Structural Design of Sound Walls with Emphasis on Vehicular Impact

by

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Thesis

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Structural Design of Sound Walls with Emphasis on Vehicular Impact

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For my Grandma Palombo

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ABSTRACT

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The current process used in Texas to design sound walls was documented by conducting a series of telephone interviews with TxDOT district engineers. The interviews focused on three major topics: the process used to select the sound wall type and material; the structural design procedure; and the major problems encountered. In addition, each of the engineers interviewed was asked to complete a mail survey pertaining to individual sound walls constructed in their district. From these surveys, it was found that the design process and design criteria are not standard in Texas. In addition, TxDOT engineers voiced the need for more research and the development of guidelines for several issues. One of these issues was vehicular impact. For this reason, preliminary research was conducted to study the dynamic response of a prototype mounted sound wall subjected to vehicular impact loads. An analytical procedure was used to assess the adequacy of the current AASHTO 45-kN (10-kip) equivalent static load provisions used to design mounted sound wall systems against vehicular impact. The results of this study indicated that the current static load provisions were inappropriate for mounted sound wall systems because of the dynamic response of the mounted sound wall. Based on these results, example design curves were generated to illustrate how this analytical procedure could be used to develop design guidelines and standard specifications, and recommendations were made

for the development of proper procedures for designing mounted sound wall systems against vehicular impact.

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VITA

Ronald Alan Peron was born in Port Chester, New York on May 25, 1972, the son of Alan and Jeanette Peron. After completing his work at Mamaroneck High School, Mamaroneck, New York, in 1990, he entered Lafayette College in Easton, Pennsylvania. After two semesters, he transferred to the University of Virginia, where he received the degree of Bachelor of Science in Engineering in 1994. During the summers, he was employed as an architects' and engineers' assistant. In September, 1994, he entered The Graduate School at the University of Texas at Austin.

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CHAPTER 1

Introduction

1.1 Terminology

In current technical literature, the terms “noise barrier” and “sound wall” are often used interchangeably. To eliminate confusion in this regard, the term “sound wall” is used exclusively in this thesis to describe any wall constructed to attenuate highway noise for receivers adjacent to the roadway. This terminology has been selected both to avoid any misinterpretation of the term “noise barrier” to mean a complete blocking of sound, and to avoid confusion between sound walls and vehicular impact barriers.

1.2 General

Increasing traffic flow on our nation’s highways has caused undesirably high noise levels to develop in our communities. In 1974, a study conducted for the US Environmental Protection Agency (EPA) judged that motor vehicle noise was the single biggest contribution to community noise [US EPA 1974]. To lessen noise levels in communities, over 1440 km (900 miles) of sound walls were constructed in the US from 1972 to 1992 at an estimated cost of over $816 million [Bowlby 1992]. In Texas alone, over 40 km (25 miles) of sound walls were constructed at a cost of nearly $19 million dollars from 1979 to 1992 [USDOT 1994]. Despite this fact, the Texas Department of Transportation (TxDOT) does not have a state-wide standard to assist district engineers confronted with designing a sound wall. Consequently, TxDOT has initiated a four-year research program (Study 1471) to document and evaluate the current design processes used throughout Texas, and to develop a design guideline and standard to assist district engineers in all aspects of sound wall design.

During a series of interviews used in this study to document the structural design process for sound walls, TxDOT engineers voiced concerns regarding several design considerations for sound walls that they felt are inadequately addressed in current technical literature. In particular, design engineers were concerned with whether current design provisions would provide sufficient safety in the event of vehicular impact.

The placement of the sound wall influences not only the acoustical performance of the sound wall, but also its structural design. To produce the largest noise reduction, a sound wall should be either close to the receiver or close to the source (roadway). If the sound wall is placed near the source, it should be designed against vehicular impact. In many cases, it is economical to combine the traffic barrier and the sound wall, thus providing, with one structure, occupant safety in the event of vehicular impact and a reduction of highway noise for residents.

To combine impact safety and noise reduction, the most common system used by the Texas Department of Transportation consists of a mounted sound wall system combining the safety shape traffic barrier and a panel sound wall. This system, referred to as the mounted sound wall, is constructed by mounting a sound wall atop the safety shape impact barrier (T501 Barrier) using a base plate-anchor bolt connection. Although this design is currently used in Texas, several potential safety concerns have been identified regarding the structural performance of this wall system in the event of vehicular impact.

When a structure is modified by adding, replacing, or removing elements, the response of the modified structure differs from that of the original. This is especially important when considering dynamic load cases, due to the fact that forces and displacements can be amplified depending on the load characteristics and the properties of the wall. For this reason, preliminary research has begun to analytically model the response of a prototype combined sound wall / traffic barrier system to vehicular impact loads. The primary objectives of this research are to assess the current procedures used to design sound walls against vehicular impact based on their response to dynamic impact loads, and to develop and recommend proper design procedures. The preliminary results of this research are presented in this thesis.

1.3 Scope and Objectives

1.3.1 Objectives of TxDOT Project 1471 (Effective Sound Wall Solutions For TxDOT)

The main objective of the TxDOT Project 1471 is to develop a guideline to assist TxDOT personnel in the design of sound walls. To that end, the current sound wall design process and current sound wall systems used in Texas were documented and reviewed. This was achieved mainly by conducting mail, telephone, and face-to-face interviews with TxDOT designers regarding their experience in sound wall design.

TxDOT Project 1471 is divided into three work phases. The first phase, which concluded with the publishing of CTR Report 1471-1 [Klingner et al. 1996], involved the documentation and evaluation of current TxDOT designs. The second phase will document designs and practices used in other states, investigate current materials and concepts being used worldwide, and examine the current tools and concepts used in acoustical modeling. The third phase will synthesize the information gathered in Phases 1 and 2 into a design procedure and design guide that will be made available to TxDOT personnel.

As presented in the TxDOT Project 1471 proposal [Klingner 1995], the objectives of this project are:

- Evaluate existing sound wall materials and systems in use by TxDOT with regard to their acoustic performance, visual aesthetics, structural requirements, and cost-effectiveness.
- Evaluate existing sound wall materials and systems in use by other states and the feasibility of new products and materials in comparison to existing TxDOT systems.
- Develop performance criteria for different geometric and terrain conditions that permit the quantification of acoustic performance, aesthetics, structural soundness, and life-cycle costs.
- Develop a methodology for selecting application-specific designs based upon the roadway geometry, the surrounding terrain and cultural features, and the environment.
- Develop a model for evaluating parallel reflections of sound walls and make recommendations as to when it should be used for design.

1.3.2 Scope and Objectives of Thesis

The work presented in this thesis is a composite of research performed for TxDOT Study 1471 regarding sound wall design, and of research performed in response to concerns voiced by TxDOT personnel regarding vehicular impact. For this reason, this thesis is divided into two sections.

The first section presents documentation of the current sound wall design practice used in Texas. The objectives of this section are:

- To provide the reader with an overview of the current sound wall design process used by TxDOT.

- To identify and describe the various sound wall systems and materials used in Texas.
- To identify topics that are inadequately defined in the structural design process.

The second section of this thesis presents the results from preliminary research on the dynamic response of a prototype combined sound wall / traffic barrier, referred to as a mounted sound wall system. The objectives of this second section are:

- To study and compare the responses of a traffic barrier and of a mounted sound wall system to vehicular impact.
- To evaluate the appropriateness of current AASHTO design provisions for the design of sound walls against vehicular impact.
- To show how the analytical approach used in this research can be used to develop practical engineering design procedures for sound walls exposed to vehicular impact.
- To present an example design procedure based on the results of this research.

A completed TxDOT standard specification and design criteria for structural design of sound walls will be presented in the final TxDOT 1471 Report.

CHAPTER 2

Background

2.1 Introduction

This chapter presents an overview of the generalized process used in designing sound walls. Like any structure, a sound wall is designed to resist the loads that it will experience during its service life. Two categories of loads are addressed in sound wall design: conventional loads and vehicular impact loads. The governing conventional load case is lateral wind loading, applied as a lateral pressure in design. The design procedure for vehicular impact loads is not as clearly defined as for conventional loads. This chapter also reviews current literature pertaining to design of roadside structures for vehicular impact loads.

2.2 Definitions

The distinction between the meaning of the terms “right-of-way” and “clear zone” is often unclear or misunderstood. In this thesis, these terms are defined as follows [Civil Engineering Handbook 1995]:

The r*ight-of-way* is the land area (width) acquired for the provision of a highway.

The c*lear zone* is the unobstructed, relatively flat area outside the edge of the traveled way, including shoulder and sideslope, for the recovery of errant vehicles.

2.3 General Sound Wall Design Process

When the current or projected noise level determined exceeds the Federal Highway Administration (FHWA) limits in a community adjacent to a roadway, there are three options for reducing the noise level to an acceptable level. The first option is to reduce the noise produced at the source. This can be done, for example, with quieter pavements or tires. The second option (the focus of this thesis) is to place an obstruction in the path of the noise, making it follow a longer path and reducing its intensity at the receiver. The third option is to reduce the noise level at the receiver through means such as acoustic insulation.

The fundamental purpose of a sound wall is to provide a community or receiver a reduction in noise levels. Therefore, the first task in designing a sound wall is to ensure that acoustical requirements are satisfied. To accomplish this step, computer simulation models such as STAMINA 2.0 [STAMINA 1978] are used to predict the noise attenuation corresponding to a particular sound wall location and configuration. The acoustical engineer then determines the optimal wall height, length, thickness, and location consistent with the desired noise reduction.

The next stage of design is a cooperative effort among TxDOT district personnel from various offices. In most cases, these offices are Siting and Planning, Environmental Engineering, Landscape Architecture, and Structural Engineering. In addition, the receiver (community) is often consulted in this stage of design. Each TxDOT office is responsible for specific portions of the design. For example, the Structural Engineering office is responsible for designing the sound wall to resist typical design loads such as wind. A structural design example of a sound wall is located in Appendix C. Other considerations that must be addressed in the design include drainage, obstructions, aesthetics, safety, fire and utility access, maintenance, and various others. Several references have been written that discuss the overall design process and design considerations. These include [Klingner et al. 1996, Bowlby 1992, AASHTO 1992a].

2.4 Structural Design Considerations for Sound Walls

2.4.1 Structural Design of Sound Wall for Conventional Load Cases

2.4.1.1 Wind Loading on Sound Walls

Any outdoor structure is subjected to wind loads. In sound wall design, wind loading is modeled as a horizontal pressure acting on the wall. The design wind pressure is calculated using the equation located in Section 1-2.1.2 of [AASHTO 1992a]:

$$P = 0.00256\,(1.3V)^2\ C_d\ C_c$$

where P is the wind pressure, V is the design wind speed based upon 50-year mean recurrence interval, C_d is the drag coefficient (taken as 1.2 for sound walls), and C_c is the combined height, exposure and location coefficient. The wind speed is increased by a factor of 1.3 to account for the effects of gusts. As evident from this equation, the design wind pressure depends on the height of the sound wall and the setting in which it is placed. For instance, a sound wall located in the city is expected to experience lower wind loads than an otherwise identical sound wall located in the country. These factors are incorporated in the coefficient, C_c. A detailed procedure for applying design wind loads to sound walls is available in [AASHTO 1992a].

In design, the forces and moments resulting from wind loads on a sound wall must be checked against the sound wall's lateral load capacity. However, applicable codes and guidelines do not address sound wall deflections, nor do they specify deflection limits for sound walls. For most sound wall systems, deflections under design wind loads are neither a strength or a stability concern. Nor are they the subject of public attention. However, when taller sound walls are constructed, deflections may be perceived by the public as a potential safety hazard. This is especially pertinent when the design uses unbonded tendons placed at the centroid of vertical posts. This design typically has a small internal lever arm and a long length of unbonded tendon, leading to large lateral deflections.

2.4.1.2 Other Design Loads for Sound Walls

While the structural design of sound walls is usually governed by wind load, other load cases may sometimes require consideration. Examples are earthquake loads, snow loads, temperature loads, and pressure loads from flood water. In Texas, these load cases generally do not govern, and for this reason are not addressed further here.

2.4.2 Vehicular Impact Loadings on Sound Walls

Often, to achieve the required noise reduction, a sound wall must be located either close to the receiver or close to the source (roadway). In many cases, the cost of acquiring the property adjacent to the roadway dictates that the sound wall be constructed adjacent to the roadway. When this is the case and sound walls are constructed near a roadway, vehicular impact loading must be addressed in their design.

When considering vehicular impact, several solutions can be applied:

- Place the sound wall beyond the clear zone.
- Use landscaping to redirect vehicles before they can impact the sound wall.
- Place a traffic barrier in front of the sound wall to prevent impact.
- Mount the sound wall on top of a traffic barrier.
- Design the sound wall for vehicular impact.

As mentioned above, the available space often dictates which of these solutions can be used.

Vehicular impact is not only a structural concern, but also a public safety and serviceability issue. In general, vehicular impact barriers such as the T501 traffic barrier [TxDOT 1994] are designed either to redirect the incoming vehicle, or to control the post-impact motion of the vehicle. The intent of placing a barrier such as a T501 barrier adjacent to the roadway is either to prevent the vehicle from impacting objects behind the traffic barrier (protecting the driver), or to prevent the vehicle from striking a person in the vehicle's path (protecting the public).

When designing a sound wall to act as a vehicular impact barrier, the other design considerations discussed above remain the same, and vehicular impact is added to them. In addition to its effect on the impacting vehicle, the impact response of the sound wall itself must also be considered. One danger is that the dynamic excitation caused by vehicular impact may cause the sound wall to collapse. Another safety concern is that the vehicular impact may result in detached elements or fragments from the sound wall penetrating the vehicle or scattering, endangering residents behind the sound wall.

2.5 Current Literature on the Structural Design of Sound Walls

In 1989, AASHTO published a set of recommended guidelines [AASHTO 1992a] pertaining to the design of sound walls. Revised in 1992, those guidelines outline design requirements, including load cases, foundation design, and material detailing requirements. Although those guide specifications provide a good first reference for design engineers, they do not adequately address several key structural issues. Most notably, design issues such as deflection limits and vehicular impact loads are not clearly defined by [AASHTO 1992a].

The AASHTO *Specifications* address vehicular impact loads by stating that these need to be applied only to those sound walls that are mounted on concrete traffic barriers. Otherwise, a traffic barrier "should be considered for use when the sound wall is located inside the clear zone" [AASHTO 1992a]. The engineer must determine the appropriate loads and method of applying them. An alternate reference used for this purpose by TxDOT district engineers is [AASHTO 1992b].

That reference uses an equivalent static force method for design of traffic impact barriers against vehicular impact. The traffic barrier is designed for a static load of 45 kN (10 kips), which is intended to simulate the effect of an automobile impact. Although this provision is intended to ensure that the traffic barrier has adequate strength to safely re-direct an errant automobile, it does not consider the dynamic response of the structure.

CHAPTER 3

Common Types of Sound Walls Used in Texas

3.1 Introduction

Over the past decade, the Texas Department of Transportation (TxDOT) has constructed sound walls of various types and materials. The lessons learned from each of these projects represent a storehouse of knowledge pertaining to sound wall design. By gathering and documenting this information, a design reference can be produced and made available to TxDOT personnel to use when designing a sound wall. Such a compilation was one goal of this study.

To accomplish this goal, telephone surveys were conducted with TxDOT district engineers regarding their experience with sound wall design. Five district engineers were interviewed, each having designed at least one sound wall. The information gathered from these interviews is presented in Chapter 5. In addition to the telephone interviews, each of the engineers was asked to complete a mail survey pertaining to individual sound walls constructed in their district. The survey asked for the completion of an information sheet on each sound wall, and the inclusion of any specifications and plans that exist. The information collected was used to create a "Sound Wall File." This chapter summarizes and presents the information gathered from the districts.

3.2 Sound Wall File

The Sound Wall File is a synthesis of responses to the mail survey completed by the Texas districts. The primary objectives of the Sound Wall File were to assist our research team in evaluating the design criteria currently used for sound wall design throughout Texas, and to create a database to be included in the final design guidelines as a reference for TxDOT personnel in designing sound walls. To provide a usable database, information was gathered on several examples of different types of sound walls constructed throughout Texas. Currently, the Sound Wall File contains an information sheet on 15 TxDOT sound walls, as well as available district plans, standards, and specifications. A sample information sheet is given in Appendix A, and a sample set of construction plans for the Fort Worth Mounted Sound Wall System is given in Appendix E.

In total, information was received for 15 different sound walls from 5 districts: Austin, Dallas, Fort Worth, Houston, and San Antonio. These 15 sound walls comprise a complete database of the different wall systems with which TxDOT personnel have experience. A summary of these systems is provided at the end of this chapter. The database contains the following items:

- a list of sound walls (district, location, description);
- an information sheet on each sound wall;
- a picture or slide of each sound wall;
- structural plans for at least one sound wall in each district; and
- a complete set of plans and specifications for two Austin and one Dallas sound walls.

Each district also sent a set of structural plans for their most common sound wall.

3.3 Sound Wall Classifications

Sound walls were classified according to the following parameters:

- Materials;
- Foundations;
- Influence of Adjacent Utilities;
- Aesthetic Finishes;
- Drainage Issues;
- Vehicular Impact Considerations;

- Maximum Design Wind Load;
- Height and Length; and
- Costs.

The results of these classifications are presented here in outline form.

3.3.1 Materials for Texas Sound Walls

For the 15 sound walls in the Sound Wall File, only three materials were reported: concrete, masonry, and earth. The most common material is concrete, used for 12 walls. The systems most often used in Texas are constructed using a precast concrete panel system. This system is preferred due to its fast installation time and its ability to be replaced or removed easily. Reinforced concrete block masonry has been used in two walls; and one earth berm wall has been constructed.

3.3.2 Foundations for Texas Sound Walls

As noted from the phone interviews, pier and beam foundations were the most common. Overall, 9 of the 15 sound walls used some form of pier and beam foundation. Several other foundation types were reported, including fan-wall systems, earth embankments, spread footings, and embedded anchor bolts (used in mounted sound walls on T501 traffic barriers).

3.3.3 Influence of Adjacent Utilities on Texas Sound Walls

The presence of electric, water, gas, telephone and other utilities adjacent to the sound wall is of concern when selecting a foundation. This is exemplified by the masonry sound wall project located in the Austin District on Parmer Lane (designed by Joe Tejidor, Austin District). Overall, 5 sound walls were reported as having buried utilities, 5 with overhead utilities, and 3 without utilities crossing the line of the wall. For 2 sound walls, this information was not available.

3.3.4 Aesthetic Finishes for Texas Sound Walls

The most common aesthetic finish was an exposed-aggregate or split-faced surface. In total, 10 of the 15 sound walls reported have this type of finish; 3 walls were either painted or left plain; and one wall was plain with tile inserts.

3.3.5 Drainage Issues for Texas Sound Walls

Seven walls were reported to have drainage holes at their bases; 6 walls had no provision for drainage; and only one wall had landscaping (earth contouring) to provide additional drainage. As a result of the telephone interviews, it was concluded that drainage and flood control, while considered, were not critical issues in most projects.

3.3.6 Vehicular Impact Considerations for Texas Sound Walls

Vehicular impact was considered in only 5 of the 15 sound walls. This was most commonly achieved by mounting the sound walls atop a T501 traffic barrier, or by giving the lower portion of the sound walls a so-called “safety shape,” intended to re-direct vehicles. For the remaining 10 cases, the wall was placed beyond the clear zone. Although vehicular impact was not an explicit design criterion for these cases, the district engineers noted that they had considered vehicular impact in some manner (AASHTO static load). The engineers expressed concern over the adequacy of their provisions.

3.3.7 Maximum Design Wind Load for Texas Sound Walls

In the Houston District, the maximum design wind speed was 160 kph (100 mph) corresponding to a wind pressure of 146 kg/m^2 (30 psf). In all other cases except one, the maximum design wind speed was 144 kph (90 mph) - 122 kg/m^2 (25 psf). For that remaining sound wall, a design wind load of 128 kph (80 mph) - 98 kg/m^2 (20 psf) was used. The wind speed was selected based on the 50-year mean recurrence interval, as suggested in [AASHTO 1992a].

3.3.8 Heights and Lengths of Texas Sound Walls

Sound walls varied in length. Heights varied from 2.9 m to 6.9 m (9 feet 6 inches to 22 feet). Most walls had an average height of 3.6 to 4.9 m (12 to 16 feet).

3.3.9 Costs of Texas Sound Walls

Costs were reported for 7 sound walls. The cost per square meter of wall ranged from $118 to $269. The Fort Worth district reported walls ranging from $118 to $172 per square meter; they were primarily 3 m to 3.6 m (10 feet to 12 feet) tall, concrete panel sound walls mounted atop T501 traffic barriers (not included in the cost figures). The most expensive sound wall reported was a 4.5-m (15-foot) tall, concrete panel wall located in Dallas. One earthen sound wall was reported to have a cost of $1.82 per cubic meter.

3.4 Comments Regarding Sound Wall Classifications in Texas

Examination of the information gathered in the Sound Wall File reveals several similarities in design choices among districts. However, there is little consistency among districts, and even among designs in each district. This suggests that external factors such as material availability or public involvement influence the design process, and also that the design process and design criteria are not standard. In both cases, if a database was available from which district engineers and planners could select standard, approved sound wall systems, this would greatly reduce the design cost of each new wall, and would thereby increase the walls' cost-effectiveness.

CHAPTER 4

Common TxDOT Sound Walls

4.1 Introduction

As mentioned in Chapter 1, the material presented in this section of the thesis was performed for the TxDOT Project 1471 for which the author of this thesis is an assistant researcher. This chapter is taken from the TxDOT Project 1471 research report [Klingner et al. 1996] and is presented here verbatim for completeness.

As noted in Chapter 3, the research team held 5 informational meetings in early 1995, meeting with TxDOT personnel in Austin, San Antonio, Fort Worth, Dallas and Houston. One purpose of those meetings was to gather information about the state-of-the-art in sound wall design in Texas.

After each informational meeting, our research team visited, studied and photographed examples of the different types of sound walls found in the host district. The photographs were assembled into a slide database, and also incorporated into a Sound Wall File containing information on each typical wall. The purpose of this chapter is to present information from that file in narrative form, and thereby review the different types of sound walls most commonly found in Texas today.

4.2 Highway Sound Wall Systems Used in Texas

Because highway sound walls that are distinct in appearance may actually be quite similar in function, it is useful to assign them to particular “systems.” This classification is not definitive nor unique, and is adopted primarily for convenience. For purposes of this report, sound wall systems used in Texas are classified as follows:

- Sound Walls Not Intended to Resist Vehicular Impact
    - prefabricated separate post-and-panel system
    - prefabricated integral post-and-panel system
    - constructed-in-place post-and-panel system
    - fan-wall system
    - reinforced earth berms
- Sound Walls Intended to Resist Vehicular Impact
    - prefabricated, barrier-mounted post-and-panel system
    - prefabricated safety-shape wall system

In the remainder of this chapter, each system is described, and is illustrated using photographs of example walls.

4.3 Sound Walls Not Intended to Resist Vehicular Impact

4.3.1 Prefabricated, Separate Post-and-Panel System

The prefabricated, separate post-and-panel system is the most common system used for sound walls in Texas. This system consists of prefabricated panels, placed between posts, as shown schematically in Figure 4.1. The panels are usually of precast concrete, but can also be of other materials. The space between the posts can be filled either with a single panel, or with several shorter panels, stacked vertically. The posts are usually of either concrete or steel. Figure 4.2 shows a typical prefabricated, separate post-and-panel wall, made of full-height, precast concrete panels placed between steel posts, constructed in the Houston District. Figure 4.3 (a close-up view of the same sound wall) shows the

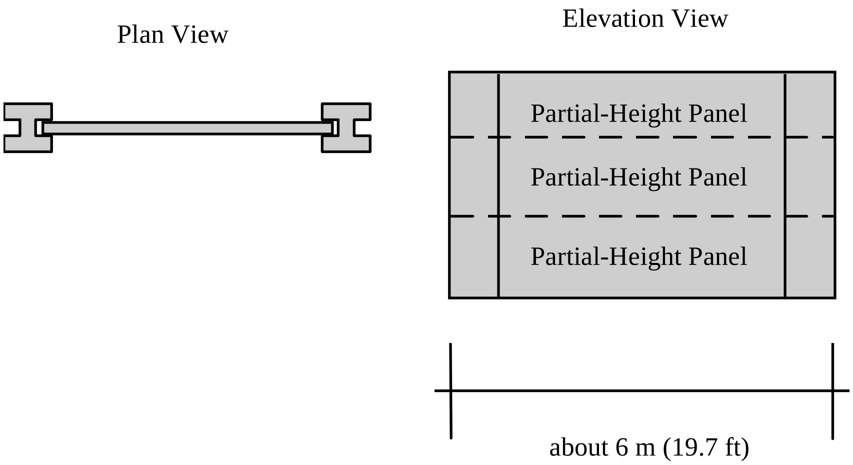

Figure 4.1. Schematic Illustration of Prefabricated, Separate Post-and-Panel System for Highway Sound Walls

FPO

Photograph #10

Figure 4.2. Example of Prefabricated, Separate Post-and-Panel Sound Wall (Houston District, precast concrete panels, steel columns with concrete fascia panels)

FPO

Photograph #11

Figure 4.3. Close-up View of Column on Sound Wall of Figure 4.2

precast concrete fascia plate, intended to provide an aesthetic cover for the steel column and the joint between the panel and the column.

This system has no grade beam. The panels span between the posts, whose spacing is often dictated by the type and layout of the foundation used. As discussed further in the chapter dealing with performance criteria, the post spacing ranges from 3.0 to 7.5 m (10 to 25 feet). Drilled shafts without grade beams are the standard foundation type for all sound walls in the Houston District. The precast panels are typically of reinforced concrete, and are “flown” into place between the columns using an overhead crane.

The prefabricated, separate post-and-panel system has several advantages:

- It is versatile, lending itself to a wide range of construction materials, panel heights, and aesthetic treatments. For example, since the choice of post material (concrete, steel, or other) is a contractor option, several sound walls, such as the one shown in Figure 4.4, have concrete posts. If the presence of overhead utilities or restrictions on crane operation so dictate, the required lifting height or panel weight can be reduced by using multiple, partial-height panels, rather than a single large panel. The panels can have a wide variety of surface textures and colors.

- It is easily constructible, requiring relatively little disruption of traffic.
- It is relatively easy to repair, by removing and replacing the damaged component.

FPO

Photograph #1

Figure 4.4. Example of Prefabricated, Separate Sound Wall System (Houston District, precast concrete posts and precast concrete panels)

4.3.2 Prefabricated, Integral, Post-and-Panel System

The prefabricated, integral post-and-panel system is a slight variation of the prefabricated, separate post-and-panel system discussed above. It offers the same advantages. The difference is that instead of being free-standing, the posts are integral with the panels. This system is illustrated schematically in Figure 4.5. After the integral post-and-panel elements are placed, the post ends of the panels are usually bolted from the top panel to the drilled shaft foundation, or are posttensioned using a cable embedded into the drilled shaft and threaded through the panel or panels as they are lowered into place.

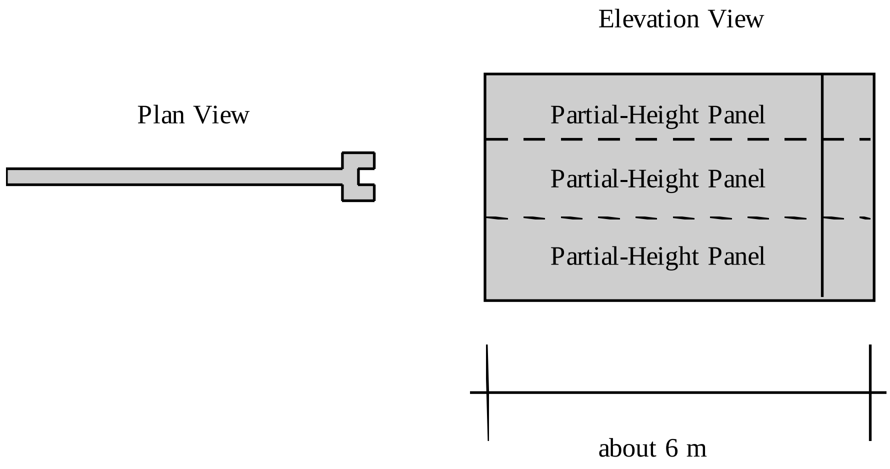

Figure 4.5. Schematic Illustration of Prefabricated Integral System for Highway Sound Walls

4.3.3 Constructed-in-Place Post-and-Panel System

This system is superficially similar to the prefabricated post-and-panel systems discussed above. However, the posts and panels are constructed in place, using reinforced concrete or reinforced masonry. The panels must either be constructed using self-supporting formwork, or on top of shoring or a grade beam. A grade beam increases the cost of the foundation. The principal disadvantage of this system is the potential disruption of traffic associated with construction. This is not always critical. Figure 4.6 shows an example of this system, constructed in reinforced masonry in the Austin District. The San Antonio District has a nearly identical design.

Although constructed-in-place concrete walls are possible, our research team has not identified any walls of this type in Texas. One wall in Dallas, however, has a cast-in-place base topped by precast panels, and is shown under construction in Figure 4.7. It separates an exclusive residential neighborhood from the LBJ Freeway. As a result of negotiations, the neighborhood gave TxDOT the right-of-way for the freeway widening, and TxDOT was required to retain an architect acceptable to the neighborhood, for the design of the sound wall.

FPO

Photograph #3

Figure 4.6. Constructed-in-Place, Post-and-Panel System in Austin (reinforced masonry posts and panels)

The result is an architecturally pleasing but very massive sound wall costing approximately $42 per square foot, more than twice the statewide average. The architectural treatment includes small areas of decorative tile cemented into recesses in the precast concrete panels, and a contrasting white decorative cap placed on top of the panels.

FPO

Photograph #4

Figure 4.7. Example of Constructed-in-Place Post-and-Panel System (Dallas LBJ Freeway, cast-in-place concrete with precast concrete panels, during construction)

4.3.4 Fan-Wall System

A fan wall system is generally composed of full-height, precast panels placed in a zigzag configuration in plan and inter-connected using bolts or cables. This zigzag configuration provides overturning stability, permitting the elimination of posts. In certain areas with very good soil conditions, the foundation can consist only of a compacted base. This system has the potential advantage of low cost, due to the elimination of posts and foundation. However, its zigzag footprint requires more right-of-way than a straight wall. A fan wall can be constructed with less concern for disturbing buried utilities. However, it can make subsequent access to such utilities more difficult, because its overturning stability can be endangered if it is necessary to dig along a significant length of the wall. The fan wall constructed in the Austin District, shown in Figure 4.8, was specifically chosen due to the presence of buried utilities.

FPO

Photograph #7

Figure 4.8. Example of Fan-Wall System
(Austin District, precast panels interlocked with steel cables)

The Houston District has constructed examples of the fan-wall system (Figure 4.9). The fan-wall system used in Houston differs in footprint from that of the Austin wall, being wider and requiring more right-of-way. Even though this wall has no drilled-shaft foundations, the Houston District now requires drilled shafts under all future walls because of the possibility of overturning due to trench excavation. The Houston District has also noted that the irregular shape of fan walls make it difficult to mow next to them, and can provide criminals with places for concealment.

FPO

Photograph #12

Figure 4.9. Example of Fan-Wall System (Houston District)

One type of fan wall, the staggered sound wall system, alternates straight and angled wall sections while incorporating stackable post-and-panel construction. The staggered wall is interrupted at regular intervals with a short section perpendicular to the roadway. As shown in Figure 4.10, a staggered wall is less monotonous than a straight one. Its footprint provides some inherent lateral stability. This configuration is usually used with the prefabricated post-and-panel system, but it could be used with other systems as well.

4.3.5 Earth Berms

The earth berm system is simply an earthen hill. In some instances, the center of the berm is filled with alternate materials (such as recycled tires) to reduce costs. Earth berms have the aesthetic advantages of being less imposing and more natural in appearance than sound walls of other materials. Vegetation on the berm can enhance this aesthetic appeal. However, trees planted on an earth berm sound wall can reduce the wall's acoustical effectiveness by scattering noise that otherwise would have been directed over the receivers. The main disadvantage of earth berm sound walls is the right-of-way they require. Earth berms are an ideal solution if space is available. The Fort Worth District has one such wall.

FPO

Photograph #2

Figure 4.10. Example of Staggered Wall System (Houston District)

4.4 Sound Walls Intended to Resist Vehicular Impact

4.4.1 Prefabricated, Barrier-Mounted, Post-and-Panel System

The prefabricated, barrier-mounted, post-and-panel system is another variation of the post-and-panel system, involving structural steel posts anchored atop a TxDOT T501 traffic barrier (“safety shape barrier”). The traffic barrier is used to reduce potential hazards during vehicular impact, while supporting the post and panel elements used for sound attenuation. This system is widely used in the Fort Worth District, and has also been adopted by the Texas Turnpike Authority for the North Dallas Tollway. Figure 4.11 shows a typical Fort Worth

District sound wall constructed using this system. In the Fort Worth District, the precast panels are constructed either with exposed aggregate or with smooth-finished concrete.

FPO

Photograph #6

Figure 4.11. Example of Prefabricated, Barrier-Mounted, Post-and-Panel System (Fort Worth)

The posts are typically attached to the traffic barrier using a base plate and embedded anchor bolts. This connection is often difficult and costly to construct in the field due to the tight tolerances resulting from the narrow barrier top, which is only 150 mm (6 inches) wide. Because the barrier top is narrow, the base plate is also narrow, and the overturning resistance of the connection is low. As a result, the post spacing must be close—Fort Worth uses a spacing of only 1.5 m (5 feet). The panels must therefore be short. While more panels are required than if the posts were farther apart, the smaller panels are easier to disassemble if necessary. The short panel length and numerous exposed steel posts have decreased the aesthetic appeal of this design.

4.4.2 Prefabricated “Safety Shape” Wall Systems

The “safety shape” sound wall system, originated in Texas in the Houston District, combines the potential vehicular impact resistance of the mounted post-and-panel system with the aesthetic advantages of prefabricated, separate or integral systems. This system, shown in Figure 4.12, consists of a full-height precast panel and integral column, anchored to a lower portion that is trapezoidal in cross-section. The panel and lower portion of the wall are locked together by anchor keys cast into the panels and grouted in place as the panel is lowered onto the trapezoidal lower panel. The final connection to the drilled shaft is made with a long bolt introduced from the top and screwed into an insert cast into the drilled shaft.

The safety-shape system is intended to reduce the hazards of vehicular impact. However, neither the Fort Worth barrier-mounted, post-and-panel system nor the safety-shape system is designed to a specific vehicular impact standard. The Houston District designs the bottom panel to withstand a 45-kN (10-kip) concentrated static load, intended to simulate vehicular impact.

FPO

Photograph #9

Figure 4.12. Example of Safety-Shape Sound Wall System (Houston District)

4.5 Summary of Sound Wall Systems Used in Texas

Many different sound wall systems are used in Texas. They can be classified as in this chapter. Other states and countries use sound wall systems not addressed in this chapter. The following chapter describes the results of our questionnaires and interviews with engineers responsible for the design and construction of each sound wall system.

CHAPTER 5

Current TxDOT Design Process For Sound Walls

5.1 Introduction

As mentioned in Chapter 3, telephone interviews were conducted with TxDOT district personnel regarding their experience with sound wall design. This chapter summarizes and presents the information gathered from those interviews.

5.2 Summary of Phone Interviews with TxDOT District Personnel (11/94 - 5/95)

The primary objective of the phone interviews was to assist our research team in evaluating the current processes used in sound wall design throughout the state of Texas. Since TxDOT does not now have standard guidelines for sound wall design, each district has a different method of selecting and designing a sound wall. The interviews focused on the structural considerations in the design process, such as foundation design and material selection. The questionnaire is given in Appendix A.

The phone interviews were conducted with structural engineers from the 5 districts that currently have designed and constructed at least one sound wall. These 5 districts are the Dallas, Fort Worth, Austin, San Antonio, and Houston districts; and the contacts' names and addresses are listed in Appendix B. In talking with each engineer, the need for standard design guidelines became evident.

The interviews focused on three major topics: the process used to select the sound wall type and material; the structural design procedure; and the major problems encountered. Each district had different procedures for handling each step of the design process.

5.3 Design Process for Sound Walls

The first questions for each survey recipient dealt with the structural design process; that is the structural design of a sound wall whose existence, height and length have already been determined by acoustical considerations. All districts were familiar with the AASHTO *Structural Design Specifications for Sound Barriers* [AASHTO 1992a], and used it as a first reference. Several other references were cited:

- TEK Manual published by the National Concrete Masonry Association [NCMA 1984];
- *Uniform Building Code* [UBC 1991];
- AASHTO Bridge Specifications [AASHTO 1992b];
- LRFD Design Manual [AISC 1992], ACI 318 [ACI 1995], and other material codes; and
- Other applicable codes such as the Structural Welding Code [AWS 1988].

Some districts noted that the above references did not address some important design parameters, and did not consider all design conditions. In particular, the districts identified a need for guidelines on the minimum thickness of a free-standing sound wall, on deflection limits (serviceability), and on vehicular impact requirements.

In all districts, the structural engineer was responsible for selecting and developing numerical design parameters, and for applying the design. For the Houston District, the most common sound walls involve proprietary systems. The proprietary designers and contractors involved in the construction of these walls were ultimately responsible in the design; however, they received assistance from fabricators, TxDOT engineers (using in-house standards), or both. In each such case, the TxDOT district engineer was still required to approve each project.

5.4 Factors Influencing Design of Sound Walls

Design of a sound wall begins with the determination of the height and the location relative to the roadway. These parameters are dictated by acoustical requirements, and determined by the environmental engineer. Once these parameters have been determined, the structural design of the sound wall can proceed.

The structural design of sound walls was principally controlled by these factors: aesthetics; cost; maintenance; local influences; and structural constraints. Although important in each sound wall design, cost was not the controlling factor for most designs. In Austin and San Antonio, aesthetic considerations controlled. In Fort Worth, design was dictated by structural constraints due to the placement of the sound walls on traffic barriers (mounted sound walls). In Houston, local influences dictated that the sound walls be built of concrete, the primary building material for the region. Overall, the primary factors that determined the final sound wall design varied from project to project and district to district, making the standard design process difficult to describe.

In addition to the structural factors mentioned above, several other factors influence the final design of sound walls. These include drainage, landscape, road access, vehicular impact, foundations, environmental impact, community impact, sight distance, right-of-way width, and soil conditions. Several of these factors are discussed in a later section. Consideration of these factors depends highly on the situation and conditions in which the sound wall is to be placed, and will be discussed in more detail in the final design guideline of this research project.

Currently, 4 of the 5 Texas districts polled have no personnel assigned specifically to the design of sound walls. Houston has had the most experience with sound walls, and has assigned a permanent staff member (Mark Anthony) to sound wall study and plan preparation. Most projects are handled by the Special Task Department, and are usually a cooperative effort between the Environment and Structural Engineering divisions.

5.5 Contracting Process for Sound Walls

Most sound wall projects were let, and the contractor selected, by bid. Some districts used only prequalified contractors on projects, and did not allow the projects to be bid. In most cases, alternates were allowed to be bid by the contractors. In such cases, requirements were defined for the alternates. As with the design criteria, the alternate designs were required to satisfy the most important design parameters discussed above.

5.6 Special Details for Sound Walls

5.6.1 Provisions for Openings in Sound Walls

In one location in San Antonio, a metal door was placed to allow the utility company access to a telephone pole located behind the sound wall. In all other districts, no doors were placed in the constructed sound walls.

5.6.2 Provisions for Vehicular Impact

In most districts, vehicular impact is considered for sound walls placed within the lateral clear zone, although a few engineers expressed concern over these provisions. In the Houston district, sound walls are designed using the 45-kN (10-kip) equivalent static load as recommended in [AASHTO 1992b]. The

Fort Worth district uses mounted sound walls. For the mounted sound wall system, only the T501 traffic barriers were designed for vehicular impact using [AASHTO 1992b]. In Dallas, the structural engineer imposed extra live and dead load in order to account for impact, although no formal requirements were specified.

5.6.3 Drainage, Flood Control

In many districts, drainage and flood control were not critical. Most districts provided drainage holes or rip-rap at the base of the sound wall or traffic barrier. In Houston, one sound wall was constructed with an error in the drainage hole size. The opening was made too tall, which raised several concerns, including child safety. An additional concern is obstruction of drain holes by garbage or debris.

5.6.4 Foundations of Sound Walls

In most cases, drilled-shaft foundations were used. Some exceptions were noted. In Fort Worth, sound walls are mounted on traffic barriers. Therefore, standard traffic barriers were constructed, and embedded anchor bolts were used as panel foundations (see Additional Concerns). For the masonry sound wall in Austin, buried utilities dictated shallow foundations, and a spread footing was selected.

5.6.5 Service Life Performance of Sound Walls

Several cases of minor cracking, spalling, and deterioration of connections between structural elements have been observed. These problems were attributed to improper detailing and to inexperience with sound wall design. In addition to design oversights, several sound walls have experienced vehicular impact that caused cosmetic damage. In only 4 reported cases did vehicular impact cause severe damage to a sound wall. All of these cases occurred in the Houston District.

In one of these cases, a truck impacted a sound wall, causing fragments to scatter into a nearby recreational area. In another case, a car impacted a sound wall at the center of a panel. The impact cracked the bottom sound wall panel vertically along its centerline and the leading edge of the car was reported to have penetrated the sound wall. All those sound walls were repaired by replacing the damaged panels. No post-impact effects remain (such as post tilting or cracking in adjacent panels).

5.7 Additional Concerns Regarding Sound Walls

Some problems were noted with mounted sound wall systems. The most serious occurred when the T501 traffic barriers were cast by slip-forming, which prohibits the placement of anchor bolts extending above the barrier top. A mechanical coupling system must therefore be used to attach the anchor bolts with an embedded bar. This procedure is very costly, and presents construction problems when embedded bars are cast improperly at a small angle. Due to the narrow top surface of the traffic barrier, the tolerances allowed in the posts are small, and field alterations must be made to align the bolts. A more serious problem arises when the cage or anchor bolts is struck by the form during construction. If the anchor bolt couplers are shifted forward or backward, the moment arm between the tension bolt and the compression concrete is reduced in one direction. This reduction in moment arm causes a reduction in the moment capacity of the post connection. This could cause potential structural problems.

5.8 Comments Regarding Phone Interviews

From these surveys, the need for a TxDOT design standard for sound walls is apparent. Although the structural design of a sound wall is relatively simple, each project in the different districts is being approached separately. This leads to inefficient use of time, and to incomplete consideration of the various design options and design criteria. In addition, currently available technical literature does not adequately address such structural factors as vehicular impact, repair, deflections, and limitations on sound wall dimensions.

CHAPTER 6

Application of Specialized Analytical Procedure to Study Sound Walls Subjected to Vehicular Impact

6.1 Objectives of Specialized Analytical Procedure

As outlined in Chapter 2, the governing load cases for sound wall design (wind and vehicular impact) are well established. However, as shown in Chapter 5 from interviews conducted with TxDOT district engineers, the response of sound walls to vehicular impact is not well understood. Consequently, design loads and procedures for this case are not clearly defined. The objective of this section is to show how a sophisticated analytical approach (nonlinear, finite element analysis) can be used to develop practical engineering design procedures for sound walls exposed to vehicular impact.

Sound walls exposed to vehicular impact are often placed on top of a traffic barrier. This system, referred to as a "mounted sound wall system," is described in Chapter 4. It is used as an example in this research. Current AASHTO provisions [AASHTO 1992a] require that only the traffic barrier itself be designed against vehicular impact, using an equivalent static force. This approach may not be appropriate, because of the possible dynamic response of the combined system. These concerns have led to the preliminary research presented in this section.

For this study, a particular mounted sound wall design was selected as a prototype. Construction plans are shown in Appendix E. The prototype mounted sound wall system, previously designed in the Fort Worth district, consists of a panel sound wall mounted on top of a T501 traffic barrier using anchor bolts. To study the response of this system, a finite element analytical model was developed and subjected to actual load histories previously obtained from field crash tests [Beason 1989]. Chapter 7 describes the results, and the application of those results to develop simplified design procedures.

6.2 Scope of Specialized Analytical Procedure

The analytical procedure was divided into three phases:

1. Application of static loads;
2. Application of dynamic load cases and assessment of current AASHTO static equivalent load provisions; and
3. Development of simplified analytical procedures for use in design.

The first phase concerns the response of the finite element models to static loads. Its objectives were to ensure that the analytical model displayed reasonable load-deflection behavior, and also to provide an understanding of the mechanisms affecting its response.

In the second phase, the dynamic responses of a traffic barrier and of a mounted sound wall system are examined, using dynamic load cases obtained from actual field crash tests. These results are also used to assess the current AASHTO procedures for designing sound walls against vehicular impact.

The third phase involves the application of the analytical results to the formulation of TxDOT standard specifications and design criteria. The completed guidelines and specifications will be presented in subsequent TxDOT Study 1471 reports.

6.3 Advantages and Limitations of the Finite Element Model

The finite element analysis was performed using ABAQUS, a powerful commercial structural analysis program [ABAQUS 1995]. The finite element method was chosen for this study due to its ability to handle complex, non-linear material behavior and dynamic loads. A model with these characteristics can be used without modification for a variety of load cases, wall configurations, and boundary conditions. The finite element method allows stresses and displacements to be monitored during the load history, thus facilitating an understanding of the structure's behavior.

The finite element analysis performed in this study has several important limitations:

- For practical reasons, the model did not include localized crushing around the load point, nor debonding of the reinforcement and anchor bolts. These features may cause localized failures in the actual sound wall, and therefore control its behavior.
- Since previous impact-related research on this configuration of sound wall does not exist, it was impossible to validate the model developed in this study using results from other studies. Due to financial and time constraints of this study, it was also not possible to perform actual crash tests to validate the full model. To ensure that this sound wall model provides reasonable results, the initial response of the mounted sound wall was calculated by hand (Appendix D), and was compared to the results of the static load case.

6.4 Description of Finite Element Model Used to Study Response of Mounted Sound Walls to Vehicular Impact

The mounted sound wall and model schematic are shown in Figures 6.1 and 6.2, respectively. Based on the typical spacing of 6.1 m (20 ft) between construction joints in a traffic impact barrier, a model of a 6.1-m (20-ft) portion of the mounted sound wall was developed. To reduce computational time and effort, a plane of symmetry was considered to exist at the center of the 6.1-m (20-ft) section, and only half the section was modeled. This was allowed due to the geometry of the barrier, as well as the symmetrical stationary loading pattern which was applied to the model.

The finite element model included four types of elements: the traffic barrier was modeled using 8-noded reinforced concrete solid elements with cracking and crushing capabilities; the sound wall panels were modeled using 8-noded linear solid elements; the foundation bars were modeled using beam elements; and the sound wall posts were modeled using 4-noded shell elements. Figure 6.3 and 6.4 show the finite element mesh for the sound wall.

6.5 Material Properties For Finite Element Model

The material strengths used in the model were those specified on the TxDOT construction drawings obtained from the Fort Worth District (Appendix E). For modeling purposes, typical minimum specified material strengths were used for concrete, steel, and reinforcement. Table 6.1 summarizes the material properties used in the ABAQUS model input file.

For the concrete elements with cracking and crushing capabilities, the ratio of maximum tensile to compressive strength and the maximum plastic strain were set to 0.09 and 0.0035 respectively, based on typical values found in technical literature. The steel was assumed to be elasto-plastic, with a maximum plastic strain of 0.01.

Table 6. 1 - Material Strengths Used in Finite Element Model

Material	Modulus of Elasticity MPa (ksi)	Yield Strength kPa (ksi)	Ultimate Comp. Strength kPa (ksi)	Ultimate Tensile Strength kPa (ksi)
Concrete	24.7 (3600)	---	27.4 (4)	2.53 (0.369)
Reinforcement	200	276 (40)	---	345 (50)
Structural steel	200 (29000)	247 (36)	---	253.8 (58)

6.6 Modeling of Support Conditions and Structural Connections between Elements in Mounted Sound Wall System

6.6.1 Boundary Conditions

The interface between the traffic impact barrier and the pavement was modeled as a contact surface. The bond between the pavement and the traffic barrier was assumed to be broken, and thus was modeled without any tensile capacity. In the static load cases, the interface was modeled as a frictional surface. little slip was observed. Based on this observation, for the subsequent dynamic load cases, the lower back edge of the traffic barrier was modeled as simply supported, to facilitate convergence of the solution.

Pinned and symmetry constraints were applied at the base of the foundation bars and along the plane of symmetry, respectively. At the construction joints, the traffic barrier was assumed to be unrestrained by the adjacent barrier. However, the mounted sound wall panel system above the traffic barrier is continuous. As shown in Figure 6.2, the post above the construction joint was therefore prevented from rotating about a vertical axis, to account for the restraint provided by the adjacent sound wall panels.

6.6.2 Panel-to-Panel Connections

As shown in Figure 6.5, the sound wall panels are simply stacked atop one another, and are separated only by a 50-x50-x6-mm (2-x2-x1/4-inch) elastomeric pad placed at each end. For this reason, each panel was modeled separately, and no panel-to-panel constraints were used.

6.6.3 Post-Barrier Connection

The post is connected to the T501 barrier through an anchored base plate. The anchor bolts are spaced at 76 mm (3 in) perpendicular to the barrier longitudinal axis, as shown in Figure 6.6. To reduce computational time and effort, the connection is modeled as rigid.

6.6.4 Post-Panel Connection

The connection detail is shown in Figure 6.7. The panel is simply inserted between the flanges of the steel posts; the gaps are closed with a backer rod and silicone sealant. This connection was assumed to provide little rotational restraint around the vertical axis at the ends of the panels, and thus was modeled as a pinned connection. To simplify the analysis, the sealant and backer rod was assumed to prevent any movement of the panels between the flanges. Thus, no gap was modeled between the panels and the flanges.

6.6.5 Foundation Bar Connection

As seen in Figure 6.8, the traffic impact barrier is anchored to the pavement by U-shaped #5 reinforcing bars extending from the barrier into the pavement. To account for localized crushing around the bars, and also to properly reflect the axial stiffness of those bars, truss-type elements with an effective length of 216 mm (8.5 in) were used. This length was chosen based on engineering judgment, as about one-third the required development length of a #5 reinforcing bar [ACI 1995].

6.7 Dynamic Load Cases Used in Specialized Analytical Procedure

The vehicular impact forces were modeled as a time-varying dynamic lateral pressure. As summarized in Table 6.2, three dynamic load histories were obtained from the results of field crash tests [Michie 1981, Beason 1989]. Beason measured the forces experienced during vehicular impact against a specially designed and instrumented rigid wall. Due to the rigidity of the traffic barrier addressed in this example, the results from that rigid-wall study are applicable here. Load histories for each case are shown in Figures 6.9 through 6.11.

Table 6.2 - Summary of Dynamic Load Cases Used in Finite Element Analysis [Michie 1981, Beason 1989]

Vehicle Designation	Weight of Vehicle	Incident Angle	Speed at Impact	Maximum Force
car (car1560)	946 kg (2083 lbs)	15 degrees	96 km/h (60 mph)	90 kN (20.2 kips)
light truck (trk2064)	2452 kg (5400 lbs)	20 degrees	103 km/h (64 mph)	222 kN (50.0 kips)
tractor truck (tract1550)	22700 kg (50000 lbs)	15 degrees	80 km/h (50 mph)	666 kN (150.0 kips)

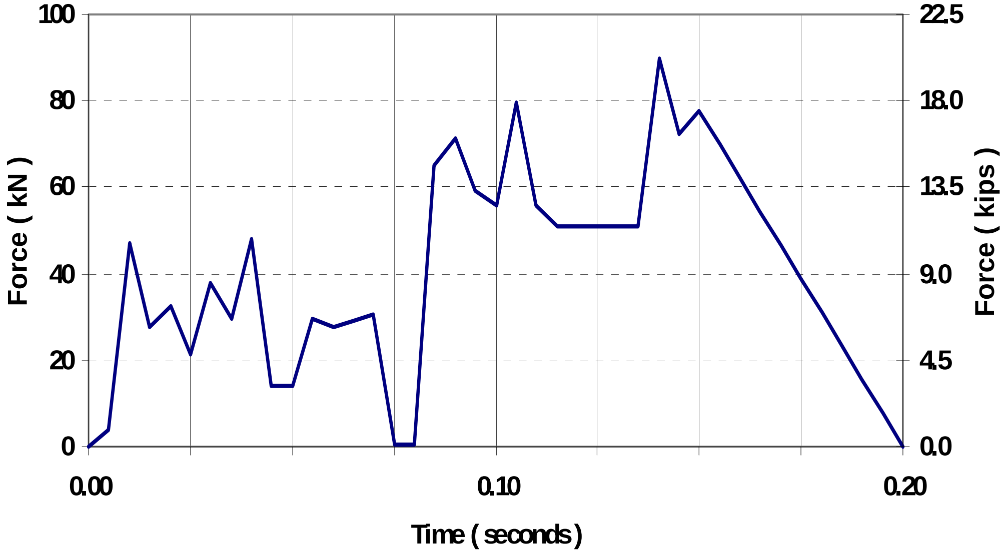

Figure 6.9 - Load History (Load Case “car1560” [Michie 1981])

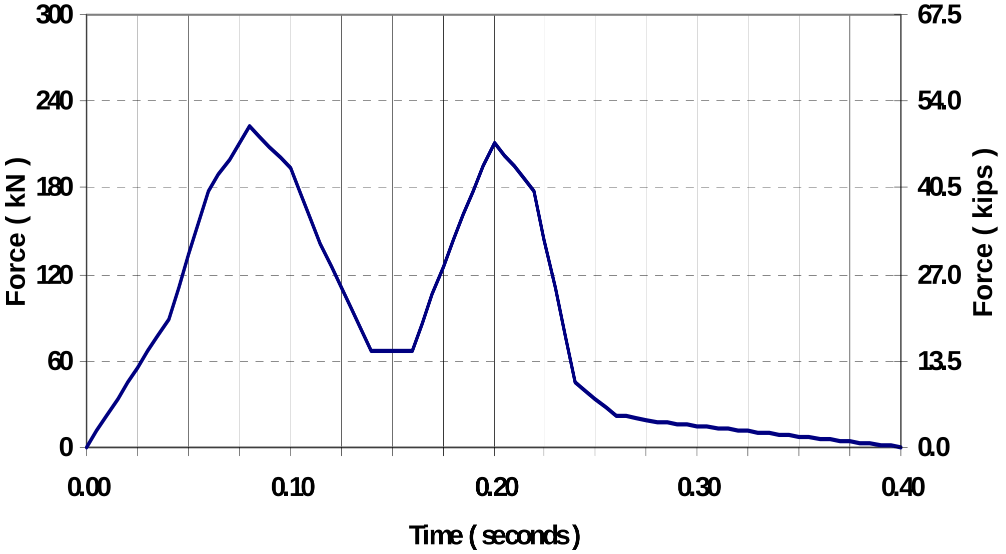

Figure 6.10 - Load History (Load Case “trk2064” [Beason 1989])

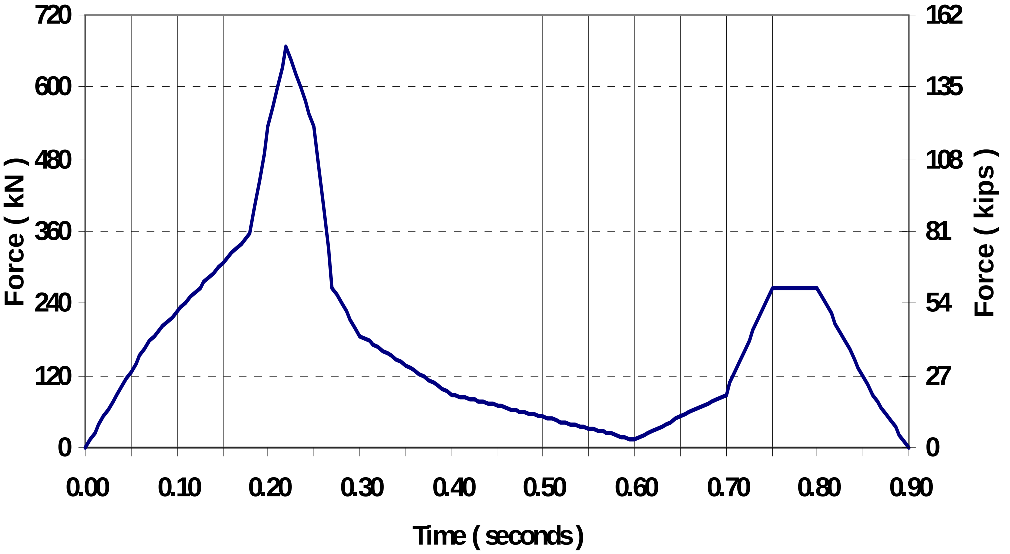

Figure 6.11 - Load History (Load Case “tract1550” [Beason 1989])

The load histories are characterized by two peaks. This pattern is due to impact of the front of the vehicle, followed by impact of the rear of the re-directed vehicle. For the case involving the car, the lateral accelerations presented in [Michie 1981] were multiplied by the vehicle mass to obtain the load history. This approach assumes that the vehicle is a rigid body. As concluded in [Beason 1989], this assumption is valid only for a small car. For the truck and tractor cases, the load histories were based directly on impact forces recorded on the specially instrumented rigid wall rather than on those obtained by multiplying the vehicle acceleration by its mass. As observed in [Beason 1989], the use of vehicle accelerations to calculate forces imparted to a wall can significantly overestimate the actual force from heavy vehicles. Therefore, the forces recorded by instruments located on the wall were considered to be more realistic.

CHAPTER 7

Results of Analytical Procedure Used to Study Sound Wall Systems Subjected to Vehicular Impact

7.1 Overview of Analytical Procedure

The finite element model described in Chapter 6 was used to study and compare the dynamic response of a traffic barrier and of a prototype mounted sound wall system subjected to vehicular impact loads. These responses are used to assess the current AASHTO procedures for designing sound walls against vehicular impact. From the results of this study, recommendations are made for the development of design procedures for mounted sound wall systems exposed to vehicular impact.

7.2 Parameters Studied in Finite Element Analysis

Three response parameters were used to compare and evaluate the traffic barrier and the mounted sound wall system. These are as follows:

1) Deflection at the loaded point;
2) Maximum axial stress in the foundation bars; and
3) Moment at the base of the posts.

The first two parameters were used primarily to describe the response of the structure. Since they are relevant both to the traffic barrier and the mounted sound wall system, they enabled the responses of both structures to be compared for the various load cases as well as for the 45-kN (10-kip) AASHTO static load provision. The last parameter was used to describe the dynamic response of the mounted sound wall.

7.3 Results from Static Load Case

As seen in Figure 7.1, the response of the mounted sound wall system was similar to that of the traffic barrier. Both structures experienced some initial sliding, after which their initial stiffness (at the loaded point) was approximately 18 MN/m (1000 kips/inch). This initial stiffness was confirmed by hand (Appendix D).

The flexibility of the mounted sound wall system depends primarily on the axial stiffness of the foundation bars. When these yielded, at a load of 252 kN (57 kips), the stiffness significantly decreased, as seen in Figure 7.1. This behavior is important because it changes the overall dynamic response of the mounted sound wall system, and can increase the post moments.

To assess the AASHTO static load provision, the values of the three response parameters were recorded at a load of 45 kN (10 kip) and are tabulated in Table 7.1. As seen in this table, only small moments occurred at the base of

Table 7.1 - Forces and Displacements in Mounted Sound Wall System and Traffic Barrier due to the AASHTO 45-kN (10-kip) Equivalent Static Load

Structure	**Deflection at Loaded Point mm (in)**	**Axial Stress in Foundation Bar MN/m^2 (ksi)**	**Moments at Base of Posts MN-m (kip-in)**
Traffic Barrier	0.36 (0.0140)	57.2 (8.3)	----
2.4-m (8-ft) Mounted Sound Wall System	0.34 (0.0134)	52.4 (7.6)	0.1 (1)

the

posts in the mounted sound wall system. This is significant because the dynamic response of the mounted sound wall can produce much greater moments in the posts.

7.4 Results from Dynamic Load Cases (Traffic Barrier)

7.4.1 Displacement at the Loaded Point and Foundation Bar Stress

Figures 7.2 and 7.3 present typical histories of displacement at the loaded point and foundation bar stress for the traffic barrier. As seen in these figures, the shapes of these response curves essentially follow those of the applied load histories. This indicates that the traffic barrier alone responds primarily as a rigid body.

7.5 Results from Dynamic Load Cases (Mounted Sound Wall Systems)

For the load case involving the tractor trailer, significant inelasticity was experienced in the traffic barrier portion of the mounted wall system. Due to limitations in the computer memory available and in ABAQUS, the analysis was not able to be completed for this load case. Therefore, the cracking and crushing capabilities of the traffic barrier portion of the model were removed for this load case only and the analysis completed. Undoubtedly, this model limitation affects the results obtained for this load case. However, it is anticipated that the short duration of the loading should reduce the error in the wall response. To check this assumption, the analysis using load case “trk2064” was performed using both the elastic and inelastic barrier properties. The difference in the response was found to be small.

7.5.1 Displacement at the Loaded Point and Foundation Bar Stress

Figures 7.4 and 7.5 present typical histories of displacement at the loaded point and foundation bar stress for the mounted sound wall system. As with the traffic barrier, the shapes of these response curves are similar to the applied load histories. However, there is a slight lag between the histories of the response and the applied load. This is due to the dynamic response of the mounted sound wall.

7.5.2 Post Moments

Figure 7.6 shows the post moment history for a 3.0 m (8-ft) mounted sound wall system. The oscillation of the post moments indicate the dynamic response of the mounted sound wall to vehicular impact.

The mounted sound wall system can be thought of as a cantilevered wall placed on top of a rigid base (traffic barrier). When the vehicle impacts the traffic barrier, it produces a response (or motion) in the traffic barrier, as shown in Figure 7.4. This in turn excites the mounted sound wall as an appendage.

By understanding this behavior, the parameters which affect the dynamic response of the mounted sound wall can be identified. These variables are:

- The mass and impact characteristics of the vehicle;
- The mass and anchorage of the traffic barrier; and
- The mass and stiffness of the mounted sound wall.

These variables should be examined in future parametric studies.

7.5.3 Effect of Wall Height on Post Moments

As mentioned above, one of the variables affecting the dynamic response of a mounted sound wall system is its properties such as its height. In this study, wall heights of 1.8 m (6 ft), 2.4 m (8 ft) and 3.0 m (10 ft) were used to examine the effect of height on the dynamic response. Figure 7.7 shows the histories of post moments for mounted sound wall systems of different heights. As seen in this figure, the height of the mounted sound wall not only affects the maximum moment, but also the shape of the response curves.

The static design wind moment for the 3.0-m (8-ft) high mounted sound wall is shown on Figure 7.7 for reference. As seen in this figure, the maximum post moment is greater in magnitude than the static wind moment. This result indicates that the post moments due to the dynamic response are significant, and therefore must be considered in design.

7.6 Comparison of Dynamic Responses of Traffic Barrier and Mounted Sound Wall System

7.6.1 Displacement at the Loaded Point and Foundation Bar Stress

Figures 7.8 and 7.9 present the histories of displacement at the loaded point and foundation bar stress, respectively, for the traffic barrier and the mounted sound wall system. As seen in these figures, the response of the mounted sound wall is generally similar to that of the traffic barrier alone. This result indicates that the traffic barrier response is not significantly affected by the addition of a mounted sound wall.

7.6.2 Post Moments

The generation of oscillating post moments illustrate that there is a fundamental difference between the response of the traffic barrier and the mounted sound wall system. In Figure 7.10, the post moments resulting from the dynamic load cases are compared to the design post moment due to wind loads for each mounted sound wall height. As seen in this figure, the post moments generated during the dynamic load cases involving heavy vehicles can exceed the design wind moment. This is important because it will be the controlling design load case for the post and post-barrier connection, which are critical to the performance of the mounted sound wall system.

7.7 Evaluation of Current AASHTO Design Provisions for Vehicle Impact

The current AASHTO provisions are based on the performance of traffic barriers during crash tests involving small automobiles. The 45-kN (10-kip) static load used in the current provisions is intended to simulate the impact of an automobile, thus ensuring that the traffic barrier has the strength to safely re-direct the vehicle.

As shown in Figure 7.11, the 45-kN (10-kip) equivalent static load provides a good estimate of the traffic barrier displacements and forces developed for the dynamic load case involving a compact car. This is true for both the traffic barrier and the mounted sound wall system. This suggests that the traffic barrier will safely re-direct the vehicle regardless of the addition of the mounted sound wall.

Although the current equivalent static load provision ensures that the traffic barrier will have adequate strength to safely redirect a vehicle, it does not provide information on the forces resulting from its dynamic response. For a traffic barrier, this approach is satisfactory. However, it is not appropriate for designing mounted sound wall systems. As seen in Figure 7.7, the dynamic excitation of the mounted sound wall during vehicular impact generate large post moments, unaccounted for in the equivalent static load provisions. Neglect of these moments may lead to poor designs.

7.8 Recommendations for Formulation of Proper Design Procedures against Vehicular Impact for Mounted Sound Wall Systems

The purposes of this section are to assess the adequacy of the current AASHTO design provisions to predict appropriate design forces, and to recommend a procedure that can be used to develop new design provisions.

This study shows that the response of the mounted wall system produces significant moments at the base of the posts, unaccounted for by the AASHTO static equivalent load provisions. Based on these findings, an example set of design curves were generated using the analytical model described in Chapter 6. These are shown in Figure 7.12.

The example design curves presented here provide design post moments as a function of the mounted sound wall height for a given design vehicle. Design curves were chosen because they are an efficient way of displaying the pertinent design information. The application of the finite element method to develop these design curves was found to be very effective. Once a general finite element model was created, the height of the mounted sound wall could be changed with little effort. This allowed for easy generation of design curves.

The design curves presented here were derived from the study of a limited number of wall configurations and design parameters. However, the procedure used in this research to develop these guidelines could efficiently be used for future studies.

CHAPTER 8

Summary, Conclusions, and Recommendations

8.1 Summary of Thesis

The work presented in this thesis is divided into two sections. The first section documents the current structural design process for noise walls. The second section presents the results of preliminary research on the dynamic response of a prototype mounted noise wall system to vehicular impact.

The first section of this thesis documents the current process used in Texas to design sound walls. To accomplish this, telephone and face-to-face interviews were conducted with TxDOT district engineers regarding their experience with sound wall design. The interviews focused on three major topics: the process used to select the sound wall type and material; the structural design procedure; and the major problems encountered. In addition, each of the engineers interviewed was asked to complete a mail survey pertaining to individual sound walls constructed in their district. The information collected from these surveys was used to create a “Sound Wall File,” which is summarized in this thesis. The Sound Wall File includes a description of 15 sound walls constructed in Texas as well as district standards and specifications where available.

The second section of this thesis presents the results of preliminary research on the dynamic response of a prototype mounted sound wall to vehicular impact loads. For this purpose, an analytical model was developed and subjected to impact load histories from actual crash tests. The responses were used to assess the adequacy of the current AASHTO provisions used to design mounted sound wall systems against vehicular impact. Furthermore, example design curves were generated to illustrate how this analytical procedure could be used to develop a complete set of design guidelines and specifications. Recommendations were made for the development of proper design procedures for designing mounted sound wall systems against vehicular impact.

8.2 Conclusions

8.2.1 Documentation of the Sound Wall Design Process Used in Texas (TxDOT Project 1471)

The first section of this thesis presents the partial work completed in the first year of a four year study. As discussed above, telephone interviews and mail surveys were conducted with TxDOT engineers regarding their experience with sound wall design. From these interviews and surveys, several conclusions could be drawn:

- The current design process for sound walls is not standardized in Texas. The availability of a statewide design guideline would reduce the design cost and increase the cost-effectiveness of each new wall.
- Technical literature does not adequately address the following issues in sound wall design: vehicular impact; deflection limits; and repair methods.
- The most common type of noise wall currently used in Texas is the precast post-and-panel system with a drilled-shaft foundation.

8.2.2 Preliminary Research on Vehicular Impact

The second section of this thesis presents the preliminary results of research performed on the dynamic response of the a prototype mounted sound wall system to vehicular impact. From the results of this research, several conclusions are drawn:

- The AASHTO 45-kN (10-kip) static load provides a good estimate of the displacements and forces induced in a traffic barrier by automobile impact.
- However, the current AASHTO equivalent static load provision does not provide information on the post moments that result from the dynamic response of a mounted sound wall. The AASHTO static load provision is inappropriate for mounted sound walls.
- The actual dynamic response of the mounted sound wall to vehicular impact depends on all three of the following: the mass and impact characteristics of the vehicle; the mass and stiffness of the traffic barrier; and the mass and stiffness of the mounted sound wall.
- The actual dynamic response of a mounted sound wall is quite different from that of a traffic barrier alone. The mounted sound wall oscillates back and forth. Maximum post moments can significantly exceed those from design wind loads.
- The analytical procedure of this research was used to develop sample design curves for mounted sound walls. This process could efficiently be used for future studies.

Further investigations of sound wall design will be presented in subsequent TxDOT Project 1471 reports.

8.3 Recommendations for Future Research on Vehicular Impact

The need for future research to develop revised design guidelines for sound walls is evident from the preliminary research presented in this thesis. Future research should include the effect of the dynamic response on the critical design forces. It is necessary to investigate the dynamic properties of the sound wall as well as the characteristics of the loading.

Additional issues not addressed in this research may warrant further study:

- Design of post-barrier connection details;
- The effect of moving and repeated loads on the wall response; and
- The effect of a vehicle climbing the traffic barrier and impacting the mounted sound wall. This affects the response of the wall as well as the vehicle performance (rolling).

APPENDIX A

Telephone and Mail Survey Questionnaire

Notes:

Some questions were not answered or omitted due to lack of personal experience, or were covered in an explanation of another question.

The following are a list of questions that were covered in the phone interview. In order to receive more details, a brief follow-up mail survey was sent to each participant.

1. What design specifications do you use? AASHTO Specifications?
2. How do you decide what systems/materials to put in plans, specs., and estimates?
3. Who is responsible for deciding which performance and design criteria to apply?
4. Who is responsible for quantifying this criteria?
5. Have you ever changed any design specifications based upon experience?
6. Do you allow contractors to bid unspecified alternates or provide alternates to be bid?
7. What is your process for reviewing/approving proposed materials/systems?
8. Describe special details for the following:
   Fire Hose and Maintenance access
   provisions for vehicular impact
   drainage, flood control
   foundations
9. Have you experienced any structural or material failures with sound walls?
10. Is there any additional information that you would like to add describing what your district has learned regarding sound wall design?

Thank you very much for your time and cooperation. In order to assist our efforts, would you be able to complete a mailed survey pertaining to individual sound walls. This information will be used to create a database that will later be included in a product review section of our final design guideline.

To whom should I send it?

Sound Wall Files - TxDOT Study No. 1471

Wall No. ______

DISTRICT: ____________________

STATE: ____________________ **CITY**: ____________________ **ROUTE**: ____________________

DESIGNER: ____________________

Information:

Material(s): ____________________

Structural Type: (panel, fan, earth berm) ____________________

Height and Length: ____________________

Foundation Type: ____________________

Location with respect to ROW: ____________________

Drainage system: ____________________

Utilities: (overhead, buried) ____________________

Finishes: (color, texture) ____________________

Openings for access to ROW: ____________________

Vehicular Impact Considered? (Yes, No) ____________________

Traffic: (current, design)
ADT: ____________________
%Trucks: ____________________

Cost: ____________________

Year Constructed: ____________________ Type I or II: ____________________

Maximum Design Wind Load: ____________________

Proprietary: (Yes, No) ____________________

Included in File:

Structural Plans	Pictures
Foundation Plans	Specifications
Architectural Plans	Acoustic Test Results

Other: ____________________

Additional Information: ____________________

____

____

APPENDIX B
List of TxDOT Personnel Interviewed

Fort Worth District
John Chase
P.O. Box 6868
Fort Worth, Texas 76115
Phone: 817-370-6580

Austin District
Joe Tejidor
P.O. Drawer 15426
Austin, Texas 78761-5426
Phone: 512-832-7136

Dallas District
Van McElroy
P.O. Box 3067
Dallas, Texas 75221-3067
Phone: 214-320-6171

Houston Distict
John Vogel (engineering)
P.O. Box 1386
Houston, Texas 77251-1386
Phone: 713-802-5235

Mark Anthony (layout and planning)
P.O Box 1386
Houston, Texas 77251-1386
Phone: 713-802-5535

San Antonio Distict
Jon Kilgore
4615 NW Loop 410
P.O. Box 29928
San Antonio, TX 78284-3601
Phone: 210 615-5882

APPENDIX C
Structural Design of Example Sound Wall Design

For purposes of this report, a design is performed to illustrate the critical design loads and parameters. As an example, the actual sound wall dimensions and geometry of the Fort Worth mounted sound wall are used.

Specifications used: 1992 *AASHTO* Guide *Specifications for Structural Design of Sound Barriers [AASHTO 1992a]*

Sound Wall Dimensions:

Panel dimensions	1.47-m wide by 0.61-m tall by 0.13-m thick (4.83-ft wide by 2-ft tall by 0.416-ft thick)
Post dimensions	W6x15
Post height	2.43 m (8 ft)
Post spacing	1.52 m (5 ft)
Total wall height	3.25 m (10.7 ft)

Minimum Specified Properties (Specified on TXDOT Construction Plans):

Reinforcement Yield Strength	276 kPa	(40 ksi)
Concrete Specified Compressive Strength (f'_c)	28 kPa	(4 ksi)
Post Steel Yield Strength	247 kPa	(36 ksi)

Parameters Used:

Design wind speed	128 kph (80 mph)
Exposure category	Exposure B2
Design Wind Pressure	P = 958 Pa (20 psf) (AASHTO Table 1-2.1.2C)

Load Cases Considered: Wind, Gravity

Load Combination: (1.3 or 1.0) D + 1.3W

Wind Load Analysis

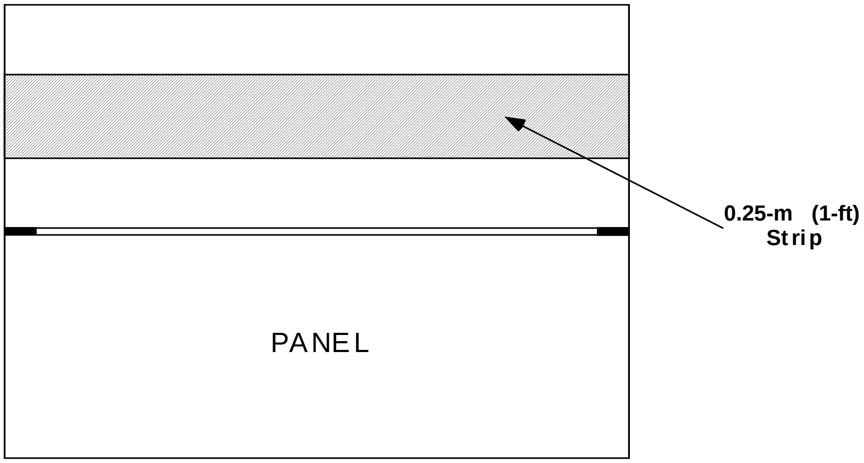

Figure C1 - Horizontal Strip for Panel Design (Wind Load)

Panel Design

Lateral flexural check: *Consider 0.3 m (1-ft) horizontal strip as shown. Assume simply supported panels.*

$$M = \frac{wL^2}{8} = \frac{(958Pa \cdot 0.3m)(1.5m)^2}{8} = 0.081 \text{ kN-m (0.75 kip-in)}$$

ϕM_n = 0.9 A_s f_y (0.9d) = 1 kN-m (8.91 kip-in)

M_u = 1.3 M = 0.105 kN-m < ϕM_n = 1 kN-m OK

Lateral shear check: *Consider 0.3 m (1-ft) horizontal strip as shown. Assume simply supported panels.*

$$V = \frac{wL}{2} = \frac{(958Pa \cdot 0.3m)(1.5m)}{2} = 0.22 \text{ kN (50 lbs)}$$

ϕV_n = 0.85 x 2 ($\sqrt{f'_c}$) bd = 28.7 kN (6.45 kips)

V_u = 1.3 V = 0.29 kN < ϕV_n = 28.7 kN OK

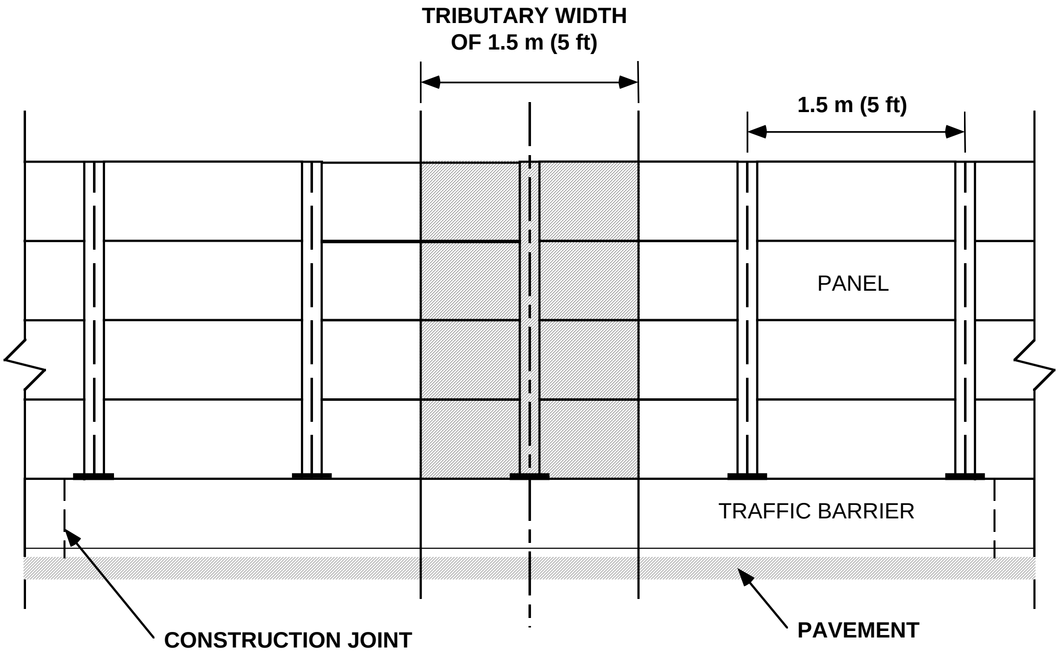

Figure C2 - Tributary Width for Post Design (Wind Load)

Post Design

Flexural check: *Consider a 1.5-m (5-ft) tributary width as shown.*

$$M = \frac{wH^2}{2} = \frac{(958 Pa \cdot 1.5 m)(2.4 m)^2}{2} = 4.34 \text{ kN-m (3.2 kip-ft)}$$

$\phi M_n = 0.9\ S_x\ f_y = 49$ kN-m (38.2 kip-ft)

$M_u = 1.3\ M = 5.64$ kN-m $< \phi M_n = 49$ kN-m OK

Shear check: *Consider a 1.5-m (5 ft) tributary width as shown.*

V = wH = (958 Pa x 1.5 m)(2.4 m) = 2.22 kN (0.5 kips)

$\phi V_n = 0.85$ x A $F_y = 1239$ kN (278.5 kips)

$V_u = 1.3\ V = 2.89$ kN $< \phi V_n = 278.5$ kips OK

Anchor bolt check: *Based on LRFD design* [LRFD 1986]

Bolt type:	A325 Headed Bolt
Bolt size:	19 mm (¾”) ϕ
Bolt area:	284 mm^2 (0.44 in^2)
Embedment length:	0.46 m (18 in.)
Yield strength:	F_y = 724 MN/m^2 (105 ksi)
Ultimate Strength:	F_u = 827 MN/m^2 (120 ksi)

Tension capacity,

$$T_u = \phi F_u A_g$$
$$= 0.75 \text{ x } 827 \text{ MN/m}^2 \text{ x } 284 \text{ mm}^2$$
$$= 177 \text{ kN } (39.76 \text{ kips})$$

Using LRFD Table 8-26, the minimum embedment length is 17d or 324 mm (12.75 in), which is provided. However, the minimum edge distance required is 7d or 133 mm (5.25 in), which is not satisfied in this design. To prevent a side blow-out failure, reinforcing bars form a closed loop around the anchor bolts. Since the anchor bolts intersect the vertical reinforcement in the traffic barrier, the anchor bolt capacity was assumed to be that of a lap splice connection with the reinforcing bar. This capacity was calculated using the ACI Code [ACI 1995] provision for splice length.

Lap splice capacity,

$$\text{Required development length of \#5 bar} = \frac{0.04 A_b f_y}{\sqrt{f_c'}} = 197 \text{ mm } (7.75 \text{ in})$$

The minimum lap splice is 305 mm (12 in), which is greater than 1.3 ℓ_d. Therefore, use the minimum splice length.

Required length of splice = 381 mm (15 in) > 305 mm (12 in).

Therefore, the #5 reinforcing bar can develop its full capacity and will control the splice capacity.

$$T_u = \phi F_y A_g = 0.75 \text{ (276 kPa) } 0.198 \text{ m}^2 = 41 \text{ kN (9.2 kips)}$$

Use this capacity for the capacity of the anchor bolts.

Axial force in anchor bolt due to post flexure: (4 bolts per post)

Assume 0.127m (5 in) between concrete compression block and anchor bolt in tension.

$$2T = M / (\text{lever arm})$$
$$= 4.34 \text{ kN-m} / (0.127 \text{ m})$$
$$= 34.2 \text{ kN}$$
$$T = 17.1 \text{ kN per bolt (7.68 kips per bolt)}$$

1.3 T = 22.2 kN < T_u = 41.0 kN OK

In a typical design, the foundations and base plates would need to be designed. Additional load cases such as seismic and flood may also be checked when applicable in the design or analysis.

APPENDIX D

Hand-Calculated Stiffness of Mounted Sound Wall System

Estimate stiffness of traffic barrier:

Due to the rigidity of the traffic barrier, the stiffness was assumed to be dependent only on the axial stiffness of the foundation bars. For these estimates, assume that all the force is in the outer bars and that only 10 bars are effective for stiffness. The load is applied at a height of 0.53 m (21 in) from the pavement surface and the distance from the back edge of the traffic barrier to the outer foundation bars is 0.23 m (9 in).

∑ Moments about the back edge of barrier, P = 4.448 kN (1.0 kip)

P x Height of Loaded Point = (9.0 F_{bar}) (number of bars effective)
= 9.0 F_{bar} (10 bars)

F_{bar} = 1.02 kN (0.23 kips)

Find deflection of outer bar:
δ_{bar} = PL/AE = 1.02 kips x 216mm / 1.98 mm^2 x 200 MN/m^2
= 5.6×10^{-3} mm (2.2×10^{-4} in)

Find the corresponding deflection at the load point:
$\delta_{load} = \delta_{bar}$ (0.53m / 0.23m) = 0.13 mm (5.1×10^{-3} in)

Therefore, K_{wall} for overturning = 4.448 kN / 0.13 mm = **34 kN/mm (1960 k/in)**

APPENDIX E
TxDOT Construction Drawings

Figure E1 - TxDOT T501 Traffic Rail Construction Drawings (Sheet 1 of 2)

Figure E2 - TxDOT T501 Traffic Rail Construction Drawings
(Sheet 1 of 2 cont.)

Figure E3 - TxDOT T501 Traffic Rail Construction Drawings (Sheet 2 of 2)

Figure E4 - TxDOT T501 Traffic Rail Construction Drawings (Sheet 2 of 2 cont.)

Figure E5 - TxDOT Mounted Sound Wall Construction Drawings - Fort Worth District (Sheet 1 of 3)

Figure E6 - TxDOT Mounted Sound Wall Construction Drawings - Fort Worth District (Sheet 1 of 3 cont.)

Figure E7 - TxDOT Mounted Sound Wall Construction Drawings - Fort Worth District (Sheet 2 of 3)

Figure E8 - TxDOT Mounted Sound Wall Construction Drawings - Fort Worth District (Sheet 2 of 3 cont.)

Figure E9 - TxDOT Mounted Sound Wall Construction Drawings - Fort Worth District (Sheet 3 of 3)

Figure E10 - TxDOT Mounted Sound Wall Construction Drawings - Fort Worth District (Sheet 3 of 3 cont.)

APPENDIX F
Example ABAQUS Input File

```
*HEADING
FORT WORTH MOUNTED NOISE BARRIER - FEB. 20, 1996
************************************
** WRITTEN BY RONALD PERON
** UNIVERSITY OF TEXAS AT AUSTIN
** JANUARY, 1996
** VERSION II
**
**  NOTES:
**  Concrete around attachment rebar or bolts are modeled w/o crushing or cracking capabilities
**  Corrected geometry was inputted for traffic barrier
**  Vertical reinforcement is included
**  Foundations are modeled as beam elements
**  Post base plates are modeled
**  Two panel lengths (10 feet) is modeled with symmetry constraints on both post ends
**********************************
**  %% GENERATING NODES FOR NOISE WALL %%
**
*NODE, NSET=left
1, 0.,1.5,0.
111, 0.,17.,0.
133, 0.,1.50,3.5
243,0.,16.5,3.5
265,0.,1.50,6.6667
375,0.,14.0,6.6667
397,0.,1.500,9.8333
507,0.,11.75,9.8333
529,0.,1.5,13.
639,0.,10.5,13.
661,0.,1.5,16.166667
771,0.,9.66667,16.166667
793,0.,0.0,19.33333
903,0.,9.33333,19.33333
1321,0.,0.,32.
1343,0.,1.3125,32.
1409,0.,6.6875,32.
1431,0.,8.,32.
*NGEN, NSET=left
793,1321,132
903,1431,132
*NGEN, NSET=left
1,111,22
133,243,22
265,375,22
397,507,22
529,639,22
661,771,22
793,903,22
925,1035,22
1057,1167,22
1189,1299,22
1343,1409,22
**
**  %% COPY NODE PATTERNS FROM LEFT SIDE TO RIGHT %%
**
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0,0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=2, OLD SET=left, SHIFT
7.5,0.,0.
0,0,0,0,0,0,0
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15.0,0.,0.
0,0,0,0,0,0,0
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30.0,0.,0.
0,0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=6, OLD SET=left, SHIFT
```

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SET=left, SHIFT
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SET=left, SHIFT
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SET=left, SHIFT
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SET=left, SHIFT
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SET=left, SHIFT
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SET=left, SHIFT
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SET=left, SHIFT
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SET=left, SHIFT
97.5,0.,0.
0,0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=17, OLD
SET=left, SHIFT
105.0,0.,0.
0,0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=18, OLD
SET=left, SHIFT
112.5,0.,0.
0,0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=19, OLD
SET=left, SHIFT
117.0,0.,0.
0,0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=20, OLD
SET=left, SHIFT
120.,0.,0.
0,0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=21, OLD
SET=left, SHIFT, NEW SET=right
123.,0.,0.
0,0,0,0,0,0,0
**
**  %% GENERATING FOUNDATION
BEAM %%
**
*NODE, NSET=found
1501,0.,4.5,-5.0
1517,120.,4.5,-5.0
1518,0.,9.0675,-5.0
1534,120.,9.0675,-5.0
*NGEN, NSET=found
1501,1517,1
1518,1534,1
**
**  %% GENERATING NOISE WALL
POSTS %%
**
*NODE, NSET=post
2001,0.,1.3125,32.26
2002,0.,6.6875,32.26
2003,3.,1.3125,32.26
2004,3.,6.6875,32.26
2005,57.,1.3125,32.26
2006,57.,6.6875,32.26
2007,60.,1.3125,32.26
2008,60.,6.6875,32.26
2009,63.,1.3125,32.26
2010,63.,6.6875,32.26
2011,117.,1.3125,32.26
2012,117.,6.6875,32.26
2013,120.,1.3125,32.26
2014,120.,6.6875,32.26
*NCOPY, CHANGE NUMBER=126, OLD
SET=post, SHIFT
0.,0.,72.
```

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*NGEN
2001,2127,14
2002,2128,14
2003,2129,14
2004,2130,14
2005,2131,14
2006,2132,14
2007,2133,14
2008,2134,14
2009,2135,14
2010,2136,14
2011,2137,14
2012,2138,14
2013,2139,14
2014,2140,14
**
**  %% GENERATE NOISE WALL PANELS %%
**
*NODE, NSET=panel
2501,1.,1.5,32.30
2502,1.,6.5,32.30
2521,59.,1.5,32.30
2522,59.,6.5,32.30
*NGEN, NSET=panel
2501,2521,2
2502,2522,2
*NCOPY, CHANGE NUMBER=22, OLD SET=panel, SHIFT, NEW SET=panels
0.,0.,8.0
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0.,0.,47.8
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*NCOPY, CHANGE NUMBER=198, OLD SET=panel, SHIFT, NEW SET=panels
0.,0.,56.
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=220, OLD SET=panel, SHIFT, NEW SET=panels
0.,0.,64.
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=242, OLD SET=panel, SHIFT, NEW SET=panels
0.,0.,71.6
0,0,0,0,0,0
*NSET, NSET=panelT, GENERATE
2501,2852,1
*NCOPY, CHANGE NUMBER=500, OLD SET=panelT, SHIFT, NEW SET=panel2
60.,0.,0.
0,0,0,0,0,0
**
**  %% GENERATING BASE PLATE NODES %%
**
*NODE, NSET=base
3501,0.,0.,32.25
3512,0.,1.3125,32.25
3545,0.,6.6875,32.25
3556,0.,8.,32.25
*NGEN, NSET=base
3512,3545,11
*NCOPY, CHANGE NUMBER=1, OLD SET=base, SHIFT
3.0,0.,0.
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=2, OLD SET=base, SHIFT
7.5,0.,0.
```

```
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=3, OLD
SET=base, SHIFT
52.5,0.,0.
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=4, OLD
SET=base, SHIFT
57.0,0.,0.
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=5, OLD
SET=base, SHIFT
60.0,0.,0.
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=6, OLD
SET=base, SHIFT
63.0,0.,0.
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=7, OLD
SET=base, SHIFT
67.5,0.,0.
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=8, OLD
SET=base, SHIFT
112.5,0.,0.
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=9, OLD
SET=base, SHIFT
117.0,0.,0.
0,0,0,0,0,0
*NCOPY, CHANGE NUMBER=10, OLD
SET=base, SHIFT
120.0,0.,0.
0,0,0,0,0,0
**
*NODE, NSET=base
3601,123.0,0.,32.25
3602,123.0,1.3125,32.25
3605,123.0,6.6875,32.25
3606,123.0,8.,32.25
*NGEN, NSET=base
3602,3605,1
**
**  %% DEFINING ADDITIONAL SETS
OF NODES %%
**
*NSET, NSET=constr, GENERATE
1,22,1
*NSET, NSET=displ, GENERATE
903,903,1
2169,2181,6
*NSET, NSET=reacts, GENERATE
1,22,1
1501,1534,1
*NSET, NSET=web, GENERATE
2015,2169,14
2016,2170,14
2027,2181,14
2028,2182,14
3501,3556,11
3601,3606,1
*******************************
**  %% GENERATING ELEMENTS IN
TRAFFIC BARRIER %%
*******************************
**
**  @@ TRAFFIC BARRIER @@
**
*ELEMENT, TYPE=C3D8
1,1,2,24,23,133,134,156,155
*ELGEN
1,21,1,1,5,22,21,10,132,105
**
**  @@ FOUNDATION ELEMENTS @@
**
*ELEMENT, TYPE=B31, ELSET=fo2
2001,1501,155
2019,1518,177
*ELEMENT, TYPE=B31, ELSET=fo
2002,1502,157
2009,1509,165
2010,1510,167
2018,1517,175
2020,1519,179
2027,1526,187
2028,1527,189
2035,1534,197
*ELGEN, ELSET=fo
2002,7,1,1
2010,7,1,1
2020,7,1,1
2028,7,1,1
**
*ELEMENT, TYPE=B31, ELSET=fo2
2036,155,287
2054,177,309
*ELEMENT, TYPE=b31, ELSET=fo
```

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2037,157,289
2044,165,297
2045,167,299
2053,175,307
2055,179,311
2062,187,319
2063,189,321
2070,197,329
*ELGEN, ELSET=fo
2037,7,1,1
2045,7,1,1
2055,7,1,1
2063,7,1,1
**
**  @@ NOISE WALL POSTS @@
**
*ELEMENT, TYPE=S4R
1101,2001,2003,2017,2015
1102,2002,2004,2018,2016
*ELGEN, ELSET=flanges
1101,2,4,2,9,14,8
1102,2,4,2,9,14,8
*ELEMENT, TYPE=S4R
1105,2007,2009,2023,2021
1106,2008,2010,2024,2022
*ELGEN, ELSET=flanges
1105,2,4,2,9,14,8
1106,2,4,2,9,14,8
**
*ELEMENT, TYPE=S4R
1251,2001,2002,2016,2015
*ELGEN
1251,3,6,1,9,14,3
**
**  @@ NOISE WALL PANELS @@
**
*ELEMENT, TYPE=C3D8R
1300,2501,2503,2504,2502,2523,2525,2526
,2524
*ELGEN
1300,10,2,1,3,22,10
*ELEMENT, TYPE=C3D8R
1350,2589,2591,2592,2590,2611,2613,2614
,2612
*ELGEN
1350,10,2,1,3,22,10
*ELEMENT, TYPE=C3D8R
1400,2677,2679,2680,2678,2699,2701,2702
,2700
*ELGEN
1400,10,2,1,3,22,10
**
*ELEMENT, TYPE=C3D8R
1500,3001,3003,3004,3002,3023,3025,3026
,3024
*ELGEN
1500,10,2,1,3,22,10
*ELEMENT, TYPE=C3D8R
1550,3089,3091,3092,3090,3111,3113,3114
,3112
*ELGEN
1550,10,2,1,3,22,10
*ELEMENT, TYPE=C3D8R
1600,3177,3179,3180,3178,3199,3201,3202
,3200
*ELGEN
1600,10,2,1,3,22,10
**
**  @@ BASE PLATES @@
**
*ELEMENT, TYPE=C3D8, ELSET=pl1
1701,1321,1322,1344,1343,3501,3502,3513
,3512
1702,1343,1344,1366,1365,3512,3513,3524
,3523
1703,1365,1366,1388,1387,3523,3524,3535
,3534
1704,1387,1388,1410,1409,3534,3535,3546
,3545
1705,1409,1410,1432,1431,3545,3546,3557
,3556
*ELGEN
1701,2,1,5
1702,2,1,5
1703,2,1,5
1704,2,1,5
1705,2,1,5
*ELEMENT, TYPE=C3D8, ELSET=pl2
1711,1329,1330,1352,1351,3504,3505,3516
,3515
1712,1351,1352,1374,1373,3515,3516,3527
,3526
1713,1373,1374,1396,1395,3526,3527,3538
,3537
```

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1714,1395,1396,1418,1417,3537,3538,3549
,3548
1715,1417,1418,1440,1439,3548,3549,3560
,3559
*ELGEN
1711,4,1,5
1712,4,1,5
1713,4,1,5
1714,4,1,5
1715,4,1,5
*ELEMENT, TYPE=C3D8, ELSET=pl1
1731,1339,1340,1362,1361,3509,3510,3521
,3520
1732,1361,1362,1384,1383,3520,3521,3532
,3531
1733,1383,1384,1406,1405,3531,3532,3543
,3542
1734,1405,1406,1428,1427,3542,3543,3554
,3553
1735,1427,1428,1450,1449,3553,3554,3565
,3564
*ELGEN
1731,2,1,5
1732,2,1,5
1733,2,1,5
1734,2,1,5
1735,2,1,5
**
*ELEMENT, TYPE=C3D8, ELSET=pl4
1741,1341,1342,1364,1363,3511,3601,3602
,3522
1742,1363,1364,1386,1385,3522,3602,3603
,3533
1743,1385,1386,1408,1407,3533,3603,3604
,3544
1744,1407,1408,1430,1429,3544,3604,3605
,3555
1745,1429,1430,1452,1451,3555,3605,3606
,3566
**
**  %% GENERATING ADDITIONAL
ELEMENT SETS %%
**
*ELSET, ELSET=traf_bar, GENERATE
1,1050,1
*ELSET, ELSET=Hreinf, GENERATE
1,21,1
85,105,1
211,231,1
295,315,1
610,630,1
925,945,1
*ELSET, ELSET=UHreinf, GENERATE
841,861,1
526,546,1
*ELSET, ELSET=Vreinf, GENERATE
1,946,105
85,1030,105
3,948,105
87,1032,105
5,950,105
89,1034,105
7,952,105
91,1036,105
9,954,105
93,1038,105
11,956,105
95,1040,105
13,958,105
97,1042,105
15,960,105
99,1044,105
17,962,105
101,1046,105
19,964,105
103,1048,105
21,966,105
105,1050,105
*ELSET, ELSET=posts, GENERATE
1101,1299,1
*ELSET, ELSET=panels, GENERATE
1300,1700,1
*ELSET, ELSET=Aplate, GENERATE
1701,1750,1
*ELSET, ELSET=bottom, GENERATE
1,105,1
*ELSET, ELSET=webs, GENERATE
1251,1284,3
1252,1285,3
1253,1286,3
*ELSET, ELSET=momt, GENERATE
1101,1101,1
********************************
**  DEFINE MATERIAL PROPERTIES
AND ASSIGNING SECTIONS
*********************************
```

```
**
**  @@ TRAFFIC BARRIER @@
**  @@ CONCRETE WITH CRUSHING
AND CRACKING CAPABILITIES @@
**
*SOLID SECTION, ELSET=traf_bar,
MATERIAL=conc2
*MATERIAL, NAME=conc
*ELASTIC
3.6e6,0.15
*DENSITY
2.17164e-4
*CONCRETE
2000.,0.
3000.,0.001
4000.,0.0015
4100.,0.0035
*FAILURE RATIOS
1.16,0.1185,1.28,0.5
*TENSION STIFFENING
1.,0.
0.,2.0e-3
*SHEAR RETENTION
0.5,.003
**
**  @@ NOISE WALL PANELS AND
POINT LOADED REGIONS @@
**  @@ CONCRETE WITHOUT
CRUSHING OR CRACKING
CAPABILITIES @@
**
*SOLID SECTION, ELSET=panels,
MATERIAL=conc2
*MATERIAL, NAME=conc2
*ELASTIC
3.6e6,0.15
*DENSITY
2.17164e-4
**
**  @@ FOUNDATION BEAM
ELEMENTS @@
**  @@ USER DEFINED - STEEL
PROPERTIES @@
**    (Area, I11, I12, I22, J); cosines; (E,G)
**
*BEAM SECTION, ELSET=fo2,
SECTION=CIRC, MATERIAL=steel2
0.22097
1.0,0,0
**
*BEAM SECTION, ELSET=fo,
SECTION=CIRC, MATERIAL=steel2
0.3125
1.0,0,0
**
**  @@ REINFORCEMENT IN TRAFFIC
BARRIER AND NOISE WALL POSTS
@@
**  @@ STEEL @@
**
*REBAR, ELEMENT=CONTINUUM,
MATERIAL=steel2, SINGLE,
NAME=Hbars
Hreinf,0.20,0.5,0.5,1
*REBAR, ELEMENT=CONTINUUM,
MATERIAL=steel2, SINGLE,
NAME=UHbars
UHreinf,0.20,.9,0.5,1
*REBAR, ELEMENT=CONTINUUM,
MATERIAL=steel2, SINGLE,
NAME=Vbars
Vreinf,0.20,0.5,0.5,3
*MATERIAL, NAME=steel2
*ELASTIC
29.0e6
*DENSITY
7.3386e-4
*PLASTIC
40.0e3,0.
50.0e3,0.01
**
*SHELL SECTION, ELSET=flanges,
MATERIAL=steel
0.625
*SHELL SECTION, ELSET=webs,
MATERIAL=steel
0.125
*SHELL SECTION, ELSET=webs2,
MATERIAL=steel
0.250
*MATERIAL, NAME=steel
*ELASTIC
29.0e6
*DENSITY
7.3386e-4
*PLASTIC
```

```
36.0e3,0.
37.0e3,0.01
**
**  @@ BASE PLATE LINEAR STEEL
WITH NO FAILURE CRITERIA @@
**  @@ STEEL 2 @@
*SOLID SECTION, ELSET=Aplate,
MATERIAL=steel3
*MATERIAL, NAME=steel3
*ELASTIC
29.0e6
*DENSITY
7.3386e-4
********************************
**  %% DEFINING CONTACT
SURFACES BETWEEN PAVEMENT
AND TRAFFIC BARRIER %%
*********************************
*NODE
1701,-5.0,-5.0,-0.001
1702,125.0,-5.0,-0.0001
1703,-5.0,22.0,-0.001
1704,125.0,22.0,-0.001
*ELEMENT, TYPE=R3D4, ELSET=PAVE
1750,1701,1702,1704,1703
*RIGID BODY, ELSET=pave, REF
NODE=1704
*BOUNDARY
1704,ENCASTRE
*SURFACE DEFINITION,
NAME=SLAVE
bottom,s1
*SURFACE DEFINITION,
NAME=MASTER
PAVE,SPOS
*CONTACT PAIR, SMALL SLIDING,
INTERACTION=PAVEMENT
slave,master
*INTERFACE, ELSET=PAVE,
NAME=PAVEMENT
** *SURFACE INTERACTION,
NAME=PAVEMENT
*FRICTION
0.8
**********************************
**  %% SETTING COUPLES FOR NOISE
WALL PANELS AND POSTS %%
**********************************
```

```
*MPC
** Post to Traffic Barrier Connections  **
TIE,2001,3512
TIE,2002,3545
TIE,2003,3513
TIE,2004,3546
TIE,2005,3516
TIE,2006,3549
TIE,2007,3517
TIE,2008,3550
TIE,2009,3518
TIE,2010,3551
TIE,2011,3521
TIE,2012,3554
TIE,2013,3522
TIE,2014,3555
***  Panel to Post Connections  ***
PIN,2501,3512
PIN,2502,3545
PIN,2521,3517
PIN,2522,3550
PIN,3001,3517
PIN,3002,3550
PIN,3021,3522
PIN,3022,3555
PIN,2523,2015
PIN,2545,2029
PIN,2567,2043
PIN,2589,2043
PIN,2611,2057
PIN,2633,2071
PIN,2655,2085
PIN,2677,2085
PIN,2699,2099
PIN,2721,2113
PIN,2743,2127
PIN,2765,2127
PIN,2524,2016
PIN,2546,2030
PIN,2568,2044
PIN,2590,2044
PIN,2612,2058
PIN,2634,2072
PIN,2656,2086
PIN,2678,2086
PIN,2700,2100
PIN,2722,2114
PIN,2744,2128
```

```
PIN,2766,2128
PIN,2543,2021
PIN,2565,2035
PIN,2587,2049
PIN,2609,2049
PIN,2631,2063
PIN,2653,2077
PIN,2675,2091
PIN,2697,2091
PIN,2719,2105
PIN,2741,2119
PIN,2763,2133
PIN,2785,2133
PIN,2544,2022
PIN,2566,2036
PIN,2588,2050
PIN,2610,2050
PIN,2632,2064
PIN,2654,2078
PIN,2676,2092
PIN,2698,2092
PIN,2720,2106
PIN,2742,2120
PIN,2764,2134
PIN,2786,2134
PIN,3023,2021
PIN,3045,2035
PIN,3067,2049
PIN,3089,2049
PIN,3111,2063
PIN,3133,2077
PIN,3155,2091
PIN,3177,2091
PIN,3199,2105
PIN,3221,2119
PIN,3243,2133
PIN,3265,2133
PIN,3024,2022
PIN,3046,2036
PIN,3068,2050
PIN,3090,2050
PIN,3112,2064
PIN,3134,2078
PIN,3156,2092
PIN,3178,2092
PIN,3200,2106
PIN,3222,2120
PIN,3244,2134
PIN,3266,2134
PIN,3043,2027
PIN,3065,2041
PIN,3087,2055
PIN,3109,2055
PIN,3131,2069
PIN,3153,2083
PIN,3175,2097
PIN,3197,2097
PIN,3219,2111
PIN,3241,2125
PIN,3263,2139
PIN,3285,2139
PIN,3044,2028
PIN,3066,2042
PIN,3088,2056
PIN,3110,2056
PIN,3132,2070
PIN,3154,2084
PIN,3176,2098
PIN,3198,2098
PIN,3220,2112
PIN,3242,2126
PIN,3264,2140
PIN,3286,2140
**********************************
**  %% SPECIFYING GLOBAL
BOUNDARY CONSTRAINTS %%
**********************************
*BOUNDARY
Constr,PINNED
found,PINNED
left,XSYMM
web,xsymm
*********************************
**  %% SPECIFY LOADINGS %%
**  (type of vehicle, degree of impact, speed
of impact)
*****************************
*AMPLITUDE,
DEFINITION=TABULAR,
NAME=car1560
** VEHICLE MASS OF 2083 SLUGS
0.000,0.0000,0.005,0.0083,0.010,0.1062,0.0
15,0.0625
0.020,0.0729,0.025,0.0479,0.030,0.0854,0.0
35,0.0666
```

```
0.040,0.1083,0.045,0.0312,0.050,0.0312,0.0
55,0.0666
0.060,0.0625,0.070,0.0687,0.075,0.0010,0.0
80,0.0013
0.085,0.1458,0.090,0.1604,0.095,0.1333,0.1
00,0.1250
0.105,0.1791,0.110,0.1250,0.115,0.1146,0.1
35,0.1146
0.140,0.2020,0.145,0.1625,0.150,0.1750,0.2
00,0.0000
1.000,0.0000
*AMPLITUDE,
DEFINITION=TABULAR,
NAME=trk2045
0.000,0.0000,0.050,0.1500,0.080,0.2350,0.1
20,0.2350
0.150,0.1000,0.175,0.0500,0.225,0.0500,0.2
50,0.2000
0.270,0.3000,0.275,0.3200,0.280,0.3000,0.3
00,0.2000
0.325,0.0500,0.400,0.0200,0.500,0.0000,2.0
00,0.0000
*AMPLITUDE,
DEFINITION=TABULAR,
NAME=trk2064
0.000,0.0000,0.040,0.2000,0.060,0.4000,0.0
80,0.5000
0.100,0.4350,0.120,0.2800,0.140,0.1500,0.1
60,0.1500
0.180,0.3250,0.200,0.4750,0.220,0.4000,0.2
40,0.1000
0.260,0.0500,0.280,0.0400,0.400,0.0000,2.0
00,0.0000
*AMPLITUDE,
DEFINITION=TABULAR,
NAME=Htrk1752
0.000,0.0000,0.050,0.4000,0.070,0.6100,0.1
00,0.4000
0.110,0.3500,0.130,0.3600,0.150,0.4000,0.1
60,0.4000
0.220,0.3700,0.275,0.4000,0.300,0.8500,0.3
10,0.9000
0.350,0.2000,0.370,0.0700,0.400,0.0000,2.0
00,0.0000
*AMPLITUDE,DEFINITION=TABULAR,
NAME=car1560
0.000,0.0000,0.070,0.4000,0.100,0.3500,0.1
80,0.8000
0.200,1.2000,0.220,1.5000,0.250,1.2000,0.2
70,0.6000
0.300,0.4200,0.400,0.2000,0.600,0.0300,0.7
00,0.2000
0.750,0.6000,0.800,0.6000,0.860,0.2000,0.9
00,0.0000
2.000,0.0000
*AMPLITUDE,DEFINITION=TABULAR,
NAME=bus1558
0.000,0.0000,0.100,1.0000,0.150,1.0000,0.2
25,0.1000
0.250,0.1000,0.300,0.2000,0.310,0.5000,0.3
50,3.8500
0.370,3.5000,0.400,0.5000,0.420,0.0000,1.0
00,0.0000
**
**  @@ APPLY DYNAMIC LOADING
**
*STEP, INC=100
*DYNAMIC, INITIAL=NO, ALPHA=-
0.05, haftol=200000.0
0.005,0.40,1.0e-5,0.015
**
*DLOAD, AMPLITUDE=trk2064
715,P5,2105.3
716,P5,2105.3
*CONTROLS,
ANALYSIS=DISCONTINUOUS
**************************************
**  @@ SPECIFY OUTPUT OPTIONS
**************************************
*MONITOR, NODE=903, DOF=2
*NODE PRINT, FREQUENCY=1,
NSET=displ
U
*EL PRINT, FREQUENCY=1, ELSET=fo2
S
*EL PRINT, FREQUENCY=1,
ELSET=momt
S
*CONTACT PRINT, FREQUENCY=10
*RESTART, WRITE, FREQUENCY=1
*END STEP
```

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