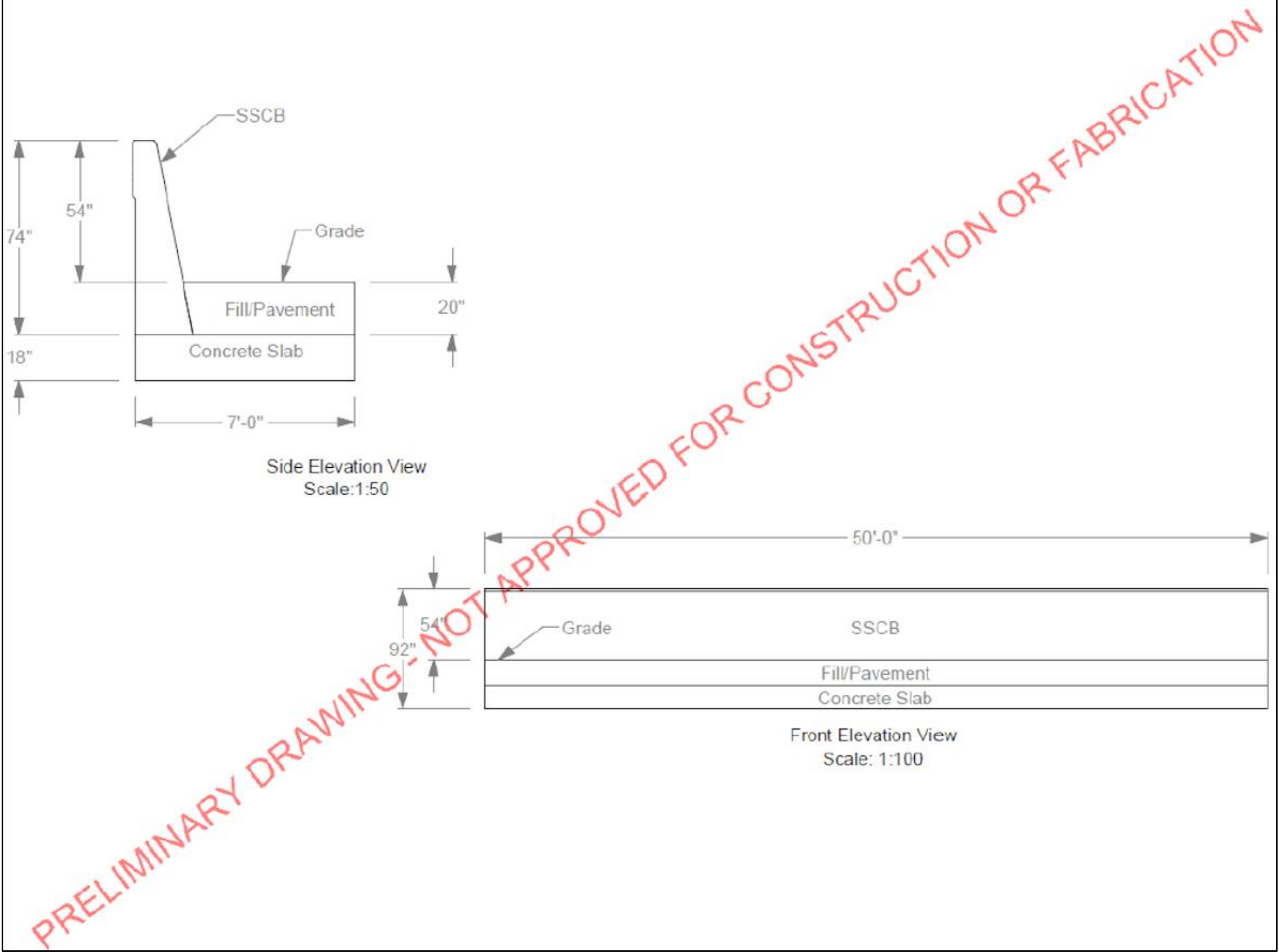


Figure 15. Design Concept 5 – Moment Slab with Overlay Design (TTI, 2017)

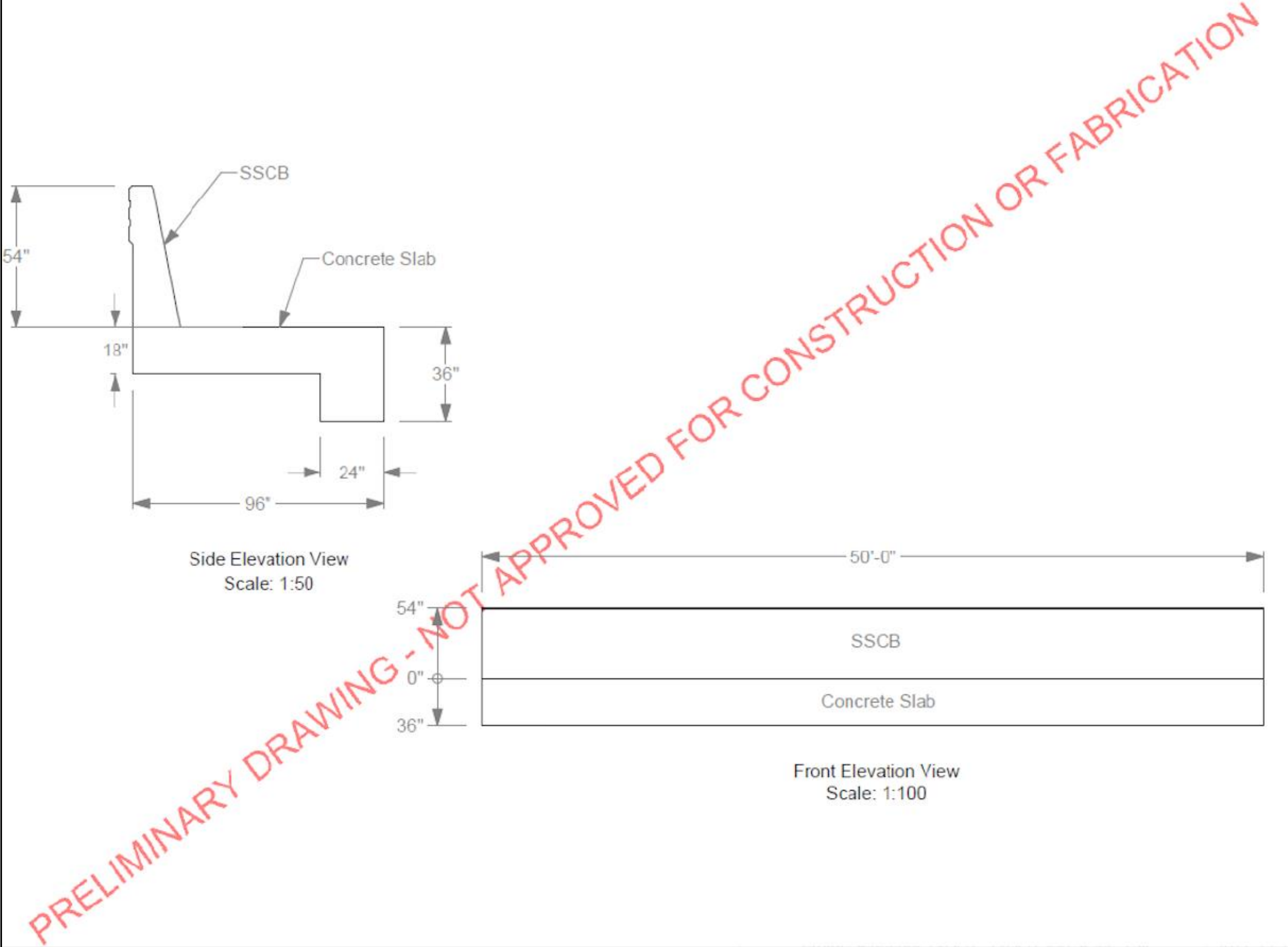


Figure 16. Design Concept 6 – Moment Slab with Concrete Beam Design (TTI, 2017)

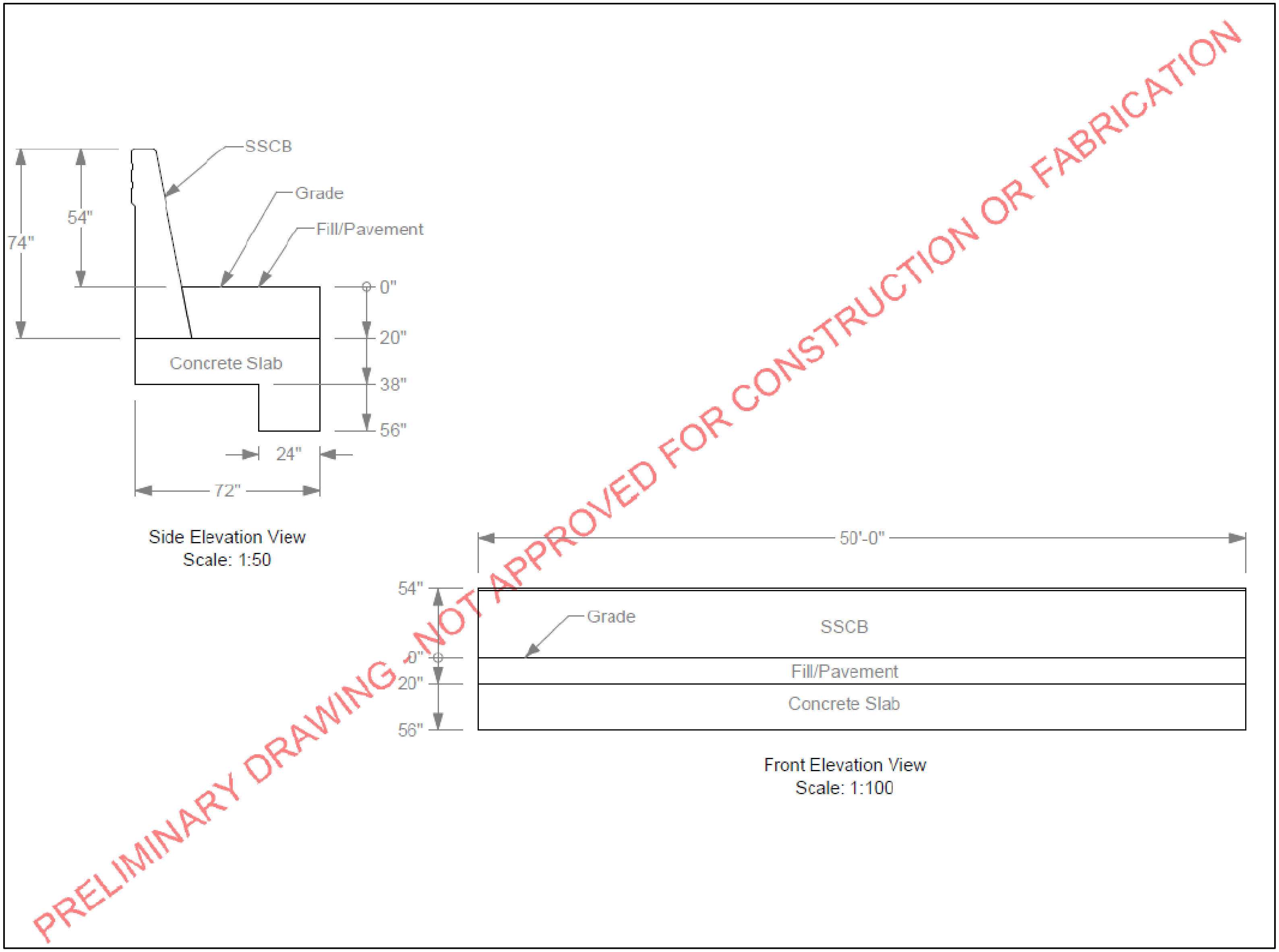


Figure 17. Design Concept 7 – Moment Slab with Concrete Beam and Overlay Design (TTI, 2017)

3.1.2. 36-inch Tall Single Slope Concrete Barrier with Structurally Independent Foundation Concepts (MASH TL-4)

For the MASH TL-4 barrier-foundation system, the experience obtained in developing the MASH TL-5 system helped to shorter the number of preliminary concepts and eventually produce two designs. An additional preliminary concept, Design Concept 3 (beam and moment slab), was submitted by TxDOT for evaluation. For the concrete barrier, the single face barrier profile shown in Figure 18 was used.

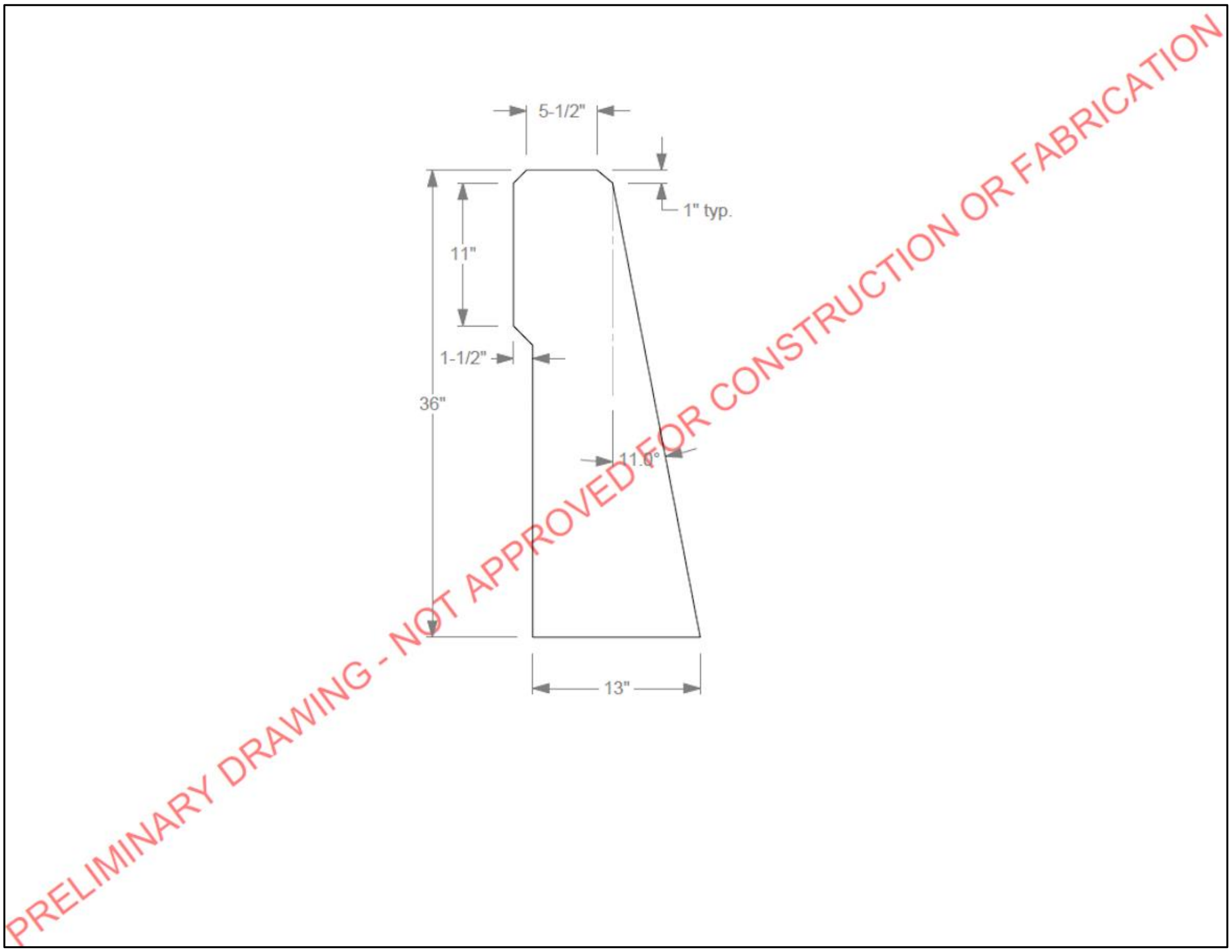


Figure 18. 36-inch Tall Single Slope Barrier Profile (TTI, 2017)

Design Concept 1 – Concrete Beam

The first preliminary option developed and proposed for the MASH TL-4 test level is the same design as Concept 2 (concrete beam) of the MASH TL-5 system. This concept is shown in Figure 19. The foundation beam width is initially chosen to be 18 inches and the depth is designed as 27 inches. For the advantages, disadvantages and how this system works, please see Design Concept 2 in Section 3.1.1.

Design Concept 2 – Moment Slab

The second preliminary design concept developed and proposed is the moment slab foundation systems as shown in Figure 20. This concept is the same design as Design Concept 4 of MASH TL-5 system. Further information about the pros and cons of this option is given in Section 3.1.1.

Design Concept 3 – Concrete Beam and Moment Slab

The third preliminary design concept was proposed by TxDOT. This design features a hybrid concept with a concrete beam and a moment slab covered by soil. The dimension specifications of the initial model are shown in Figure 21.

Selected Concepts for FEM Analysis

All the above concepts were considered for further optimization and evaluation.

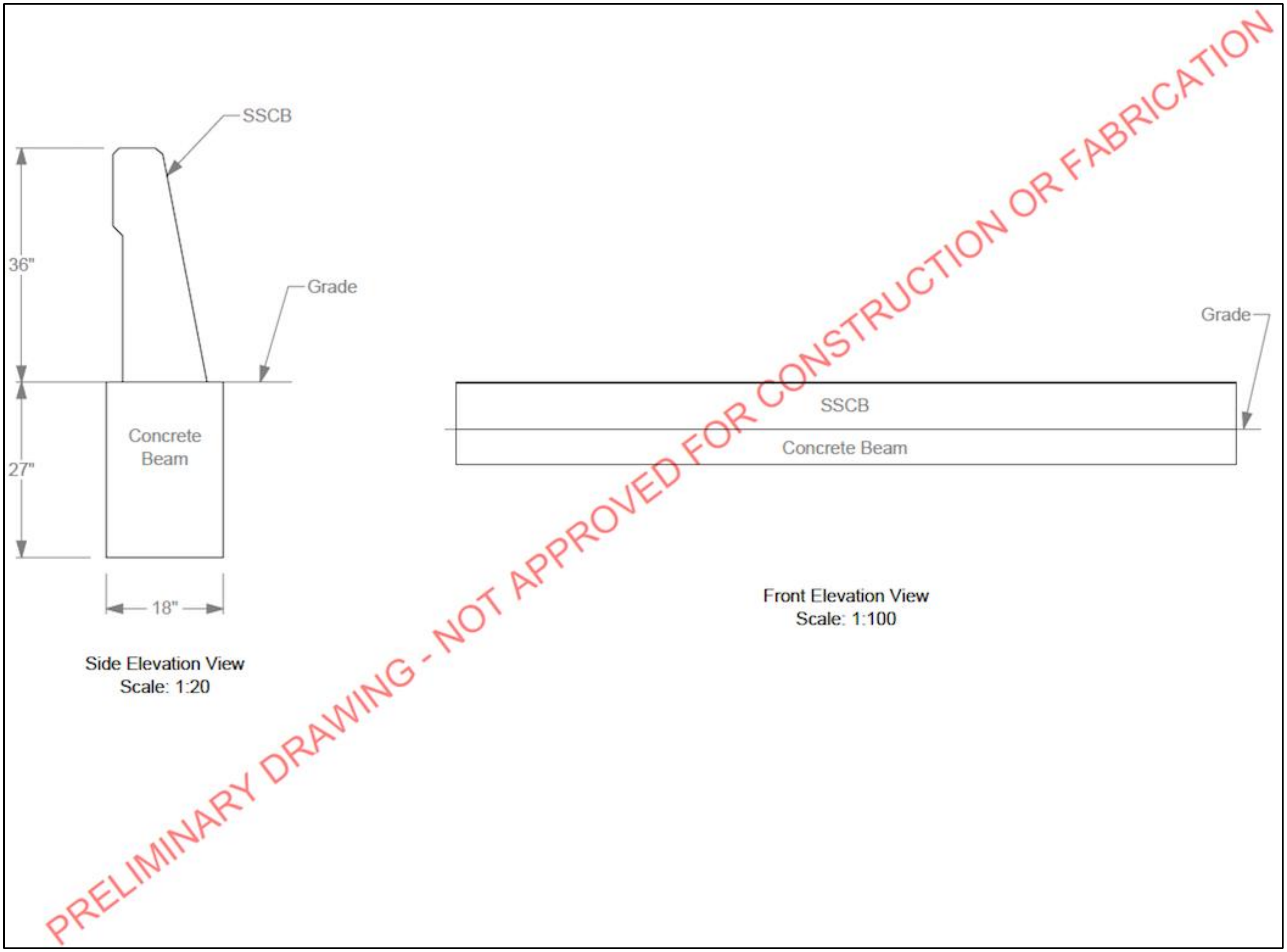


Figure 19. Design Concept 1 – Concrete Beam Foundation (TTI, 2017)

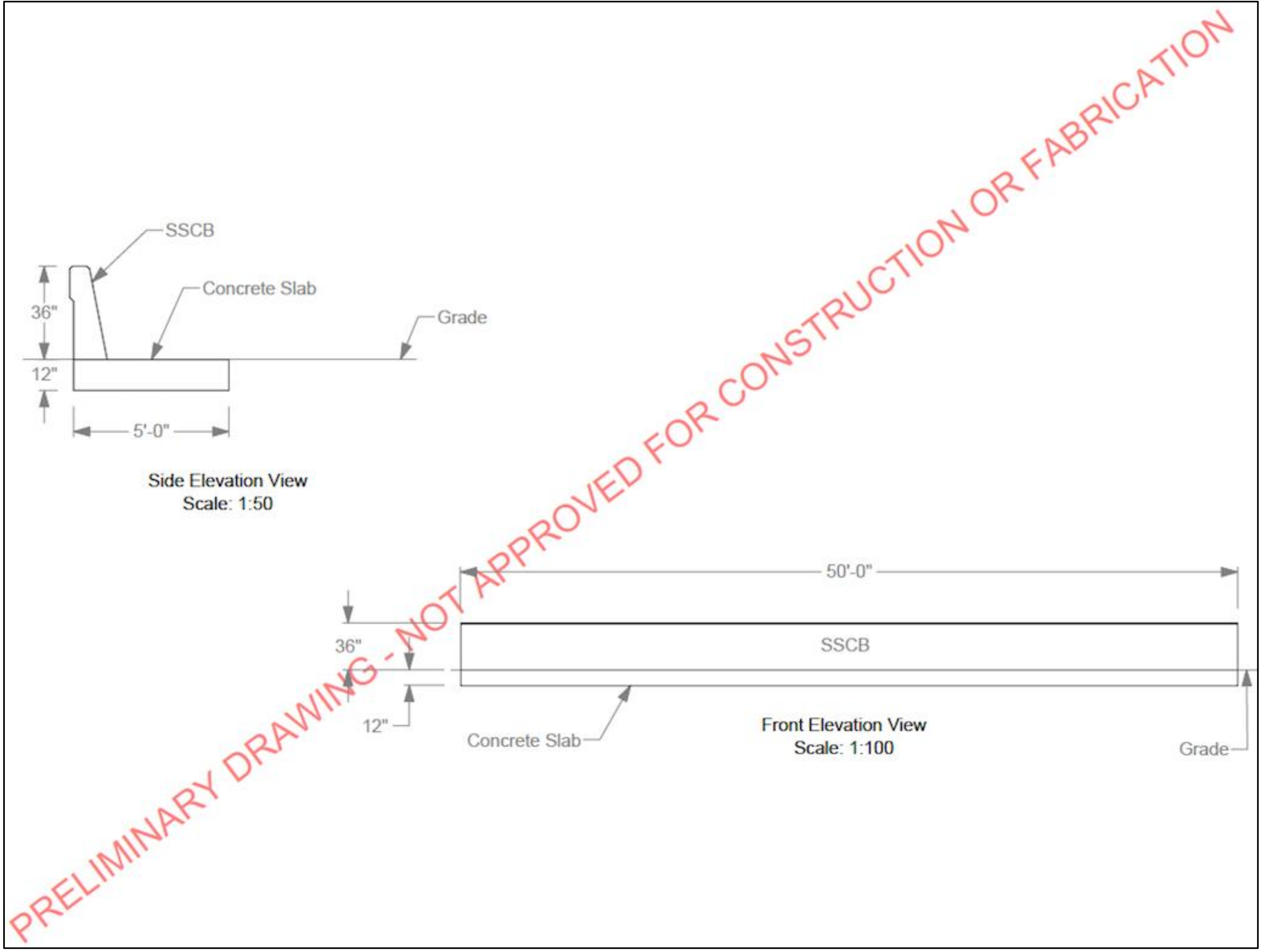


Figure 20. Design Concept 2 – Moment Slab Foundation (TTI, 2017)

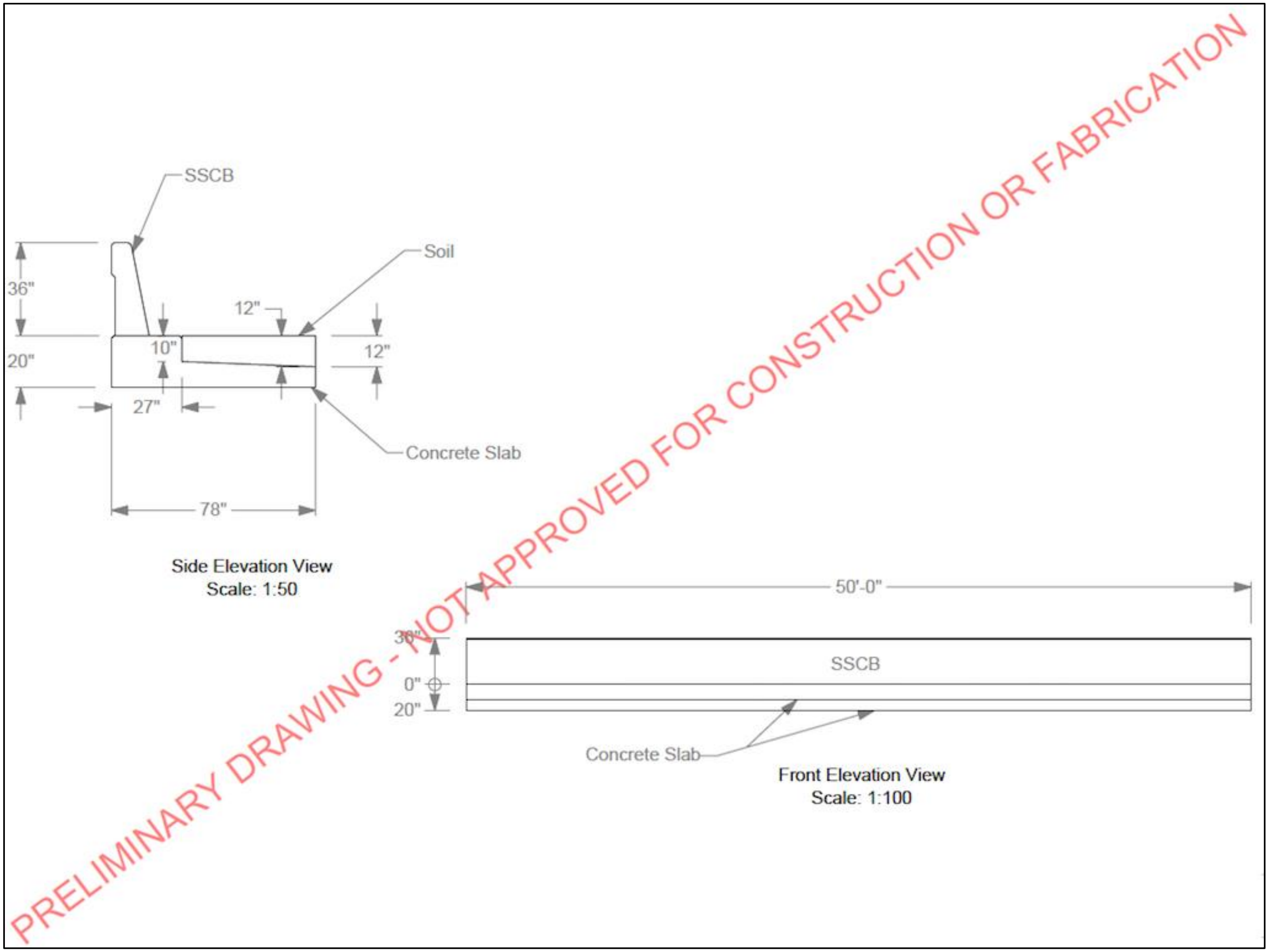


Figure 21. Design Concept 3 – Concrete Beam and Moment Slab Hybrid Foundation (TTI, 2017)

3.2. Finite Element Modeling and Simulation Analysis

Full-scale dynamic crash simulations of the selected barrier-foundation systems for MASH TL-4 and MASH TL-5 were conducted.

Since the rigid single slope concrete barrier had previously been successfully tested for MASH Test 5-11 and Test 5-10 by Williams et al. (2011), the selected systems were investigated towards MASH Test 5-12 and MASH Test 4-12 requirements. Per AASHTO, MASH Test 5-12 consists of a 79,300-pound tractor-trailer impacting the selected barrier at 15 degrees and 50 mph. MASH Test 4-12 involves a 22,000-pound single unit truck impacting the selected barrier at 15 degrees and 55 mph.

Furthermore, the working height and width of the vehicle for both test levels and each of the considered systems were measured. These parameters are needed to estimate the zone of intrusion of the vehicle impact as shown in Figure 22. The zone of intrusion will then be used to calculate the minimum distance that the bridge column may be constructed from the back of the barriers to avoid any touch with the over leaning vehicle.

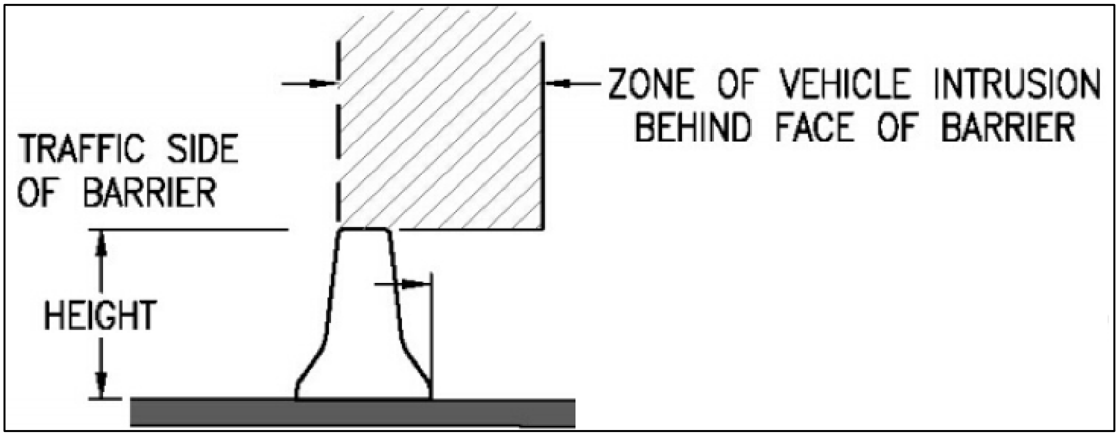


Figure 22. Zone of Intrusion Graphic (Hobbs, 2010)

As mentioned in Section 3.1, after performing simulations for the preliminary concepts, the designs were optimized and additional simulations were performed for each concept. During the optimization process, it was managed to significantly reduce some of the dimensions for each of the preliminary concepts and thus, cutting the cost of construction and implementation. The results of these simulations are presented in Chapter 4.

Software

All the simulations were performed utilizing the finite element method. HyperMesh was used to build the full-scale finite element models of the barriers for both test levels and the selected foundation systems. HyperMesh is a commercially available tool, recognized for its ability and expertise in fine meshing. LS-DYNA was used to run the simulations, also commercially available general purpose, elastic-viscoplastic finite element analysis and non-linear software.

Selection of Rigid Material

The 3D foundation and single slope barrier were built as rigid material members. Since the failure of the concrete material is not a desired outcome, the rigid material option was used to satisfy such demand and to make sure that the barrier and foundation move upon impact as one piece. This design approach also helps to obtain marginally conservative and more accurate impact load distribution from the interaction of the vehicle with the barrier-foundation system.

Concrete Material Card

The rigid Type 20 material card was used to define the concrete material of the barrier and the foundation. The properties of this material card are given in Table 1. The full card is shown in Appendix A.

Table 1. Concrete Rigid Material Card Properties

Properties	Values for Concrete Material Card
Density (RO)	2400 kg/m^3
Modulus of Elasticity (E)	21 GPa
Poisson's Ratio (PR)	0.29

3.2.1. Soil Modeling and Material Properties

Soil Material Cards

The foundation is embedded in soil modeled using HyperMesh. The soil is the most important resistance body for some concepts, such as the moment slab design, as it provides a counter balance action to the moment generated by the impact load. The material card used initially for soil was developed by Sheikh et al. in 2011, which is based on the jointed rock material model by LS-DYNA. The full original material card used is shown in Appendix A.

However, upon a request made by TxDOT, the performance of the barrier-foundation systems with weaker soil configuration was considered and evaluated. The new modified material card used for the additional simulations is shown in full in Appendix A. The elastic shear modulus (GMOD) value decreased from 20.0 MPa to 6.3 MPa. Also, the dilation angle (PSI) has changed from -0.1 radian to 0.0001 radian. This new configuration was only applied to some simulation models and the results are shown in Chapter 4.

A summary of some of the properties of the soil material cards is given in Table 2.

Table 2. Main Properties for the Soil Configurations

Properties	Stronger Soil	Weaker Soil
Density (RO)	2097 kg/m^3	2097 kg/m^3
Elastic Shear Modulus (GMOD)	20 MPa	6.3 MPa
Poisson’s Ratio (RNU)	0.35	0.35
Angle of Friction (PHI)	0.6981 radians	0.6981 radians
Angle of Dilation (PSI)	-0.1 radian	0.0001 radian

Boundary Conditions

The foundations were modeled inside a soil continuum that was built with deformable soil material properties. The boundaries of the soil continuum were constrained to maintain the shape. However, inside the external boundary constraints, the soil was free to “flow” as a result of interaction with the foundation. The barrier and the foundation could move in the soil due to impact from the tractor-trailer. Figure 23 shows an isometric view of a part of Design Concept 1 (concrete beam) for MASH TL-4 and the boundary constraints applied. The numbers 1, 2 and 3 represent the applied constraints in the x, y and z-direction, respectively. The soil is not constrained on the faces that touch the foundation, allowing for free interaction.

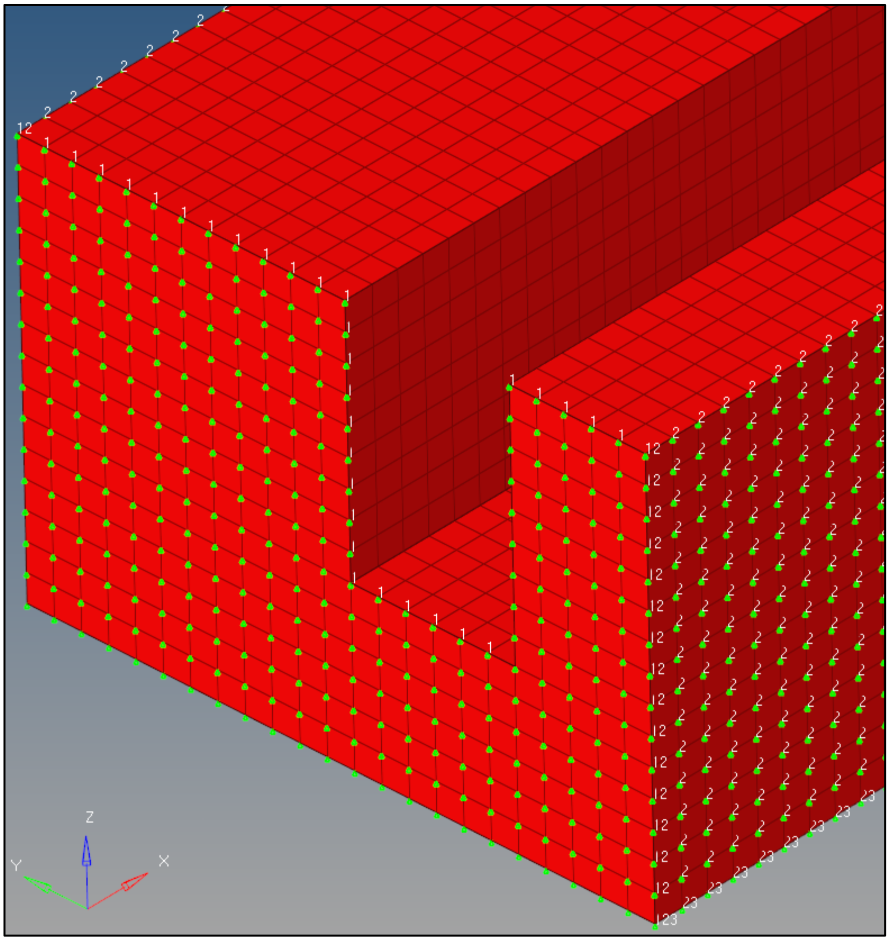


Figure 23. Boundary Constraints in MASH TL-4 Design Concept 1

Hourglass Zero Energy Modes

Hourglass control is an important feature that is used to account for the zero energy modes created by under-integrated elements as explained in *LS-DYNA Keyword User's Manual*, 2016. These modes do not produce any stress or strain and if not controlled, can interfere with the output results of the system. To model the soil part in the simulations developed in this work, single integration point solid elements were used. In these under-integrated elements, there are twelve possible hourglassing modes. Four of these non-physical modes are shown in Figure 24.

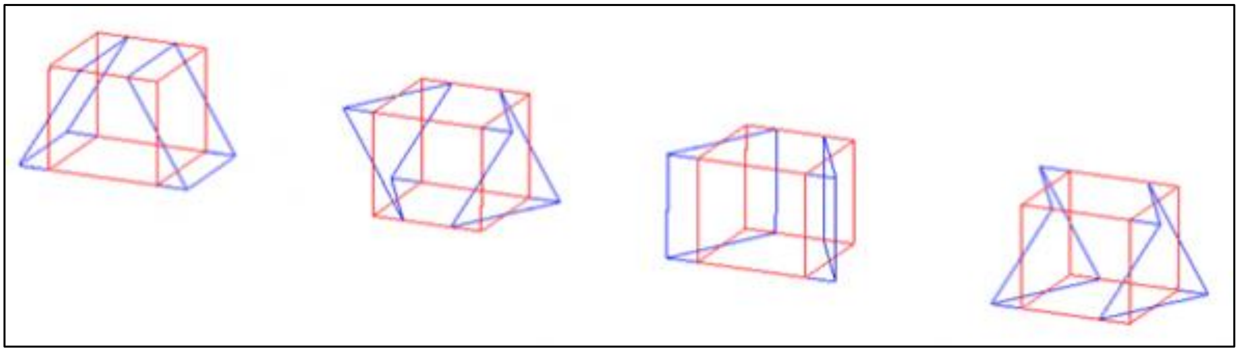


Figure 24. Four of Twelve Possible Modes (Hale, 2015)

The fully integrated elements are the most straightforward way to eliminate hourglassing, but they are more expensive as they take a longer computing time. So, it was decided to use the *HOURGLASS feature to control the zero energy non-physical modes in the soil part. There are two major forms of hourglass control, viscous forms and stiffness forms. For automotive crash simulations, *LS-DYNA Keyword User's Manual*, *Volume I* recommends the stiffness form and specifically Type 2. The hourglass control was selected to be based on the Flanagan-Belytschko stiffness form and the hourglass coefficient was set to 0.05.

The hourglass energy created by utilizing this control feature is the energy needed by the internal forces of the part to resist the hourglass non-physical modes. The produced energy is indeed part of the total physical energy of the system. Figure 25 shows the energy chart for the MASH TL-4 Design Concept 1 (concrete beam) system. The graph shows that the hourglass energy is very low as preferred.

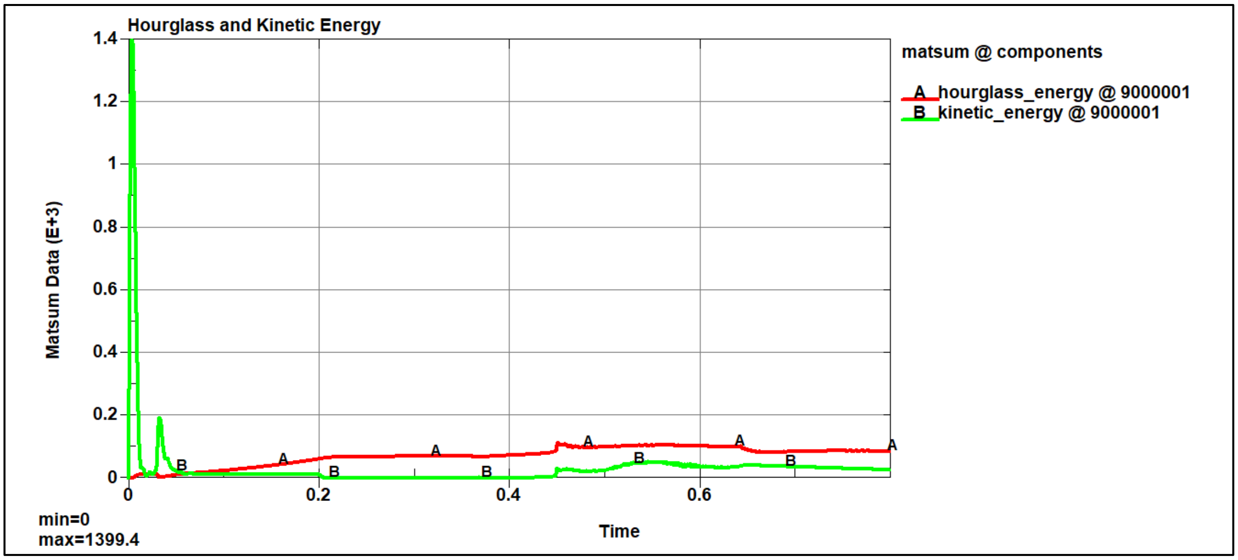
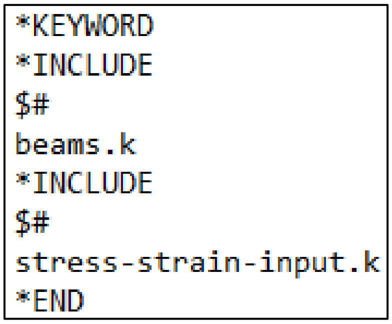


Figure 25. Hourglass and Kinetic Energy of MASH TL-4 Design Concept 1 System

3.2.2. Stress Initialization of Models

A technique called "stress initialization technique" was used for all MASH TL-5 simulation models and some MASH TL-4 models. The stress initialization technique is performed in steps and provides some advantages towards time and simulation cost. Also, it is a tool to pre-check a model before conducting the full-scale dynamic simulation crash with the vehicle.

After the finite element models of the barrier-foundation system and the soil are successfully built, they are put together for an FEA simulation run. This simulation does not include the vehicle, and only gravity load and damping are applied to the system. The simulation time was set to less than 0.5 seconds in all the simulations. The results of this run showed how the stress is distributed in the barrier-foundation system and allowed to check if the contact between the parts and their interaction were synchronized harmonically. More importantly, this technique saved time and simulation cost. When the gravity is applied to the system, it takes a while for the vibrations to settle and the system to reach stability. If the vehicle impact is to happen during this "settling time", the system would yield inaccurate results and the behavior of the system would not be realistic. There are two ways to make sure the system is at rest when the vehicle impact happens. The first option is to start the simulation with the vehicle placed in a considerable distance, allowing the barrier-foundation system to settle in soil before the impact happens. This is a very expensive approach, as it requires a longer simulation time with a significantly large file, as is the case of MASH TL-5 that includes a full-scale tractor-trailer FEM. The second option is to use the stress initialization technique. After performing a simulation for only the barrier-foundation system and the soil, the final stress and strain values for each node are exported and saved in a separate file. Then, a new main file is created where the barrier-foundation system and the new stress-strain file are included as shown in Figure 26.



```
*KEYWORD
*INCLUDE
$#
beams.k
*INCLUDE
$#
stress-strain-input.k
*END
```

Figure 26. Stress and Strain Values Included in Concrete Beam Concept Main File

This enables the stress and strain values obtained by performing the stress initialization technique to be overwritten on the corresponding nodes of the barrier-foundation system model. After this step is completed, the model is now fully stressed and it doesn’t require any time to settle into soil and reach stability. Since the system is now ready for impact, the heavy vehicle finite element model could be placed as close as preferred to the impact point. The simulation time for the large file is now significantly shorter and the results are obtained much faster.

3.2.3 Contact Cards

Contact cards have a significant importance in every simulation involving finite element models. The purpose of these cards is to regulate the interaction between parts of a simulation file. Also, friction is defined for all parts or sets of parts through the *CONTACT card in LS-DYNA. However, friction curves can also be defined separately for certain parts or sets (Dong et al., 2016). The accuracy of the results is crucially dependent on the contact interfaces modeling between the parts of the system in finite element simulations. In *LS-DYNA User's Keyword Manual*, there are over 35 types of contact algorithms that allow the interaction of the unmerged Lagrangian elements with one another.

Three types of contact models were used in this work. For the interaction between the barrier-foundation system with the soil, the automatic surface to surface Type 1 contact card was used. For the interaction between the barrier-foundation system segments with each other, the automatic single surface contact card Type 1 was selected. To account for the negative volumes that may occur in the soil (soft material), the interior Type 1 contact model was used.

All the contact cards are shown in Appendix A.

<u>*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE</u>

LS-DYNA Keywords User's Manual provides extensive information regarding automotive crash simulations and recommends the best practices that should be followed for such simulations.

To address the contact between the soil part and the barrier-foundation system elements, an automatic surface to surface contact model was used. The automatic contact types are strongly recommended due to the ability of detecting non-oriented penetration and interaction of the elements. Due to large expected deformation resulting from the vehicle impact, the automatic surface to surface contact card is recommended for its two-way symmetric treatment ability, without the need of distinguishing between the master and the slave (Bala, 2003).

LS-DYNA Keyword User's Manual recommends the contact stiffness (SOFT) value of 1 to be used in the contact card for interaction between parts with different properties.

***CONTACT_AUTOMATIC_SINGLE_SURFACE**

To control the interaction of the barrier segments with one another, the automatic single surface contact option was used. This is the most commonly used contact model for crashworthiness application. For this contact type, there is no need to define a master surface. A set ID is selected for the slave surface. For our case, the set ID includes the barrier-foundation segments. This contact type accounts for interaction between all the slave parts as well as for self-contact of the considered parts.

***CONTACT_INTERIOR**

To avoid the numerical instabilities created by elements of the soil (with soft material properties) being inverted, LS-DYNA has developed a controlling contact type. The interior contact card was developed to protect the interaction of the elements of the soft material from creating negative volumes. This control type is very common in simulations that produce large deformation from heavy loads. For this contact option, only a part set ID is required.

3.2.4. Single Unit Truck and Tractor-Trailer Finite Element Models

The heavy vehicle finite element models used were provided by Texas A&M Transportation Institute (TTI). Both models have been validated by other agencies towards NCHRP Report 350 and MASH requirements.

Single Unit Truck Model for MASH 4-12

The finite element model of the single unit truck was first developed by the National Crash Analysis Center based on a Ford F800 model. This model was later on modified and updated significantly by Battelle Memorial Institute. An exploded view of that model is shown in Figure 27.

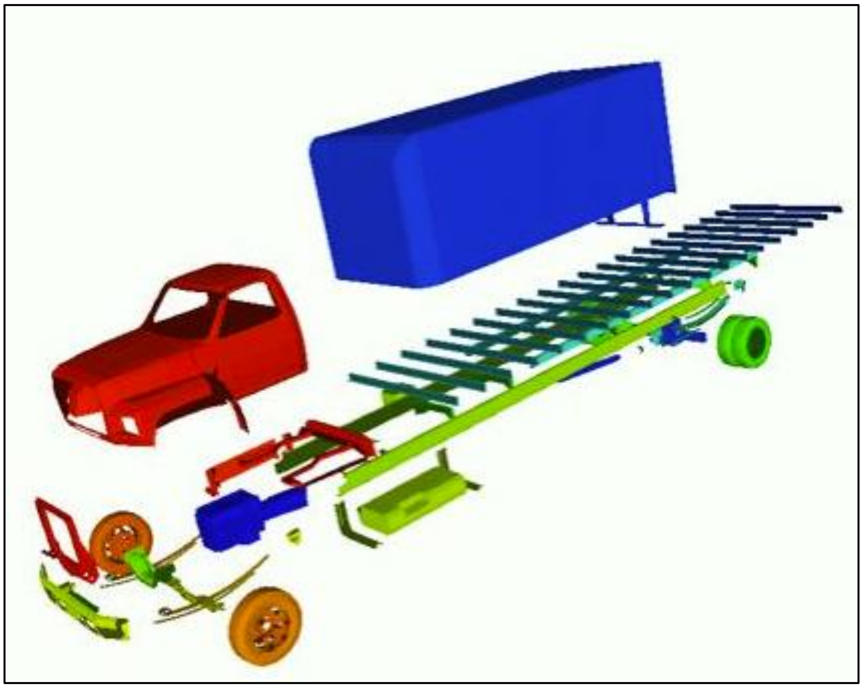


Figure 27. SUT Exploded View (Batelle Memorial Institute, 2005)

However, with the changes made under MASH for the TL-4, further improvement was required. An extensive work has been done for the validation of the SUT finite element model towards MASH 4-12 test level specifications from Sheikh et al. (2012). Several properties of the model were modified, such as the wheelbase, to realistically match the vehicle characteristics.

Tractor-Trailer Model for MASH 5-12

Similarly to the SUT model, the finite element model of the tractor-trailer was originally developed by the National Crash Analysis Center, and was then updated by Battelle Memorial Institute with the sponsorship of Federal Highway Administration (FHWA) (Miele et al., 2010).

The original finite element model of this heavy vehicle was built based on the 1992 Freightliner FLD120 tractor. Improvements over this vehicle model have been made throughout the years also by Texas A&M Transportation Institute. A profile view of the finite element model for the tractor-trailer used in this thesis is shown in Figure 28.

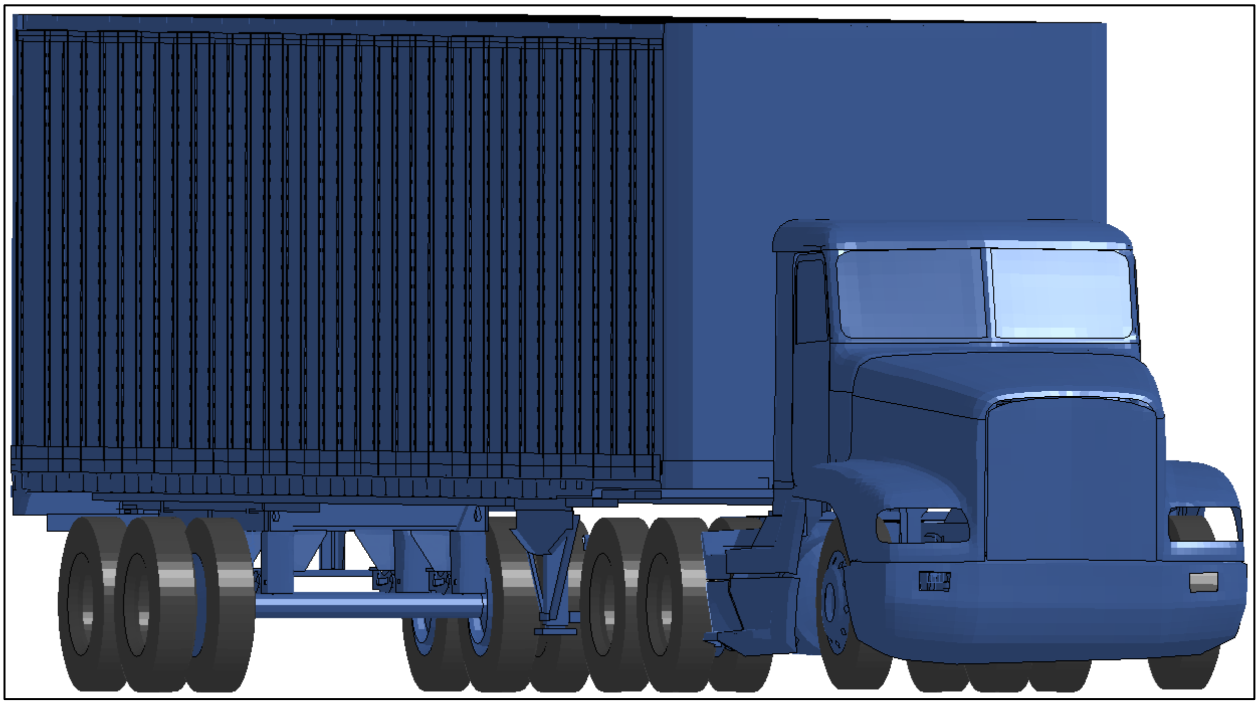


Figure 28. Tractor-Trailer FEM Used for MASH 5-12

3.2.5. Impact Point Selection

The total length of the system was initially proposed to be 150 feet, with three 50-foot barrier segments for both test levels. However, after performing the first few simulations and optimization the dimension of the systems, the length for some of the tests was decreased. To select the most critical impact point for each test level, it was referred to Table 2-8 from MASH 2016.

This is shown in Table 3 below.

Table 3. Critical Impact Point for Heavy Vehicle Tests (MASH, 2016)

Test Designation	*x* Distance
MASH 4-12	5.0ft
MASH 5-12	-1.0ft

The *x* distance given in Table 3 is illustrated in Figure 29 below. The positive values of *x* indicate that the critical point is in the direction of the vehicle movement. The negative values indicate the opposite.

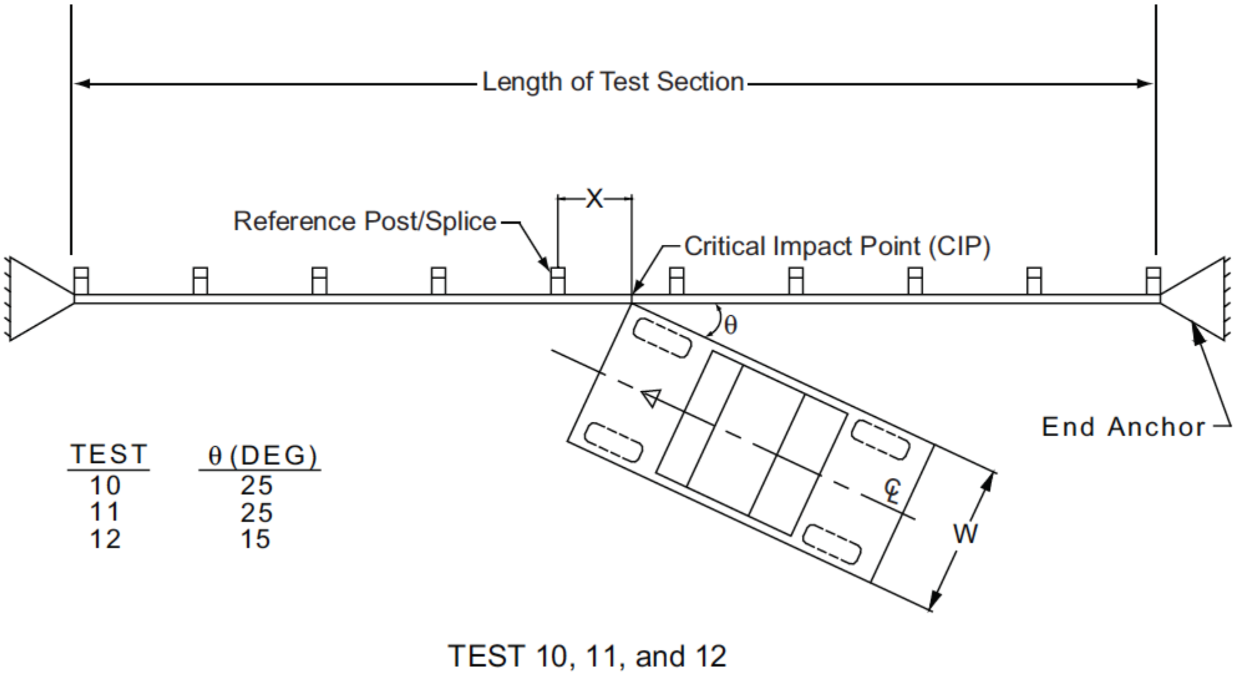


Figure 29. Illustration of Impact Point and Angle (MASH, 2016)

Unlike tests for automobiles and pickup trucks, the critical impact point for these heavy vehicle tests is selected to yield the maximum load being applied to the joints and splices of the barrier system.

4. RESULTS AND EVALUATION

The results obtained from the simulations and evaluations are presented. This chapter is divided into two major parts, the MASH TL-5 and MASH TL-4 systems results. As mentioned in Chapter 3, TxDOT requested that some of the designs to be evaluated for a weaker soil configuration. To accommodate for these additional simulations, the results part for each test level is also divided into two sections, one for the stronger soil and one for the weaker option. The results are summarized in Chapter 5.

4.1. MASH TL-5 Systems Results

For the 54-inch tall single slope concrete barrier with structurally independent foundation, TxDOT decided to select three preliminary designs as follows:

- Drilled-shaft foundation
- Vertical-wall/beam foundation
- Moment slab foundation

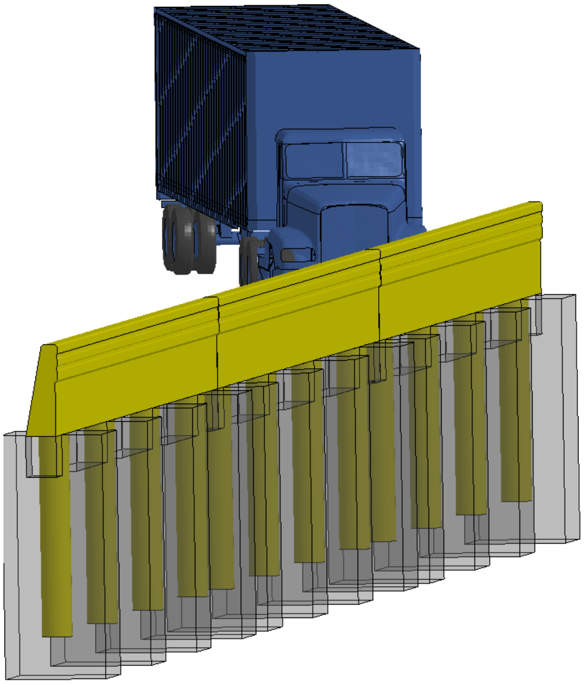
Since the original designs of all three options yielded very conservative results, they were further optimized. Some of these optimized versions were also performed under a weaker soil configuration.

4.1.1. Stronger Soil Configuration MASH TL-5 Systems Results

<u>Drilled Shaft Foundation Design</u>

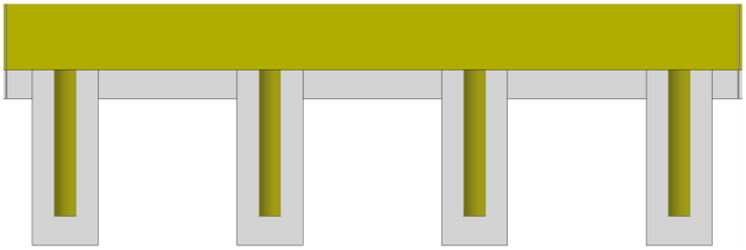
This foundation design was comprised of TxDOT standard shafts with diameter of 18 inches and length of 10 feet. Each 50-foot segment of the barrier had four drilled shafts. The centers of the shafts were spaced at 14 feet from each other, with the two end shafts at 4 feet offset from the ends of the segments. The finite element model of this barrier and foundation is shown in Figure 30. The results of the MASH Test 5-12 impact simulation with the tractor-trailer vehicle model are shown in Figure 31. As can be seen from the sequential images of the impact, there was very little movement of the barrier and the foundation. The vehicle was successfully contained and redirected by the barrier and the foundation system. As summarized in Table 4, the maximum dynamics deflection of the barrier was 1.5 inches and the maximum permanent deflection was 0.75 inch. The working width of the barrier and the foundation system was 29.5 inches at the height of 149.6 inches.

Encouraged by the low deflection of the foundation design, the depth of drilled shafts was reduced to 6 feet (Figure 32). A finite element model of this modified foundation is shown in Figure 33 and the results of the simulation are shown in Figure 34. As summarized in Table 5, the maximum dynamics deflection of the barrier was 3.4 inches and the maximum permanent deflection was 2.4 inches. The working width of the barrier and foundation system was 35.1 inches at the height of 148.4 inches.

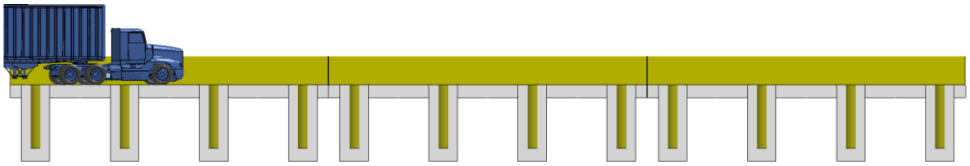


Overall System Model

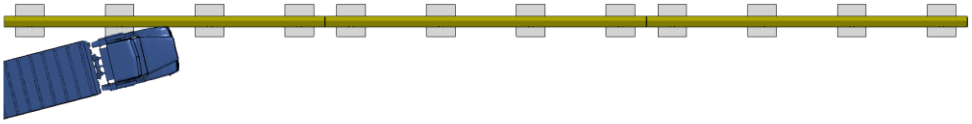
Top View of a Barrier Segment*



Side View of a Barrier Segment*



System Model (Side View)



System Model (Top View)

*Soil shown with transparency to show the drilled shafts

Figure 30. Drilled Shaft Foundation Simulation Model Details with 10ft Deep Shafts

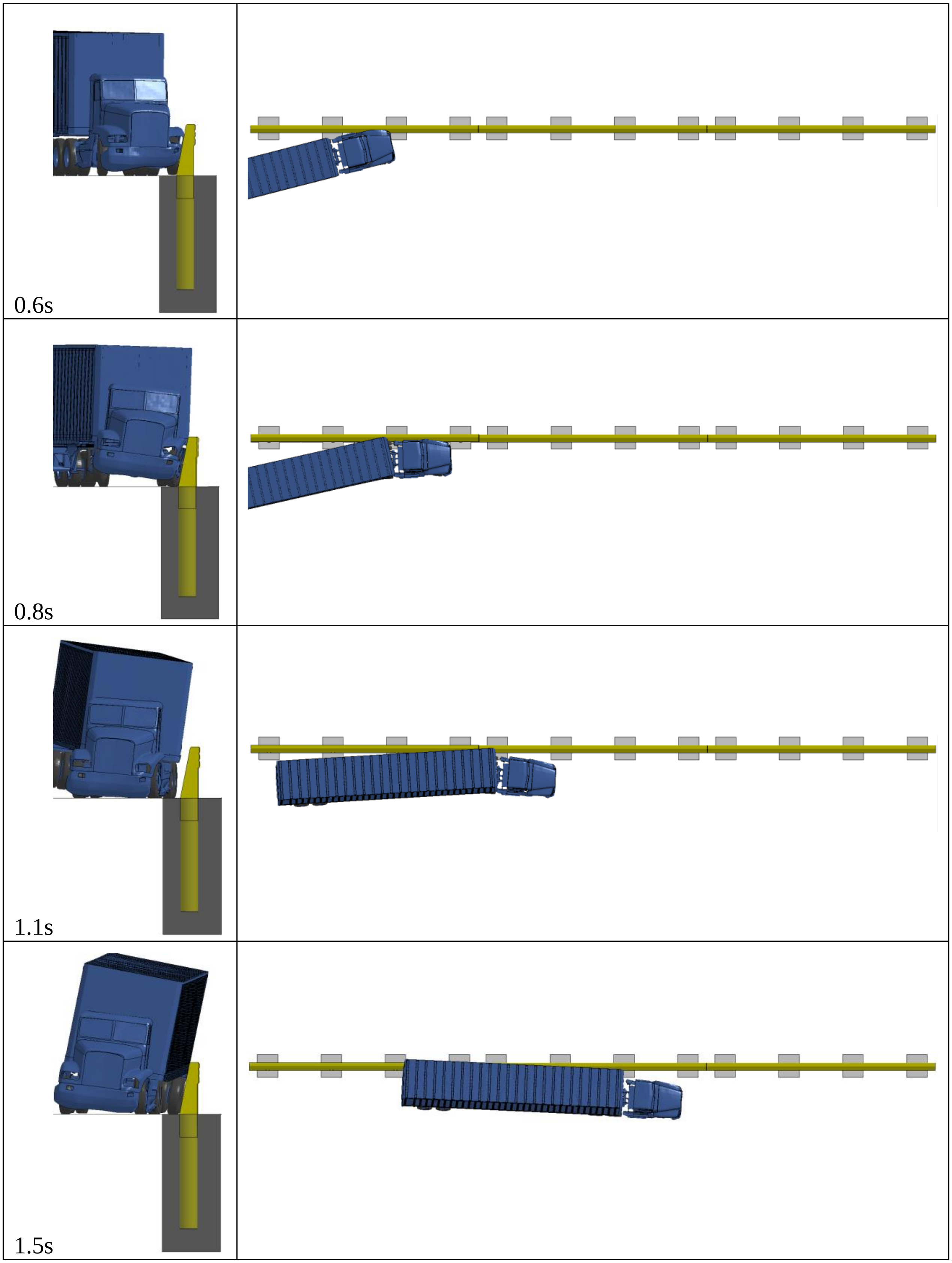
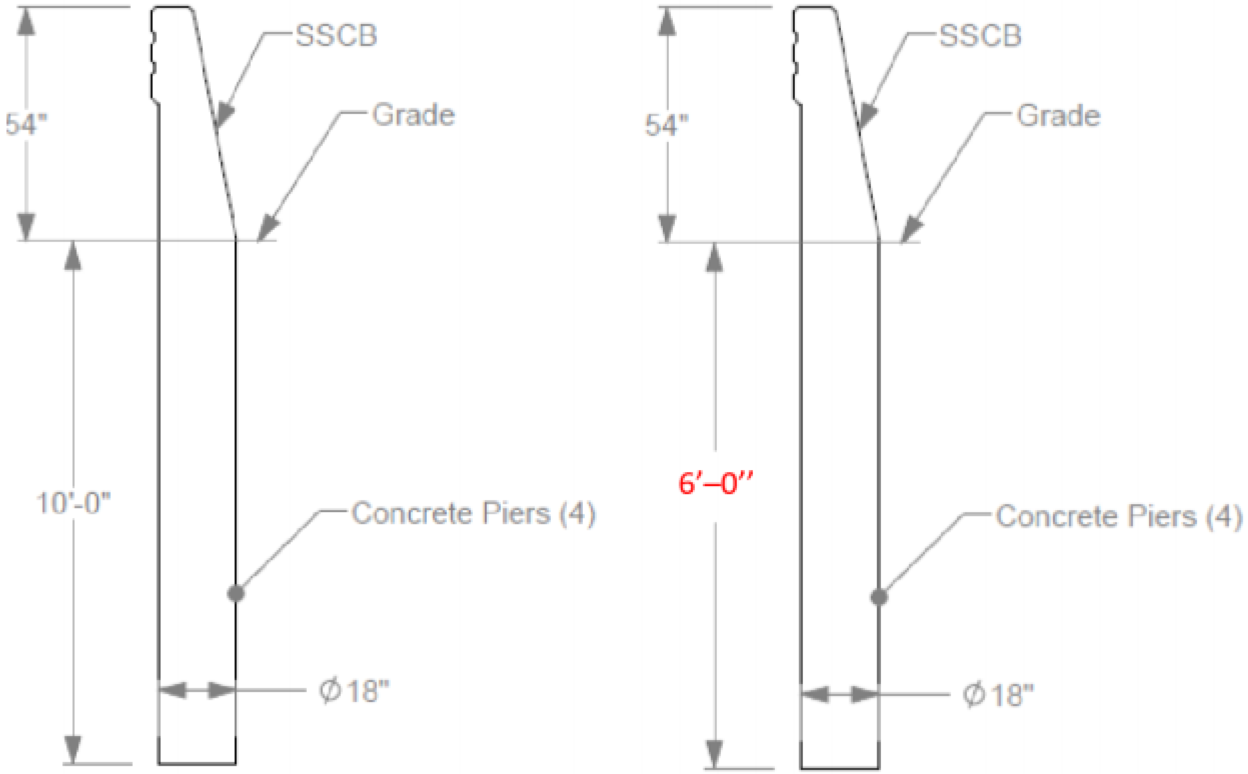


Figure 31. Impact Simulation for Drilled Shaft Foundation with 10ft Deep Shafts

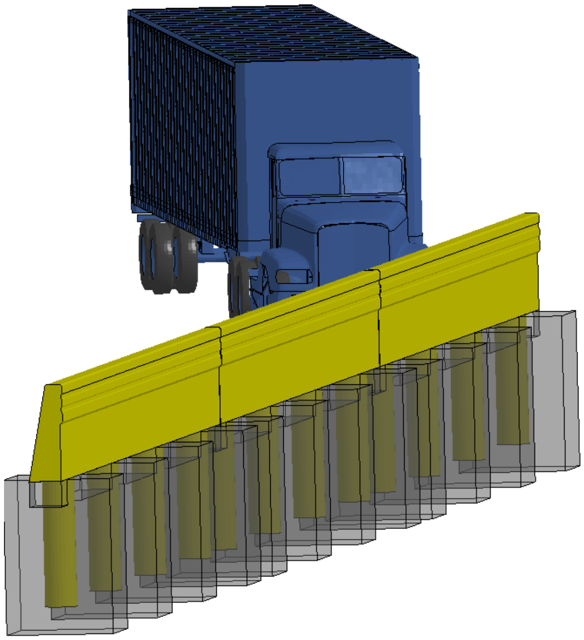
Table 4. Barrier Deflections for 10ft Deep Drilled Shaft Foundation Concept

Maximum Dynamic Deflection	1.46in
Permanent Deflection	0.75in
Working Width	29.5in
Working Width Height	149.6in



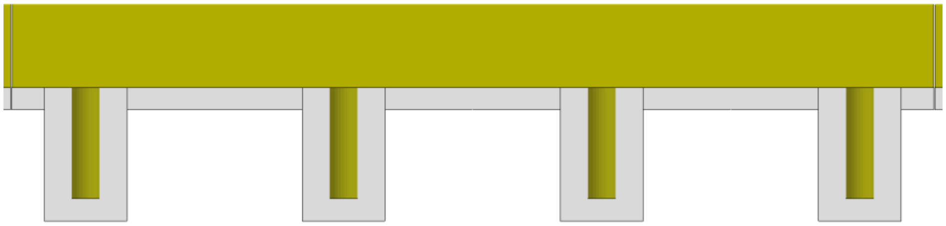
Dimensions in red are not to scale.

Figure 32. Original Drilled Shaft Foundation Design (left) and Optimized Design (right)

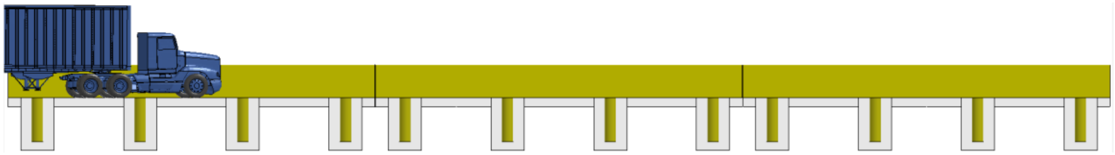


Overall System Model

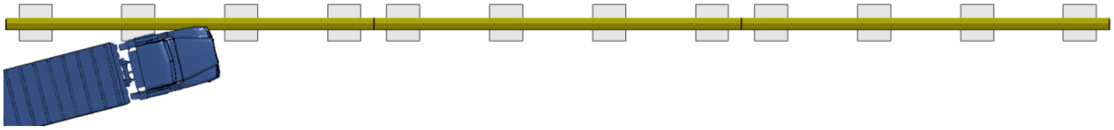
Top View of a Barrier Segment*



Side View of a Barrier Segment*



System Model (Side View)



System Model (Top View)

*Soil shown with transparency to show the drilled shafts

Figure 33. Optimized Drilled Shaft Foundation Model Details with 6ft Deep Shafts

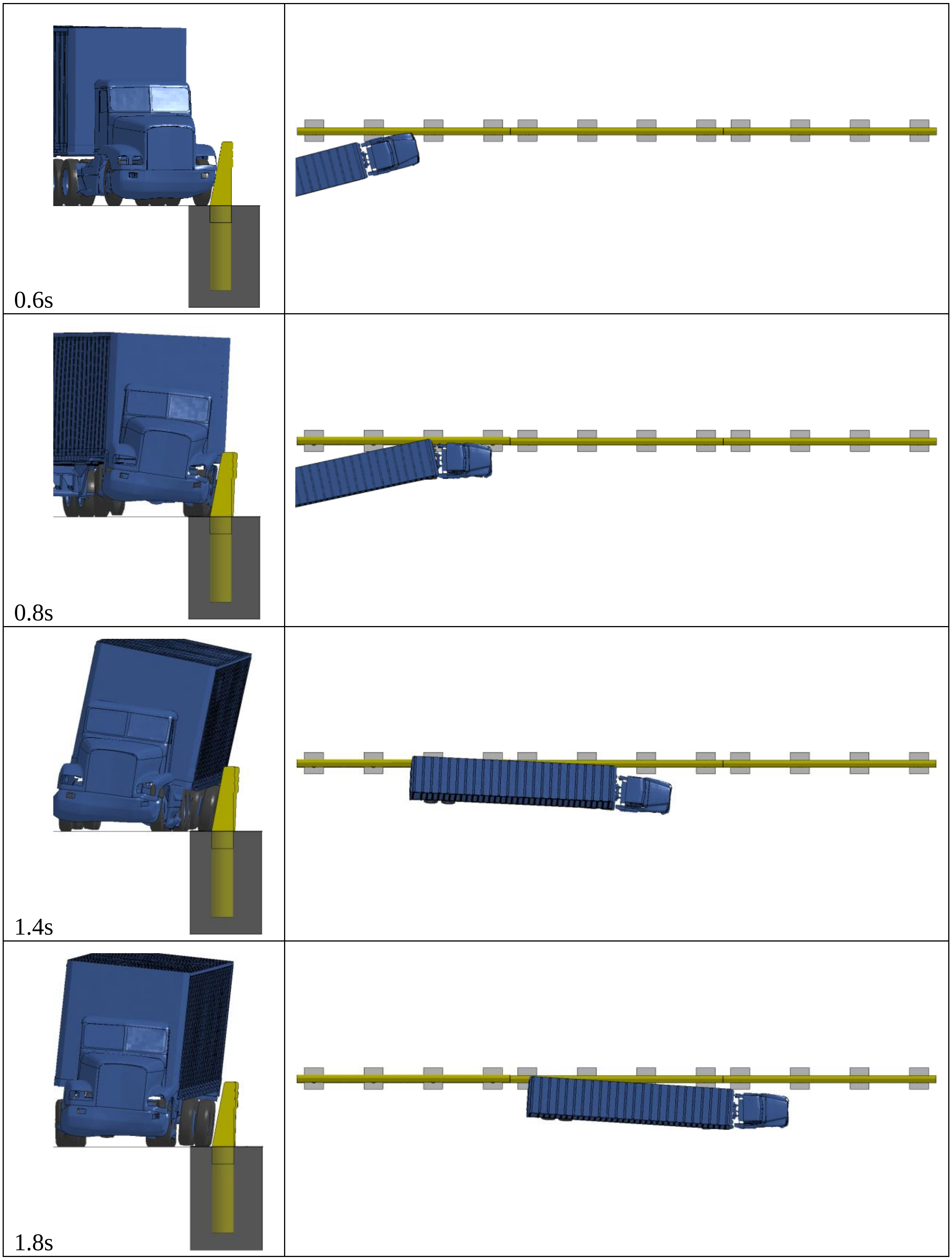


Figure 34. Impact Simulation for Drilled Shafts Foundation Concept with 6ft Deep Shafts

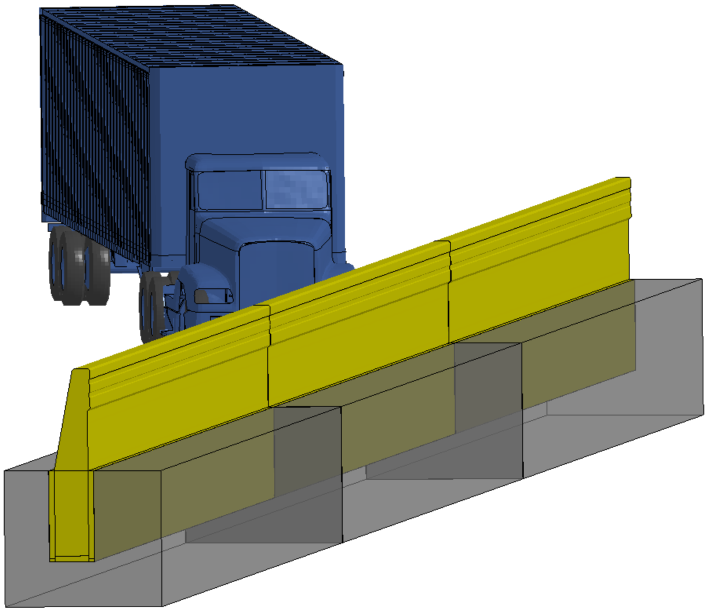
Table 5. Barrier Deflections for 6ft Deep Drilled Shaft Foundation

Maximum Dynamic Deflection	3.41in
Permanent Deflection	2.4in
Working Width	35.1in
Working Width Height	148.4in

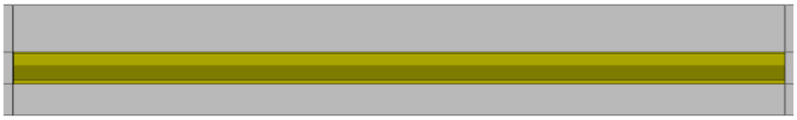
Concrete Beam Foundation Design

This foundation design was comprised of a 48-inch deep and 24-inch wide concrete beam that was attached to the base of the single slope barrier and ran through the entire length of the 50-foot segment. The finite element model of this barrier and foundation is shown in Figure 35. The results of the MASH Test 5-12 impact simulation with the tractor-trailer vehicle model are shown in Figure 36. As can be seen from the sequential images of the impact, there was very little movement of the barrier and the foundation. The vehicle was successfully contained and redirected by the barrier and the foundation system. As summarized in Table 6, the maximum dynamics deflection of the barrier was 1.8 inches and the maximum permanent deflection was 0.4 inch. The working width of the barrier and the foundation system was 33.0 inches at the height of 148.4 inches.

Encouraged by the low deflection of the foundation design, the depth and width of the concrete beam were reduced to 36 inches and 18 inches (same as the base width of the single slope barrier), respectively (Figure 37). A finite element model of this modified foundation is shown in Figure 38 and the results of the simulation are shown in Figure 39. As summarized in Table 7, the maximum dynamics deflection of the barrier was 2.5 inches and the maximum permanent deflection was 1.2 inches. The working width of the barrier and foundation system was 33.6 inches at the height of 148.0 inches.

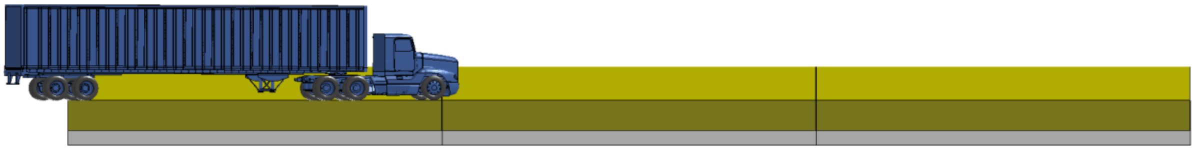


Overall System Model

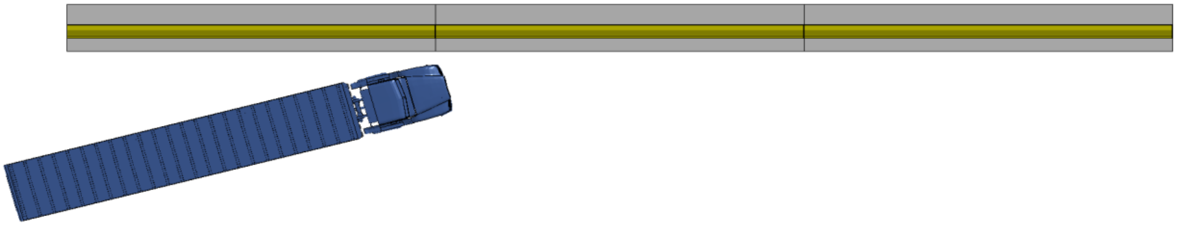


Top View of a Barrier Segment*

Side View of a Barrier Segment*



System Model (Side View)



System Model (Top View)

*Soil shown with transparency to show the beams

Figure 35. Preliminary Concrete Beam Foundation Simulation Model Details

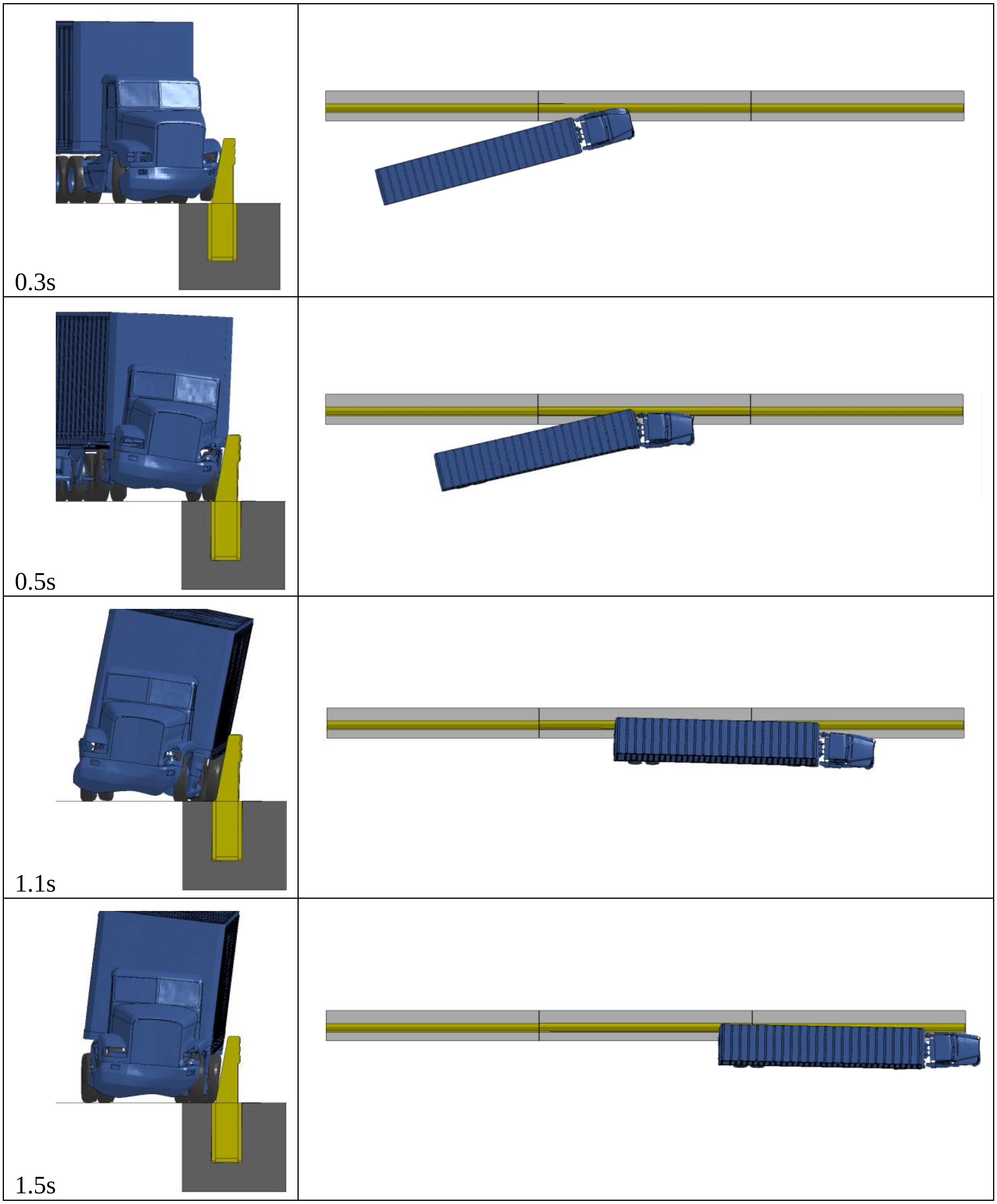
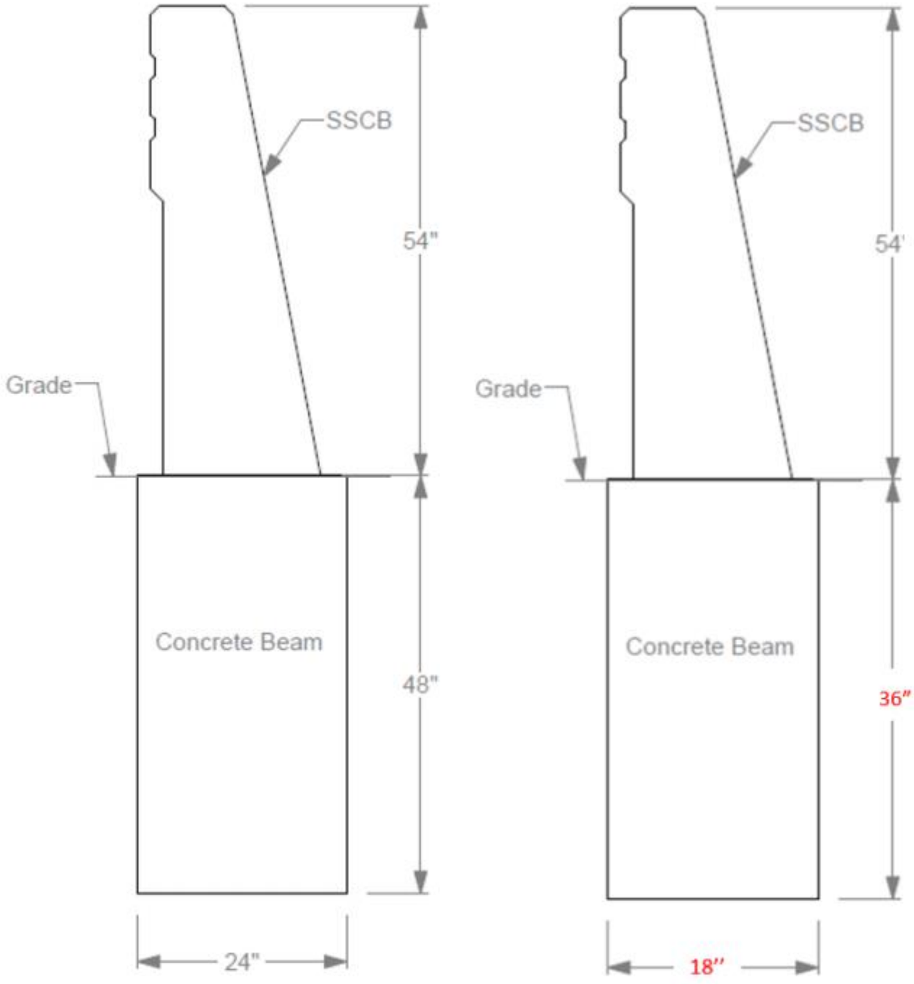


Figure 36. Impact Simulation for Preliminary Concrete Beam Foundation Design

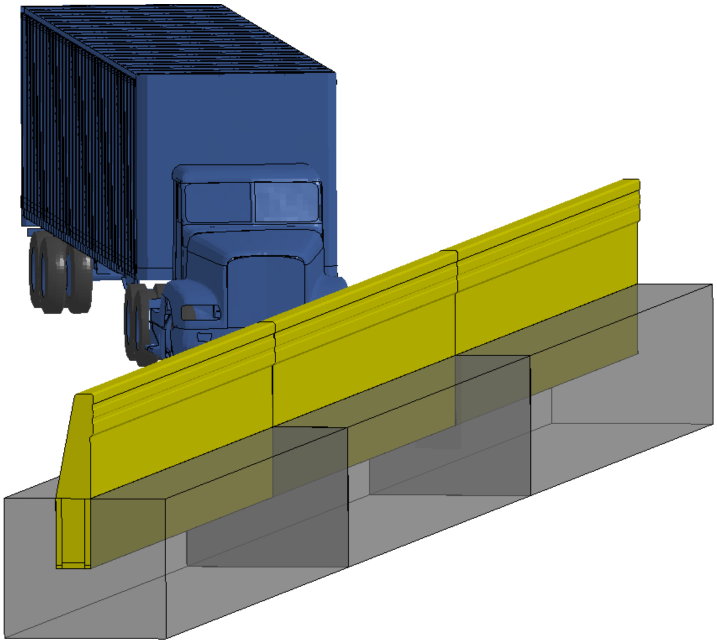
Table 6. Barrier Deflections for Preliminary Concrete Beam Foundation Design

Maximum Dynamic Deflection	1.8in
Permanent Deflection	0.4in
Working Width	33in
Working Width Height	148.4in

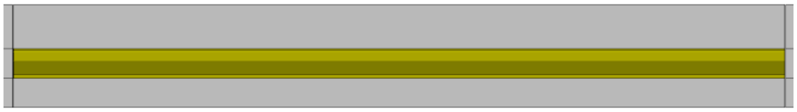


Dimensions in red are not to scale

Figure 37. Preliminary Concrete Beam Foundation (left) and Optimized Design (right)

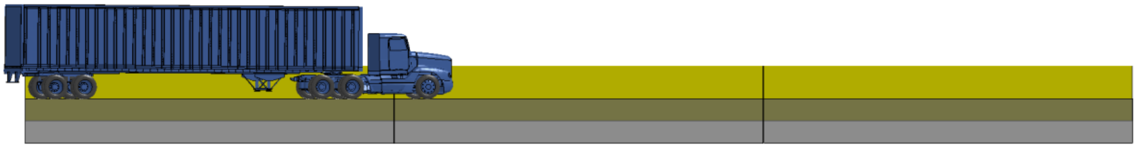


Overall System Model



Top View of a Barrier Segment*

Side View of a Barrier Segment*



System Model (Side View)

System Model (Top View)

*Soil shown with transparency to show the beams

Figure 38. Optimized Concrete Beam Foundation Simulation Model Details

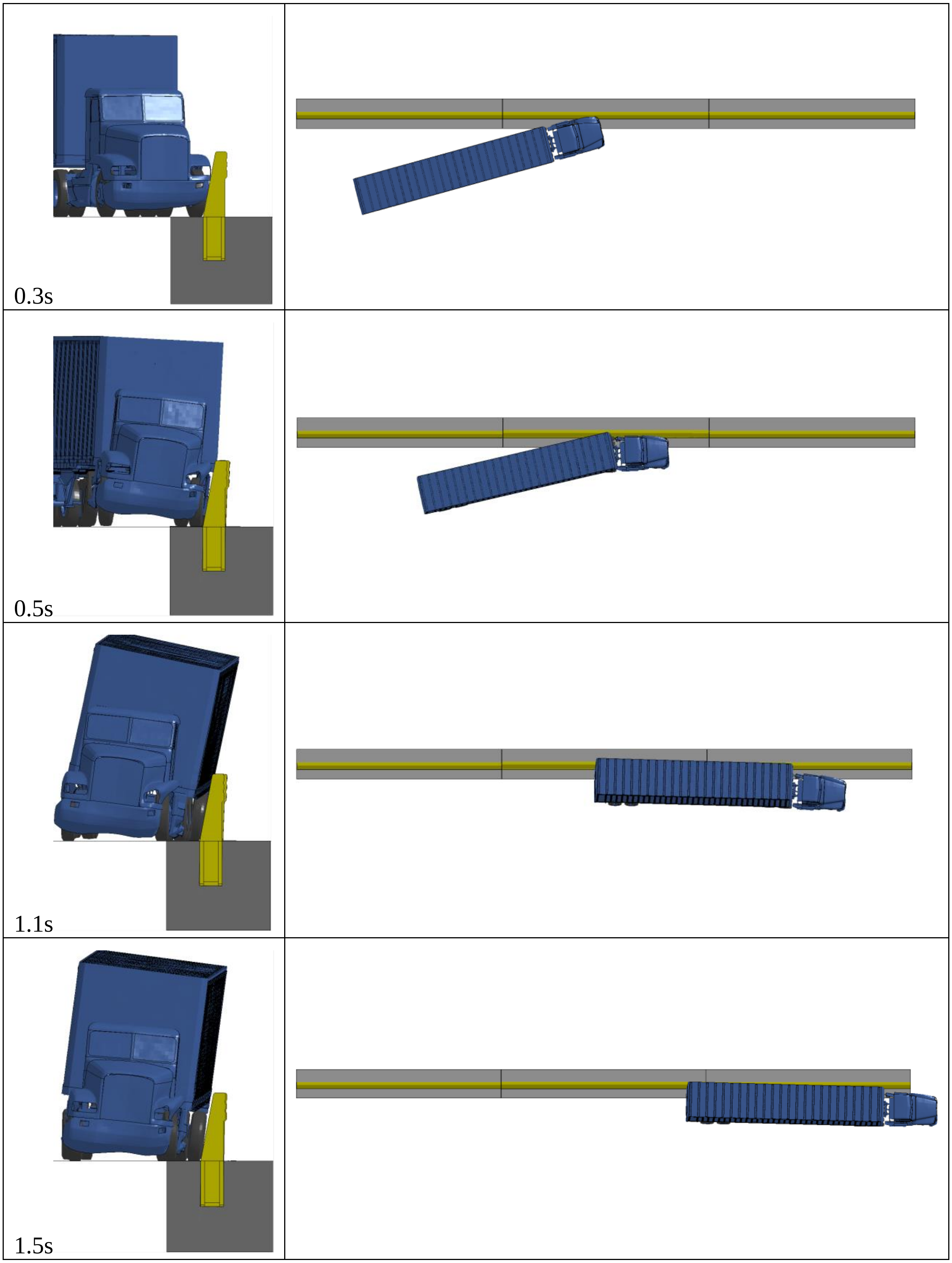


Figure 39. Impact Simulation for Optimized Concrete Beam Foundation Design

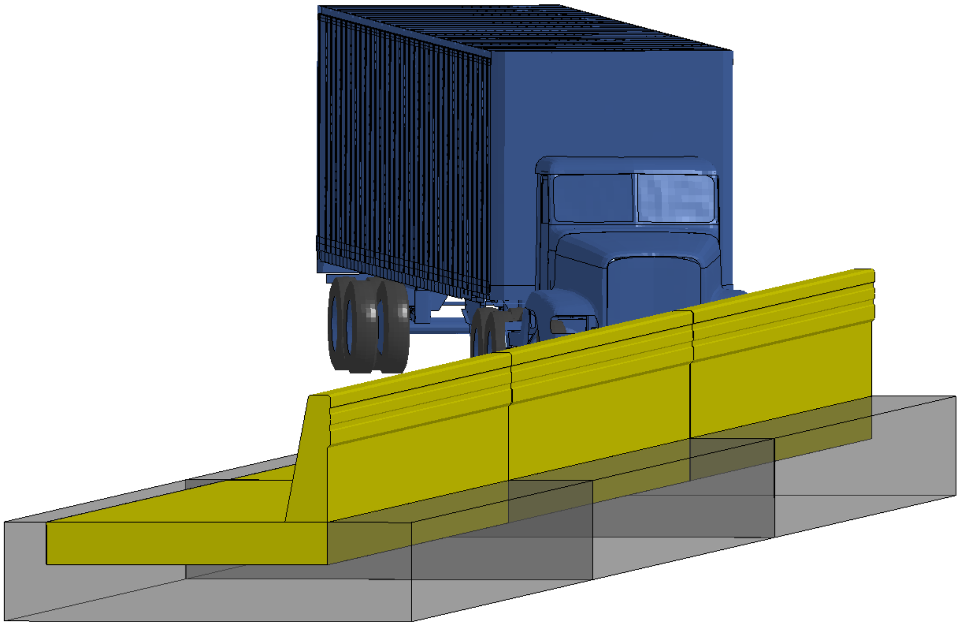
Table 7. Barrier Deflections for Optimized Concrete Beam Foundation Design

Maximum Dynamic Deflection	2.54in
Permanent Deflection	1.18in
Working Width	33.6in
Working Width Height	148in

Moment Slab Foundation Design

This foundation design was comprised of an 18-inch deep and 10-foot wide moment slab that was attached to the base of the single slope barrier and ran through the entire length of the 50-foot segment. The finite element model of this barrier and foundation is shown in Figure 40. The results of the MASH Test 5-12 impact simulation with the tractor-trailer vehicle model are shown in Figure 41. As can be seen from the sequential images of the impact, there was very little movement of the barrier and the foundation. The vehicle was successfully contained and redirected by the barrier and the foundation system. As summarized in Table 8, the maximum dynamics deflection of the barrier was 0.6 inches and the maximum permanent deflection was 0.0 inch. The working width of the barrier and the foundation system was 36.3 inches at the height of 148.0 inches.

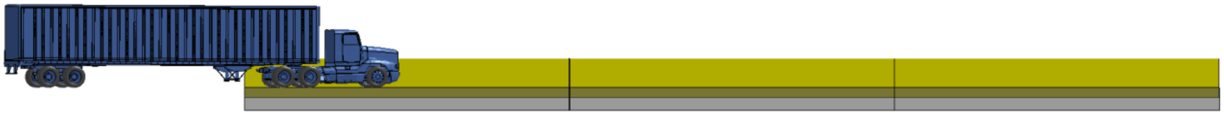
Encouraged by the low deflection of the foundation design, the width of moment slab was reduced to 6 feet while keeping the same depth (Figure 42). A finite element model of this modified foundation is shown in Figure 43 and the results of the simulation are shown in Figure 44. As summarized in Table 9, the maximum dynamics deflection of the barrier was 3.1 inches and the maximum permanent deflection was 0.1 inches. The working width of the barrier and foundation system was 38.0 inches at the height of 149.2 inches.



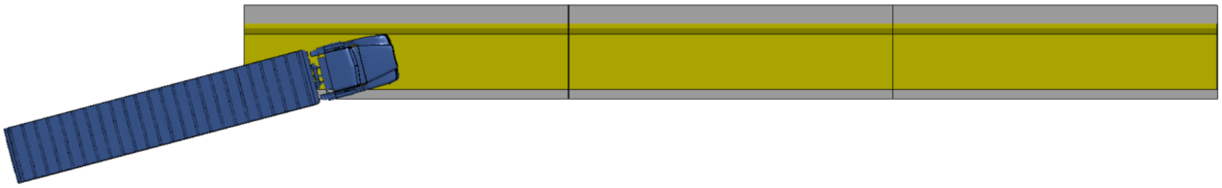
Overall System Model

Top View of a Barrier Segment*

Side View of a Barrier Segment*



System Model (Side View)



System Model (Top View)

*Soil shown with transparency to show the moment slab

Figure 40. 10ft Wide Moment Slab Foundation Simulation Model Details

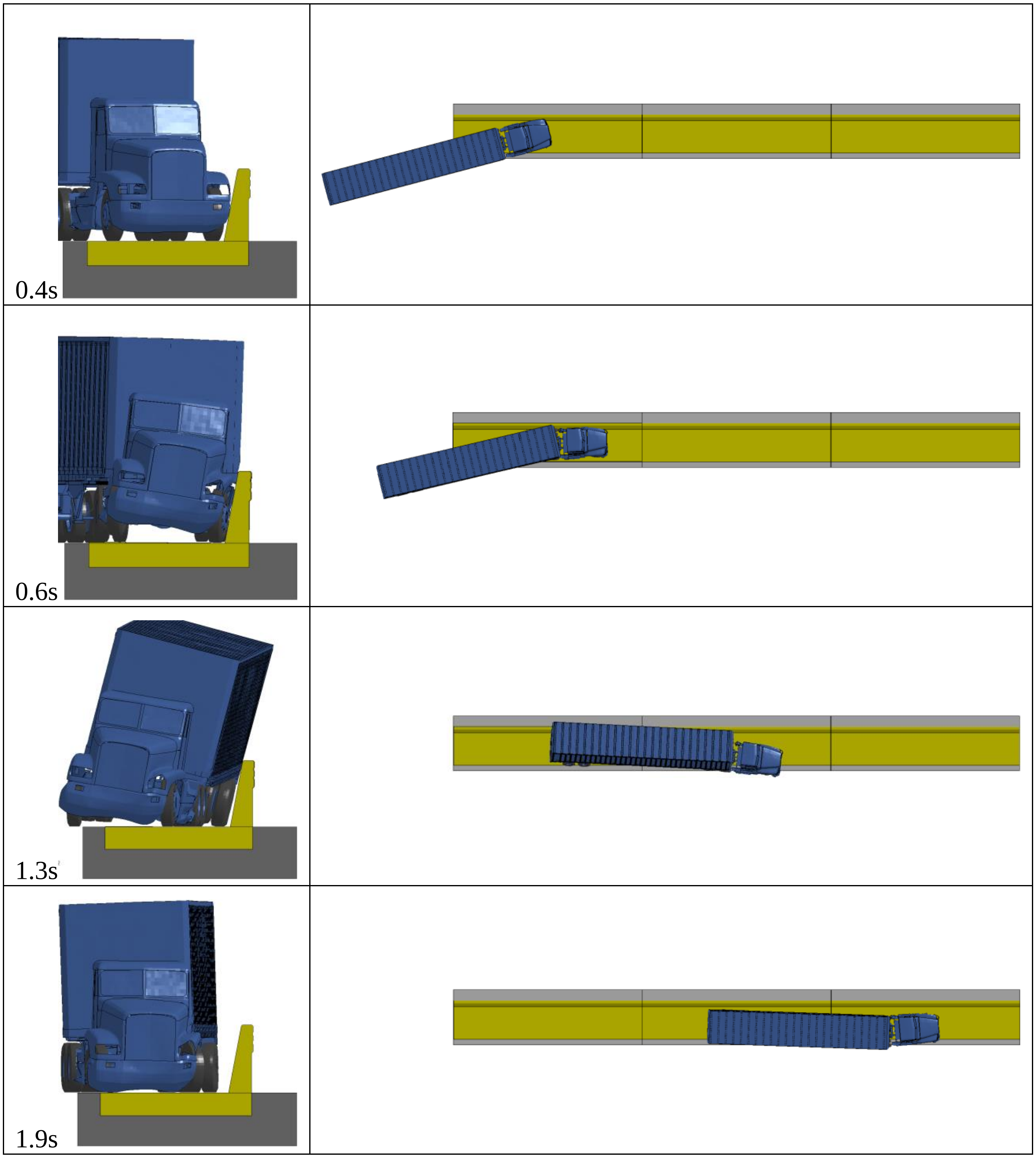
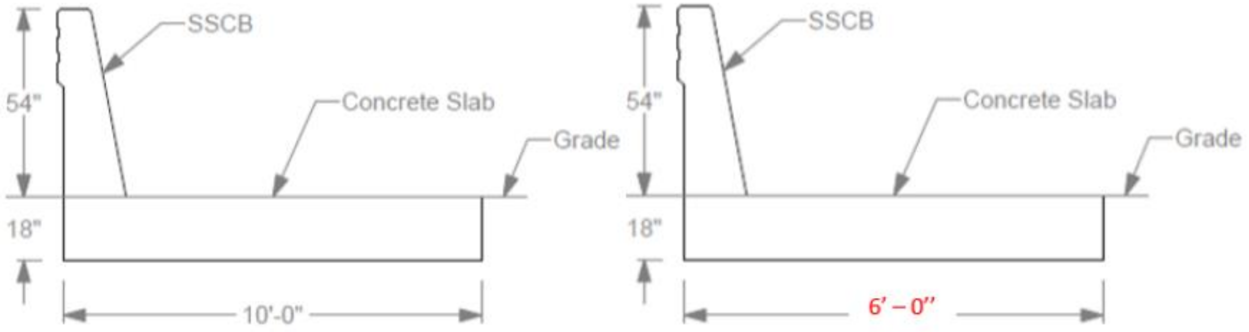


Figure 41. Impact Simulation for 10ft Wide Moment Slab Foundation

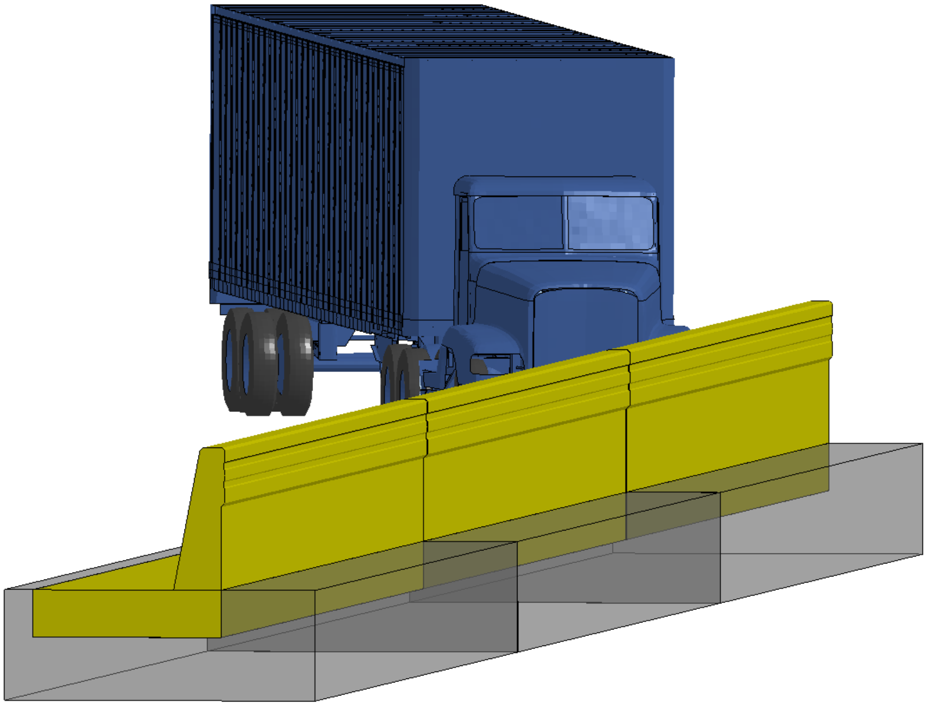
Table 8. Barrier Deflections for 10ft Wide Moment Slab Foundation

Maximum Dynamic Deflection	0.56in
Permanent Deflection	0.0in
Working Width	36.3in
Working Width Height	148in



Dimensions in red are not to scale

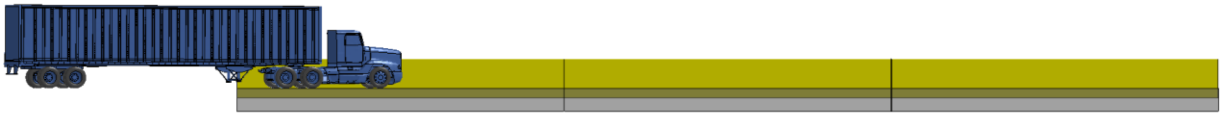
Figure 42. 10ft Wide Moment Slab Foundation (left) and Optimized 6ft Design (right)



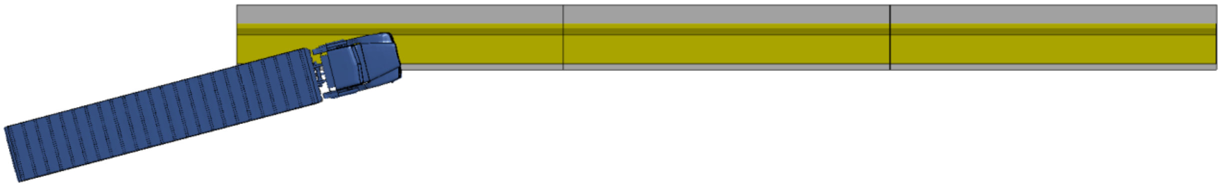
Overall System Model

Top View of a Barrier Segment*

Side View of a Barrier Segment*



System Model (Side View)



System Model (Top View)

*Soil shown with transparency to show the moment slab

Figure 43. 6ft Wide Moment Slab Foundation Simulation Model Details

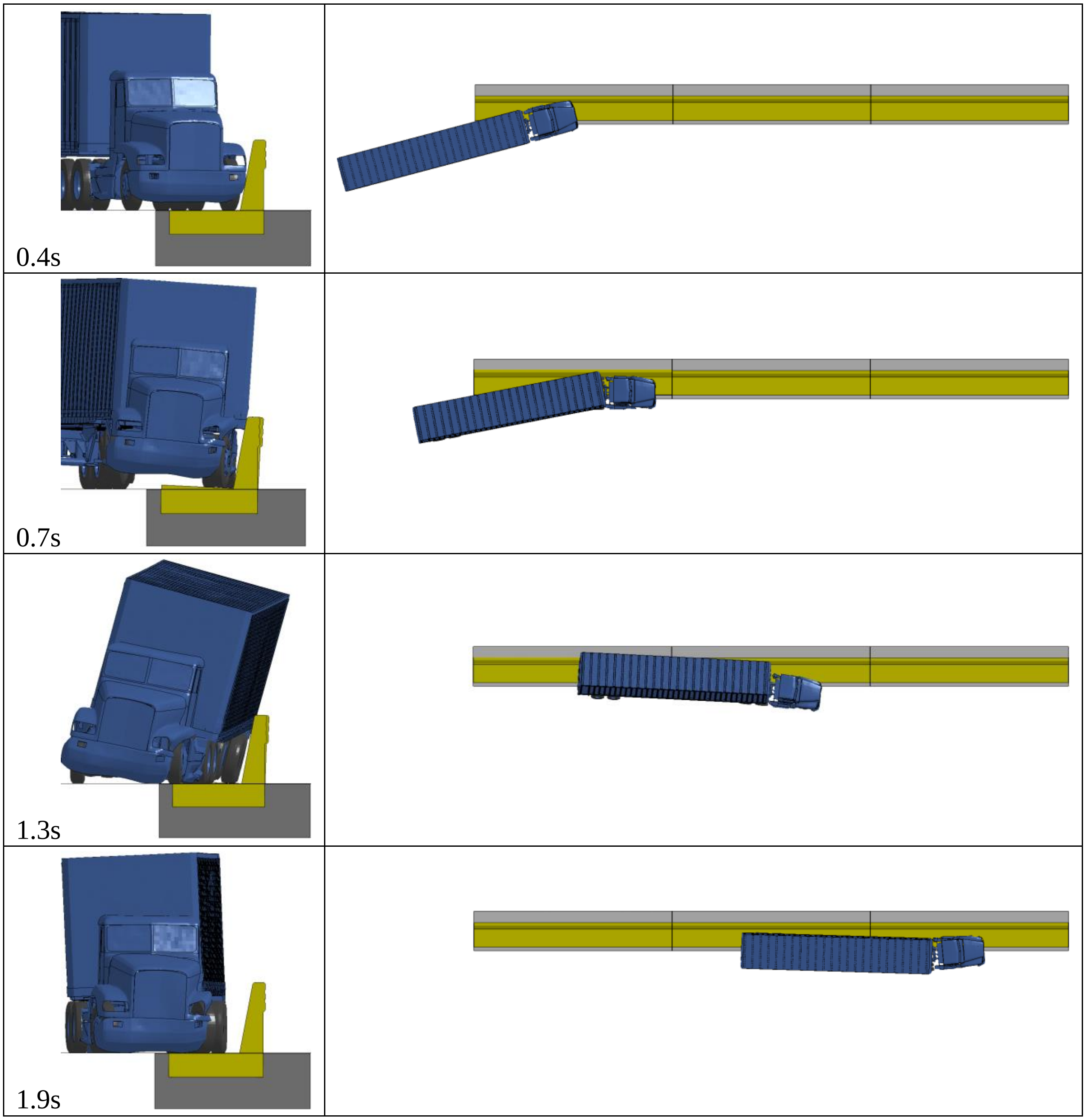


Figure 44. Impact Simulation for the 6ft Wide Moment Slab Foundation

Table 9. Barrier Deflections for 6ft Wide Moment Slab Foundation

Maximum Dynamic Deflection	3.07in
Permanent Deflection	0.04in
Working Width	38in
Working Width Height	149.2in

4.1.2. Weaker Soil Configuration MASH TL-5 Systems Results

After initially presenting the results with the stronger soil configuration, TxDOT asked to evaluate two additional design variations through finite element analysis simulation.

The first request was to rerun the optimized drilled shaft foundation simulation using weaker soil properties, and if necessary (if the deflection are not close to the stronger soil option), add another shaft to the design concept. The second request was made regarding the beam foundation. The use of the standard TxDOT Traffic Rail Foundation (TRF) was requested.

Drilled Shaft Foundation Design

With the weaker soil, the dynamic and permanent deflection of the single slope barrier increased to 6.3 inches and 4.3 inches, respectively – up from 3.4 inches and 2.4 inches for the previously performed simulation in the stronger soil. Since this was higher deflection than desired, additional (fifth) shaft was added to the design. With weaker soil and five 6-foot drilled shafts, the dynamic and permanent deflections were 3.75 inches and 1.25 inches, respectively. These deflections are comparable to the optimized drilled shaft foundation with stronger soil. Figure 45 shows the design of the drilled shaft foundation with five shafts. Figure 46 shows the maximum dynamic and permanent movement of the barrier with the 5-shaft foundation design. Table 10 summarizes the results of the additional simulation featuring a weaker soil configuration for the drilled shaft foundation concept.

Table 10. Barrier Deflections for 6ft Deep Shaft Foundation with Weaker Soil

	4-drilled shafts foundation	5-drilled shafts foundation
Maximum Dynamic Deflection	6.3in	3.75in
Permanent Deflection	4.3in	1.25in

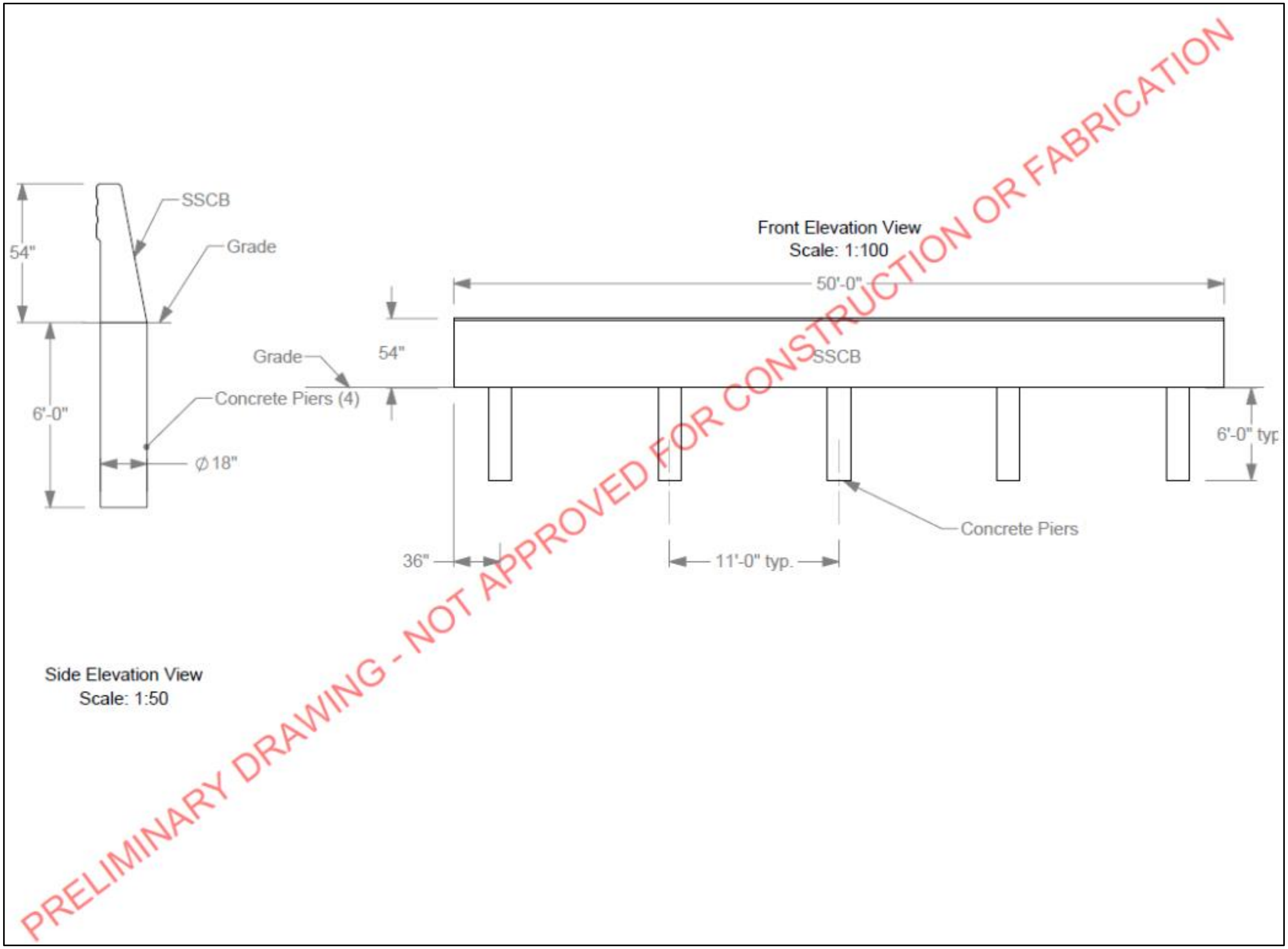


Figure 45. Optimized Design Concept 1 with Additional Shaft for MASH TL-5

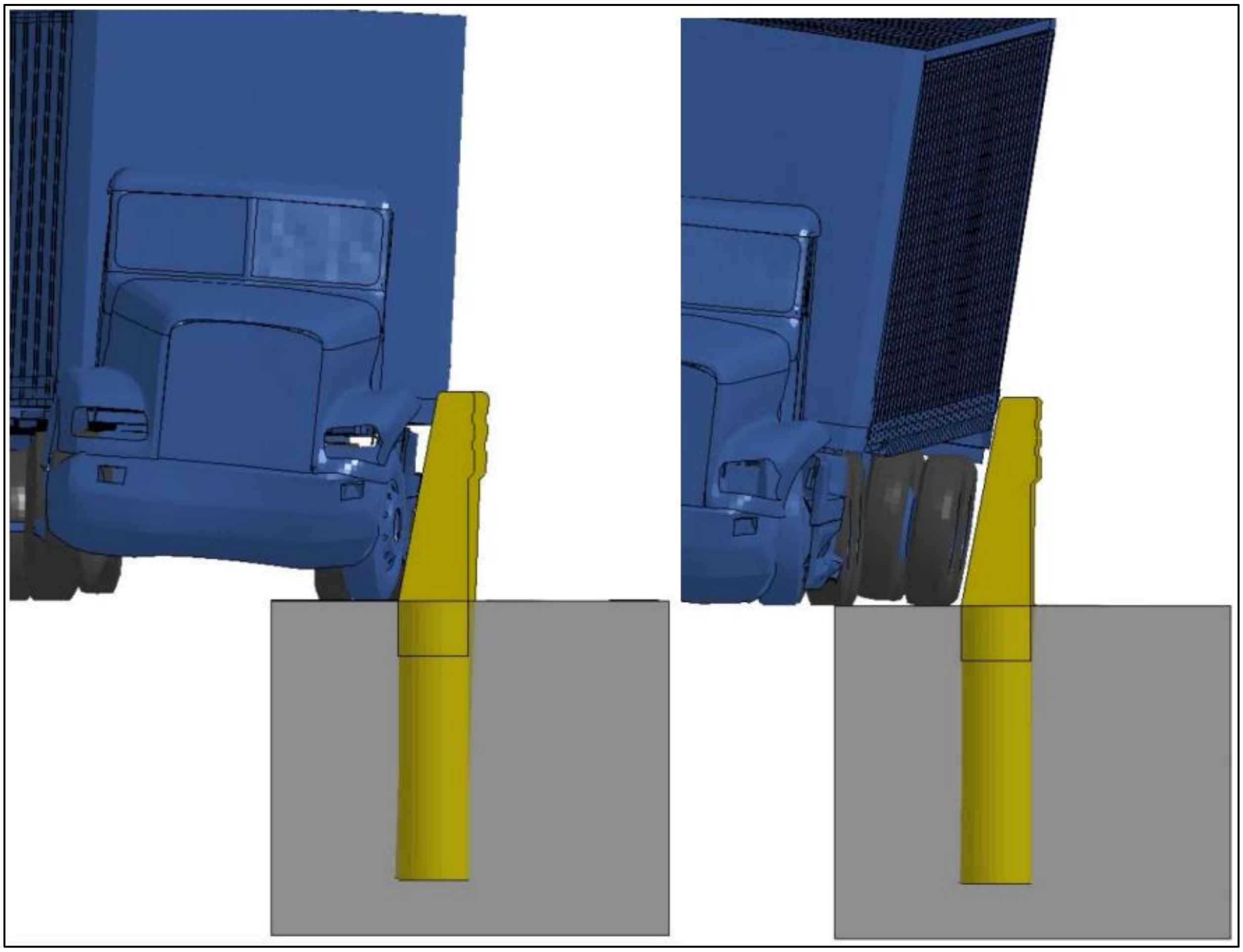


Figure 46. Maximum Dynamic (left) and Permanent (right) Barrier Deflection Due to Impact

Concrete Beam Foundation Design

The simulation performed with TxDOT's TRF foundation (33-inch deep and 19-inch wide) with weaker soil resulted in maximum dynamic and permanent deflection of 3.6 inches and 0.35 inch, respectively. These are also comparable to the deflections of the drilled shaft foundation presented above. Figure 47 shows the impact sequences of the simulation performed for this variation. Figure 48 provides a closer view to the barrier deflection. The results are summarized in Table 11.

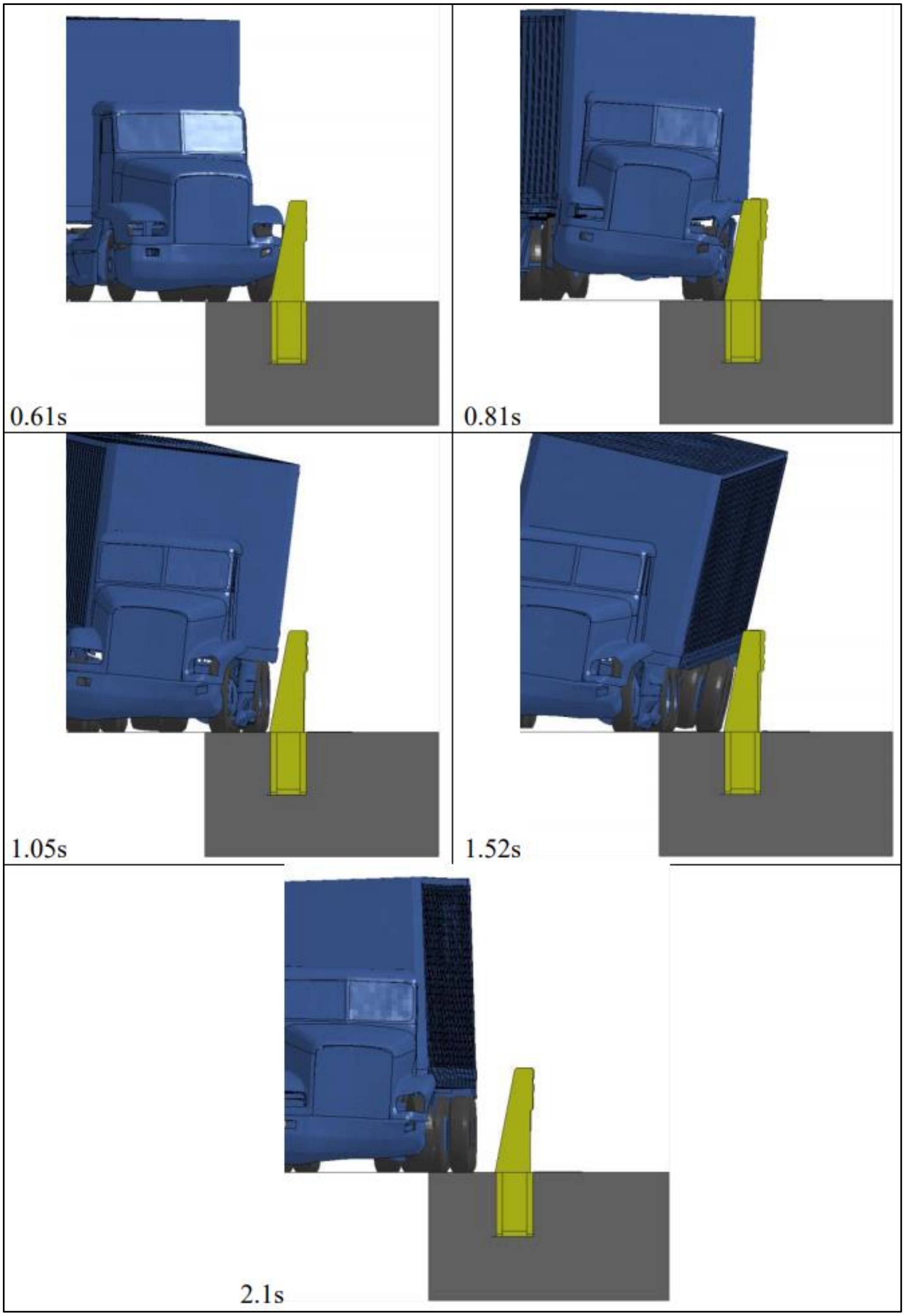


Figure 47. Impact Simulation of 54-inch SSB with TxDOT's TRF Foundation

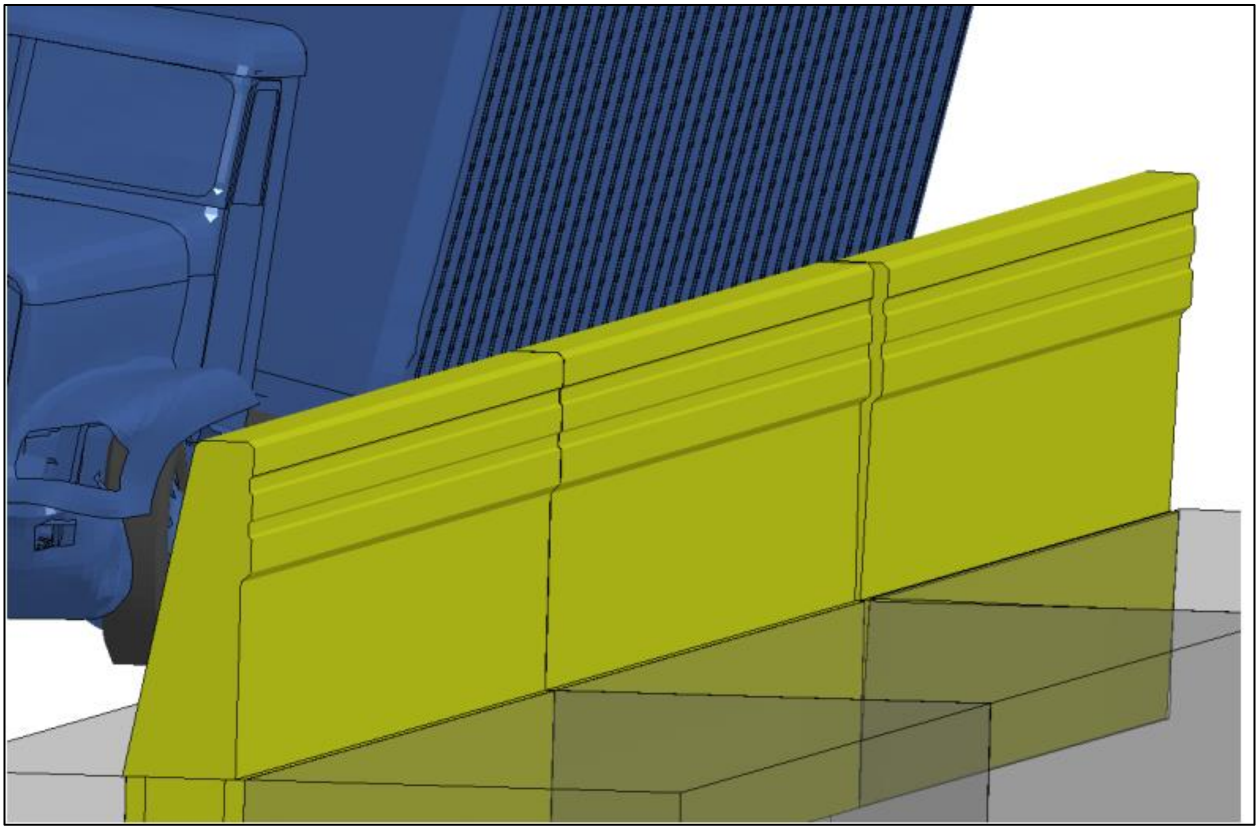


Figure 48. Maximum Dynamic Deflection Occurs at 1.52 Seconds

Table 11. Barrier Deflections for Optimized Concrete Beam Foundation with Weaker Soil

Maximum Dynamic Deflection	3.6in
Permanent Deflection	0.35in
Working Width	34.2in
Working Width Height	149.2in

4.2. MASH TL-4 Systems Results

For the 36-inch tall single slope concrete barrier with structurally independent foundation, TxDOT decided to proceed with all the three preliminary designs proposed. The designs are as follows:

- Vertical-wall/beam foundation
- Beam and Slab foundation
- Moment slab foundation

Subsequent to the simulation of the preliminary foundation design, additional simulations for each of the three design concepts were performed. In these simulations, some of the design dimensions and the length of the barrier segments were reduced with the goal of achieving a more optimized design. Some of these optimized versions were also tested under a weaker soil configuration.

Moreover, additional designs were requested to be evaluated featuring different geometries of the soil and the single slope concrete barrier with the weaker soil configuration.

Details of all the simulation models and the results of the simulation analyses are presented below.

4.2.1. Stronger Soil Configuration MASH TL-4 Systems Results

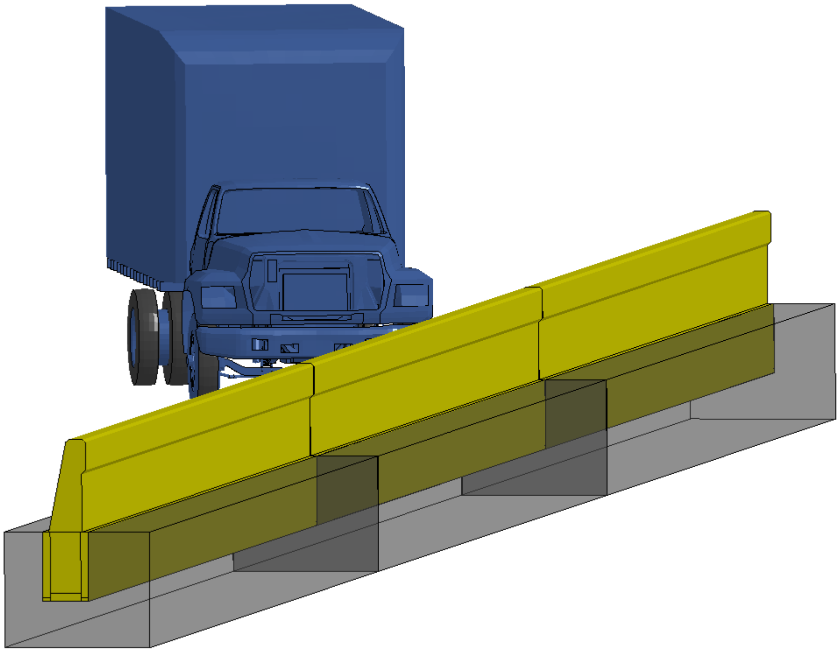
Concrete Beam Foundation Design

This foundation design was comprised of a 27-inch deep and 18-inch wide concrete beam that was attached to the base of the single slope barrier and ran through the entire length of the 50-foot segment.

The finite element model of this barrier and foundation is shown in Figure 49. The results of the MASH Test 4-12 impact simulation with the single unit truck model are shown in Figure 50. As can be seen from the sequential images of the impact, there was very little movement of the barrier and the foundation. The vehicle was successfully contained and redirected by the barrier and the foundation system. As summarized in Table 12, the maximum dynamics deflection of the barrier was 0.15 inches and the maximum permanent deflection was 0.01 inch. The working width of the barrier and the foundation system was 96.4 inches at the height of 138.6 inches.

Encouraged by the low deflection of the foundation design, the depth and width of the concrete beam were reduced to 10 inches and 13 inches (same as the base width of the single slope barrier), respectively (Figure 58). A finite element model of this modified foundation is shown in Figure 59 and the results of the simulation are given in Table 12. The maximum dynamic deflection of the barrier was 0.95 inches and the maximum permanent deflection was 0.16 inches. The working width of the barrier and foundation system was 103.4 inches at the height of 133.9 inches.

Also, a model featuring the preliminary foundation design with five 30-foot segments was developed, keeping the total length of the barrier at 150 feet. The finite element model of this design is shown in Figure 60 and the results are given in Table 13. The maximum dynamic deflection of the barrier was 0.3 inch and the maximum permanent deflection was 0.05 inch. The working width of the barrier and foundation system was 116.3 inches at the height of 125.6 inches.

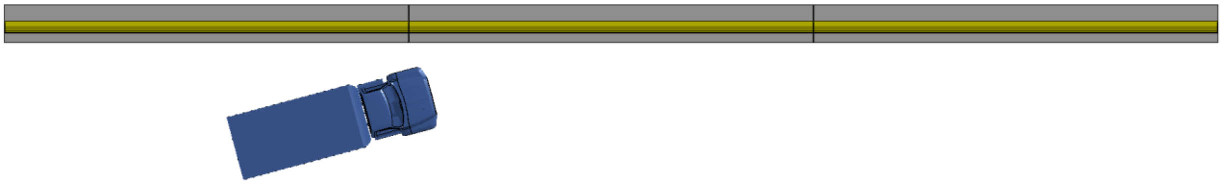


Overall System Model

Top View of a Barrier Segment*

Side View of a Barrier Segment*

System Model (Side View)



System Model (Top View)

*Soil shown with transparency to show the beams

Figure 49. Preliminary Concrete Beam Foundation Simulation Model Details

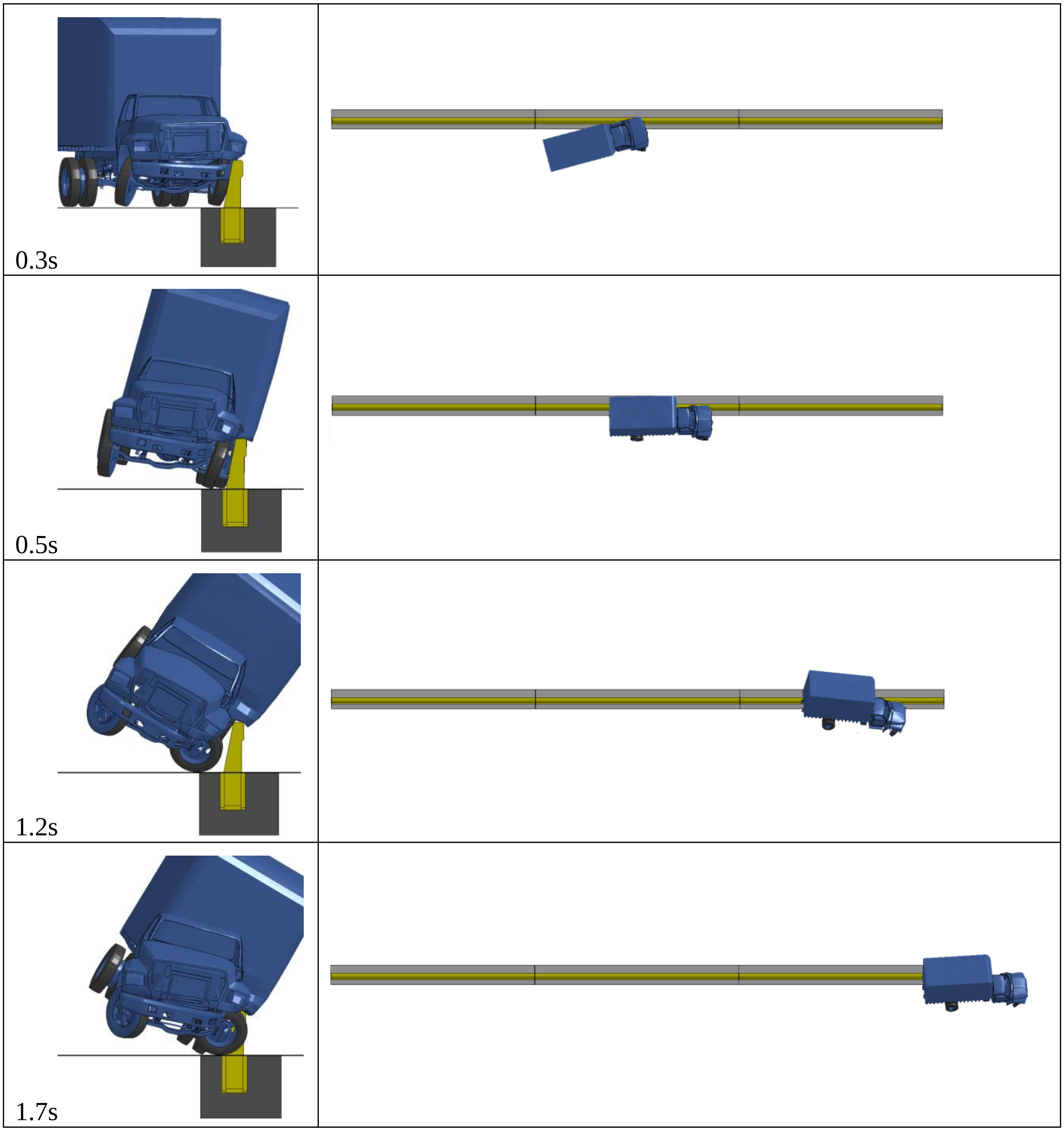
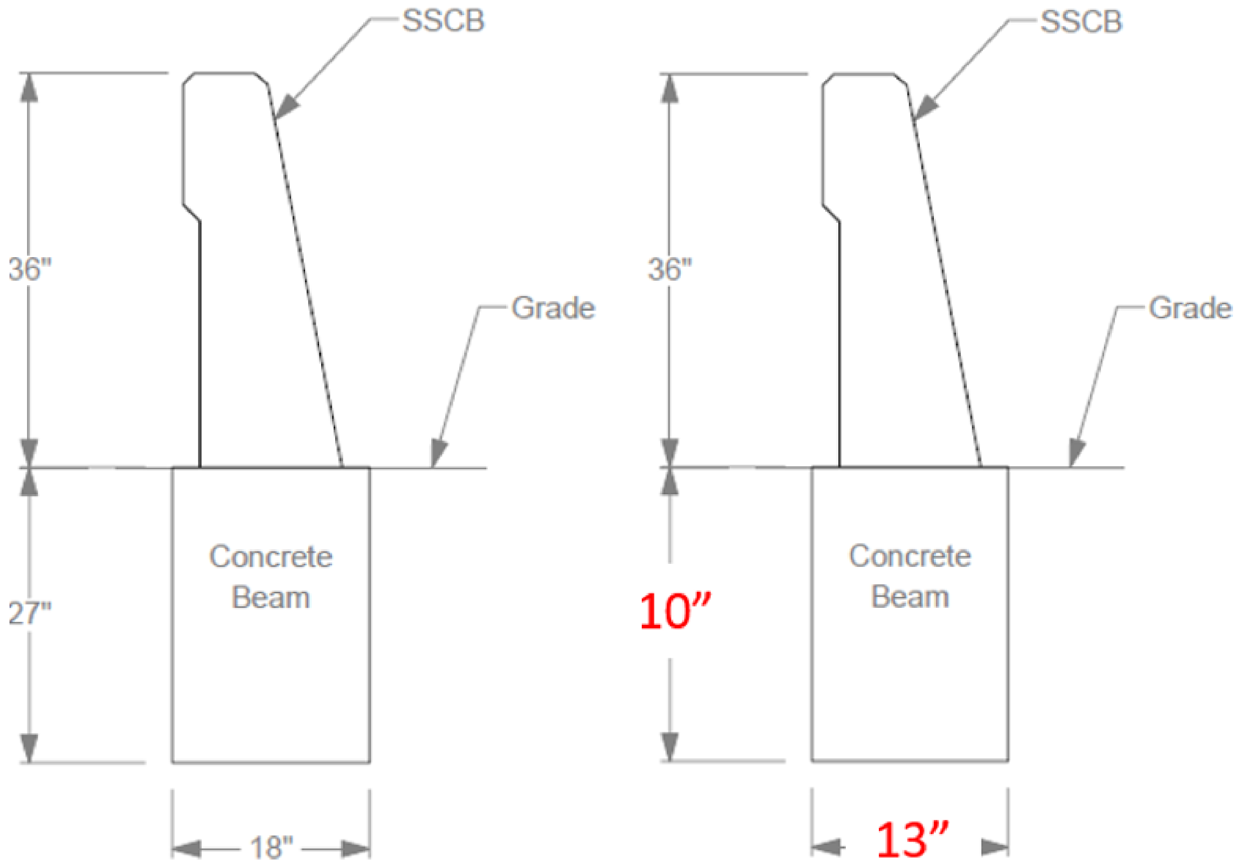


Figure 50. Impact Simulation for Preliminary Concrete Beam Foundation Design

Table 12. Barrier Deflections for Preliminary Concrete Beam Design

Maximum Dynamic Deflection	0.15in
Permanent Deflection	0.01in
Working Width	96.4in
Working Width Height	138.6in



Dimensions in red are not to scale

Figure 51. Preliminary Concrete Beam Foundation (left) and Optimized Design (right)

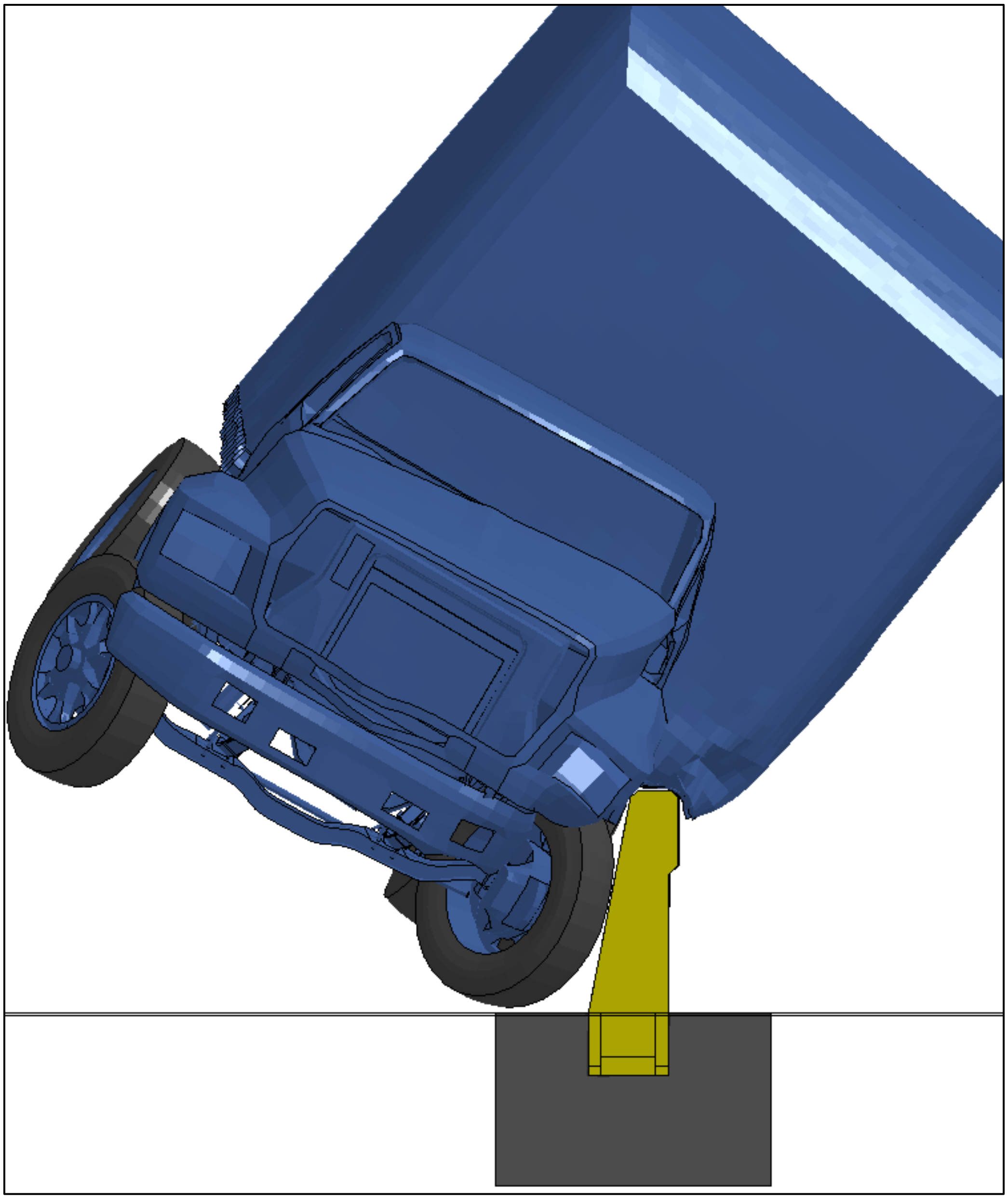


Figure 52. Optimized Concrete Beam Foundation Impact Simulation Model

Table 13. Barrier Deflections for Optimized Concrete Beam Foundation Design

Maximum Dynamic Deflection	0.95in
Permanent Deflection	0.16in
Working Width	103.4in
Working Width Height	133.9in

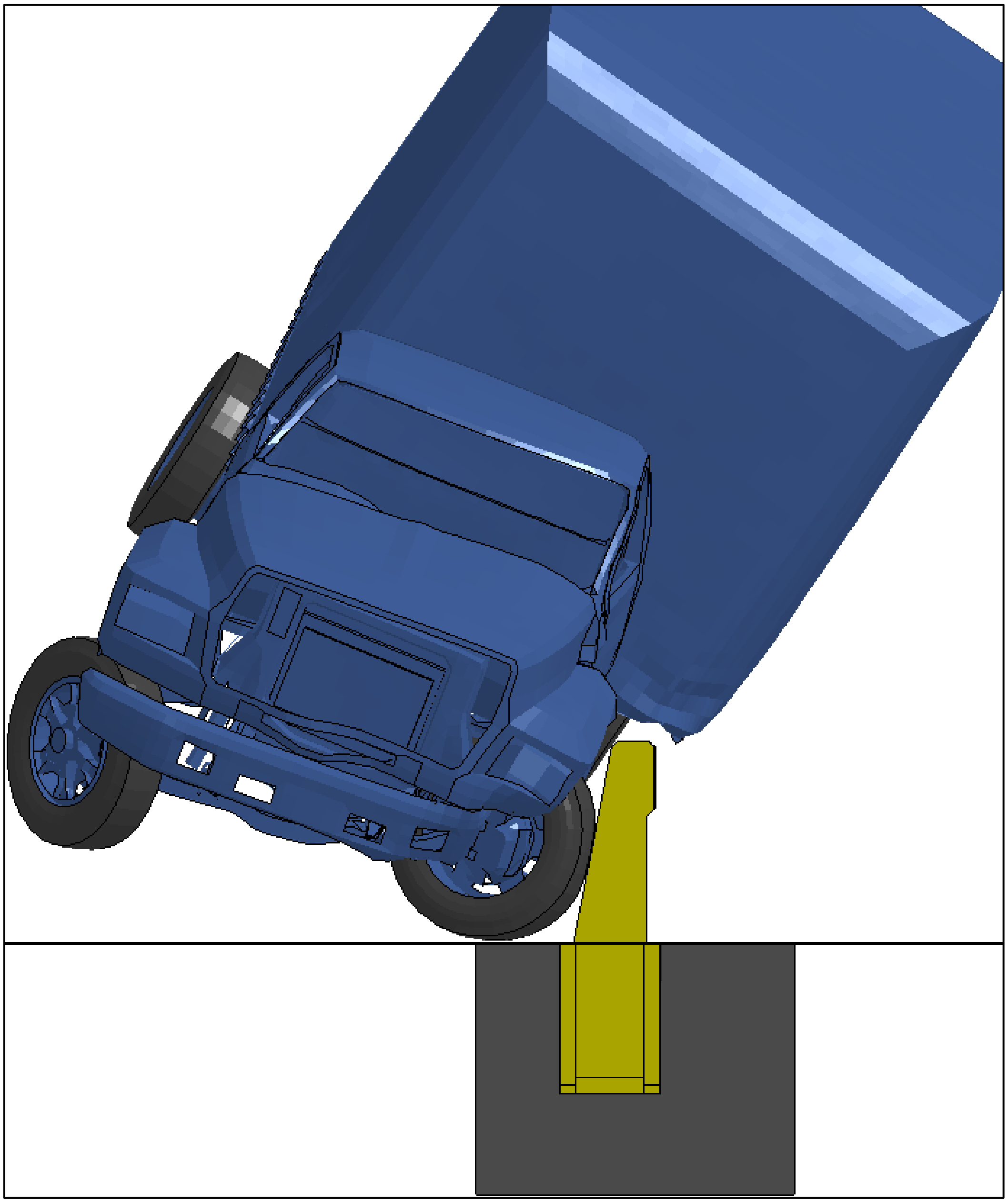


Figure 53. Preliminary Beam Foundation with Five Shorter 30ft Segments Simulation

Table 14. Barrier Deflections for Preliminary Beam Foundation with Shorter Segments

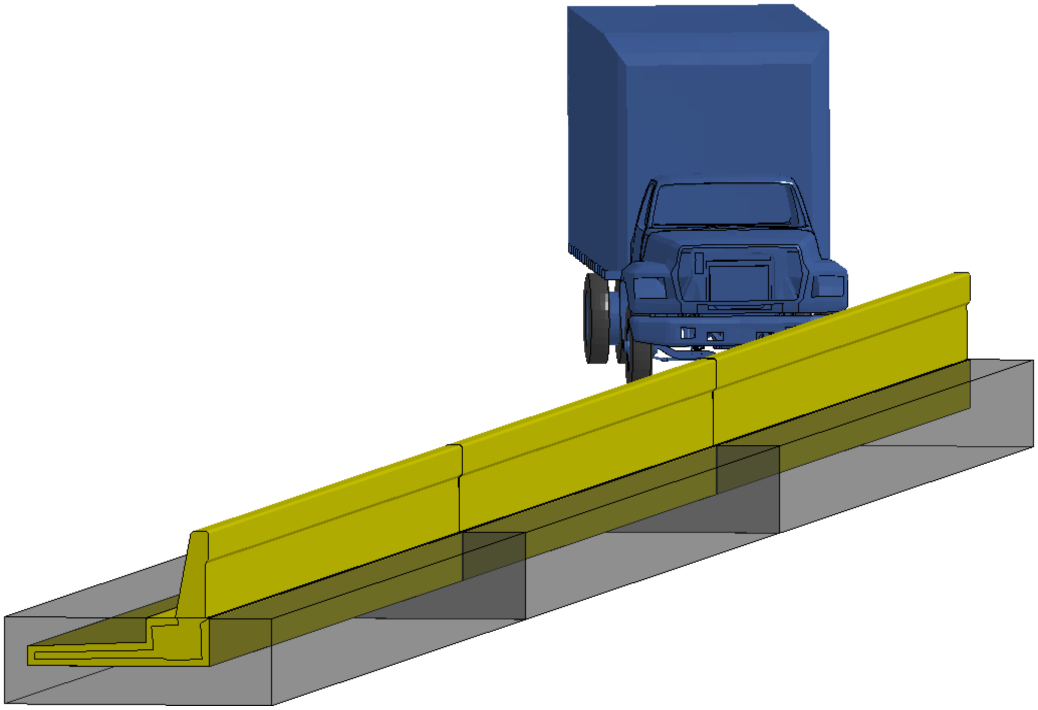
Maximum Dynamic Deflection	0.3in
Permanent Deflection	0.05in
Working Width	116.3in
Working Width Height	125.6in

Beam and Slab Foundation Design

This foundation design was comprised of a 20-inch deep and 27-inch wide beam with a 78-inch sloped moment slab that was attached to the base of the single slope barrier and ran through the entire length of the 50-foot segment.

The finite element model of this barrier and foundation is shown in Figure 54. The results of the MASH Test 4-12 impact simulation with the single unit truck model are shown in Figure 55. As can be seen from the sequential images of the impact, there was very little movement of the barrier and the foundation. The vehicle was successfully contained and redirected by the barrier and the foundation system. As summarized in Table 15, the maximum dynamics deflection of the barrier was 0.06 inches and the maximum permanent deflection was 0.01 inch. The working width of the barrier and the foundation system was 105.7 inches at the height of 108.7 inches.

Encouraged by the low deflection of the foundation design, the width of moment slab and the depth of the beam were reduced to 31.3 inches and 12 inches, respectively (Figure 56). A finite element model of this modified foundation is shown in Figure 57 and the results of the simulation are given in Table 16. The maximum dynamics deflection of the barrier was 0.35 inches and the maximum permanent deflection was 0.07 inches. The working width of the barrier and foundation system was 108 inches at the height of 137 inches.

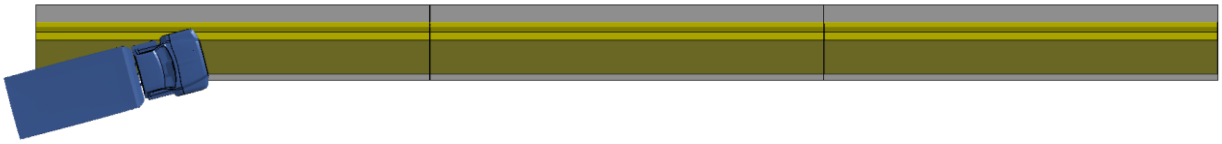


Overall System Model

Top View of a Barrier Segment*

Side View of a Barrier Segment*

System Model (Side View)



System Model (Top View)

*Soil shown with transparency to show the foundation

Figure 54. Preliminary Beam and Slab Foundation Simulation Model Details

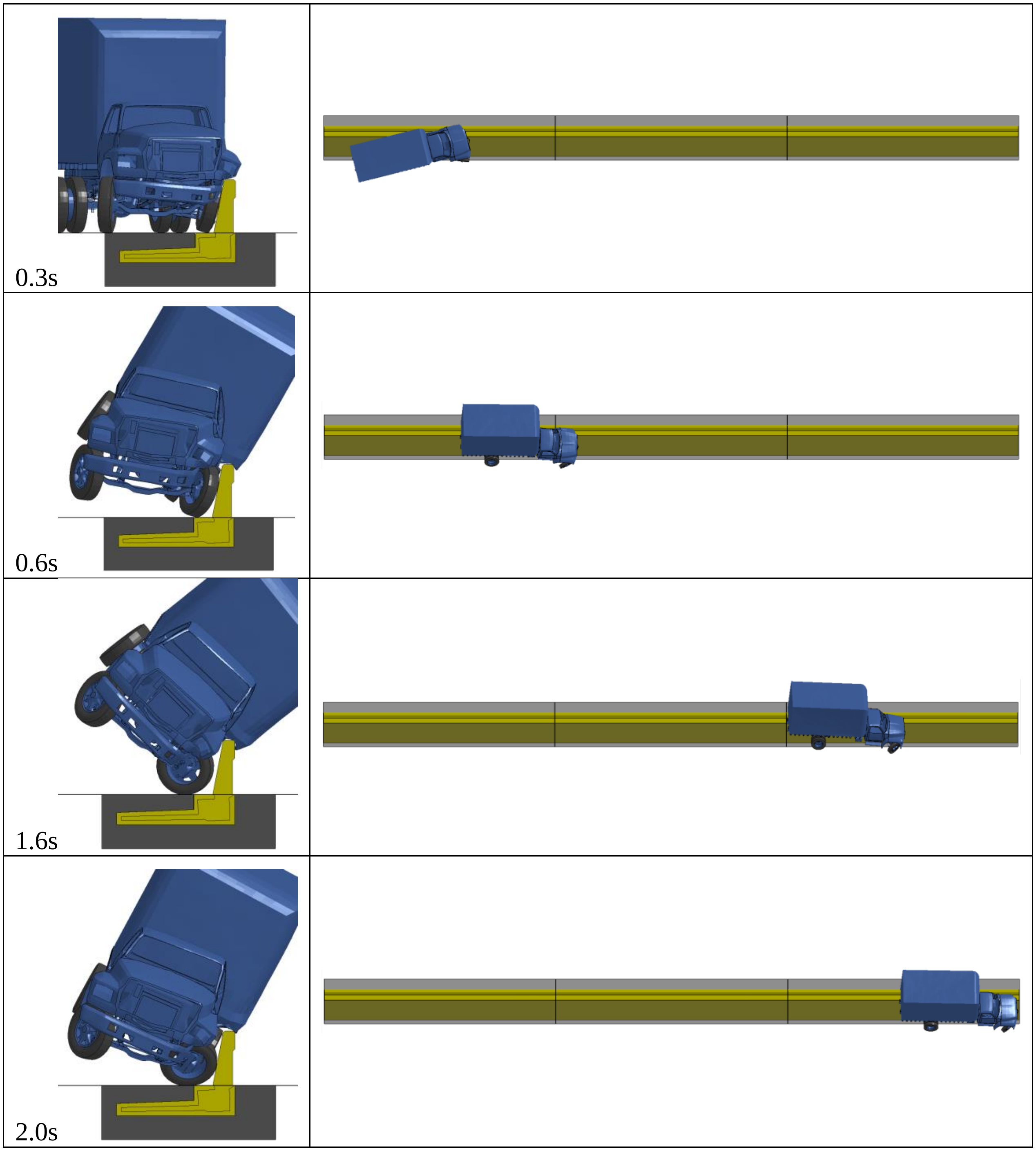
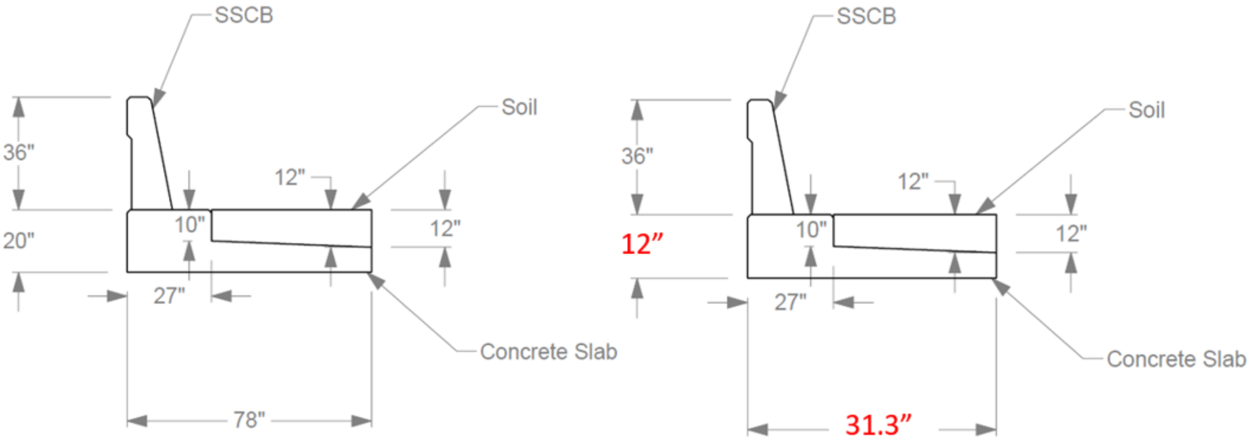


Figure 55. Impact Simulation for Preliminary Beam and Slab Foundation Design

Table 15. Barrier Deflections for Preliminary Beam and Slab Foundation Design

Maximum Dynamic Deflection	0.06in
Permanent Deflection	0.01in
Working Width	105.7in
Working Width Height	108.7in



Dimensions in red are not to scale

Figure 56. Preliminary Beam and Slab Foundation (left) and Optimized Design (right)

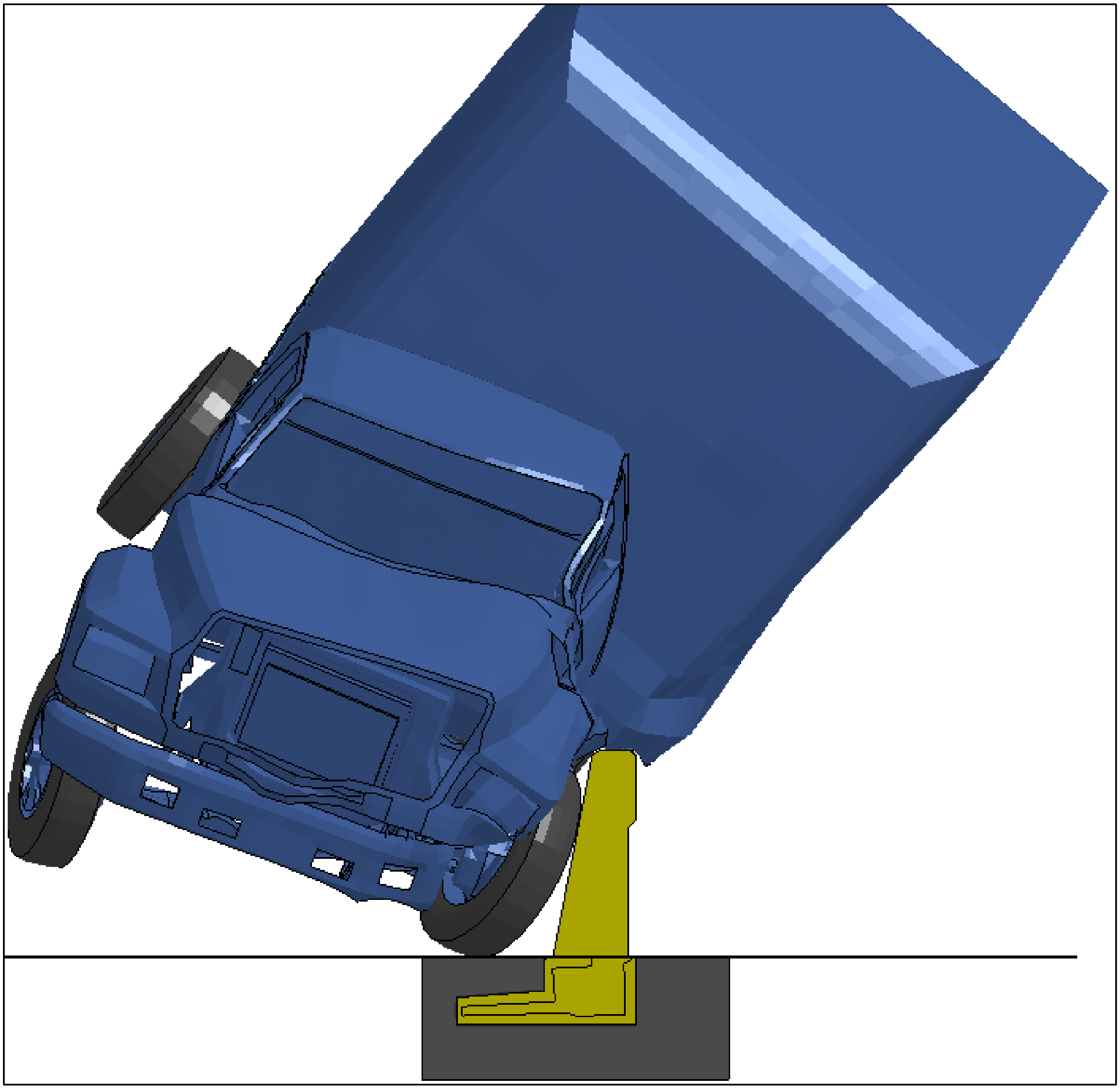


Figure 57. Optimized Beam and Moment Slab Foundation Impact Simulation Model

Table 16. Barrier Deflections for Optimized Beam and Moment Slab Foundation Design

Maximum Dynamic Deflection	0.35in
Permanent Deflection	0.07in
Working Width	108in
Working Width Height	137in

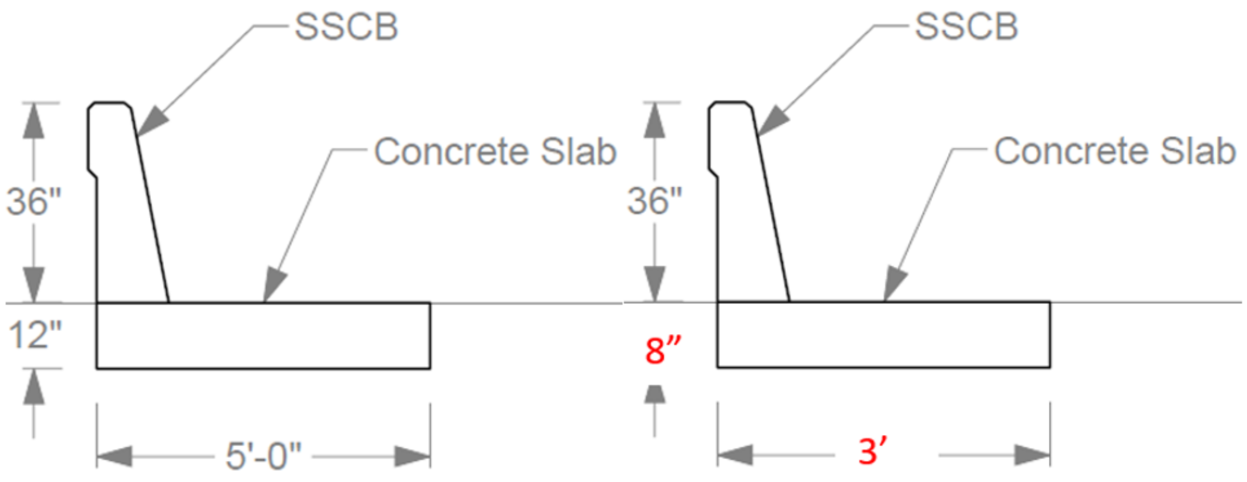
Moment Slab Foundation Design

The preliminary foundation design was comprised of a 12-inch deep and 5-foot wide moment slab that was attached to the base of the single slope barrier and ran through the entire length of the 50-foot segment.

Since the deflections of the preliminary design were very small (negligible), the results from that simulation are not featured in Chapter 4.

Encouraged by these very low deflections, the width of moment slab and the depth were reduced to 3 feet and 8 inches, respectively (Figure 58). The finite element model of this barrier and foundation is shown in Figure 59. The results of the MASH Test 4-12 impact simulation with the single unit truck model are shown in Figure 60. As can be seen from the sequential images of the impact, there was very little movement of the barrier and the foundation. The vehicle was successfully contained and redirected by the barrier and the foundation system. As summarized in Table 17, the maximum dynamic deflection of the barrier was 0.62 inches and the maximum permanent deflection was 0.23 inch. The working width of the optimized barrier and the foundation system was 109.4 inches at the height of 151.2 inches.

Also, a model featuring the preliminary foundation design with six 20-foot segments was developed, making the total barrier length 120 feet. The finite element model of this design is shown in Figure 61 and the results are given in Table 18. The maximum dynamic deflection of the barrier was 0.56 inch and the maximum permanent deflection was 0.05 inch. The working width of the barrier and foundation system was 107 inches at the height of 124.4 inches.

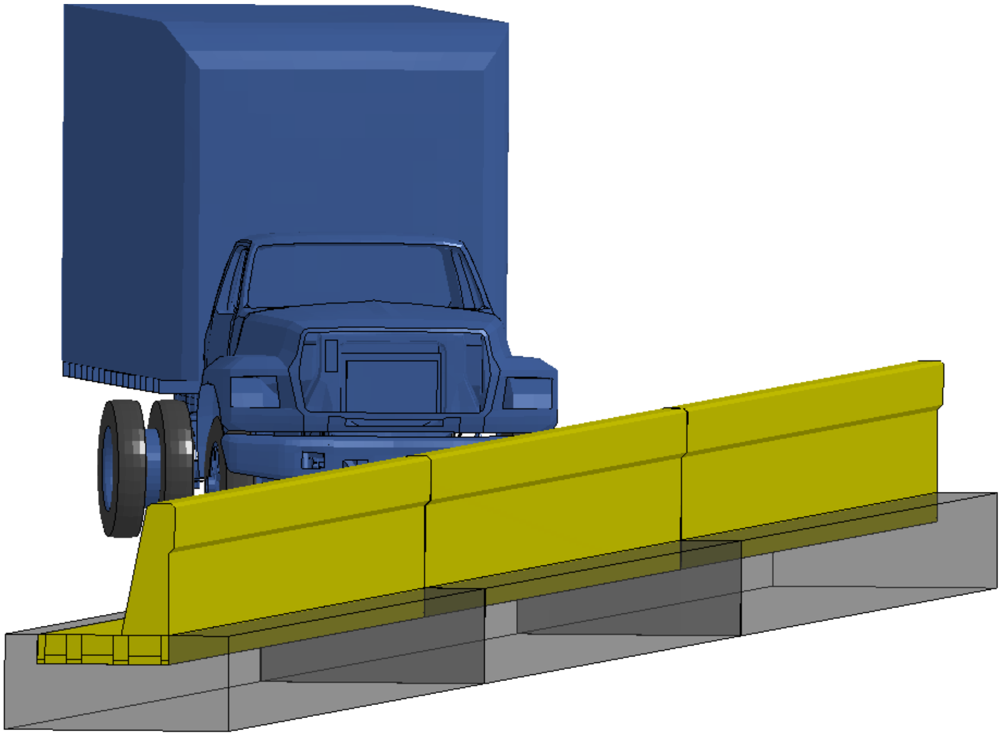


Dimensions in red are not to scale.

Figure 58. Preliminary Moment Slab Foundation (left) and Optimized Design (right)

Table 17. Barrier Deflections for Optimized Moment Slab Foundation

Maximum Dynamic Deflection	0.62in
Permanent Deflection	0.23in
Working Width	109.4in
Working Width Height	151.2in

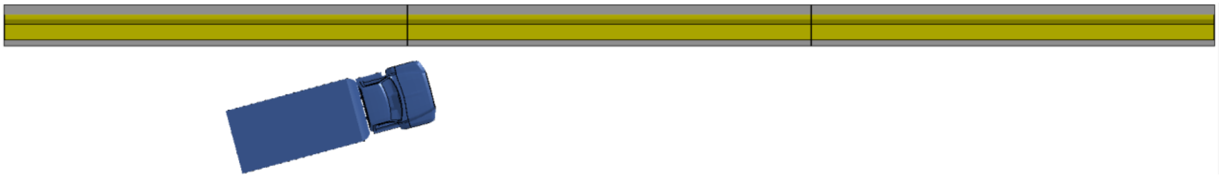


Overall System Model

Top View of an Optimized Barrier Segment*

Side View of an Optimized Barrier Segment*

System Model (Side View)



System Model (Top View)

*Soil shown with transparency to show the foundation

Figure 59. Optimized Moment Slab Simulation Model Details

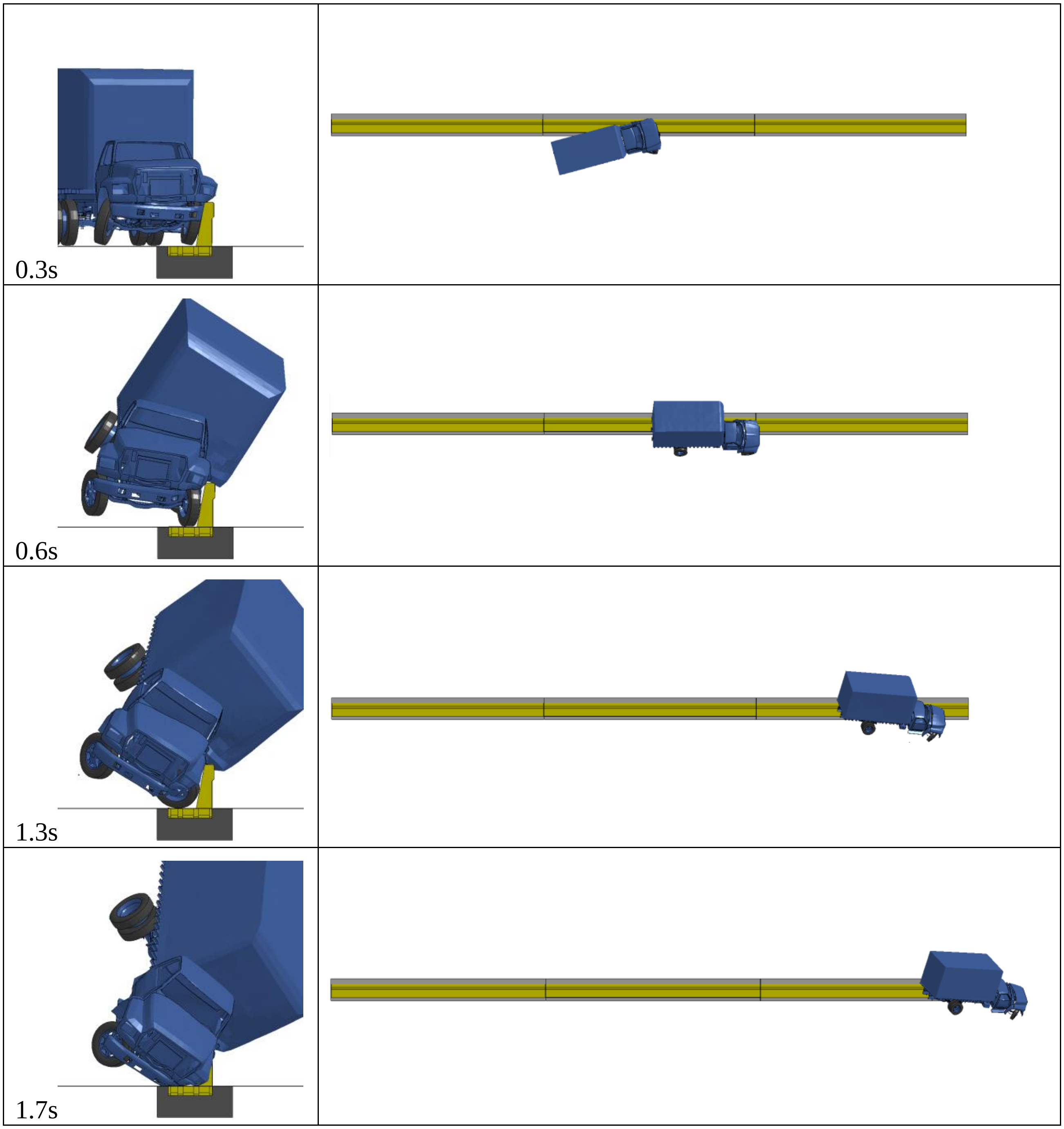


Figure 60. Impact Simulation for Optimized Moment Slab Foundation

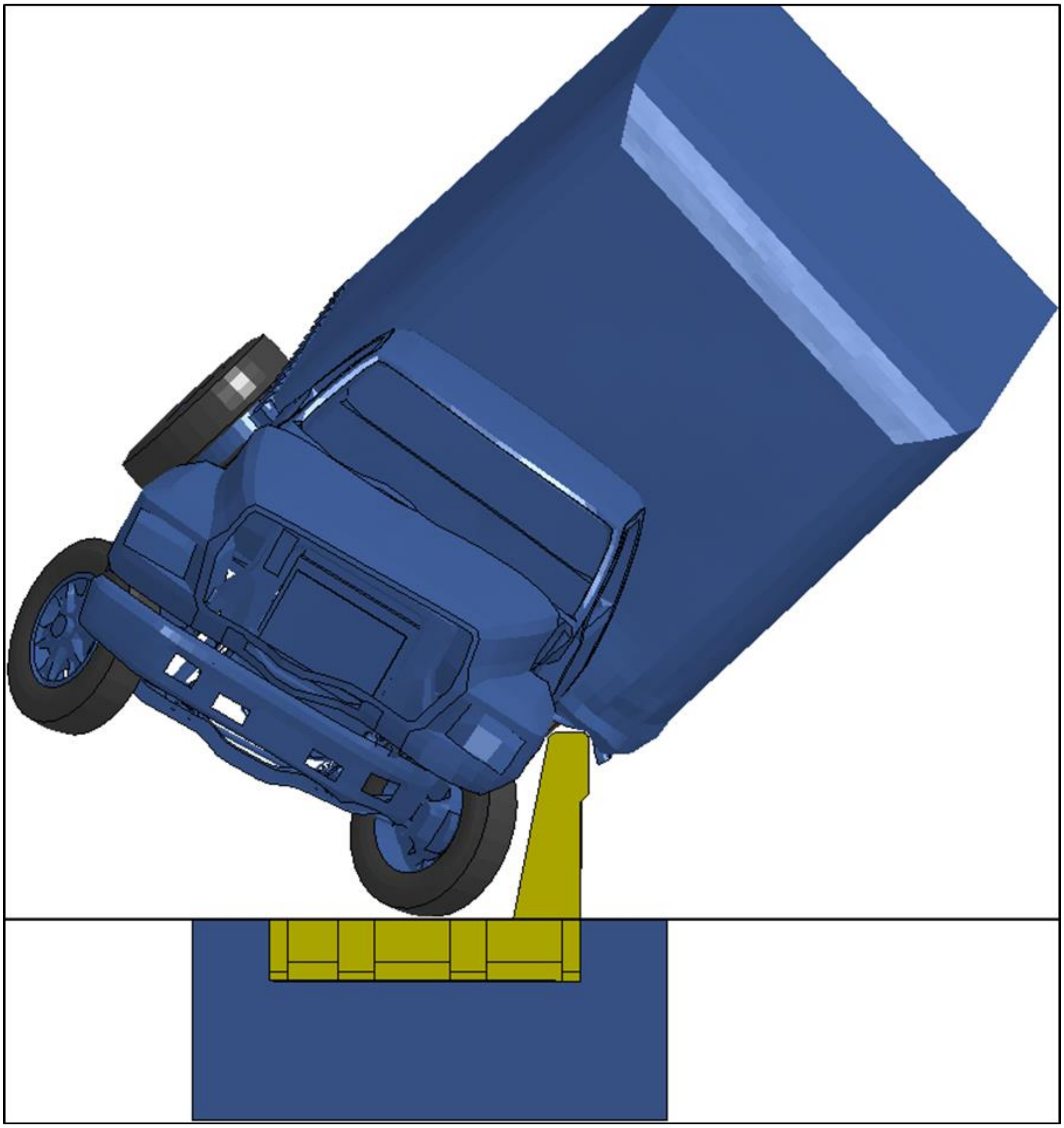


Figure 61. Simulation for Preliminary Moment Slab Foundation with 20ft Segments

Table 18. Barrier Deflections for Moment Slab Foundation Model with 20ft Segments

Maximum Dynamic Deflection	0.56in
Permanent Deflection	0.05in
Working Width	107in
Working Width Height	124.4in

4.2.2. Weaker Soil Configuration MASH TL-4 Systems Results

After initially presenting the results with the stronger soil configuration, TxDOT asked to evaluate four additional design variations through finite element analysis simulation.

Two new beam foundation designs were requested to be evaluated. One of them features the reduced segment length of the preliminary foundation tested with a weaker soil foundation. The second one introduces new soil geometry with a 2H to 1V back-slope soil profile. The other two requests were made for the moment slab foundation concept. One of the requests suggested the evaluation of the 20-foot segment moment slab foundation with a weaker soil configuration. The last request featured a shorter segment of 15 feet of the moment slab design with a weaker soil simulation.

All the simulations featuring a weaker soil configuration are presented below.

Concrete Beam Foundation with Back-Slope Soil

This design features the preliminary concrete beam foundation design for MASH TL4 with 27 inches length and 18 inches width. The barrier segments for this variation have been reduced to 15 feet. The geometry of the soil with weaker properties involves a 2H to 1V back-slope profile. The details of the model and the sequential presentation of the simulation are shown in Figure 62. The impact of the vehicle with the barrier occurs at 0.485 seconds.

As shown in Figure 62, the system fails to contain and redirect the vehicle. The critical moment that the barrier starts to roll back is shown in Figure 63.

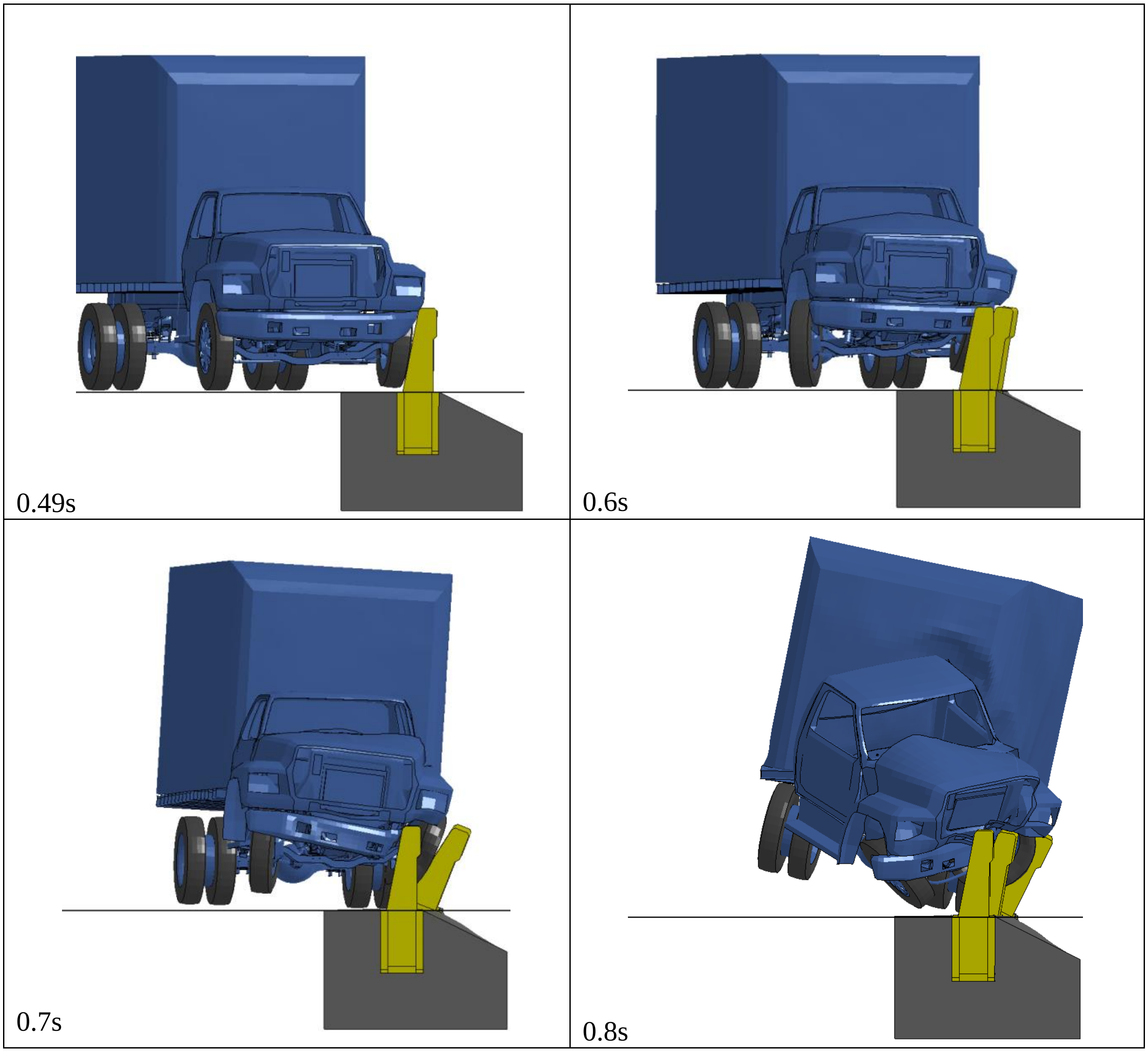


Figure 62. Sequential Frames of Simulation for 15ft Beam Foundation Segments

This simulation showed that the systems involving 15-foot segments and the back-slope soil profile had a significantly higher chance of failing.

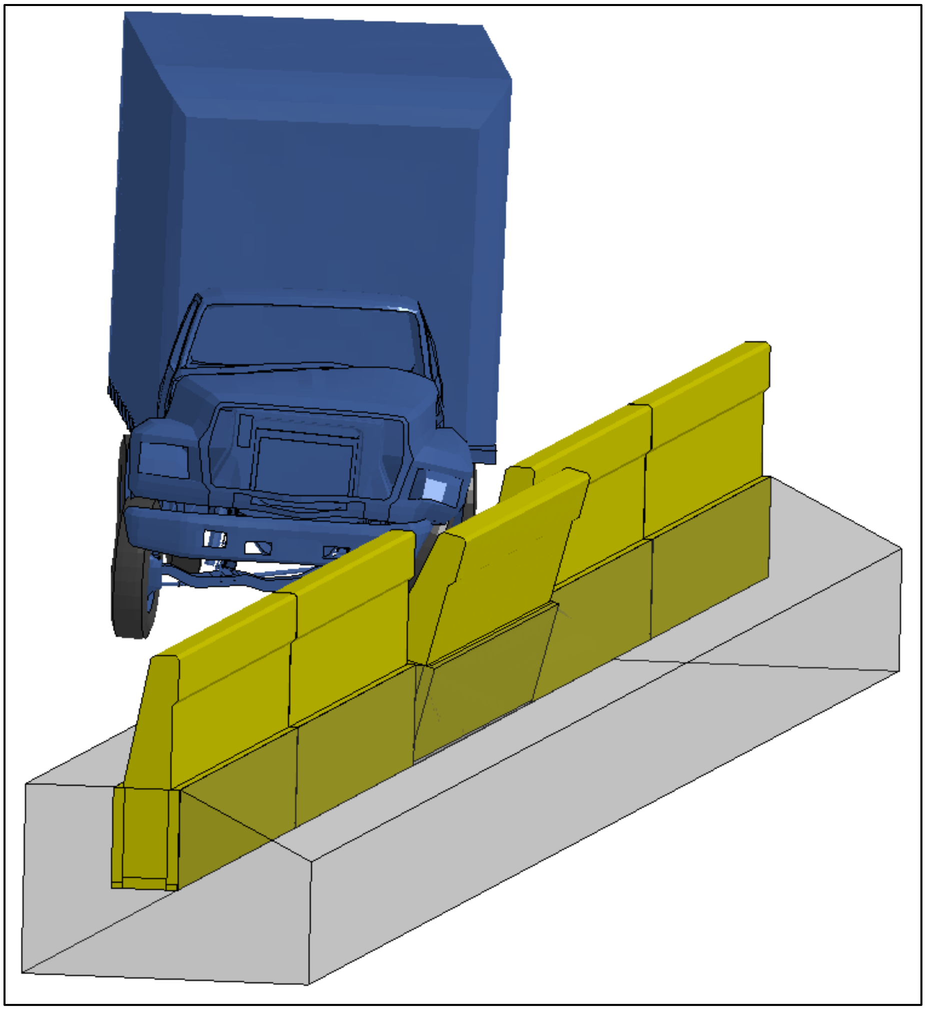


Figure 63. Isometric View of Critical Moment at 0.635 Seconds

Concrete Beam Foundation with 30-foot segments

This design was previously tested with the stronger soil configuration and the results are presented in Section 4.2.1. That simulation was repeated with weaker soil properties. The system successfully contains and redirects the vehicle. As expected, the deflections seem to be slightly higher than the simulation featuring the stronger soil configuration. However, this change is only observed for the dynamic deflection as the permanent deflection is measured to be the same (0.1 inch). The sequential frames of the simulation are shown in Figure 64. The impact of the vehicle with the barrier occurs at 0.49 seconds. The maximum deflection occurs at 0.6 seconds and that critical moment is shown in Figure 65. Table 19 summarizes the results of this simulation.

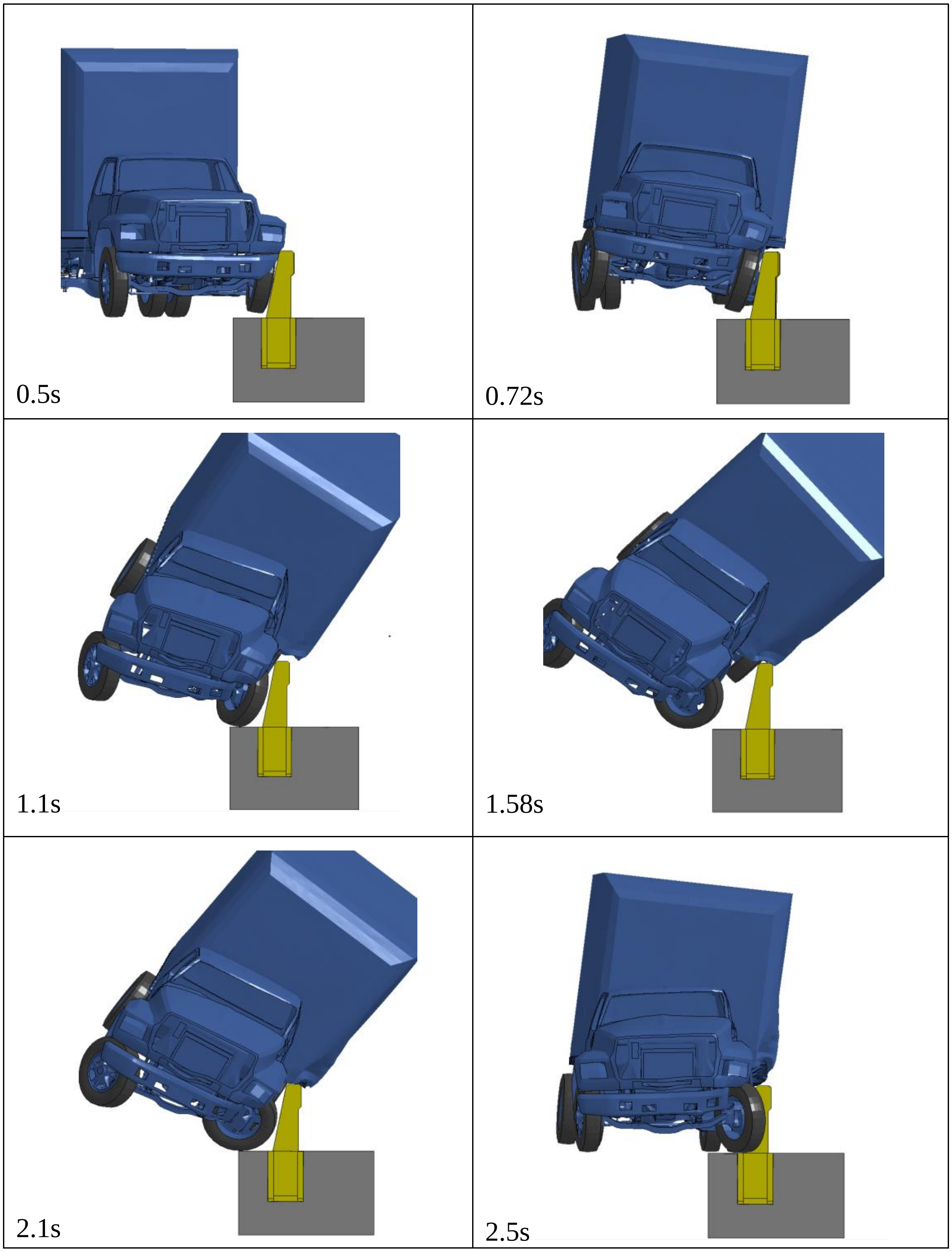


Figure 64. Impact Simulation of Beam Foundation Design with Weaker Soil Properties

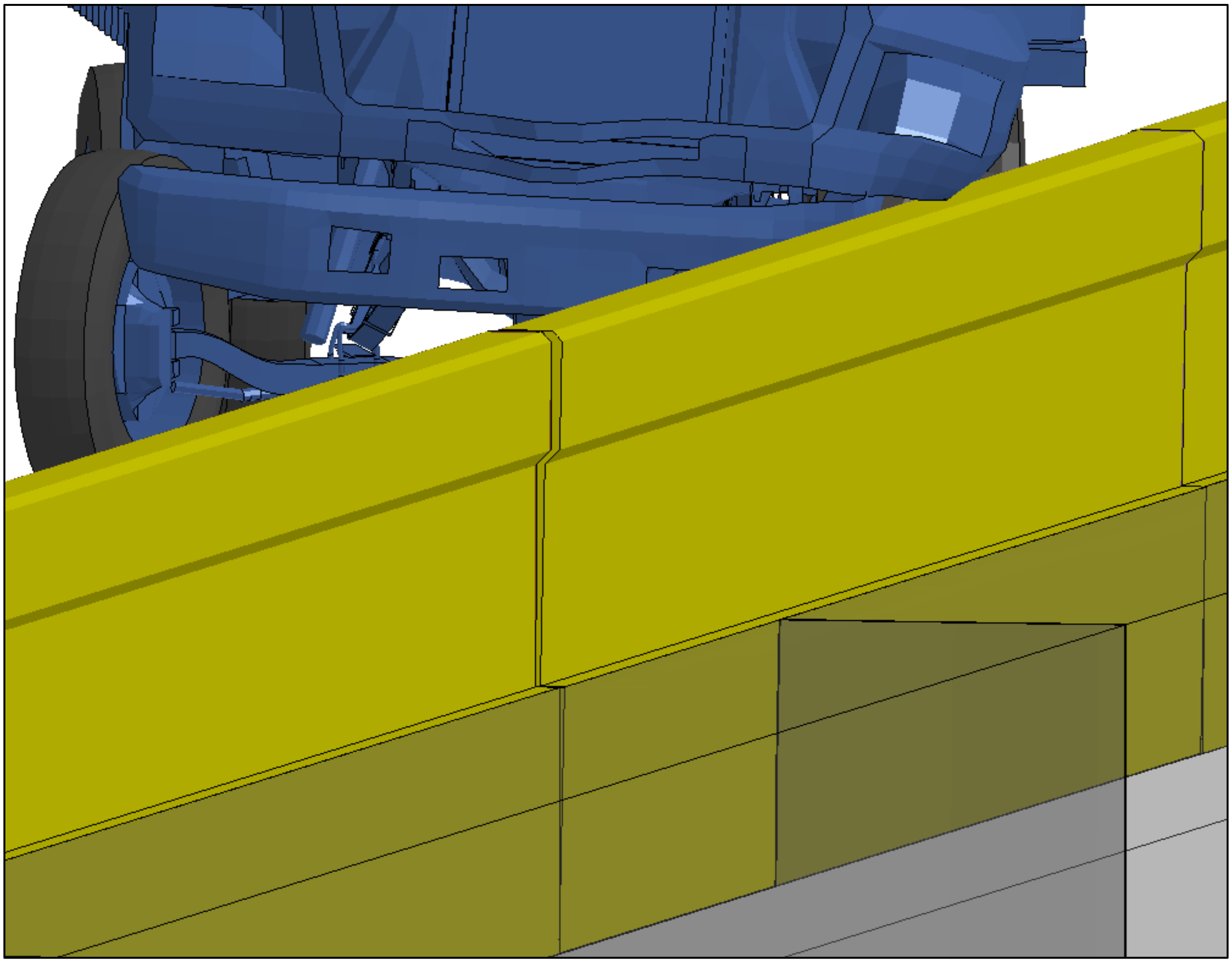


Figure 65. Maximum Dynamic Deflection Occurs at 0.6 Seconds

Table 19. Barrier Deflection for Beam Foundation Concept with Weaker Soil Properties

Maximum Dynamic Deflection	1.7in
Permanent Deflection	0.079in
Working Width	193in
Working Width Height	131in

Moment Slab Foundation with No Soil behind the Barrier

This design features the preliminary moment slab concept for MASH TL-4 with reduced barrier segment length of 15 feet and with no supporting soil behind the barrier. This system fails to contain and redirect the vehicle. A sequential presentation of the simulation is shown in Figure 66 and the critical moment of the impact is shown in Figure 67. The impact of the vehicle with the barrier occurs at 0.49 seconds.

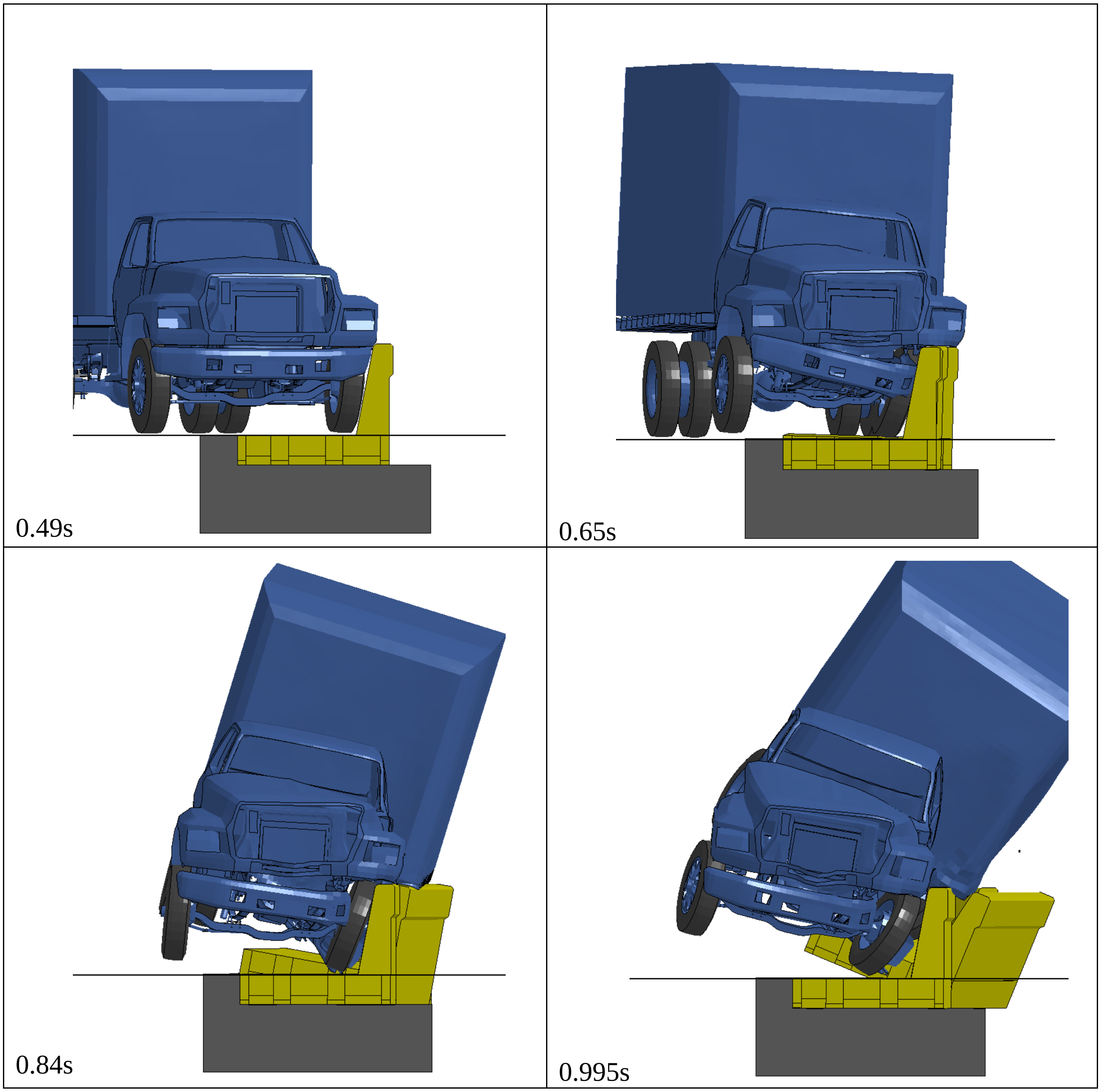


Figure 66. Impact Simulation for Moment Slab Design with No Soil behind Barrier

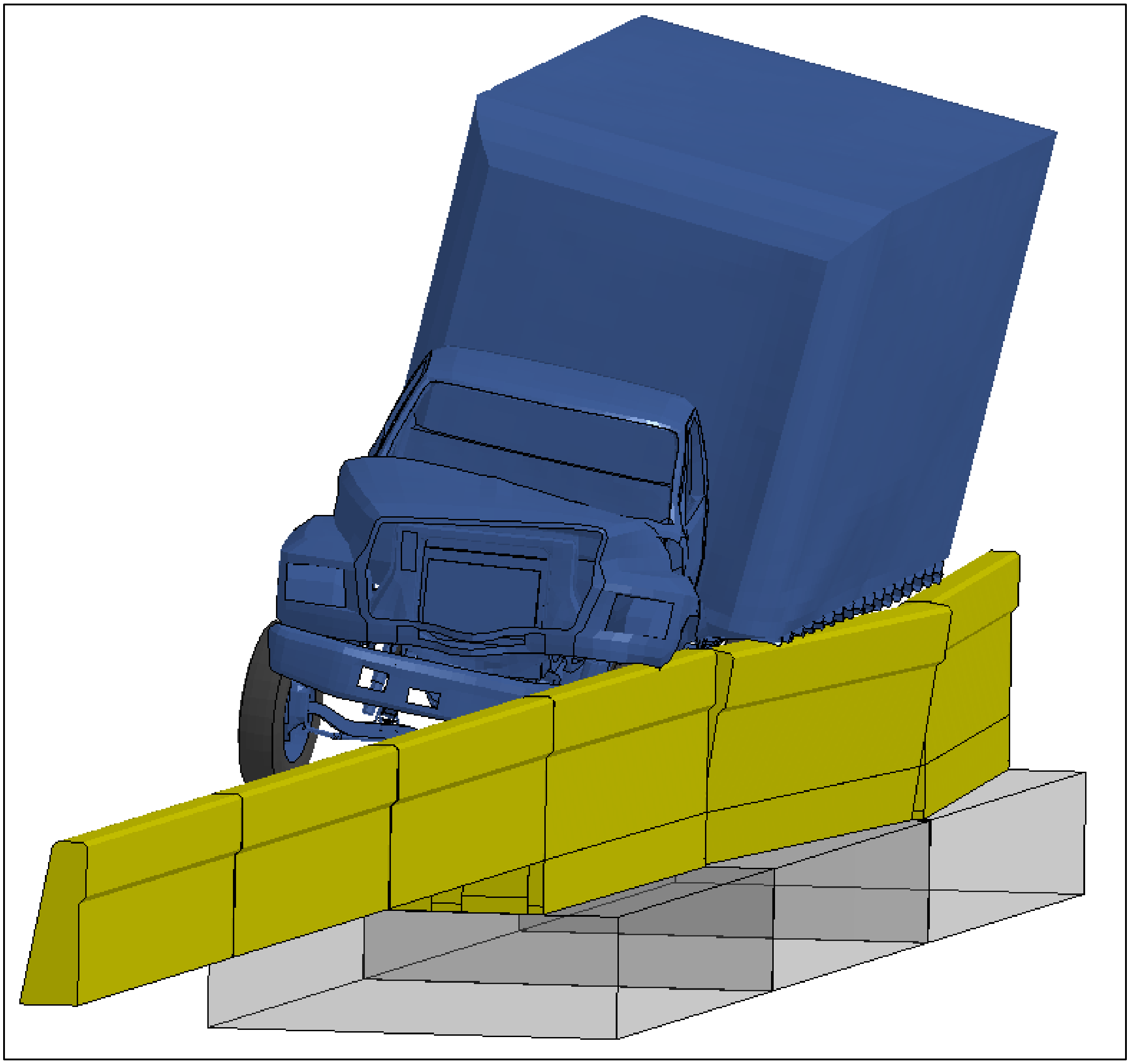


Figure 67. Isometric View of Critical Moment at 0.81 Seconds

<u>Moment Slab Foundation with 20-foot Segments</u>

This design was previously tested with the stronger soil configuration and the results are presented in Section 4.2.1. That simulation was repeated with weaker soil properties. The system successfully contains and redirects the vehicle. As expected, the deflections seem to be slightly higher than the simulation featuring the stronger soil configuration. However, this change is only observed for the dynamic deflection as the permanent deflection is measured to be the same (0.1 inch). The maximum deflection occurs at 0.615 seconds and that critical moment is shown in Figure 68. The sequential frames of the simulation are shown in Figure 69. The impact of the vehicle with the barrier occurs at 0.49 seconds. Table 20 summarizes the results of this simulation.

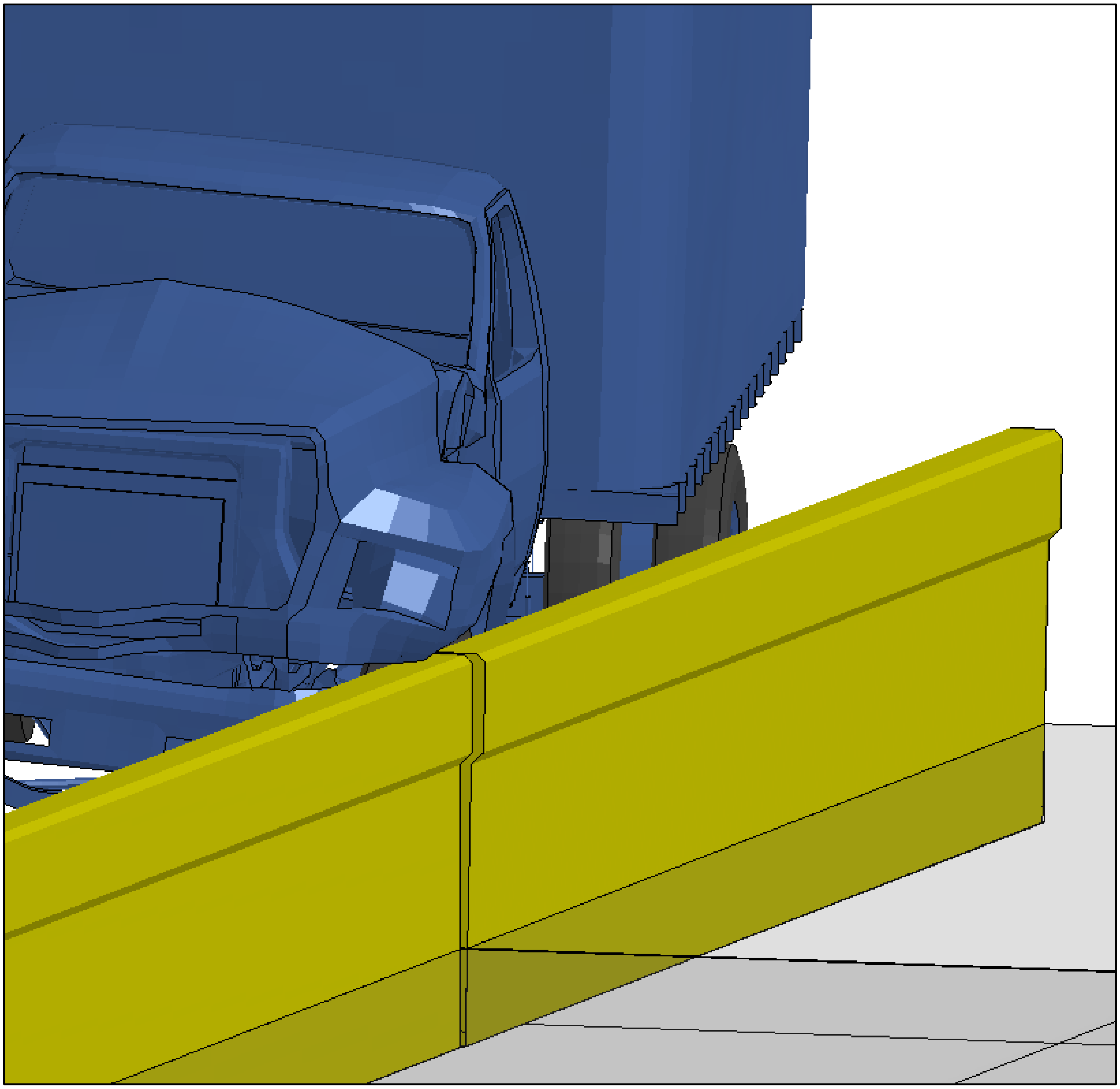


Figure 68. Maximum Dynamic Deflection Occurs at 0.615 Seconds

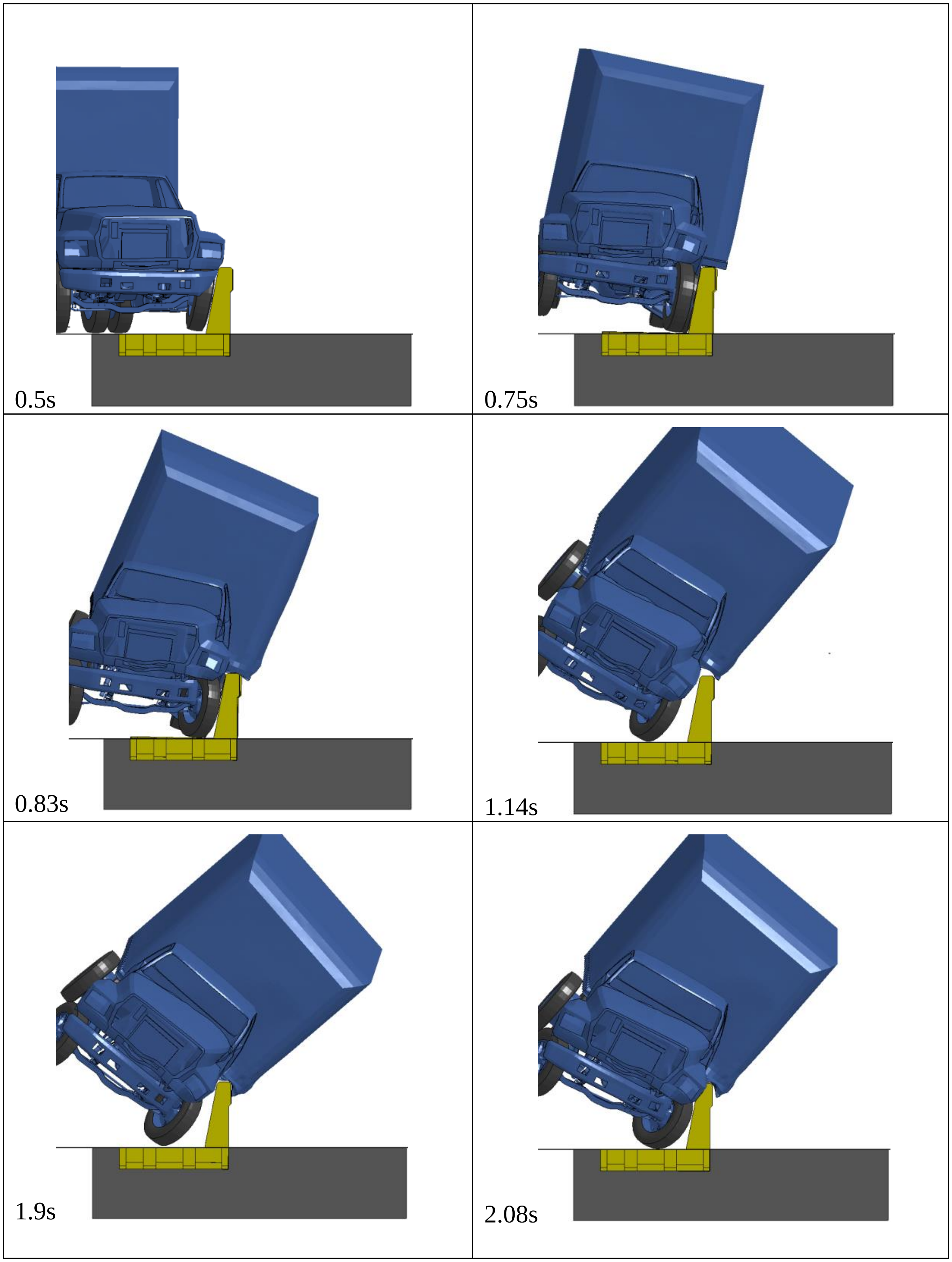


Figure 69. Impact Simulation for Moment Slab Foundation with Weaker Soil Properties

Table 20. Barrier Deflections for Moment Slab Concept with Weaker Soil Properties

Maximum Dynamic Deflection	1.401in
Permanent Deflection	0.0315in
Working Width	109.94in
Working Width Height	120.08in

5. SUMMARY AND CONCLUSIONS

The primary considerations in the development of the barrier's foundation design were to have minimal offset between the barrier and the protected bridge column, and to have minimal movement of the barrier so that it doesn't need maintenance or resetting after a tractor-trailer (for MASH TL-5) or a SUT (for MASH TL-4) impact. The results of the simulations performed and presented in Chapter 4, show that for all the foundation concepts with the stronger soil configuration, the barrier deflection is not very high for the preliminary designs and the optimized variations. However, when the barrier segment length was reduced and the soil material properties were changed to a weaker profile, the deflections increased and some designs failed to contain the vehicle. A summary of the results and respective recommendations for each test level system are presented below.

5.1. MASH TL-5 Simulation Results Summary

For the 54-inch tall single slope concrete barrier with a structurally independent foundation, a total of nine systems were tested. Six of these systems featured the stronger soil configuration while three of them were evaluated with a weaker soil profile. Table 21 summarizes the number of systems tested per each design.

Table 21. Number of Systems Evaluated per Each Foundation Concept

	With the Stronger Soil Card	With the Weaker Soil Card
Drilled Shaft Foundation	2	2
Concrete Beam Foundation	2	1
Moment Slab Foundation	2	0

5.1.1. Simulation Results with Stronger Soil Configuration

The most crucial data for the design of MASH TL-5 barrier-foundation system are the permanent deflection and the working width. These dimensions will determine the type of the foundation and also the distance that this system is recommended to be placed with regard to the bridge pier.

For all the three selected preliminary foundation concepts and the three respective optimized designs evaluated with the stronger soil properties, the permanent deflections were almost negligible and the working widths ranged from 2.5 inches to 38 inches. Table 22 summarizes the results of the simulations conducted with the stronger soil material properties.

Table 22. Results for Permanent Deflection and Working Width with Stronger Soil

	Permanent Deflection	**Working Width**
Drilled Shaft Foundation		
10-ft deep	0.75in	29.5in
6-ft deep	2.4in	35.1in
Concrete Beam Foundation		
48-in x 24-in	0.4in	33.1in
36-in x 18-in	1.2in	33.6in
Moment Slab Foundation		
10-ft wide	0.0in	36.3in
6-ft wide	0.1in	38.0in

5.1.2. Simulation Results with Weaker Soil Configuration

A total of three systems were requested to be tested with the weaker soil properties. Two of these systems were modifications of the optimized drilled shaft foundation (with 6-foot deep shafts). The first simulation was a rerun of the optimized concept with the weaker soil card. Since the permanent deflection appeared to be significantly large, the system with an additional shaft was evaluated. The third request was for the concrete beam foundation to be modified as the standard TRF of TxDOT. A summary of the maximum dynamic deflection and the permanent displacement for each of these additional simulations in given in Table 23.

Table 23. Results for Dynamic and Permanent Deflection with Weaker Soil Configuration

	Permanent Deflection	**Dynamic Deflections**
Drilled Shaft Foundation		
6-ft deep	4.3in	6.3in
6-ft deep with 5 shafts	1.25in	3.75in
Concrete Beam Foundation		
TRF Standard of TxDOT	0.35in	3.6in

5.2. MASH TL-4 Simulation Results Summary

For the 36-inch tall single slope concrete barrier with a structurally independent foundation, a total of twelve systems were tested. Eight of these systems feature the stronger soil configuration while four of them are evaluated with a weaker soil profile. Table 24 summarizes the number of systems tested per each design.

Table 24. Number of Systems Evaluated per Each Foundation Concept

	With the Stronger Soil Card	**With the Weaker Soil Card**
Concrete Beam Foundation	3	2
Beam and Slab Foundation	2	0
Moment Slab Foundation	3	2

5.2.1. Simulation Results with Stronger Soil Configuration

For all the three selected preliminary foundation concepts and the three respective optimized designs evaluated with the stronger soil properties, the permanent deflections were very small. Since the beam and moment slab had relatively larger deflections compared to the other designs, it was not selected for any further optimization and evaluation. For the concrete beam and the moment slab foundation concepts, the barrier segment length was reduced to 30 feet and 20 feet, respectively. The systems' performance was studied. Table 25 summarizes the results of the simulations conducted with the stronger soil material properties. The results from the original preliminary design concept of the moment slab foundation were not reported due to the negligible values (very close to zero), and thus are not given in Table 25.

Table 25. Results for Permanent Deflection and Working Width with Stronger Soil

	Permanent Deflection	**Working Width**
Concrete Beam Foundation		
27-in x 18-in	0.01in	96.4in
10-in x 13-in	0.16in	103.4in
30-ft segments for 27-in x 18-in	0.05in	116.3in
Beam and Slab Foundation		
Original	0.01in	105.7in
Optimized	0.07in	108in
Moment Slab Foundation		
3-ft wide	0.23in	109.4in
20-ft segments for 5-ft wide	0.05in	107in

5.2.2. Simulation Results with Weaker Soil Configuration

A total of four systems were requested to be tested with the weaker soil properties. Two of these systems were modifications of the preliminary beam foundation concept. The first simulation was a rerun of the 30-foot segment barrier length concept with the weaker soil card. The second system tested for the beam foundation involved a 2H to 1V back-slope soil with the weaker material properties and 15-foot segments. The latter system failed to contain the vehicle. The other two requests were for the moment slab foundation concept. The first system to test was the previously evaluated moment slab foundation with 20-foot segments with the weaker soil configuration. The other request for the moment slab foundation was to test a system with no supporting soil behind the barrier and with reduced 15-foot segments. This latter system also failed to contain and redirect the vehicle.

A summary of the maximum dynamic deflection and the permanent displacement for each of these additional simulations in given in Table 26.

Table 26. Results for Dynamic and Permanent Deflection with Weaker Soil Configuration

	Permanent Deflection	**Dynamic Deflections**
Concrete Beam Foundation		
30-ft segments for 27-in x 18-in	0.1in	1.7in
15-ft segments with back-slope soil	System Failed To Contain Vehicle	
Moment Slab Foundation		
20-ft segments for 5-ft wide	0.1in	1.4in
15-ft segments with no supporting soil	System Failed To Contain Vehicle	

5.3. Recommendations

Based on the results presented in Chapter 4, it was recommended that all the designs that passed the weaker soil configuration test, to be further evaluated. The models tested under the weaker soil configuration were considered as more reliable and less costly.

Future Work

Detailed reinforcement design for all the ultimately selected concepts is to follow the conclusions of this work. Only one design per MASH test level will be then selected for the execution of a full-scale crash test.

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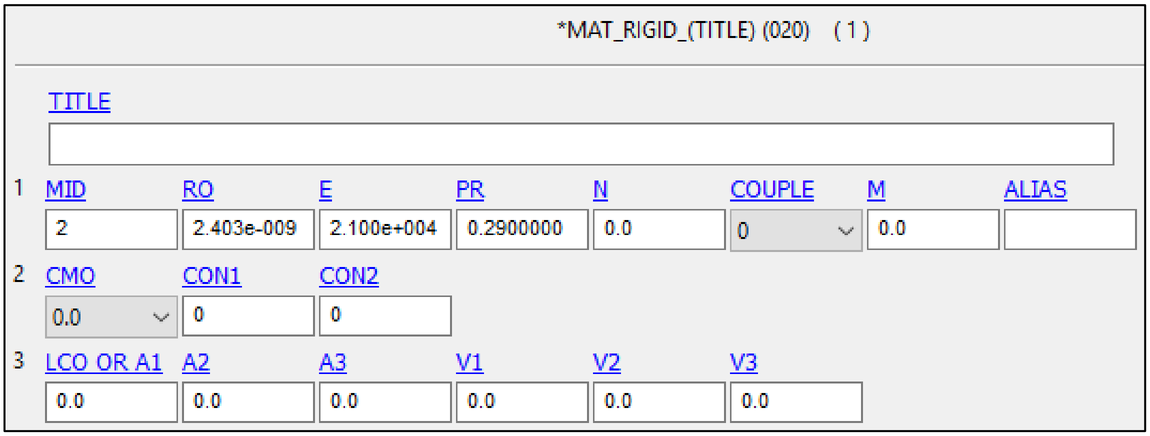
APPENDIX A

This appendix shows the full material cards and automatic contact cards used in this thesis.

The material card used for the barrier and the foundation is shown in Figure 70. The material cards for the stronger and weaker soil configuration are shown in Figure 71 and Figure 72, respectively.

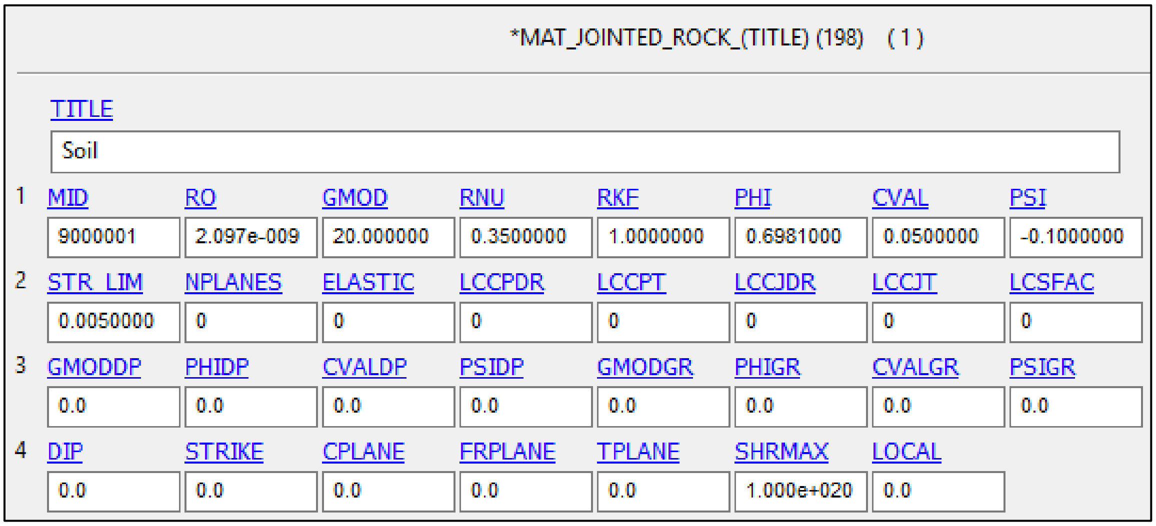


*MAT_RIGID_(TITLE) (020) (1)

TITLE

1	MID	RO	E	PR	N	COUPLE	M	ALIAS
	2	2.403e-009	2.100e+004	0.2900000	0.0	0	0.0	
2	CMO	CON1	CON2					
	0.0	0	0					
3	LCO OR A1	A2	A3	V1	V2	V3		
	0.0	0.0	0.0	0.0	0.0	0.0		

Figure 70. Concrete Rigid Material Card Type 20



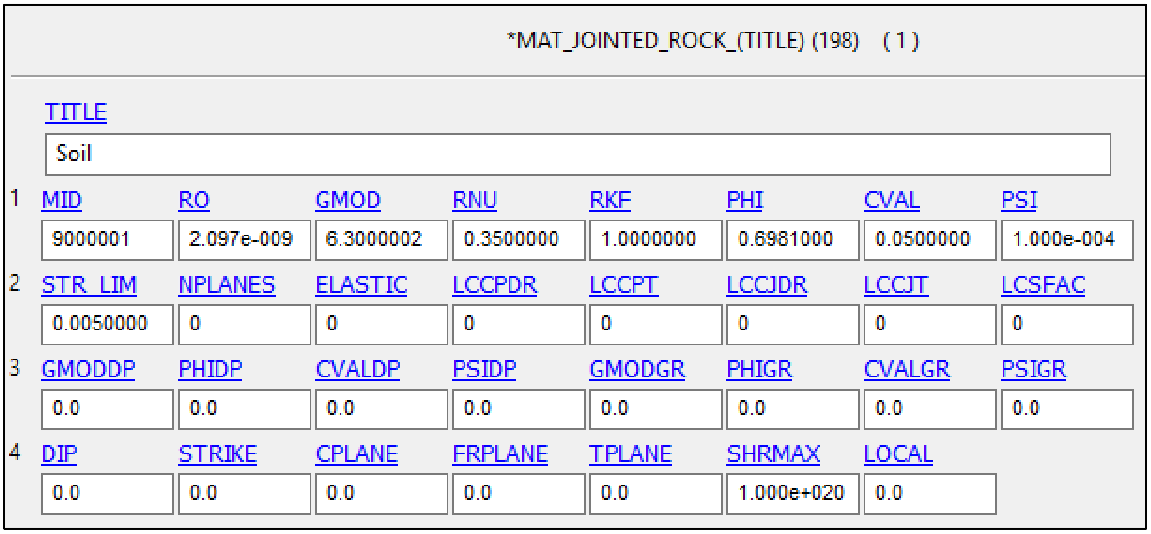
*MAT_JOINTED_ROCK_(TITLE) (198) (1)

TITLE

Soil

1	MID	RO	GMOD	RNU	RKF	PHI	CVAL	PSI
	9000001	2.097e-009	20.000000	0.3500000	1.0000000	0.6981000	0.0500000	-0.1000000
2	STR_LIM	NPLANES	ELASTIC	LCCPDR	LCCPT	LCCJDR	LCCJT	LCSFAC
	0.0050000	0	0	0	0	0	0	0
3	GMODDP	PHIDP	CVALDP	PSIDP	GMODGR	PHIGR	CVALGR	PSIGR
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	DIP	STRIKE	CPLANE	FRPLANE	TPLANE	SHRMAX	LOCAL	
	0.0	0.0	0.0	0.0	0.0	1.000e+020	0.0	

Figure 71. Stronger Soil Material Card



*MAT_JOINTED_ROCK_(TITLE) (198)   (1)

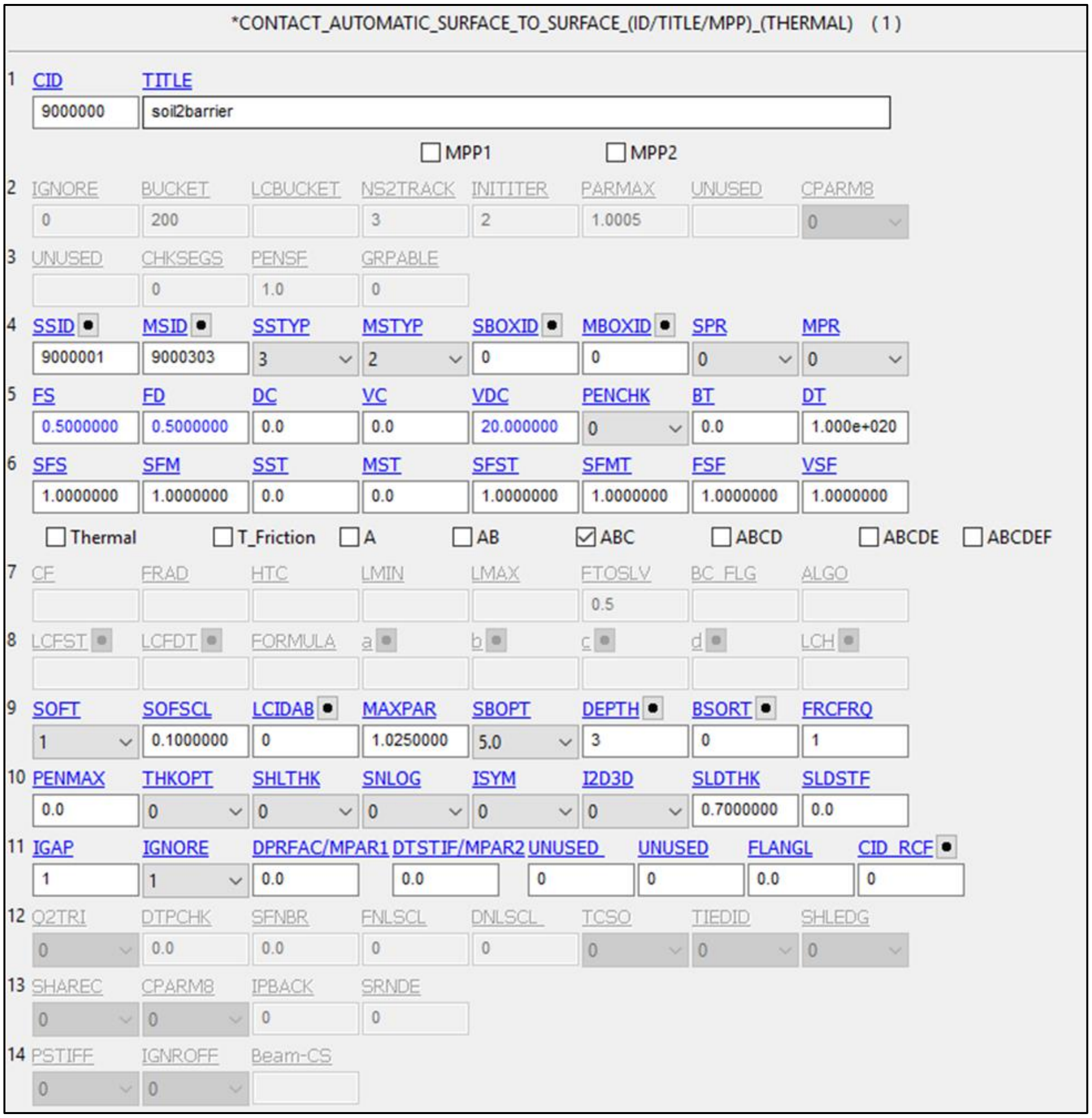
TITLE

Soil

1	MID	RO	GMOD	RNU	RKF	PHI	CVAL	PSI
	9000001	2.097e-009	6.3000002	0.3500000	1.0000000	0.6981000	0.0500000	1.000e-004
2	STR_LIM	NPLANES	ELASTIC	LCCPDR	LCCPT	LCCJDR	LCCJT	LCSFAC
	0.0050000	0	0	0	0	0	0	0
3	GMODDP	PHIDP	CVALDP	PSIDP	GMODGR	PHIGR	CVALGR	PSIGR
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	DIP	STRIKE	CPLANE	FRPLANE	TPLANE	SHRMAX	LOCAL	
	0.0	0.0	0.0	0.0	0.0	1.000e+020	0.0	

Figure 72. Weaker Soil Material Card

The contact card used to regulate the relationship between the barrier-foundation system and the soil in this work is shown in Figure 73. Set ID 9000001 consists of only one part, the soil, as it modeled as a continuous part along the whole length of the barrier-foundation system. Set ID 9000303 consists of all the barrier segments. More information about the specifications of this card can be found in *LS-DYNA's Keyword User's Manual* by Livermore Technology Corporation.

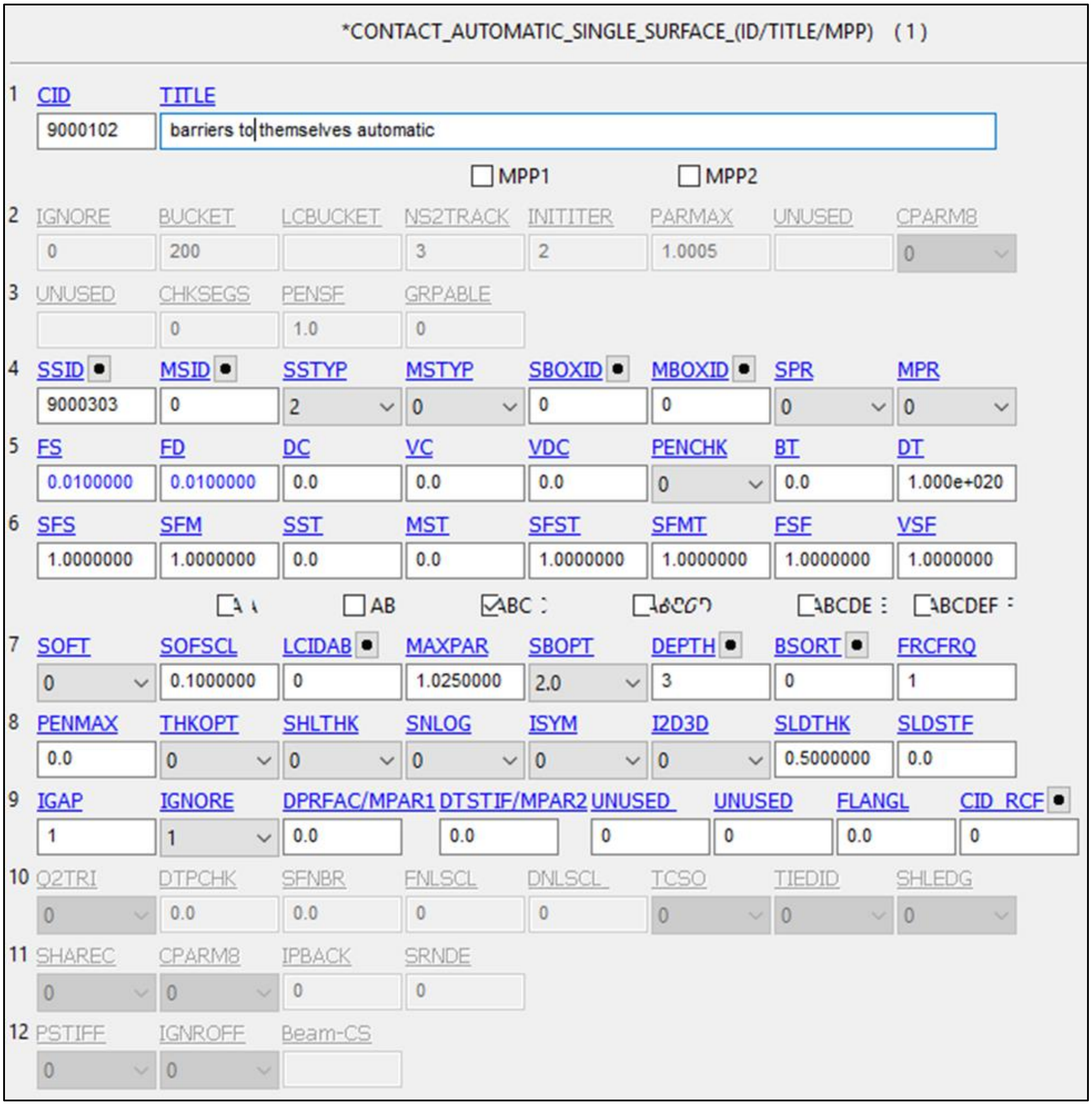


*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_(ID/TITLE/MPP)_(THERMAL) (1)

1	CID	TITLE						
	9000000	soil2barrier						
				☐ MPP1		☐ MPP2		
2	IGNORE	BUCKET	LCBUCKET	NS2TRACK	INITITER	PARMAX	UNUSED	CPARM8
	0	200		3	2	1.0005		0
3	UNUSED	CHKSEGS	PENSF	GRPABLE				
		0	1.0	0				
4	SSID	MSID	SSTYP	MSTYP	SBOXID	MBOXID	SPR	MPR
	9000001	9000303	3	2	0	0	0	0
5	FS	FD	DC	VC	VDC	PENCHK	BT	DT
	0.5000000	0.5000000	0.0	0.0	20.000000	0	0.0	1.000e+020
6	SFS	SFM	SST	MST	SFST	SFMT	FSF	VSF
	1.0000000	1.0000000	0.0	0.0	1.0000000	1.0000000	1.0000000	1.0000000
	☐ Thermal	☐ T_Friction	☐ A	☐ AB	☑ ABC	☐ ABCD	☐ ABCDE	☐ ABCDEF
7	CF	FRAD	HTC	LMIN	LMAX	FTOSLV	BC_FLG	ALGO
						0.5		
8	LCFST	LCFDT	FORMULA	a	b	c	d	LCH
9	SOFT	SOFSCL	LCIDAB	MAXPAR	SBOPT	DEPTH	BSORT	FRCFRQ
	1	0.1000000	0	1.0250000	5.0	3	0	1
10	PENMAX	THKOPT	SHLTHK	SNLOG	ISYM	I2D3D	SLDTHK	SLDSTF
	0.0	0	0	0	0	0	0.7000000	0.0
11	IGAP	IGNORE	DPRFAC/MPAR1	DTSTIF/MPAR2	UNUSED	UNUSED	FLANGL	CID_RCF
	1	1	0.0	0.0	0	0	0.0	0
12	Q2TRI	DTPCHK	SFNBR	FNLSCL	DNLSCL	TCSO	TIEDID	SHLEDG
	0	0.0	0.0	0	0	0	0	0
13	SHAREC	CPARM8	IPBACK	SRNDE				
	0	0	0	0				
14	PSTIFF	IGNROFF	Beam-CS					
	0	0						

Figure 73. Automatic Surface to Surface Contact Card Used

The automatic single surface card used in this work is shown in Figure 74. This card regulates the interaction of the barrier segments with each other.



*CONTACT_AUTOMATIC_SINGLE_SURFACE_(ID/TITLE/MPP) (1)

1	CID	TITLE						
	9000102	barriers to themselves automatic						
				☐ MPP1		☐ MPP2		
2	IGNORE	BUCKET	LCBUCKET	NS2TRACK	INITITER	PARMAX	UNUSED	CPARM8
	0	200		3	2	1.0005		0
3	UNUSED	CHKSEGS	PENSF	GRPABLE				
		0	1.0	0				
4	SSID ●	MSID ●	SSTYP	MSTYP	SBOXID ●	MBOXID ●	SPR	MPR
	9000303	0	2	0	0	0	0	0
5	FS	FD	DC	VC	VDC	PENCHK	BT	DT
	0.0100000	0.0100000	0.0	0.0	0.0	0	0.0	1.000e+020
6	SFS	SFM	SST	MST	SFST	SFMT	FSF	VSF
	1.0000000	1.0000000	0.0	0.0	1.0000000	1.0000000	1.0000000	1.0000000
		☐ A	☐ AB	☑ ABC	☐ ABCD		☐ ABCDE	☐ ABCDEF
7	SOFT	SOFSCL	LCIDAB ●	MAXPAR	SBOPT	DEPTH ●	BSORT ●	FRCFRQ
	0	0.1000000	0	1.0250000	2.0	3	0	1
8	PENMAX	THKOPT	SHLTHK	SNLOG	ISYM	I2D3D	SLDTHK	SLDSTF
	0.0	0	0	0	0	0	0.5000000	0.0
9	IGAP	IGNORE	DPRFAC/MPAR1	DTSTIF/MPAR2	UNUSED	UNUSED	FLANGL	CID_RCF ●
	1	1	0.0	0.0	0	0	0.0	0
10	Q2TRI	DTPCHK	SFNBR	FNLSCL	DNLSCL	TCSO	TIEDID	SHLEDG
	0	0.0	0.0	0	0	0	0	0
11	SHAREC	CPARM8	IPBACK	SRNDE				
	0	0	0	0				
12	PSTIFF	IGNROFF	Beam-CS					
	0	0						

Figure 74. Automatic Single Surface Contact Card Used