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16. Abstract

The current TxDOT design process for highway noise barriers is reviewed. Design requirements for highway noise barriers are then presented. These include acoustical requirements, structural requirements, safety requirements, aesthetic requirements, and cost considerations. Examples are given of different highway noise barriers used in Texas. Sample plans and specifications are presented. Design requirements are broadly grouped into acoustical requirements, environmental requirements, traffic safety requirements, and structural requirements; those requirements are again presented, drawing on the material presented in the preceding chapters.

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DESIGN GUIDE FOR HIGHWAY NOISE BARRIERS

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Research Report 0-1471-4

Research Project 0-1471
Effective Noise Barrier Solutions for TxDOT

conducted for the
Texas Department of Transportation
in cooperation with the
U. S. Department of Transportation
Federal Highway Administration
by the
Center For Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

November 2003

Implementation Statement

This design guide is intended to provide Texas Department of Transportation (TxDOT) designers with background information, specific design procedures, and sample plans and specifications for the design of highway sound walls. TxDOT personnel should use the design procedures recommended in this Guide.

Disclaimer

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Table of Contents

List of Figures

List of Tables

Preface

When Study 1471 began almost 10 years ago, it was intended to provide general and specific information to TxDOT personnel regarding almost all aspects of noise barriers:

- background on acoustics and acoustical functioning of noise barriers;
- background on environmental criteria ("triggers") for noise barriers;
- background on existing noise barriers in Texas;
- background on structural performance of noise barriers;
- background on aesthetic criteria for noise barriers;
- examples of structural designs and specifications for noise barriers;
- examples of performance criteria for proprietary noise-barrier systems; and
- software that would help neighborhoods understand the visual and acoustical effects of hypothetical noise barriers.

Over the first four years of Study 1471's existence, its deliverables were expanded even more, to include a study of parallel-barrier reflection. Researchers proposed that the study deliverables be packaged in separate binders, each dealing with different aspects of the study. In that format, three study reports were published by TxDOT. The process of finishing the fourth and final report, and its associated summary report, encountered unexpected challenges. In the remainder of this Preface, those challenges are discussed, presented, along with the ways in which they were resolved.

Challenge 1:

Over the course of Study 1471, unforeseen events outside of TxDOT overtook and in some ways superseded the original deliverables of that project. For example, in February 2000, FHWA published a comprehensive handbook[1] on the design of highway noise barriers. That handbook contains comprehensive background material on acoustics and the acoustical functioning of highway noise barriers, and also some background on aesthetics. In the authors' opinion, the treatment in that handbook is excellent, and supersedes many of the needs envisaged by TxDOT for that deliverable from Study 1471. Although the visualization software developed by Study 1471 would have met needs not addressed by the

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[1] Knauer, H. S., Pedersen, S., Lee, C. S. Y. and Fleming, G. G., *FHWA Highway Noise Barrier Design Handbook* (Report No. FHWA-EP-00-005), US Department of Transportation, Federal Highway Administration, Washington, DC, February 2000.

FHWA handbook, that software was probably not sufficiently user-friendly to be useful to TxDOT on a day-to-day basis.

Challenge 2:

Over the course of Study 1471's existence, evolution of TxDOT policies and associated TxDOT publications led to other ways of addressing many of the areas originally intended to be addressed by Study 1471 deliverables. Some examples are as follows:

a) Evolution of TxDOT policy. The Environmental Affairs Division of TxDOT took a more active role in the development, maintenance and promulgation of criteria (triggers) for highway noise barriers. That group has published its "Guidelines," which reflect official TxDOT policy[2]. It is clearly not in TxDOT's interest to have another publication (for example, a Study 1471 deliverable) that differs, even in the slightest detail, from those "Guidelines." For that reason, the need envisaged by TxDOT for that deliverable from Study 1471 no longer exists.

b) Evolution of combined TxDOT and FHWA policies. For historical reasons, TxDOT has built in the past some types of sound walls (such as those mounted on traffic barriers) that would probably not be their design choices today. The existence of such walls led to the inclusion, in draft deliverables for Study 1471, of the performance of mounted barriers, including structural performance under vehicular impact. In the meantime, TxDOT's Design Division and the FHWA had determined independently that barrier-mounted noise barriers were much less viable than other solutions (damage-resistant lower sections on existing sound walls, or placement of noise barriers behind vehicular barriers). The evolution of FHWA requirements for crash-testing of barriers also made moot a discussion of structural design criteria for vehicular impact on sound walls, since performance under impact would have to be verified by crash testing in any event. As a result, much of the material developed by Study 1471 dealing with vehicular impact would not be useful to TxDOT designers today, could be misinterpreted by those unfamiliar with FHWA criteria, and would not be a useful to include in a Study 1471 deliverable now.

Challenge 3:

Over the course of Study 1471's existence, unforeseen changes occurred in the professional affiliations of some Study 1471 researchers. Dr. Michael McNerney left the Center for Transportation Research for a position in the Dallas area; Prof. Irene Busch-Vishniac left The University of Texas at Austin to become Dean of Engineering at the Johns Hopkins University; and other project-specific researchers have graduated or moved on.

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[2] *Guidelines for Analysis and Abatement of Highway Traffic Noise*, Texas Department of Transportation, June 1996 (Change 1, July 1997.

In response to these challenges, the researchers of Study 1471 and related TxDOT personnel have agreed to take the following steps:

- o to take those deliverables in Study 1471 that are still relevant, still consistent with TxDOT policy, and still useful to TxDOT personnel, to augment those deliverables appropriately, and to package those deliverables in a useful format as Report 1471-4.

- o to publish Report 1471-S as a summary of the most important deliverables from Study 1471, plus a positively worded summary of the evolution of that study from its inception to its present conclusion.

This final report is the first of those steps.

CHAPTER 1
THE TXDOT DESIGN PROCESS FOR HIGHWAY NOISE BARRIERS

Introduction

Highway noise barriers (sometimes referred to as “noise walls” or “sound walls”) are intended to mitigate the effects of highway noise on activities near the highway. They do this primarily by blocking the direct path that sound must travel between the source of sound on the highway and the receiver exposed to the sound. The terms *noise barrier* and *sound wall* are used nearly interchangeably in this report. Noise barriers are designed for acoustic performance; they need not specifically be walls. Walls are designed structurally to withstand their design loads.

The Federal Highway Administration (FHWA) has recently published a comprehensive *Design Handbook* for traffic noise barriers (FHWA 2000). This report was originally developed prior to that *FHWA Design Handbook,* and has been updated and reformatted to complement the FHWA document. This report is intended to guide the designer of noise barrier walls in Texas, and to provide a catalog of experience on which TxDOT district offices can rely. Much of the information on structural design in this report is practical guidance for design engineers.

Basic Types of Noise Barriers

Many different noise barrier systems are used in Texas. In Chapter 7, these are described more completely. Because highway noise barriers that are distinct in appearance may actually be quite similar in function, it is useful to classify them. This classification is neither definitive nor unique, and is adopted primarily for convenience. For purposes of this design guide, noise barrier systems used in Texas are classified as follows:

- prefabricated, integral post-and-panel system
- constructed-in-place post-and-panel system
- fan-wall system
- earth berms
- prefabricated, barrier-mounted, post-and-panel system
- prefabricated, sloped-face wall system

Current TxDOT policy is that all highway noise barriers located within the clear zone must be protected by a separate traffic barrier. If the noise barrier is integrated with the traffic barrier, it is required to resist vehicular impact. To meet FHWA guidelines, all such barriers must be crash-tested. In practical terms, the most effective way to meet these requirements is to put a crash-tested vehicle impact barrier in front of the noise barrier. Then the noise barrier itself would not have to be designed for vehicular impact.

In the past, some highway noise barriers have been integrated with vehicular barriers. One example of this is the prefabricated, barrier-mounted, post-and-panel system that was developed and constructed in the Fort Worth District (TxDOT 1996). In later sections of this report, that design is discussed. According to current TxDOT policy, that barrier is no longer recommended. This is an example of how the design of noise barriers must be integrated with the design of other related highway elements.

TxDOT Policy Issues for Noise Barriers

TxDOT policy regarding highway noise barriers is discussed in the Department's Guidelines for Analysis and Abatement of Highway Traffic Noise (TxDOT 1996), and is not repeated here.

TxDOT Noise Barrier Design Process

Because each District Office has the authority to implement the design of noise barriers as the District Engineer decides, a summary of the TxDOT experience was collected for this design guide. Telephone interviews were conducted with the Texas Department of Transportation (TxDOT) district personnel regarding their experience with sound-wall design. This chapter summarizes and presents the information gathered from those interviews.

Interviews with TxDOT District Personnel

The primary objective of the telephone interviews was to assist the research team in evaluating the current processes used in sound wall design throughout the state of Texas. Because 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 phone interviews were conducted with structural engineers from five districts that currently have designed and constructed at least one sound wall. These five districts were the Dallas, Fort Worth, Austin, San Antonio, and Houston districts. 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 of these three topics.

Structural 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 American Association of State Highway and Transportation Officials (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)
- Load and resistance factor design (LRFD) manual (AISC 1992), American Concrete Institute (ACI) 318 (ACI 1995), and other material codes
- Other applicable codes such as the Structural Welding Code (AWS 1981)

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. While the proprietary designers and contractors involved in the construction of these walls were ultimately responsible for the design, 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.

Factors Influencing Design of Sound Walls

Design of a sound wall begins with the determination of its height and location relative to the roadway. These parameters are dictated by acoustical requirements, and are 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 the following factors: aesthetics, cost, maintenance, local influences, and structural constraints. Cost, although important, was not the controlling factor for most designs. In Austin and San Antonio, aesthetic considerations controlled. In Houston, local influences suggested that the sound walls be of concrete, the primary building material for the region. Overall, the primary factors determining 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.

Currently, four of the five Texas districts polled have no personnel assigned specifically to the design of sound walls. Houston has had the most experience with sound walls and had assigned a permanent staff member (Marc Anthony) to study sound walls and prepare plans for them. Most projects are handled by the special project department and are usually a cooperative effort between the environment and structural engineering departments.

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.

Special Details for Sound Walls

Provisions for Doors in Sound Walls

In one location in San Antonio, a metal door was installed 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.

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 at one time used sound walls mounted on T501 barriers, and designed only the T501 barrier for vehicular impact. This type of mounted sound wall is no longer recommended, however. In Dallas, the structural engineer imposed extra live and dead load in an attempt to account for impact, although no formal requirements were specified. While some districts prefer to strengthen the lower portions of sound barriers to improve durability, these barriers should never be placed inside the clear zone in lieu of a traffic barrier. For liability reasons, the language on a standard detail for a sound wall should never imply that the sound wall is designed as a traffic barrier. Noise barriers designed for vehicular impact typically must be crash-tested in accordance with NCHRP 350, Test Level 3, to gain FHWA acceptance (NCHRP 1993; FHWA 1996b).

Drainage, Flood Control

In many districts, drainage and flood control were not critical. Most districts provided drainage holes or riprap 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.

Foundations of Sound Walls

In most cases, drilled-shaft foundations were used. Some exceptions were noted. For a masonry sound wall in Austin, buried utilities dictated shallow foundations, and a spread footing was selected for a free-standing fan wall.

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 four 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 of those sound walls were repaired by replacing the damaged panels. No post-impact effects remain (such as post tilting or cracking in adjacent panels).

CHAPTER 2
ACOUSTICAL CONSIDERATIONS IN NOISE-BARRIER DESIGN

Definition of Acoustical Terms and Principles

Measurements of Noise

Sound is a wave. It exerts pressure on the human eardrum and on noise-measuring instruments. Sound intensity is proportional to the square of the pressure. Levels of sound (noise) are measured in decibels (dB), a logarithmic measure of sound intensity. Small changes in dB levels imply large changes in actual sound intensity. Noise levels expressed in dBA are weighted so that sound levels are more important if they are at frequencies to which the human ear is more sensitive. Different dBA levels are described in Table 2.1.

TABLE 2.1 TYPICAL BACKGROUND NOISE LEVELS

Situation	Associated Noise Level (dBA)
Recording Studio	20–30
Quiet Room	45
Typical Library	50–55
Typical Speech Range	55–70
Air Compressor at 50 feet	80
Tractor-Trailer Traveling at 60 MPH at 50 feet	90
Jackhammer (at Operator's Ear)	100

Highway noise levels vary over time. To describe them in terms of a single number, the concept of *equivalent sound level* (L_q) has been developed. L_{eq} is the constant sound level that contains the same average acoustic energy as the original time-varying sound level.

How Noise Barriers Work

Basically, noise barriers reduce the sound level reaching receivers by blocking the straight-line path from the source to the receiver. While the perceived noise does not disappear, it is significantly reduced. By blocking the straight-line path even slightly, the noise barrier attenuates (reduces) the sound level at the receiver by about 5 dB. This attenuation is roughly equivalent to reducing the source noise by a factor of three (one-third the traffic). Making the barrier even higher, so that the sound is forced to travel along a longer path, usually produces an additional attenuation of at least 3 dB. The combined effect (a noise attenuation of 8 dB) is roughly equivalent to reducing the traffic by a factor of 6.

Definition of Transmission Loss

The transmission loss associated with a barrier is the amount by which the sound is reduced when it is forced to travel through the barrier. A 30-dB transmission loss means that practically all (99.9%) of the sound is being blocked. The required thickness in inches for a 30-dB transmission loss at 100 Hz is given in Table 2.2.

TABLE 2.2 REQUIRED THICKNESS IN INCHES FOR 30-DB TRANSMISSION LOSS

Material	Thickness in inches for 30-dB Transmission Loss at 100 Hz
Steel	0.21
Concrete or Masonry	0.63
Plastic	1.81
Wood	3.66

Definition of Insertion Loss

Assuming that it is thick enough to practically stop all of the sound going through it, a noise barrier blocks sound by forcing it to travel a longer path over or around the barrier. The loss of sound is termed *insertion loss*. Insertion loss is therefore the difference between the sound level if no barrier were present, and the sound level that results when a barrier is inserted between the receiver and the noise source

Effect of Different Levels of Insertion Loss

On a rule-of-thumb basis, different levels of insertion loss have the effects shown in Table 2.3.

TABLE 2.3 EFFECTS OF DIFFERENT LEVELS OF INSERTION LOSS

Decrease in dBA Level	Corresponding Ratio of Sound Intensity	Corresponding Ratio of Perceived Loudness	Notes
10 dB	One-Tenth	Half	One-Tenth Times Traffic Volume
6 dB	One-Fourth	–	Double Distance to Point Source
4 dB	–	–	Double Distance to Traffic (Including Reflection)
3 dB	One-Half	–	Half Traffic Volume
2 dB	--	--	Smallest Perceptible Difference

Properties of Sound

To fully appreciate how highway noise barriers attenuate sound, it is necessary to understand some attributes of sound. Sound is typically characterized in terms of two main properties: frequency and intensity. The *frequency* of a sound is the objective measure of its *pitch* (subjective measure). The range of human hearing is about 20 Hz to 20,000 Hz. Cars produce noise in the range of 20 to 2,000 Hz. Trucks produce noise in the range of 10 to 1,000 Hz. In both cases, the typical sound has a broad peak at about 125 Hz, but this number is misleading because the ability of humans to hear sounds is not uniform throughout the audible frequency range. As a result of the skewing of the sound by our hearing system, typical car and truck noise has a broad perceptual peak at about 500 Hz. Because speech is concentrated from about 300 to 3,300 Hz, car and truck noise is quite effective at intruding on speech, a fact of which we are all painfully aware.

The *intensity* of a sound is the objective measure of its *loudness* (subjective measure). Intensity is a measure of the sound energy. Humans have an ability to perceive a wide range of sound intensities. Indeed, our hearing range is significantly broader than that of any of our other senses. Partly because of this, we use a logarithmic scale for intensity. The specific scale employed is the decibel or dB, named after Alexander Graham Bell. It is defined as $dB = 10 \log_{10}(W/W_{ref})$, where W is the sound power or a quantity proportional to energy (such as intensity or pressure squared), and W_{ref} is a reference sound power (or intensity or pressure squared) defined as the standard for comparison. The dB measure is termed a *level.* If the quantity used is energy, the result is the sound energy level; if the quantity in the logarithm is intensity, it is the sound intensity level; if the quantity is pressure squared, the result is the sound pressure level.

Given this definition, a doubling in the intensity of a sound corresponds to an increase of 3 dB in the sound level. We do not generally perceive a doubling of intensity as a doubling in loudness, however. The general rule of thumb is that a doubling of loudness (in the speech range) corresponds to a 10-dB increase in intensity; that is, to an increase in the energy by an order of magnitude. Figure 2.1 shows the sound pressure levels associated with a variety of situations and sources. The levels are presented in terms of dBA. Here the “A” indicates that “A-weighting” was used to account for the human hearing variations as a function of frequency. The dBA scale is accepted worldwide as the best predictor of human response to sound. Note that the figure shows that the range of hearing spans orders of magnitude of intensity. The federally mandated levels at which noise mitigation for residences should be considered is also shown in the figure.

An important property of sound that plays a key and essential role in noise barrier operation is called *geometrical spreading.* Geometrical spreading refers to the fact that sound, very much like light, reduces in intensity as it propagates from a source. One can determine the attenuation produced by geometrical spreading by noting that sound energy is approximately conserved as the sound spreads from the source. For a source concentrated at a point in space (a point source), such as shown in Figure 2.2, the sound spreads uniformly on the surface of a spherical wave front. The total energy of a source can be found by multiplying the intensity at a set distance from the source by the area over which that intensity is distributed. Because the surface area of a sphere increases in proportion to the square of the distance from the center, the energy is proportional to intensity at a point, multiplied by the square of the distance from the source to that point. Since total energy is conserved, doubling the distance from *d* to *2d* must result in a drop in intensity by a factor of four (6 dB). Most traffic sound sources are moving point sources. A continuous stream of such moving point sources can be idealized as a line source. Sound energy from a line source is attenuated over a cylindrical wave front and is attenuated inversely with distance. Thus, noise from real traffic sources will be attenuated by a factor between $1/d$ and $1/d^2$, where *d* is the distance from the source. Hence, for road noise sources, it is reasonable to assume that a doubling of the distance from source to receiver will result in a drop of at most 6 dB in the sound level. Geometrical spreading is one of the mechanisms by which highway noise barriers attenuate sound, by making it travel farther so that its intensity and perceived loudness drop.

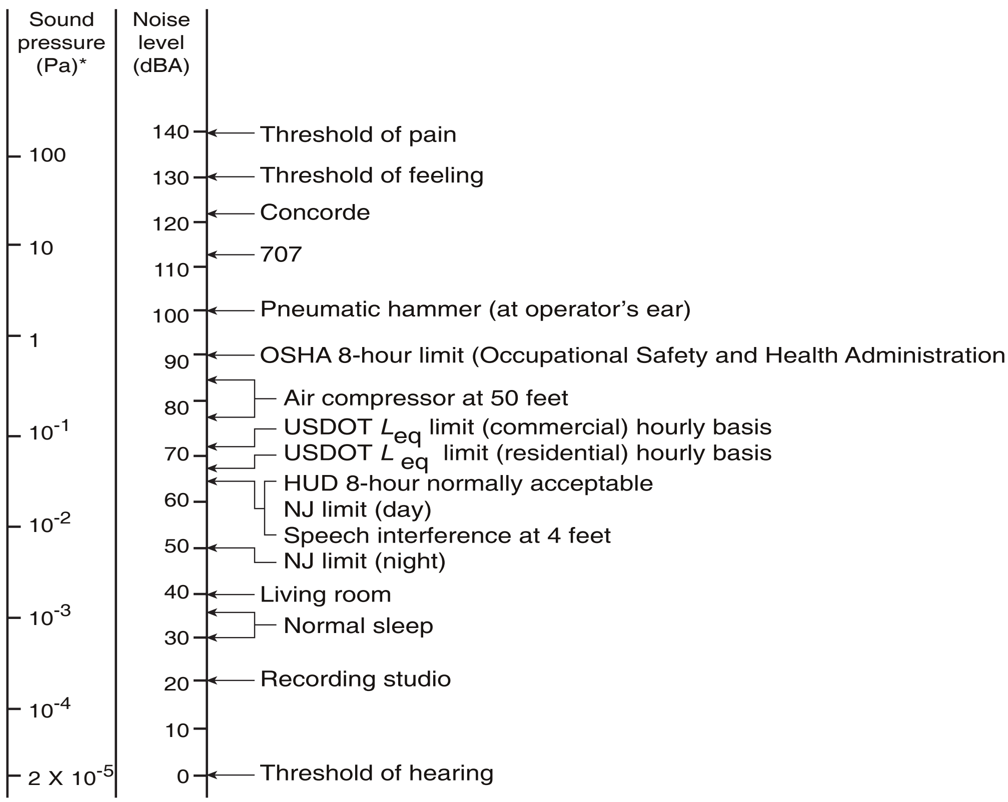

Figure 2.1 Typical sound pressure levels in dBA

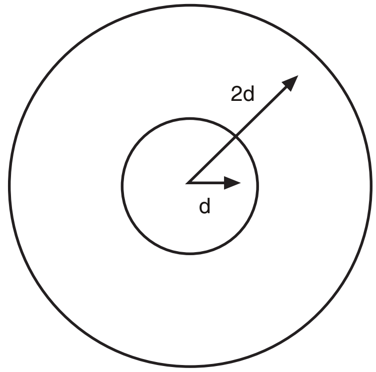

Figure 2.2 Geometrical spreading of sound from a point source

Hand Calculations of Insertion Loss

Insertion loss can be estimated by using the model proposed by Kurze and Anderson (Kurze 1971). It is the result of compiling data of many researchers onto a single plot and developing a curve fit for a point source. The equation is below and the plot is shown in Figure 2.4.

$$\begin{aligned} &\mathrm{IL} = 5dB + 20\log\left(\frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}}\right)dB \qquad \text{up to N} = 12.5 \\ &\mathrm{IL} = 20\ dB \qquad\qquad\qquad\qquad\qquad\qquad \text{for N} > 12.5 \end{aligned} \tag{2.1}$$

N is defined as the Fresnel number, a nondimensional measure of how much farther the sound must travel as a result of the barrier. It is calculated with the following equation:

$$\mathrm{N} = \frac{(a + b - \ell)f}{c_o} \tag{2.2}$$

ℓ is the original length of the direct path from source to receiver

a and b are the lengths of the two straight-line segments comprising the path as modified by the noise barrier

f is the sound frequency in Hz

c_o is the speed of sound propagation in air (approximately 1100 ft/sec)

The illustration below is used in an example calculation. The noise wall is 12 ft from the nearest tire, and is 12 ft tall. A house is 15 ft beyond the barrier and has a window at a height of 4 ft.

The length of the original direct path is :

$$\ell = 27^2 + 4^2 = 27.3\,feet$$

The lengths of the segments comprising the modified path are :

$$a = 12^2 + 12^2 = 17 \text{ feet}$$

$$\text{b} = 15^2 + 8^2 = 17 \text{ feet}$$

Hence :

$$a + b - \ell = 34 - 27.3 = 6.7\,feet$$

at f = 100 Hz, the Fresnel number is

$$N = \frac{6.7 * 100}{1100} = 0.61$$

and the insertion loss calculated from the equation is

$$\text{IL} = 5 + 20\log\frac{\sqrt{2\pi * 0.61}}{\tanh\sqrt{2\pi * 0.61}} \approx 10\,dB$$

The calculated insertion loss can be compared with the predicted value in the graph below (referred to as Eqn 19). The calculated insertion loss is close to the measured value from experimental data.

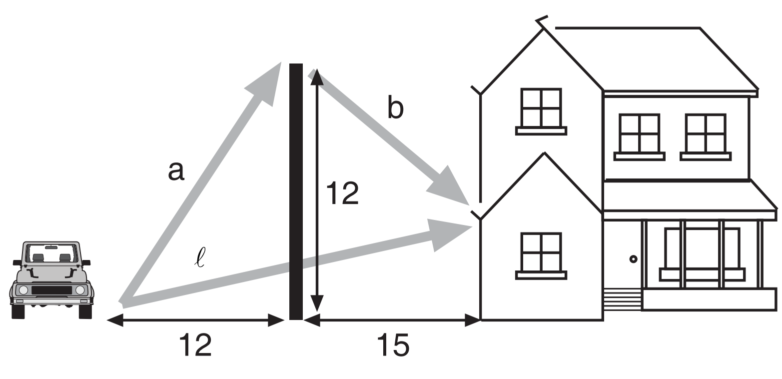

Figure 2.3 Illustration of lengthened sound path due to noise barrier

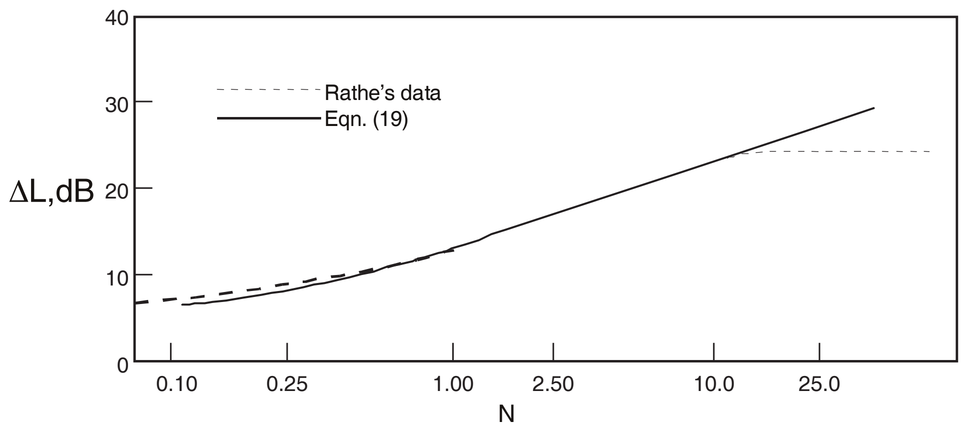

Figure2.4 Insertion loss versus Fresnel number for experimental and empirical data

While the above calculation may seem extremely simple-minded, it is precisely the computation conducted for computer-aided noise models used to predict the effectiveness of noise barriers. In those models, discussed immediately below, predicted traffic volume is used to establish the location of vehicles of various types on roadways. The major noise sources associated with each vehicle are then identified, and the noise at specified locations is determined using geometrical spreading and the barrier model above. The total noise at any location is found by simply adding the noise from each source.

Calculations of Insertion Loss Using Computer Models

Field measurements can provide very accurate sound data for the time monitored. However, unless measurements are repeated many times at each site, it is difficult to determine whether the recorded noise levels are representative. This is because environmental conditions such as wind and temperature gradients can significantly alter sound levels. Recorded noise levels also can be influenced by typical urban noises that are not traffic-related, such as aircraft flyovers, fire sirens, construction activities or even animal or insect noises. It is possible to avoid these nontraffic-related noises, but the duration of monitoring must be substantially increased and some recorded data may be invalidated.

In summary, field measurements are very costly and labor-intensive. Computer models can overcome these disadvantages. Several such models have been developed for predicting the effectiveness of highway noise barriers. Typical of these computer models are STAMINA 2.0, OPTIMA and Traffic Noise Model (TNM). STAMINA 2.0 and OPTIMA have largely been replaced by TNM. In this chapter, these models are briefly discussed. Their basic principles are reviewed, their most common applications are discussed, and their capabilities and limitations are noted.

STAMINA 2.0 and OPTIMA

STAMINA 2.0 was formerly the most commonly used model for predicting highway noise attenuation by a barrier. It was developed for the Federal Highway Administration (FHWA) by the acoustical consulting firm of Bolt, Beranek and Newman. It is designed to model up to 30 roadways, 20 barriers, and 40 receivers in a single run. It creates a data file for use by another program, called OPTIMA, which determines the most effective barrier heights and lengths for the specified geometry. As many as 8 barrier heights can be modeled in each OPTIMA run.

STAMINA is the traffic noise prediction program most commonly used by state highway agencies, including the Texas Department of Transportation (TxDOT). Many states, including Texas, have developed input modules to make STAMINA easier to use. In fact, so many input modules have been developed and widely distributed that even the FHWA does not possess any original versions of the program.

The major limitation of the STAMINA program stems from the limitations of computer hardware that prevailed at the time of its development. STAMINA was initially developed for use on mainframe computers, because those were the only ones available with the necessary computational power. Because mainframe computer time was expensive, STAMINA was written to use only a single frequency of 500 Hz for analysis of noise, rather than a 1/3-octave band analysis.

Highway traffic produces a range of noise within the human hearing spectrum from 100 to 4,000 Hz. Trucks produce a different noise-frequency spectrum than do passengers cars. As reported earlier, the attenuation of sound and the perceived annoyance of sound are frequency-dependent. The choice (for STAMINA) of the single 500-Hz frequency is a good compromise between the most dominant traffic noise frequencies, and the more-annoying, slower-attenuating, lower-frequency noise. However, a single-frequency analysis has limitations in analyzing specific situations.

Traffic volumes in STAMINA 2.0 are based on Design Hourly Volume (DHV). Usually, Level of Service C traffic volumes and associated running speeds are used to predict the worst-case scenario. From this information, STAMINA 2.0 calculates the equivalent sound pressure level, L_{eq} (the constant sound level that would deliver the same sound energy as the given time-varying signal).

The current version of STAMINA 2.0 is a single-screen model that is independent of ground impedance. It uses an incoherent line-barrier algorithm based on the work of Kurze and Anderson (Kurze 1971), and a single wall design curve for point sources from Maekawa's (1968) work. Noise attenuation is first calculated for a point source, and then expanded to a line source via integration over the barrier length.

Three types of barriers can be modeled in STAMINA 2.0: absorptive, reflective, and structural. Other factors used by the model are "alpha factors" and “shielding factors.” Alpha factors describe the effect of hard or soft ground on noise propagation from the source to the receiver. Shielding factors account for additional noise attenuation attributable to buildings, trees, or terrain features. The default alpha factor of STAMINA 2.0 corresponds to “hard ground.” When an earth berm is used, the predicted attenuation is increased by 3 dB because of these soft-ground propagation effects.

When estimating the noise attenuation by a barrier, STAMINA 2.0 uses source heights of 0 m, 0.7 m, and 2.4 m for automobiles, medium trucks, and heavy trucks, respectively.

An evaluation by Hatano indicated that STAMINA 2.0 tends to overpredict before-barrier noise levels by an average of 2.9 dBA and after-barrier noise levels by 3.8 dBA (Hendricks 1987).

The following rules of thumb are often used to check results of computer simulations:

1. If the traffic volume is doubled and the roadway geometry does not change, the noise level will increase by 3 dB. If the traffic volume is increased 10 times, the noise level will increase by 10 dB.
2. If average vehicle speed increases by 8 kph (5 mph), and the percentages of cars, medium trucks, and heavy trucks do not change, the noise level will increase by 1 dB.
3. If one traffic lane is added, the noise level will increase by 1 dB.
4. If the distance from the roadway to the receiver is doubled, the noise level will decrease by 4.5 dB for soft ground and 3 dB for hard ground. Conversely, halving the distance will increase the noise level by 3 or 4.5 dB depending on the ground hardness.

Calculations of Insertion Loss Using TNM

Traffic Noise Model (TNM)

The FHWA’s Traffic Noise Model (TNM) is a computer program intended for use in computing highway traffic noise at nearby receivers and to aid in the design of roadway noise barriers. This entirely new, Windows-based computer program uses state-of-the-art emission levels and acoustical algorithms to compute noise levels along highways. This overview, adapted from an article in the *Wall Journal* (FHWA 1996a), is intended to summarize the basic features of the program as they have been presented to the technical community.

The program’s release was originally scheduled for Spring 1996. The release actually took place in spring 1998. Because of this delay, Research Study 1471 was not able to use the program until the research was almost concluded. For much of the study, the necessary research was conducted using the program RAYVERB**,** which is computationally consistent with the model of TNM. The following explanation is relevant to RAYVERB as well as TNM.

Input to TNM

Within Windows, TNM allows digitized input using a generic Windows digitizer driver, plus the import of DXF files from CAD programs and input files from Stamina 2.0. To aid during input, TNM shows and plots the following graphical views:

- plans;
- skew sections;
- perspectives; and
- roadway profiles, which help during input of roadway Z coordinates.

These input graphics are dynamically linked to input spreadsheets, where noncoordinate input may be entered, and digitized input may be modified.

Vehicle Noise Emissions Considered by TNM

TNM includes noise sources based on 1994−1995 data for the following cruise-throttle vehicle types:

- automobiles;
- medium trucks;
- heavy trucks;
- buses; and
- motorcycles.

Noise emissions are characterized in terms of A-weighted sound levels, 1/3-octave-band spectra, and subsource-height strengths for three pavement types:

- dense-graded asphaltic concrete (DGAC);
- Portland-cement concrete (PCC); and
- open-graded asphaltic concrete (OGAC).

The FHWA-required analysis is only permitted to use the composite pavement, however, which is the default setting of the average of the three different pavement types.

In addition, TNM addresses noise emissions for vehicles on upgrades and vehicles accelerating away from traffic-control devices:

- stop signs;
- toll booths;
- traffic signals; and
- on-ramp startpoints.

TNM combines these noise emissions with its internal speed computations to account for the full effect (noise emissions plus speed) of roadway grades and traffic-control devices.

TNM also allows user-defined vehicles. For each, the user enters three measured parameters for A-level emissions as a function of speed (cruise throttle, average pavement).

To document input, TNM plots its input graphics and the following input tables:

- roadways;
- traffic for TNM vehicles;
- traffic for user-defined vehicles;
- receivers;
- barriers;
- building rows;
- terrain lines;
- ground zones;
- tree zones;
- noise contour zones;
- receiver adjustment factors;
- structure barriers; and
- barriers with important reflections.

Calculation and Sound Propagation in TNM

TNM calculates the propagation of sound energy, in 1/3-octave bands between roadways and receivers. Calculation of sound propagation takes the following factors into account:

- divergence;
- atmospheric absorption;
- intervening ground (acoustical characteristics and topography);
- intervening barriers (walls, berms, and combinations or sequences thereof) intervening areas of dense trees and undergrowth.

TNM computes the effect of intervening ground (defined by its type, or optionally, by its flow resistivity) using acoustical theory calibrated against field measurements. In addition, TNM allows sound to propagate underneath selected intervening roadways and barriers, rather than being blocked by them. TNM also computes single reflections from vertical wall barriers, with user-selected Noise Reduction Coefficients.

Noise-Barrier Design Using TNM

During calculation, TNM varies the height of proposed barriers above and below the input height in order to calculate the effect of perturbations in barrier height. During the barrier-design phase, using selected receivers, TNM dynamically displays sound-level results for any combination of height perturbations selected by the designer. TNM also contains an input-height check, to determine if noise barriers break the lines of sight between sources and receivers.

Output from TNM

TNM produces the following output tables:

- sound levels;
- diagnosis by barrier segment;
- diagnosis by vehicle type;
- barrier descriptions (including cost/benefit information); and
- barrier segment descriptions.

Each of these tables is dynamically linked to TNM's barrier-design perspective so that tabulated results change dynamically as the user modifies the heights of barrier segments.

TNM computes three measures of highway traffic noise:

- L_{aeq1h} (hourly, A-weighted equivalent sound level);
- L_{dn} (day-night average sound level); and
- L_{den} (Community Noise Exposure Level, where "den" means "day/evening/night").

TNM computes these three noise measures at user-defined receiver locations. In addition, it computes three types of contours:

- sound-level contours;
- insertion-loss contours for noise barriers; and
- level-difference contours between any two noise-barrier designs.

How TNM Considers Effects of Insertion-Loss Degradation Due to Parallel Barriers

For selected cross sections, TNM also computes the effects of multiple reflections between parallel barriers or retaining walls flanking a roadway. The resulting parallel-barrier degradations are entered as adjustment factors for individual receivers in TNM's full set of calculations.

To document parallel-barrier input and results, TNM produces the following parallel-barrier tables:

- roadways for TNM vehicles;
- roadways for user-defined vehicles;
- cross section; and
- analysis locations (including results).

Absorptive Materials and Highway Noise Barriers

Potential Advantages of Absorptive Materials

The purported advantages of using sound-absorptive material on noise barrier surfaces are (*Wall Journal*, 1996):

1. Reflected noise is reduced or eliminated. In situations involving a single noise barrier, unprotected residences (or other locations of interest on the opposite side of the highway) experience less of an increase in noise levels. In situations involving parallel noise barriers (one on each side of the highway), each of the noise barriers' performance is degraded less by the presence of the other barrier.
2. Receivers behind a noise barrier lined with absorptive material on the highway side are minimally benefited by a further reduction in noise.The reduction, however, is usually less than 1 dBA.

Potential Disadvantages of Absorptive Materials

The primary disadvantage of absorptive materials is their additional cost compared to conventional materials. For highway noise barriers, the improved insertion loss is minimal and does not warrant the additional expense of absorptive materials. Sound-absorptive materials should be considered only when it can be shown through accepted modeling techniques, calibrated by reliable noise measurements, that noise reflections are a legitimate problem.

Further Comments Regarding Absorptive Materials

Ideally, an absorptive barrier would absorb all the sound incident on it. If this were the case, the receiver would hear only the smaller amount of incident sound diffracted over the top of the barrier. The far barrier that used to reflect the sound and cause it to diffract over the top of the near barrier would theoretically absorb all the sound incident on it, and the effectiveness of the two parallel barriers would be the same as a single barrier. Unfortunately, ideal absorptive barriers do not exist, and some residual noise reflects off the far barrier and diffract over the top of the near barrier, entering the residential area. Nevertheless, the overall resultant noise level should be less for absorptive barriers than reflective ones (Watts 1996). Full-scale tests by Watts confirm these ideas. He found that for a point source, the absorptive barrier "effectively eliminated the degradation since the measured increase in mean level was only 0.3 dB. The expected increase for a line source was calculated to be slightly higher at 0.5 dB" (Watts 1996).

Given these results, however, one would think that making the barriers absorptive would be a simple solution to the multiple-reflection problem. Doing so has complications, however, both in performance and in cost. Because many sound-absorbing materials function by "forcing air molecules to move in and around many tiny fibers or passages," many of them are porous (Menge 1980). In experiments by Lane (1989), porous concrete, an effective sound absorber at the typical frequency range of highway traffic noise, was tested for freeze-thaw resistance. Repeated freeze-thaw cycles resulted in a substantial loss of mass and deterioration of the surface, making porous concrete unsuitable for use in absorptive barriers in environments where they would have to endure freeze-thaw cycles (Lane 1989). In addition, absorptive barriers can be very expensive to manufacture (Menge 1978).

Characteristics of Common Barrier Materials

Highway noise barriers are made of many different materials. In this section, those materials are reviewed with particular emphasis on the specifications commonly used to identify them and prescribe their quality. Previous work by the University of Louisville (HITEC 1996) proposes the evaluation criteria summarized here. Those criteria are not intended to be all-inclusive. The information given below is proposed as a basis for TxDOT and its own materials-evaluation personnel's use in developing appropriate criteria.

In addition to meeting materials standards, noise barriers of each material must meet the requirements of the appropriate structural design code. Those requirements are discussed in Chapter 3 of this report.

Aluminum

Aluminum is useful for highway noise barriers because of its generally low maintenance requirements. It is also light in weight. Section 1.3.3 of this guide prescribes minimum thicknesses for acceptable acoustical performance. Aluminum's value in the recycling market has given TxDOT problems with thefts of aluminum components such as guardrails. This possibility should also be considered for aluminum noise-barrier components.

In specifying aluminum highway barriers, the University of Louisville recommends that panels made of aluminum have a minimum nominal thickness of 0.063 inch and conform to the thickness tolerances of the Aluminum Association. Also, any shearing, cutting, or punching of the panels should preferably be done before any coatings are applied to them.

Concrete and Portland Cement-Based Materials

Concrete and portland cement-based materials are widely used for highway noise barriers both as precast and as cast-in-place elements. Minimum practical thicknesses for fabrication are usually sufficient to ensure acoustical effectiveness. Maintenance costs are usually low. Long-term durability of concrete and other portland cement-based materials in highway noise barriers is most critically affected by resistance to freeze-thaw cycling when saturated.

Several specifications are available for evaluating resistance to freeze-thaw deterioration. The one most often used has been ASTM C666 ("Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing"). The University of Louisville, however (HITEC 1995), recommends that precast concrete panels and other Portland cement-based materials be tested for resistance to salt scaling and freeze-thaw conditions in accordance with

Section 6.3.2.1 of Canadian Standards for Noise Barrier on Roadways, which is a modified version of ASTM C672 ("Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals").

In that modified standard, a specimen's loss of mass is determined after exposure to a prescribed number of freeze-thaw cycles involving distilled water, ordinary water, or even deicing solution. The acceptance criterion is based on the effects of freeze-thaw deterioration or salt scaling, or both, on the concrete's acoustical and structural performance and on the severity of exposure anticipated in service. In general, test specimens should not exhibit any cracking, spalling, or aggregate disintegration after exposure to the required number of cycles. When severe exposure is anticipated, acceptance criteria could also include a maximum permissible loss of mass after cycling.

To date, no single, definitive, cost-effective and widely accepted method is available for evaluating noise barriers for resistance to salt scaling. The University of Louisville (HITEC 1995) recommends the modified ASTM C672 as a good starting point, but notes the possible need for future modifications. For example, the number of freeze-thaw cycles between tests might be increased in the later stages of the evaluation, to reduce testing costs without increasing the risk of unacceptable materials.

Masonry

Masonry is widely used for highway noise barriers because of its durability and aesthetic appeal. Masonry units can be laid in place or used in prefabricated panels that are later placed between post or column elements.

Masonry comprises units, mortar, grout, and accessory materials. Units must be of concrete or fired clay masonry. Concrete masonry units should be hollow load-bearing units conforming to ASTM C90. Fired clay units (solid or hollow) should conform to ASTM C62, C216, or C652. Masonry mortar should conform to ASTM C270, and masonry grout, to ASTM C476. Reinforcement can be either deformed bars or wire joint reinforcement. It and other accessories should conform to the specifications of the Masonry Standards Joint Committee (MSJC 2002a, 2002b). A panel cap or flashing should be used to protect the top course and posts of masonry walls.

Plastics

Plastics are sometimes used for highway noise barriers. Their attractive features include light weight. As noted earlier, a minimum weight is necessary for acoustical effectiveness. The principal potential drawbacks of plastics are deterioration under exposure to ultraviolet radiation and ozone.

Panels made of plastic or fiberglass should be tested for resistance to ultraviolet-light exposure in accordance with ASTM G53. The specimen is alternately exposed to ultraviolet light alone from a series of fluorescent lamps and to condensation alone in a repetitive cycle. There must be no delamination, fading, chalking, or embrittlement after 1,500 hours of exposure. All glazing material must comply with the requirements of ANSI Standard Z 26.1.

Steel

Steel is attractive for use in highway noise barriers because of its low cost. Its chief potential drawback is its vulnerability to corrosion. This vulnerability is most often counteracted by galvanizing and coating the steel.

According to the University of Louisville, all steel panels should be at least 20-gauge galvanized steel, and should also be protected with a coating with satisfactory tested resistance to weathering, fog-spray exposure, and flame spread. Whenever possible, the coating should be applied only after the steel is sheared, punched, or cut. Panels should be connected using aluminum pop rivets with an aluminum or stainless steel mandrel.

Wood

Wood is used for noise barriers in areas with abundant supplies of this material. Its principal potential drawbacks include its relatively low mass, in that a significant thickness is needed to achieve a satisfactory transmission loss. Drawbacks also include the need to avoid gaps between pieces of wood, and possibly higher maintenance costs to control decay.

Resistance to rot and decay is the most important maintenance consideration. According to the University of Louisville, any wood products used in noise barriers should either be naturally resistant to decay for a minimum period of 20 years, or be pressure-treated. All pressure-treated wood should have a Certificate of Preservative Treatment from an appropriate facility. Minimum retention should be 0.6 pound per cubic foot. The moisture content of all sheathing should be reduced to a maximum of 15 percent before and after pressure treating. Timber columns should be reduced to an exterior moisture of 15 percent to the depth of the penetration of the preservative and an interior moisture content of 30 percent maximum. All wood products should be treated to resist insect infestation, and be coated with a wood sealer or stain.

Laminated wood panels must resist warping, splitting, or loosening of particles, knots, and imperfections. Any sheathing must be double-depth, tongue-and-groove.

Glue-laminated wood containing a wet-use adhesive should conform to ANSI/AITC A 190.1. Any preservative treatment should be in accordance with AWPA C-28. Any wood to be glue-laminated should be preservative-treated under pressure, to a retention of 0.4 pound per cubic foot, prior to gluing. All glues should be water-resistant in accordance with CSA Standard 01 12-M. Nonlaminated wood should be No. 2 grade or better. Any plywood used should be an exterior type conforming to the requirements of U.S. Product Standards PS-1. Comparable ASTM standards are acceptable substitutes for the Canadian standards mentioned above.

Evaluation of Proprietary Barrier Materials

In general, barrier materials should be evaluated based on acoustical effectiveness (mass), structural integrity, durability, and initial and life-cycle cost.

- All cementitious materials should be evaluated for durability as noted above.
- All exposed metal components, including connectors, should be fabricated of nonferrous materials or of stainless steel, or be hot-dip galvanized after fabrication according to the requirements of ASTM A 123, A 153, A 307, or A 325. All exposed steel (except weathering steel) must be primed and painted in accordance with TxDOT's normal requirements for coatings.
- Any welds should conform to the ANSI/AWS DIA, Structural Welding Code for Reinforcing Steel. Where permitted, field welds should conform to CSA Standards W 186-M 1990, W 47.1, and W 59. All field welds should be cleaned and painted with an organic zinc-rich paint conforming to the requirements of CAN/CGSB 1.181-92 and matching the color of the surrounding surfaces. Comparable U.S. standards are acceptable substitutes for the Canadian standards mentioned above.
- All barrier materials should be tested in accordance with ASTM E84 to determine their flame-spread and smoke-development classifications.
- All barrier materials should demonstrate satisfactory performance under prolonged periods of exposure to moisture. Edges of absorptive materials should be sealed to preclude moisture from entering the interior. Water absorption testing should be performed in accordance with the ASTM standard appropriate for the material being tested.
- All barrier materials should demonstrate resistance to fungus in accordance with ASTM G 21 or a comparable standard.

The cost of the installed noise barrier must compare well to the moving average cost of noise barriers. All costs involved in the purchase and installation of the noise barrier system should be clearly identified. The projected or estimated life-cycle cost should be provided along with the calculations and input parameters used in determining that cost. Any material used in sound barriers should have a minimum predicted maintenance-free life span acceptable to TxDOT under the expected service conditions.

Rules of Thumb Regarding Acoustical Effectiveness of Noise Barriers

How Tall Must a Noise Barrier Be?

- To produce at least 5 dB of noise reduction, a barrier must be tall enough to block the line of sight between a source and receiver. If a barrier is too short or has gaps between barriers, the noise can travel around the end of the barrier wall reducing the effectiveness. Even with gaps, enough barrier segments may be present so that the barrier achieves a 5 dB reduction.

- Each noise barrier must be long and high enough to effectively reduce noise levels, using FHWA-approved computer model to determine the optimum overall barrier dimensions.

Noise Barriers and Neighborhood Planning

- Project design engineers should be consulted for preliminary evaluation of noise barrier locations, for input regarding sight distance requirements, right-of-way issues, utility easements, and foundation requirements.
- Noise barriers should not cause any displacements or relocations of receivers.
- It is normally not cost-effective to build a noise barrier for a single receiver.
- Large gaps for driveways and alleys entering onto a roadway greatly reduce the effectiveness of a barrier.
- Access streets should not be closed to eliminate large gaps in a noise barrier and thereby enhance its effectiveness, unless requested and approved by local government officials. Associated responsibilities should be clearly spelled out in a written agreement prior to the final environmental clearance.
- Traffic-noise analyses and any associated noise-abatement measures are not intended to be used to reshape or reconfigure existing neighborhoods.
- Earth berms, though natural in appearance, require a large plan area (right-of-way) to reach the height required to be effective.

Noise Barriers on Hilly, Elevated, or Depressed Sites

- Noise barriers are normally not effective for receivers on a hillside overlooking the highway, or for receivers at heights above the top of the noise barrier.
- Depressed and elevated roadways normally result in somewhat lower noise levels (3–5 dBA), and thereby either eliminate the need for a noise barrier, or require a lower barrier than would otherwise be required.

Effects of Holes and Surface Texture

- Small gaps and drainage holes (less than 3 percent of the total surface area) do not significantly reduce a barrier's overall acoustical effectiveness.
- The surface roughness of a barrier matters only if it is of the same order of magnitude as the wavelength of sound that the barrier is intended to attenuate. Because the wavelength of 100-Hz sound is 10 feet, ordinary surface roughness has little effect.

Multiple-Reflection Issues

- Multiple reflections of traffic noise between two parallel plane surfaces, such as noise barriers or retaining walls on both sides of a highway, can theoretically reduce the effectiveness of individual barriers and contribute to overall noise levels. Associated increases in traffic noise levels will normally not be perceptible to the human ear, however, if the distance between the barriers is at least 10 times the average height of the barriers. For example, two parallel barriers 3 meters high should be constructed at least 30 meters apart. During the preliminary design of noise barriers, the possible influence of parallel reflections should be checked.

Effects of Absorptive Materials

- Constructing barriers using sound-absorptive materials significantly reduces the noise level experienced by drivers on the roadway. It does not significantly reduce the noise level away from the highway, except when the highway has barriers on both sides. In such a parallel-barrier situation, absorptive materials can produce some noise reduction away from the highway by reducing sound that is reflected from the barrier on the side of the highway opposite to the receiver. This additional noise reduction is not always significant.

CHAPTER 3
STRUCTURAL DESIGN OF NOISE BARRIERS

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 is expected to experience during its service life The governing conventional load case usually is lateral wind loading, applied as a lateral pressure in design.

Definitions

The distinction between the meaning of the terms "*right-of-way*" and "*clear zone*" is often unclear or misunderstood. In this report, these terms are defined as follows (Civil Engineering Handbook 1995):

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

The *clear zone is* the unobstructed, relatively flat area outside the edge of the traveled way, including shoulder and sideslope, for the recovery of errant vehicles. Clear zone is defined in the TxDOT Highway Design Division Operations and Procedures Manual.

Structural Design Considerations for Sound Walls

Structural Design of Sound Walls for Conventional Load Cases

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 (1992):

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

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 (1992).

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 walls, deflections under design wind loads are neither a strength or a stability concern, nor are they the subject of public attention. When taller sound walls are constructed, however, 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.

Other Design Loads for Sound Walls

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

Current AASHTO Guidelines for Structural Design of Noise Barriers

In 1989, the American Association of State Highway and Transportation Officials (AASHTO) published a set of recommended guidelines (AASHTO 1989, 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 (1992).

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 1992). 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 (1992).

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 kip), 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 redirect an errant automobile, it does not consider the dynamic response of the structure.

In considering this issue, it is important to reiterate current TxDOT policy. All highway noise barriers located within the clear zone must be protected by a separate traffic barrier. If the noise barrier is integrated with the traffic barrier, it is required to resist vehicular impact. To meet FHWA guidelines, all such barriers must be crash-tested. In practical terms, the most effective way to meet these requirements is to put a crash-tested vehicle impact barrier in front of the noise barrier. Then the noise barrier itself would not have to be designed for vehicular impact.

Structural Design Process for Noise Barriers

Determination of Primary and Secondary Design Loads

Primary design loads are those that ordinarily are critical for the barrier's structural design. They usually consist of wind only. Vehicular impact is rarely a design consideration, and FHWA guidelines require that vehicular response be verified by crash-testing.

Secondary design loads must also be considered, but are usually not critical. These normally include loads from gravity, water pressure, snow, and earthquake.

Design of Barrier Elements for Given Loads

Although this step might seem trivial, it is not. Structural elements in noise barriers are not easily categorized as beam, columns, or barriers. Consequently, there may be confusion about which code provisions to apply. In addition, some proprietary noise-barrier systems use structural configurations or structural materials for which code design provisions are not available. In such cases, design and approval may have to be based on test data or the general provisions of the building code.

Detailing of Movement and Construction Joints

The noise barrier must be provided with joints to accommodate deformations owing to structural loads, differential settlement of the underlying soil, and differential shrinkage or expansion of barrier materials. The movement capabilities of the joints are determined by the most critical of the above effects. The joints must accommodate inter-element movements to prevent spalling, which can have structural as well as aesthetic consequences.

Any gaps introduced into the barriers by the joints must not be so large as to compromise the acoustical performance of the barrier. This requirement is usually not difficult to meet.

In particular, the connection to the foundation (usually a drilled shaft) must be carefully detailed to limit the deformations of the barrier under design loads, while permitting simple construction and replacement.

Structural Design Requirements Imposed by Adjacent Utilities

Influence of Buried Utilities

If buried utilities exist, these impose constraints on the type of foundation that can be used for the barrier. The buried utilities must be re-located, the foundation must avoid the utilities, or the barrier must be of a type not requiring a buried foundation.

Influence of Overhead Utilities

If adjacent overhead utilities exist, these impose limitations on the maximum height of the barrier and on the way cranes are used in the construction process. It may be necessary to relocate overhead utilities, or modify the alignment of the noise barrier.

Access for Future Maintenance

In addition, the presence of the noise barrier can restrict future maintenance access to the overhead utilities. This problem is handled by the utility company and should be coordinated with the Texas Department of Transportation (TxDOT) early in the design phase.

Basic Structural Choices for Noise Barriers

The following basic structural choices are available:

- ♦ Noise Barrier not Required 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
  - earth berms
- ♦ Noise Barriers Required to Resist Vehicular Impact
  - prefabricated, barrier-mounted, post-and-panel system (not recommended by TxDOT)
  - prefabricated, sloped-face wall system

In the remainder of this section, the factors favoring various choices are briefly discussed.

Preferred Structural Choices for Noise Barriers on Grade

For barriers on grade, barrier weight is not usually an issue. Earth berms, while often appealing aesthetically, require significant right-of-way. Fan-wall systems also require significant right-of-way, can be associated with higher mowing costs, and can provide undesirable places for concealment. Unless those potential drawbacks are not an issue, the best structural choice usually involves a post-and-panel system. Structural costs and utility disruption can be reduced by making the barrier self-supporting between posts, thereby eliminating the need for a continuous grade beam.

From a structural viewpoint, any material discussed in this guide can function satisfactorily. The choice of material depends on aesthetics and life-cycle cost. The choice between constructed-in-place versus prefabricated barriers is primarily one of economics. It is also influenced by the effects of any lane closures required while the barrier is being constructed.

Any barrier must be able to accommodate differential movement caused by long-term expansion (for example, clay masonry), long-term shrinkage (for example, cementitious materials), and thermal expansion or contraction (all materials).

Overall Structural Evaluation Criteria for Proprietary or Innovative Systems for Noise Barriers

Proprietary or innovative systems for noise barriers must meet the same criteria as any other barrier—acoustical, aesthetic, economic, and structural. From a structural viewpoint, such systems must embody satisfactory responses to the following questions:

1. Does the system have a clearly defined load path for transmitting its forces to the ground?
2. Is that load path sufficiently independent of construction tolerances? For example, some precast systems resist load by means of a relatively short internal lever arm between the centroid of a vertical post-tensioning bar and the compressive reaction of a precast column element on the foundation. Small changes in the position of the post-tensioning element can significantly decrease the overturning moment capacity of the barrier.
3. Is that load path sufficiently reliable? For example, will vehicular impact against one column of the system imperil its overall structural integrity?
4. Are the barrier's service-level deflections sufficiently small? For example, some precast systems use neoprene pads or other shims under precast column elements to make the construction process easier. If the spaces under those column elements are not subsequently filled with grout, the column may bear against the pads, making prestressing difficult and resulting in much larger deflections than would normally be anticipated. Also, bond deterioration around embedded elements may increase their axial flexibility.
5. Is the barrier resistant to deterioration in service? For example, are metallic connecting parts in the barrier adequately protected against corrosion caused by environmental exposure or by galvanic action between dissimilar metals within the barrier?

CHAPTER 4
SAFETY CONSIDERATIONS IN THE DESIGN OF NOISE BARRIERS

Introduction

Safety Considerations of Vehicular Impact Loadings on Sound Walls

To achieve the required noise reduction, a sound wall must often 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, vehicular impact loading must be addressed in its design.

Current TxDOT policy is that all highway noise barriers located within the clear zone must be protected by a separate traffic barrier. If the noise barrier is integrated with the traffic barrier, it is required to resist vehicular impact. To meet FHWA guidelines, all such barriers must be crash-tested. In practical terms, the most effective way to meet these requirements is to put a crash-tested vehicle impact barrier in front of the noise barrier. Then the noise barrier itself would not have to be designed for vehicular impact.

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).

TxDOT policy does permit noise barriers to be designed for reduced maintenance by making the lower portion of the barrier resistant to vehicular impact. According to FHWA guidelines, however, such barriers must be crash-tested. Any design for vehicular impact is preliminary only, and must be verified by crash testing.

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, thereby endangering residents behind the sound wall. For these reasons, sound barriers are rarely intended to function as vehicular barriers. Instead, they are placed outside the clear zone, or are protected by vehicular barriers. Analysis issues related to impact are discussed further in 1471-2 (1996).

Requirements Related to Vehicular Impact

In assessing requirements related to vehicular impact, the first decision to be made is "should the barrier be designed for vehicular impact at all?" If the barrier is within the clear zone, it must be designed for vehicular impact. If the barrier is located on the right-of-way line, general design standards would normally determine whether vehicular impact would have to be considered.

If it is decided that a noise barrier should be designed for vehicular impact, the performance criteria must then be clearly stated. Should the barrier be designed to redirect vehicles or to slow them down without serious injury to their occupants? The design forces and energy absorption demands associated with actual vehicle impacts considerably exceed the AASHTO code-mandated design loads for vehicular impact. Noise barriers designed with an integral vehicle-impact barrier in their lower portion pose additional design questions. The upper part of the barrier (the portion intended as a noise barrier only) must not collapse when a vehicle impacts the lower portion of the barrier. In such cases, it may be preferable to place the barrier so that it is not susceptible to vehicular impact or to protect it with a separate vehicular impact barrier. Although some districts prefer to strengthen the lower portions of sound barriers to improve durability, such barriers should never be placed inside the clear zone in lieu of a traffic barrier. For liability reasons, the language on a sound wall standard detail should never imply that the sound wall is designed as a traffic barrier. Noise barriers designed for vehicular impact typically must be crash-tested in accordance with NCHRP 350, Test Level 3, to gain FHWA acceptance (NCHRP 1993; FHWA 1996b).

When considering the possibility of vehicular impact, several solutions can be applied:

- place the noise barrier beyond the clear zone as defined by the AASHTO Roadside Design Guide
- place a traffic barrier in front of the noise barrier to prevent impact
- design the noise barrier with added durability if vehicle impact is possible. This solution is not recommended by TxDOT, and must be verified by crash-testing.

In addition to these considerations, noise barriers that may be impacted by vehicles must be designed so that any debris resulting from that impact does not endanger other vehicles or the neighborhood behind the barrier. This requirement applies to the entire noise barrier and is in addition to the general strength and energy absorption requirements of that portion of the barrier specifically designed to resist vehicular impact.

♦ Noise Barriers with added durability if vehicular impact is possible

- prefabricated, barrier-mounted, post-and-panel system (not recommended by TxDOT)
- prefabricated, sloped-face wall system

CHAPTER 5
AESTHETIC CONSIDERATIONS IN NOISE BARRIER DESIGN

General Guidelines for Aesthetic Design of Noise Barriers

Selected Publications on Aesthetics

Little literature is available on the subject of noise barrier aesthetics. Research is in progress at Pennsylvania State and Texas A&M Universities. Researchers at Penn State have shown slides of different wooden noise barriers to many typical residents and have asked them to rate the aesthetic appeal of each. Researchers at Texas A&M have recently concluded a two-year study (TTI 1995), prepared for the Dallas District, in which all 50 states were sent a comprehensive written survey on noise barriers and aesthetic treatments. The Texas Transportation Institute (TTI) survey notes that states use three options when designing noise barriers:

1. design the most cost-effective walls to meet noise-reduction requirements with little regard to aesthetics;

2. design the wall to perform the function of noise reduction while blending it into the surrounding environment; or

3. design the wall as an art form (line, form, color, texture, and artistic expressions) within the context of its surroundings.

The TTI survey of states also noted that a previous 1981 study indicated that only Pennsylvania and Minnesota reported aesthetic treatment of noise barriers. In the TTI survey, states reported including aesthetic criteria into several noise-abatement projects because of public involvement.

Aesthetic standards for noise wall design are more codified in Europe than in the U.S. In 1991, the Danish Ministry of Transport published Report 81, *Noise Barriers—A Catalogue of Ideas* (Denmark 1991). This report contains a comprehensive photographic database of the different types of noise barriers constructed in Denmark and other neighboring countries. In addition, it discusses in qualitative terms the factors and methodology used in planning and designing a noise wall.

In 1976, the Federal Highway Administration (FHWA) published a manual for visual quality in noise-barrier design, which is still applicable today (Blum 1976). The manual presents the basic principles that affect visual perception and to their application to highway noise barrier design. The manual is not intended to provide design solutions for noise abatement, but rather to illustrate and emphasize the need for visual quality as part of the design process. The manual should be used to supplement technical information concerning noise abatement in an effort to produce highway noise barriers that are functional, attractive, and visually related to the surrounding environment.

1995 Organization for Economic Cooperational Development—Roadside Noise Abatement

In 1995, the Organization for Economic Cooperational Development (OECD) published an excellent report on roadside noise abatement that synthesizes the experiences of Europe, Japan, Australia, and the United States. In regard to aesthetic considerations, the report discusses visual effects of both sides of noise barriers, effects on drivers, barrier termination, and graffiti. The report concludes that aesthetic design and the integration of noise barriers into the landscape and the environment are of special importance. It also states that barrier height, the choice of material, and the shape, structure, and color of the barrier are especially important considerations. The report concludes that the successful design approach for noise barriers should be multidisciplinary and should include architects, planners, landscape architects, roadway engineers, acoustical engineers, and structural engineers.

Aesthetic Requirements for Noise Barriers

The general category of aesthetic requirements includes all aspects of the impact of the noise barriers on their surroundings. These include their physical surroundings, and also their human surroundings.

Effect of Noise Barriers on Physical Surroundings

By their very presence, noise barriers affect their physical surroundings. This effect depends first on the physical setting in which the barrier is placed. A barrier that would be almost imperceptible in an urban setting could visually dominate a rural or coastal setting. Perception of noise barriers must be approached from the viewpoint of the driver and from the viewpoint of the receptor.

The visual effect of the noise barrier on the driver depends on the speed of the vehicle, the height of the barrier, the distance of the barrier from the roadway, and the surface texture of the barrier. If vehicles are generally moving rapidly, close to the barrier, drivers do not notice the details of the barrier. If the vehicles move more slowly, or if the barrier is farther away, the details of the barrier are noticeable and therefore more important. If the barrier is high and close to the driver, and particularly if it is on both sides of the roadway, it may produce, a tunnel effect in which drivers perceive themselves as being uncomfortably surrounded by the barrier.

The visual effect of the noise barrier on the receiver depends on the barrier height, the distance of the barrier from the receiver, and the surface texture and color of the side of the barrier facing the receiver. This visual effect can be accentuated if the barrier changes the pattern of light and shadow on the receptor's property. The surface texture of a noise barrier depends on the type of material used to construct the barrier. For example, wood-textured concrete can have horizontal or vertical planks. The aesthetic advantage of using horizontal planks is that the seams in stacked panels are less noticeable. Solid panels, however, may be aesthetically preferred for wall heights under 14 feet.

Two design approaches are available to mitigate any undesirable visual effect that noise barriers may have. In the first approach, the barrier is designed to be monumental, dominating the landscape. Its materials and details are selected so that it becomes a pleasing part of the landscape. In the second approach, the barrier is designed to blend with the landscape. This approach is best exemplified by the selection of a noise barrier in the form of an earth berm. While right-of-way constraints can make an earth berm impractical, other options are also available. Whichever approach is taken, it is advantageous that the visual appearance of the noise barrier reflect the historical and architectural context of the region in which it is placed. For example, noise barriers in a coastal area can be colored to blend with the sand that surrounds them; or, they can be decorated or patterned with symbols that are historically meaningful for the area.

A new concept established by the New Jersey Department of Transportation creates community themes using gateways. A *gateway* is an architectural accent that looks like a designer panel. It is located in areas that are particularly likely to attract the attention of highway users. A sequence of similar gateways would be constructed along a highway; each gateway would have a slight variation, to give the community a unique quality with which to identify (Billera 1996).

Figure 5.1 Example of the gateway concept (Billera 1996)

Role of Opacity

Another aesthetic issue related to noise barriers concerns their opacity. Most barriers in the United States are of opaque materials such as concrete, masonry, or wood. Opaque barriers can block the view of motorists and make driving monotonous. One way to overcome this problem and at the same time achieve a better aesthetic result is to use transparent materials for barriers. A variety of transparent materials has been promoted for use in highway noise barriers. The most common are thermosetting acrylic polymers, known by such trade names as Plexiglas, Butacite, Surlyn, and Lexan.

The primary advantage of transparent materials over opaque ones in noise barriers is aesthetics. Many transparent plastics become brittle or discolored in the presence of ultraviolet radiation and ozone, however. Because their transparency is degraded by highway dirt, they may require periodic cleaning. In addition, the perceived aesthetic advantage of transparent barriers for motorists are often countered by the perceived aesthetic disadvantage for residents, who may not want an unobstructed view of nearby traffic. Formal and informal research studies indicate a connection between how opaque noise barriers block the view of traffic and how they are perceived to block noise. For example, although a wooden privacy fence may be measurably ineffective as a noise barrier, it is nevertheless usually perceived by residents as effective, because it blocks their view of traffic. Conversely, transparent noise barriers may be perceived as acoustically less effective by residents, because of their transparency.

General Guidelines

The general guidelines for design of noise barriers with respect to aesthetic treatment are:

1. Do not do anything to degrade the acoustic performance of the noise barrier. For example, do not allow holes or gaps in noise barrier walls in excess of three percent of the wall. In addition, a sharp-edged, thick capstone on the top of the barrier may degrade the performance by providing two refractive edges instead of one.
2. Keep the design simple. It is possible to add architectural details or castings in concrete panels. Keep the scale of wall in mind, however. Large, simple designs are best. Intricate designs with walls close to the driver are not effective.
3. Use architectural or aesthetic treatment only if a large number of people will view it, if it contributes less than 10 percent of the cost of construction, and if it contributes to a sense of place or neighborhood.
4. Avoid designing noise barrier walls that are eyesores or maintenance liabilities. Avoid a long, high featureless wall that leaves either the driver or the receiver feeling that they are imprisoned.

CHAPTER 6
TEXAS EXPERIENCE IN NOISE-BARRIER CONSTRUCTION

Typical Types of Noise Barriers Constructed in Texas

Prefabricated, Separate Posts and Panels

The most common system used for noise barriers in Texas consists of prefabricated panels placed between posts. The system is shown schematically in Figure 6.1. The panels are usually made of precast concrete, but can also be made of other materials. The space between the posts can be either filled by a single panel, or occupied by several shorter panels, stacked vertically. The posts are usually either concrete or steel. Figure 6.2 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 6.3 (a close-up of the same noise barrier) shows the precast concrete fascia plate, intended to provide an aesthetic cover for the steel column and the joint between the panel and the column.

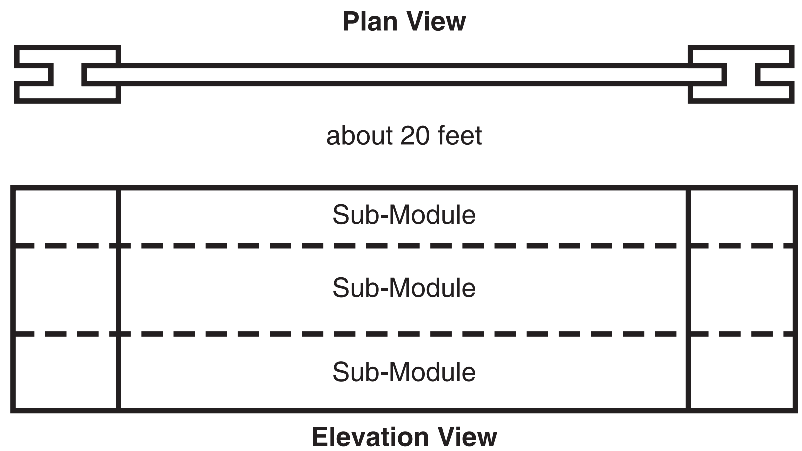

Figure 6.1 Schematic illustration of prefabricated, separate post-and-panel system for highway noise barriers

Figure 6.2 Example of prefabricated, separate post-and-panel system (Houston District)

In this system, there is no grade beam. The panels span between the posts, whose spacing is often dictated by the type and layout of the foundation used. The post spacing typically ranges from 3.0 to 7.5 m (10 to 25 feet). Drilled shafts without grade beams are the standard foundation type for all noise barriers in the Houston District. The precast panels are typically reinforced concrete and are “flown” into place between the columns, using an overhead crane.

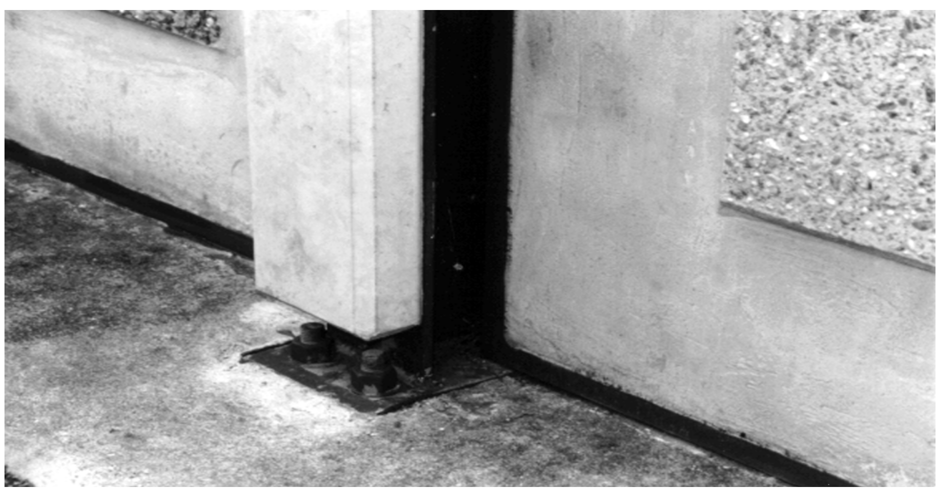

Figure 6.3 Close-up of column on noise barrier of Figure 6.2

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, because the choice of post material (concrete, steel, or other) is a contractor option; several noise barriers, such as the one shown in Figure 6.4, 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 constructable, requiring relatively little disruption of traffic.
- It is relatively easy to repair, by removing and replacing the damaged component.

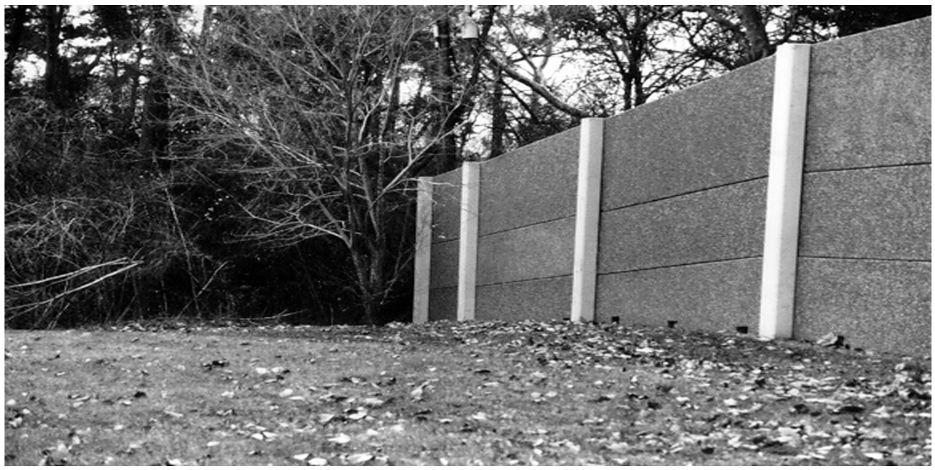

Figure 6.4 Example of prefabricated, separate noise barrier system (Houston District)

Prefabricated, Integral Posts and Panels

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 6.5. After the monolithic post-and-panel elements are placed, the post ends of the panels are most often bolted from the top panel to the drilled-shaft foundation or post-tensioned using a cable embedded into the drilled shaft and threaded through the panel or panels as they are lowered into place.

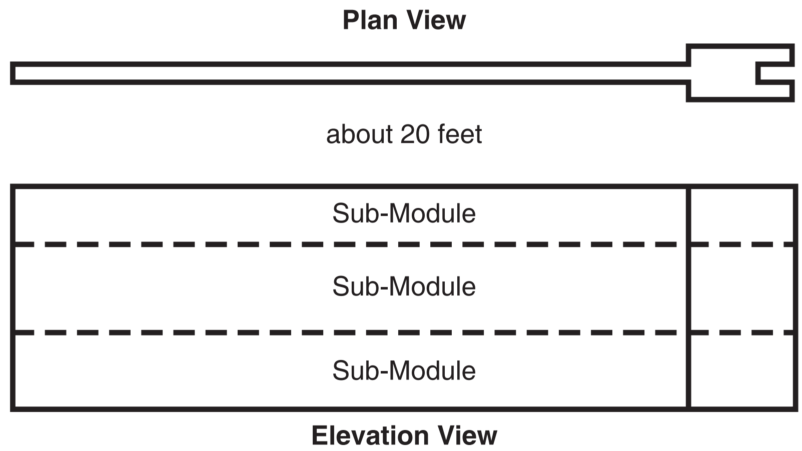

Figure 6.5 Schematic illustration of prefabricated monolithic system of highway noise barriers

Constructed-in-Place Posts and Panels

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 6.6 shows an example of this system, constructed in reinforced masonry in the Austin District. The San Antonio District used a nearly identical design.

Figure 6.6 Constructed-in-place post-and-panel system (Austin District)

Although constructed-in-place reinforced concrete barriers are possible, no barriers of this type are known to exist in Texas. Many variations of this system are possible, and this report cannot address them all.

Serpentine Walls

A serpentine-wall system is popularly known as the fan-wall system, and will be referred to as such throughout the rest of this guide. It is generally composed of full-height, precast panels placed in a zigzag configuration in plan and interconnected using bolts or cables. This zigzag configuration provides stability against overturning, 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 because of the elimination of posts and foundation. However, its zigzag footprint requires more ROW than a straight wall. A fan-wall system can be constructed with less concern for disturbing buried utilities. It can make subsequent access to such utilities more difficult, however, because its overturning stability can be endangered if it is necessary to dig along a significant length of the wall. The fan-wall system construction in the Austin District and shown in Figure 6.7 was specifically chosen because of the presence of buried utilities.

Figure 6.7 Example of fan-wall system (Austin District)

The Houston District has constructed examples of the fan-wall system (Figure 6.8). The fan-wall system used in Houston differs in footprint from that of the one used in Austin. The Houston system is wider, requiring more ROW. 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 as a result of trench excavation. The Houston District has noted that the irregular shape of the fan wall makes it difficult to mow next to the wall.

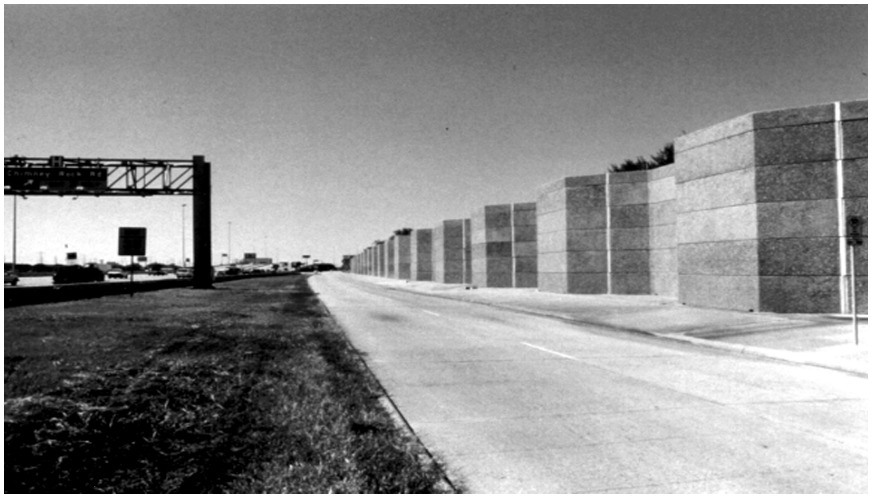

Figure 6.8 Example of fan-wall system (Houston District)

Staggered Walls

The staggered-wall system alternates straight and angled wall sections while incorporating the use of stackable, post-and-panel construction. The staggered barrier is interrupted at regular intervals with a short section perpendicular to the roadway. As shown in Figure 6.9, a staggered wall is less monotonous than a straight one. Its footprint provides some inherent lateral stability. This footprint is usually used with the prefabricated post-and-panel system, but it could be used with other systems as well.

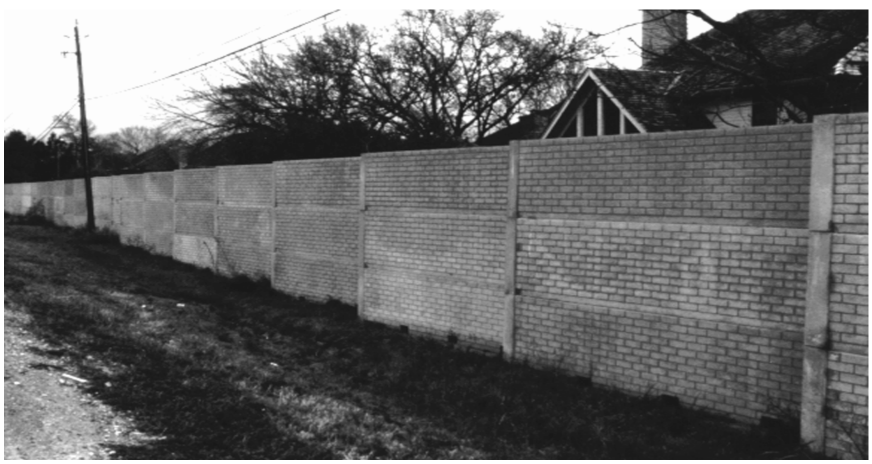

Figure 6.9 Example of staggered-wall system (Houston District)

Earth Berm

An earth berm is simply a mound of dirt. 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 noise barriers of other materials. Vegetation on the berm can enhance this aesthetic appeal. However, trees planted on an earth berm noise barrier can reduce the barrier's acoustical effectiveness by scattering noise to the receivers that otherwise would have been directed over them. Earth berms can be topped with other types of noise barriers to increase their acoustical effectiveness. The main disadvantage of earth berm noise barriers is the ROW they require. Earth berms are a practical solution if space is available. The Fort Worth District has one such barrier.

Prefabricated, Barrier-Mounted, Posts and Panels

Prefabricated, barrier-mounted, posts and panels are another variation of the post and panel system, involving structural steel posts anchored atop a TxDOT T501 traffic barrier ("Jersey barrier"). The traffic barrier is used to satisfy vehicular impact and redirection requirements for obstructions in the clear zone, while supporting the post-and-panel elements intended to achieve the desired sound attenuation. This system has been constructed in the Fort Worth District and by the Texas Turnpike Authority for the North Dallas Tollway. Figure 6.10 shows a Fort Worth District noise barrier constructed using this system. In the Fort Worth District, the precast panels were constructed with either exposed aggregate or smooth-finished concrete.

Figure 6.10 Example of prefabricated, barrier-mounted post-and-panel system (Fort Worth)

The posts are typically attached to the impact barrier using a base plate and embedded anchor bolts. This connection is often difficult and costly to construct in the field because of the tight tolerances resulting from the narrow barrier top (only 150 mm [6 inches] wide). Because the barrier top is so narrow, the base plate is also narrow, and the overturning resistance of the post is low. As a result, the post spacing must be close—Fort Worth used 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 stacked and are easier to disassemble if necessary. The short panel length and exposed steel posts have resulted in a poor aesthetic rating for this design. Wind loads also restrict the height of this barrier system. The concept was designed for ease of disassembly should ROW ownership change, but so far this feature has never been put to use.

As discussed previously in sections of this report dealing with vehicular impact, sound walls mounted on vehicular barriers are not generally recommended by TxDOT. The type of wall originally used in Fort Worth and elsewhere is no longer used for new installations. If this type of sound wall is required, an approved design now exists for a T501SW rail, which combines the features of a noise barrier and bridge rail.

Prefabricated "Sloped-Face" Barriers

The sloped-face noise barrier system, conceived in the Houston District, combines the potential vehicular redirection characteristics of the mounted post-and-panel system with the aesthetic advantages of prefabricated, separate or integral systems. The lower panel is strengthened for maintenance reasons and it is not intended as traffic barrier. This system, shown in Figure 6.11, 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 with anchor keys cast into the panels and grouted in place as the panel is lowered onto the lower panel (trapezoidal). The final connection to the drilled shaft is made with a threaded rod, introduced from the top and screwed into an insert that is cast in the drilled shaft.

The sloped-face system is intended to reduce maintenance from the hazards of a vehicular impact. Again, TxDOT preference is not to place noise barrier within the clear zone unless protected by a normal traffic barrier. Neither this system nor the Fort Worth barrier-mounted post-and-panel system is designed to a specific vehicular impact standard, however. The Houston District designs the bottom panel of this sloped-face barrier system to withstand a 10-kip concentrated static load intended to simulate a vehicular impact. However, walls serving a dual function (as traffic barriers that define the limits of the clear zone and also act as sound walls) typically must be crash-tested in accordance with National Cooperative Highway Research Program (NCHRP) 350, Test Level 3, to gain Federal Highway Administration (FHWA) acceptance (NCHRP 1993; FHWA 1996b).

Figure 6.11 Example of sloped-face noise barrier system (Houston District)

Database of Noise Barriers Constructed in Texas

Research Project 2112 completed a database with photographs of all noise barriers constructed by TxDOT.

CHAPTER 7
SAMPLE SPECIFICATIONS AND PLANS

Introduction

To be included in a Texas Department of Transportation (TxDOT) project, a highway noise barrier system must be able to be described in TxDOT contract documents (specifications and drawings).

This chapter includes a sample set of specifications, drawings, and a design example. The specifications and drawings are based on work supplied to this study by John Vogel of the Houston District. His assistance is gratefully acknowledged.

The sample specifications are applicable to most commonly used sound wall materials and systems and can address many, if not all, proprietary systems. The sample drawings are also applicable to a variety of systems and materials. The sample specifications and drawings should be adapted to the particular needs of each project.

Two sets of sample drawings are provided in this chapter to provide representative examples of effective noise barrier design.

1993 Specifications Houston District

SPECIAL SPECIFICATION

ITEM 5246

SOUND WALLS

1. DESCRIPTION. THIS ITEM SHALL GOVERN FOR FURNISHING THE MATERIALS AND CONSTRUCTING A SOUND WALL AS SHOWN ON THE PLANS AND REQUIRED BY THIS ITEM.

2. MATERIALS. ALL MATERIALS SHALL CONFORM TO THE PERTINENT REQUIREMENTS OF THE FOLLOWING STANDARD SPECIFICATION ITEMS:

- ITEM 420, “CONCRETE STRUCTURES”
- ITEM 421, “PORTLAND CEMENT CONCRETE”
- ITEM 425, “PRESTRESSED CONCRETE STRUCTURAL MEMBERS”
- ITEM 426, “PRESTRESSING”
- ITEM 427, “SURFACE FINISHES FOR CONCRETE”
- ITEM 437, “CONCRETE ADMIXTURES”
- ITEM 440, “REINFORCING STEEL”
- ITEM 44 1, “STEEL STRUCTURES”
- ITEM 442, “METAL FOR STRUCTURES”
- ITEM 445, “GALVANIZING”
- ITEM 446, “CLEANING, PAINT AND PAINTING”

- ITEM 449, “ANCHOR BOLTS”
- ITEM 575, “EPOXY”

UNLESS OTHERWISE SHOWN IN THE PLANS, SOUND WALL PANELS SHALL BE CONCRETE. SOUND WALL POSTS SHALL BE CONCRETE OR STEEL. CONCRETE FOR PRECAST AND CAST-IN-PLACE COMPONENTS SHALL BE CLASS “F” WITH $F'm = 4000$ PSI MINIMUM. CONCRETE FOR PRESTRESSED COMPONENTS SHALL BE CLASS “H” WITH $F'm = 5000$ PSI MINIMUM.

ANCHOR BOLTS, NUTS AND WASHERS SHALL BE GALVANIZED FOR CORROSION PROTECTION. ALL EXPOSED STEEL COMPONENTS SHALL BE GALVANIZED OR PAINTED WITH THE PROTECTION SYSTEM SHOWN ON THE PLANS.

JOINT FILLERS, GROUT, AND OTHER INCIDENTAL MATERIALS SHALL BE AS SHOWN ON THE PLANS OR APPROVED BY THE ENGINEER.

3. GENERAL

- OPTIONS.THE CONTRACTOR MAY FURNISH ANY PROPRIETARY SOUND WALL SYSTEM WHICH MEETS THE REQUIREMENTS OF THIS SPECIFICATION AND COMPLIES WITH THE DESIGN CRITERIA SHOWN ON THE PLANS. ALL SOUND WALL SYSTEMS SHALL UTILIZE DRILLED SHAFTS WITH THE SAME SPACING, DIAMETER, LENGTH AND REINFORCING STEEL AS SHOWN ON THE PLANS. THE CONTRACTOR SHALL PROVIDE FOR USE OF THESE SYSTEMS IN ACCORDANCE WITH ITEM 7.3.

    - WORKING DRAWINGS. PRIOR TO FABRICATION, THE CONTRACTOR SHALL PREPARE AND SUBMIT WORKING DRAWINGS AND DESIGN CALCULATIONS FOR THE PROPOSED SOUND WALL SYSTEM TO THE ENGINEER FOR APPROVAL. ALL DRAWINGS SHALL BE SUBMITTED ON 11" X 17" SIZE SHEETS.

THE CONTRACTOR SHALL SUBMIT TO THE ENGINEER SEVEN (7) SETS OF CASTING DRAWINGS FOR PRECAST SEGMENTS AND SHOP DRAWINGS FOR EACH DETAIL OF THE PLANS REQUIRING THE USE OF STRUCTURAL STEEL, SEVEN (7) SETS OF CONSTRUCTION DRAWINGS AND TWO (2) SETS OF DESIGN CALCULATIONS. UPON COMPLETION OF CONSTRUCTION, ONE (1) SET OF REPRODUCIBLE AS-BUILT DRAWINGS SHALL BE SUBMITTED TO THE ENGINEER.

CASTING DRAWINGS SHALL INCLUDE ALL INFORMATION NECESSARY FOR PRECASTING WALL ELEMENTS. CASTING DRAWINGS SHALL REFLECT THE SHAPE AND DIMENSION OF PRECAST COMPONENTS, THE SIZE, QUANTITY AND DETAILS OF THE REINFORCING STEEL, THE QUANTITY TYPE, SIZE AND DETAILS OF CONNECTION AND LIFTING HARDWARE, THE SIZE AND LOCATION OF DRAIN OPENINGS, AND ANY ADDITIONAL DETAILS NECESSARY.

CONSTRUCTION DRAWINGS SHALL INCLUDE A NUMBERED WALL COMPONENT LAYOUT, AND SHALL REFLECT FIELD VERIFIED HORIZONTAL AND VERTICAL ALIGNMENT OF THE WALL. THE DRAWINGS SHALL ALSO INCLUDE ALL INFORMATION NEEDED TO ERECT THE WALL INCLUDING THE PROPOSED DRILLED SHAFT ELEVATIONS AND LENGTH, LIMITS OF RIPRAP, THE TYPE, DETAILS, AND CONSTRUCTION PROCEDURE FOR CONNECTING THE WALL TO THE DRILLED SHAFTS, DETAILS NECESSARY TO ACCOUNT FOR CHANGE OF GRADE, ALL EXISTING AND PROPOSED UTILITIES, AND ANY ADDITIONAL DETAILS NECESSARY TO COMPLETE THE WORK.

DESIGN CALCULATIONS SHALL INCLUDE A SUMMARY OF ALL DESIGN PARAMETERS USED, INCLUDING MATERIAL TYPES, STRENGTH VALUES AND ALLOWABLE STRESSES, AND ASSUMED LOADS AND LOAD COMBINATIONS. CALCULATIONS SHALL BE SUBMITTED COVERING THE RANGE OF HEIGHTS AND LOADING CONDITIONS ON THE PROJECT.

DRAWINGS AND DESIGN CALCULATIONS SHALL BEAR THE SEAL OF A REGISTERED PROFESSIONAL ENGINEER THAT IS REGISTERED IN THE STATE OF TEXAS.

4. <u>CONSTRUCTION METHODS.</u> CONSTRUCTION OF SOUND WALLS SHALL CONFORM TO THE DESIGN AND DETAILS SHOWN ON THE PLANS AND TO THE PERTINENT REQUIREMENTS OF THE FOLLOWING ITEMS:

   - ITEM 424, "PRECAST CONCRETE STRUCTURES (FABRICATION)"
   - ITEM 429, "CONCRETE STRUCTURE REPAIR"
   - ITEM 447, "STRUCTURAL BOLTING"
   - ITEM 448, "STRUCTURAL FIELD WELDING"
   - ITEM 449, "ANCHOR BOLTS"
   - ITEM 575, "EPOXY"

   ALL POSTS SHALL BE SET PLUMB AND FIRM TO THE LINE AND GRADE SHOWN ON THE PLANS. HORIZONTAL ALIGNMENT TOLERANCE SHALL NOT EXCEED 3/4 INCH FROM POST TO POST. THE OVERALL VERTICAL SWTOLERANCE OF THE WALL (PLUMBNESS FROM TOP TO BOTTOM) SHALL NOT EXCEED 1/2 INCH PER 10 FEET OF WALL HEIGHT.

5. <u>MEASUREMENT.</u> SOUND WALLS WILL BE MEASURED BY THE LINEAR FOOT ALONG THE ALIGNMENT OF THE WALL. LENGTH WILL BE MEASURED FROM CENTER TO CENTER OF POSTS.

6. <u>PAYMENT.</u> THE WORK PERFORMED AND MATERIAL FURNISHED IN ACCORDANCE WITH THIS ITEM AND MEASURED AS PROVIDED FOR UNDER "MEASUREMENT" WILL BE PAID FOR AT THE UNIT PRICE BID FOR "SOUND WALL", OF THE HEIGHT SPECIFIED. THIS PRICE SHALL BE FULL COMPENSATION FOR FURNISHING AND INSTALLING ALL WALL MATERIALS INCLUDING ANCHORAGE INTO THE DRILLED SHAFT; FOR ALL SOUND WALL PREPARATION, HAULING AND ERECTION; AND FOR ALL LABOR, TOOLS, EQUIPMENT AND INCIDENTALS NECESSARY TO COMPLETE THE SOUNDWALL.

Houston Generic Post and Panel Noise Barrier Sample Drawings

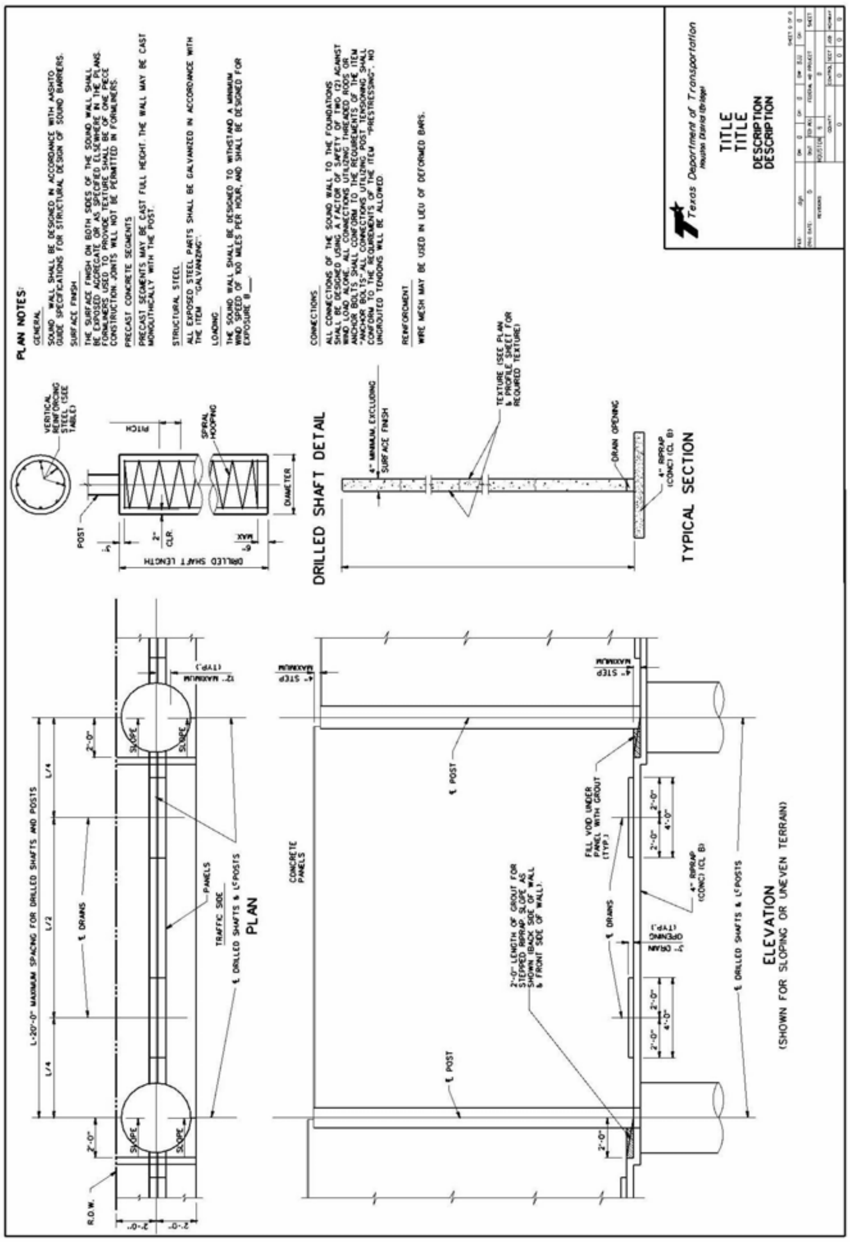

Figure 7.1 TxDOT Generic Post-and-Panel Noise Barrier Sample Drawings—Houston District (Sheet 1 of 8)

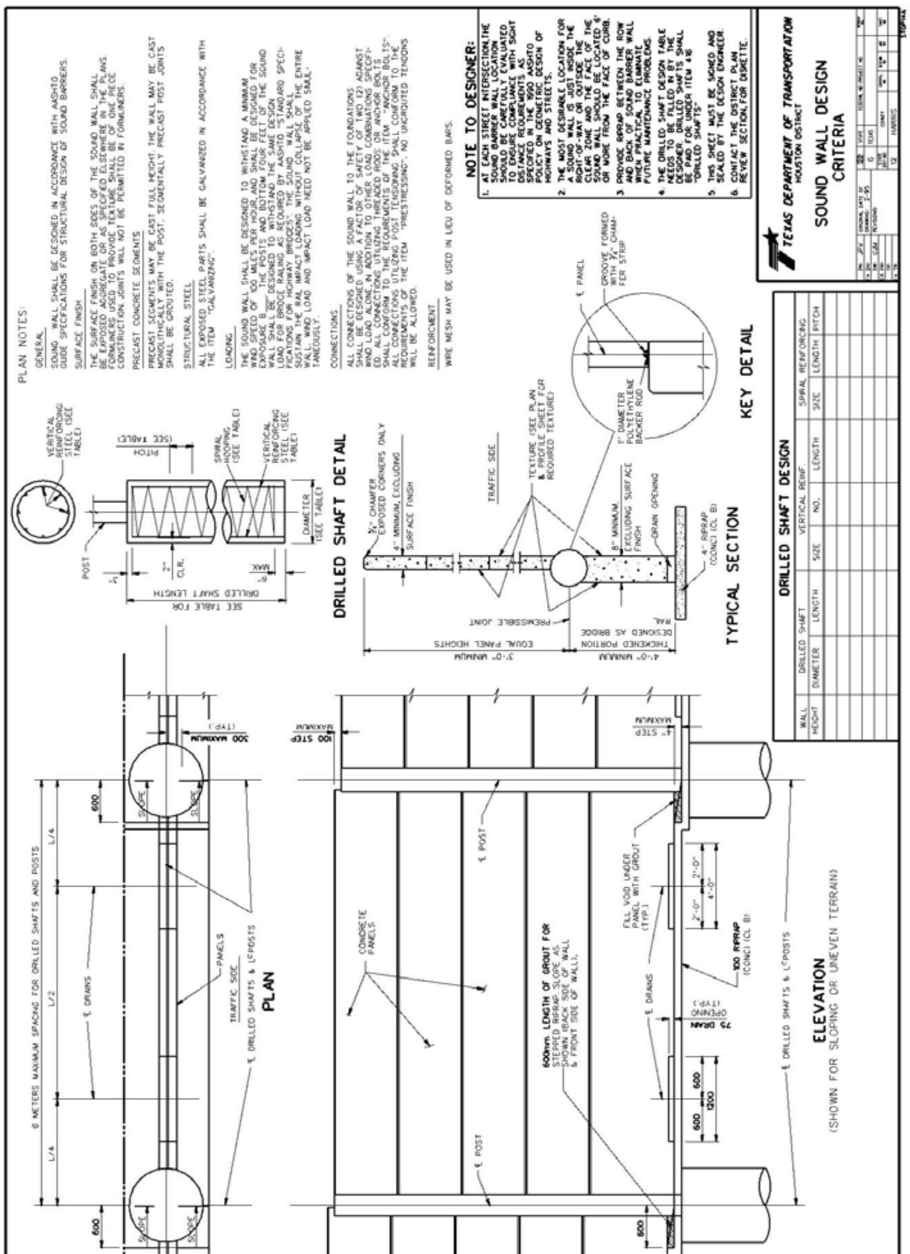

Figure 7.2 TxDOT Generic Post-and-Panel Noise Barrier Sample Drawings—Houston District (Sheet 2 of 8)

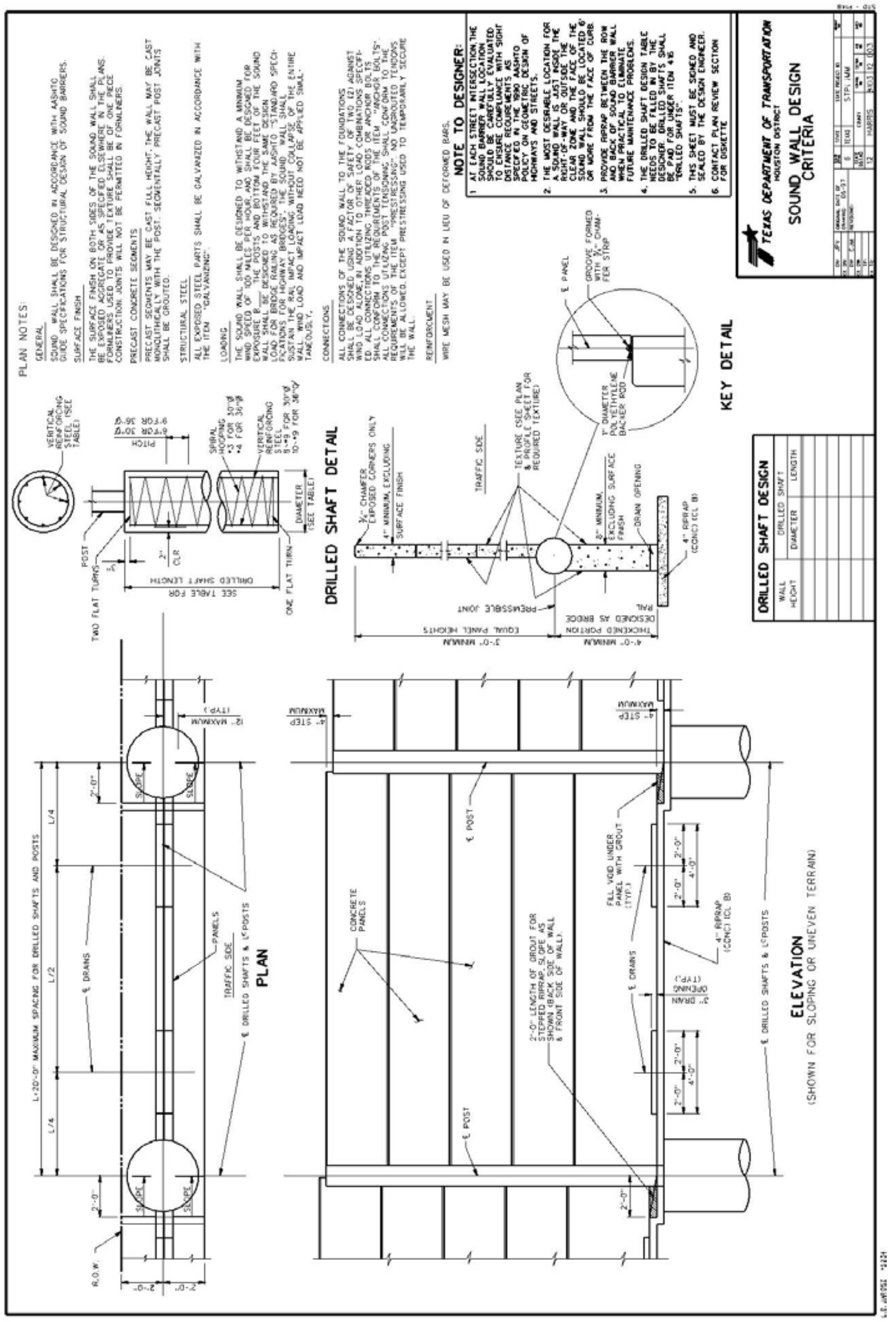

Figure 7.3 TxDOT Generic Post-and-Panel Noise Barrier Sample Drawings—Houston District (Sheet 3 of 8)

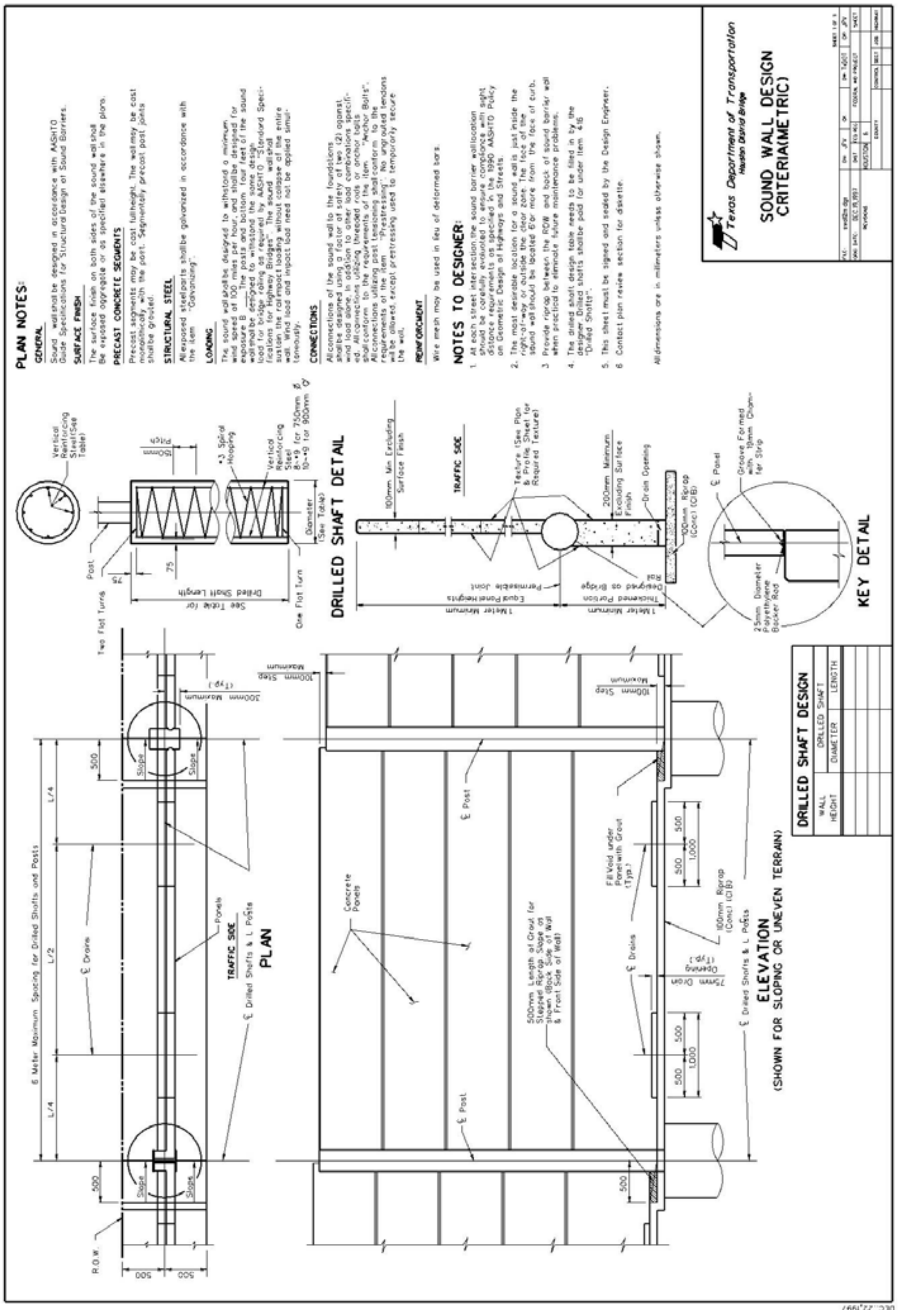

Figure 7.4 TxDOT Generic Post-and-Panel Noise Barrier Sample Drawings—Houston District (Sheet 4 of 8)

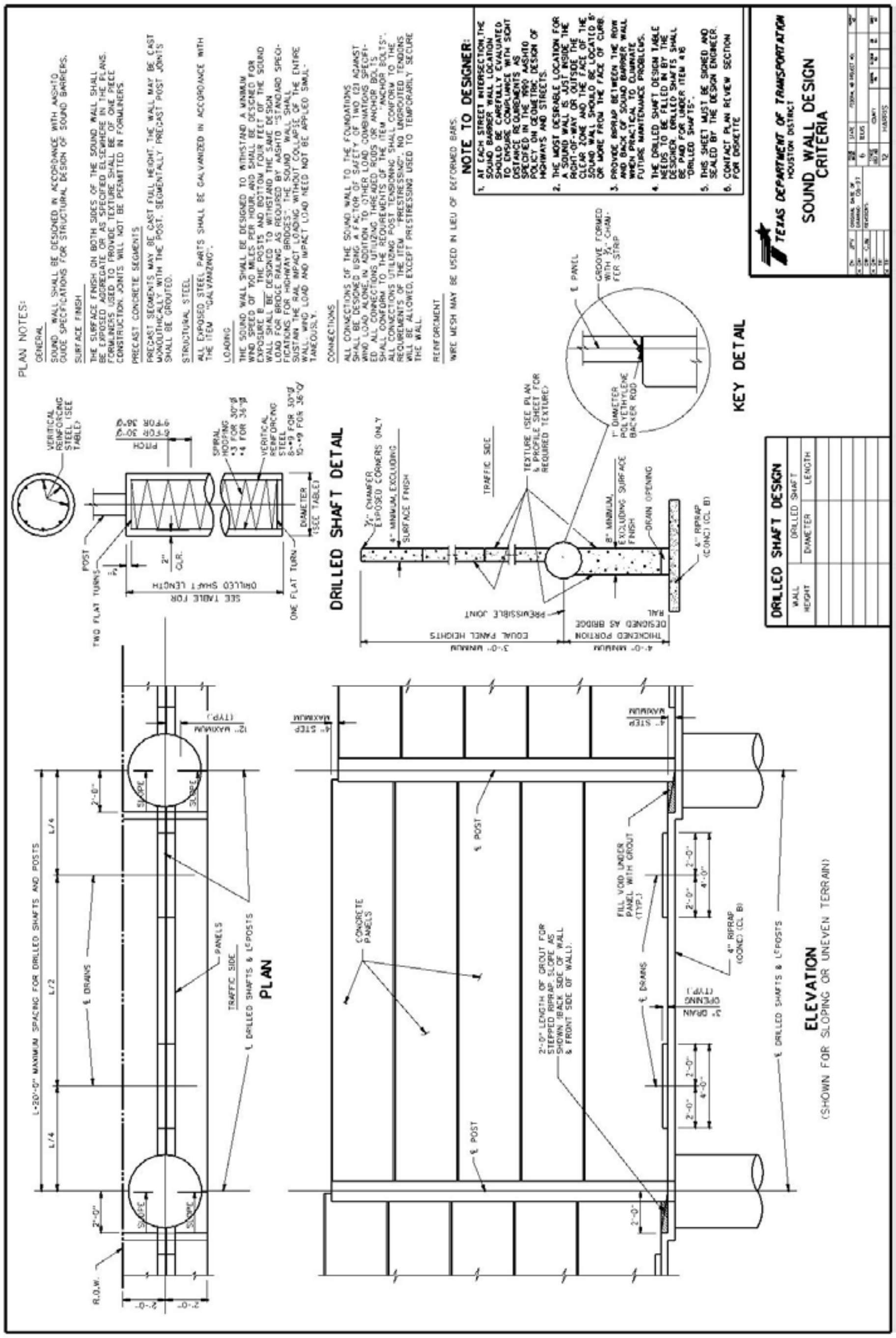

Figure 7.5 TxDOT Generic Post-and-Panel Noise Barrier Sample Drawings—Houston District (Sheet 5 of 8)

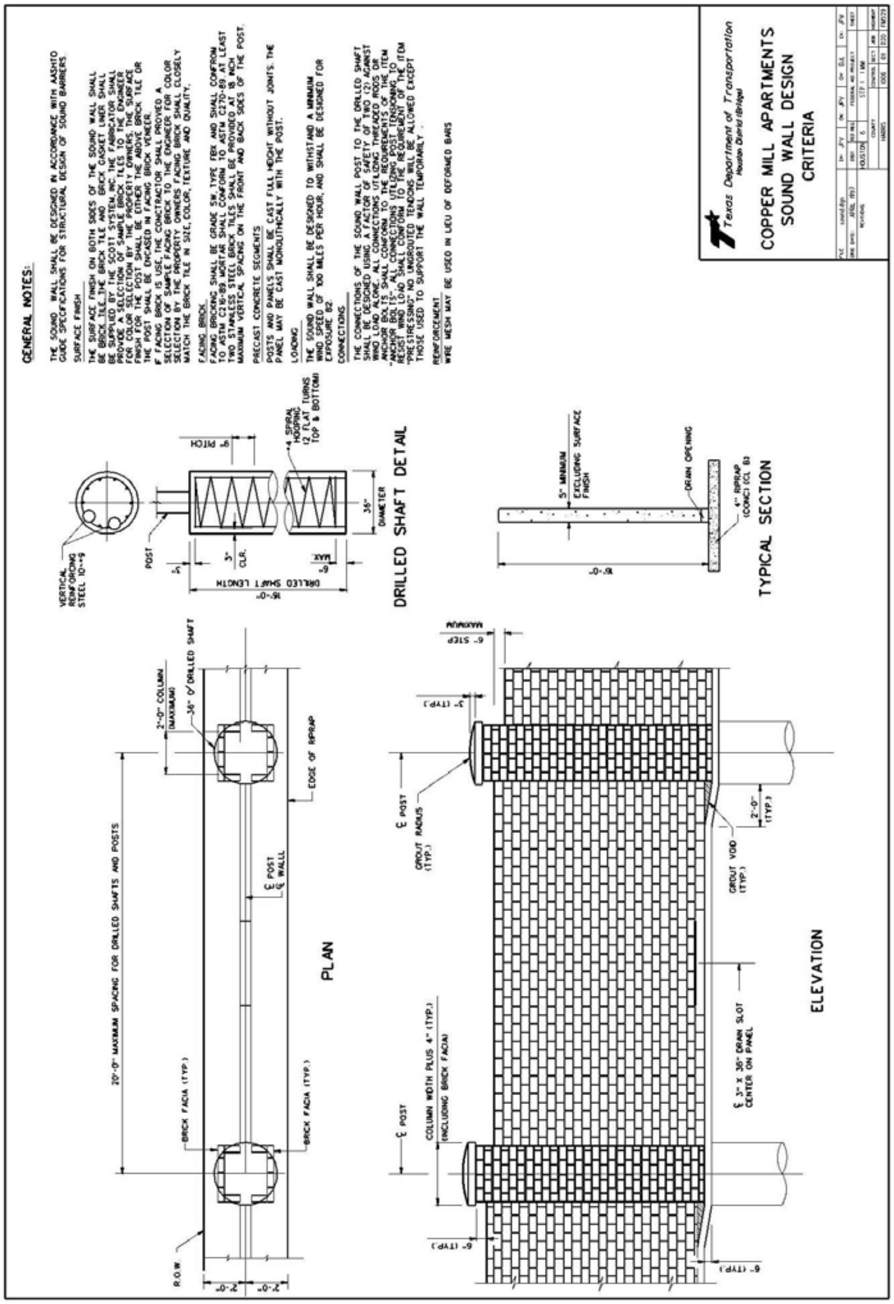

Figure 7.6 TxDOT Generic Post-and-Panel Noise Barrier Sample Drawings—Houston District (Sheet 6 of 8)

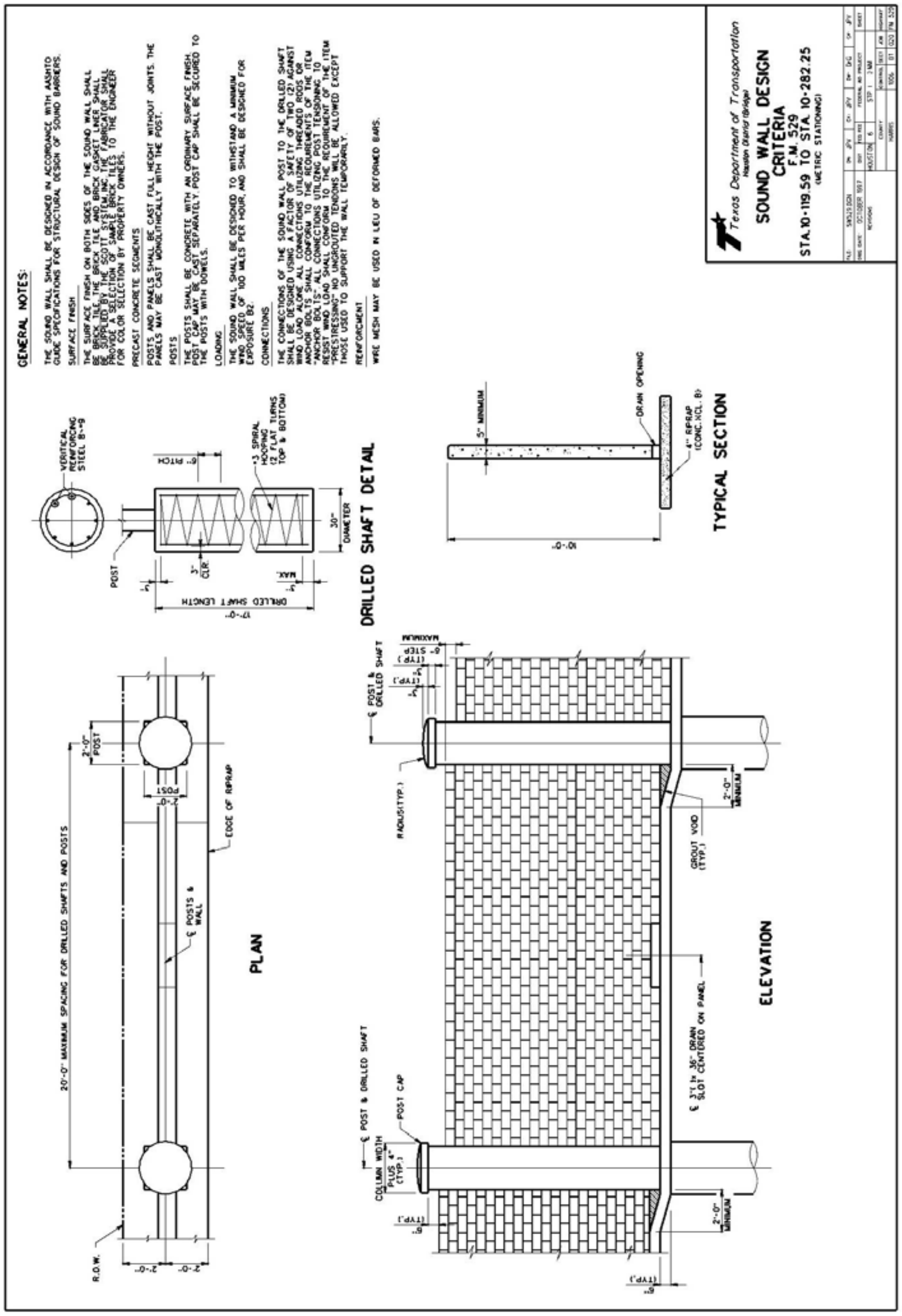

Figure 7.7 TxDOT Generic Post-and-Panel Noise Barrier Sample Drawings—Houston District (Sheet 7 of 8)

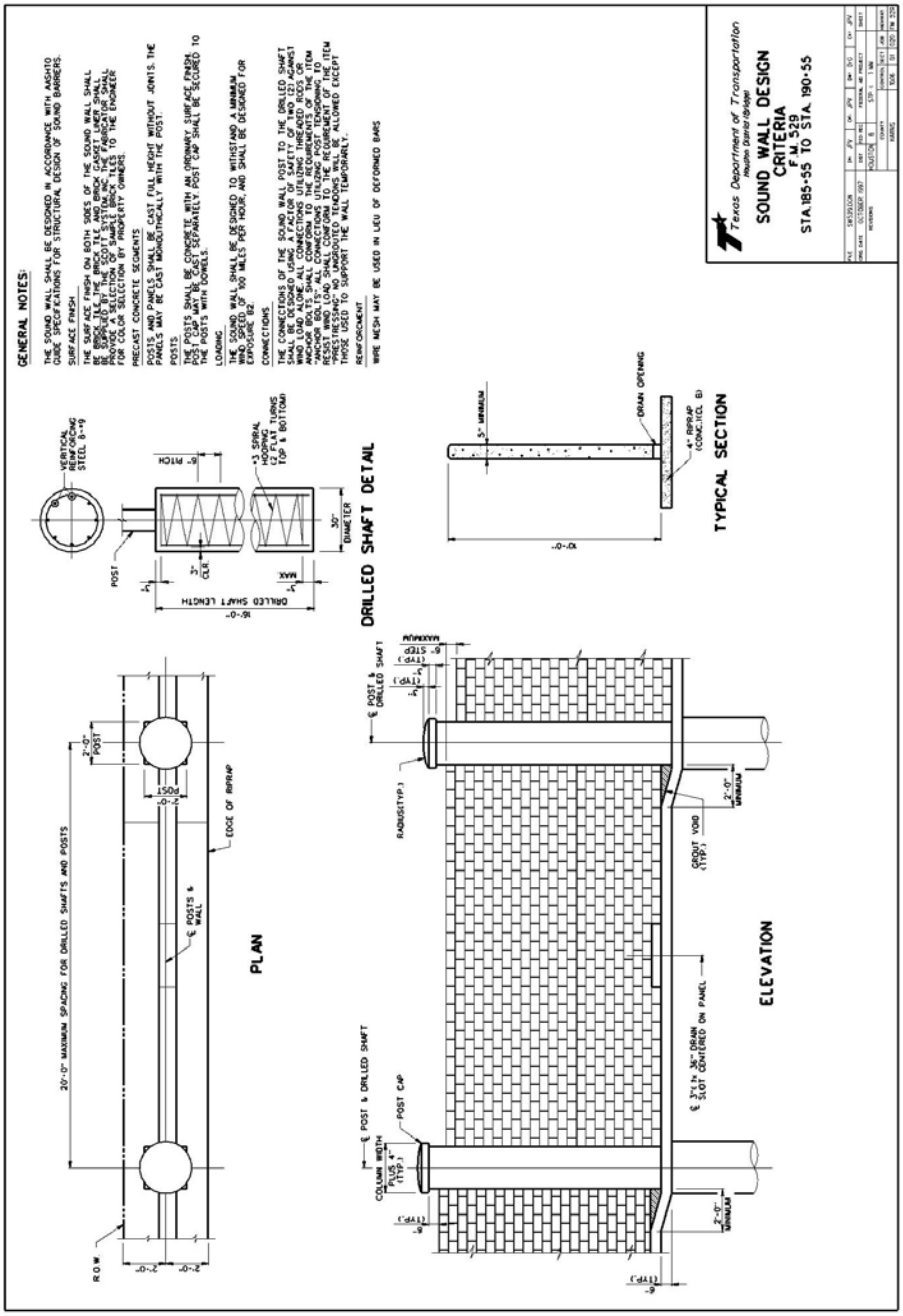

Figure 7.8 TxDOT Generic Post-and-Panel Noise Barrier Sample Drawings—Houston District (Sheet 8 of 8)

San Antonio–FM3009 Noise Barrier Drawings

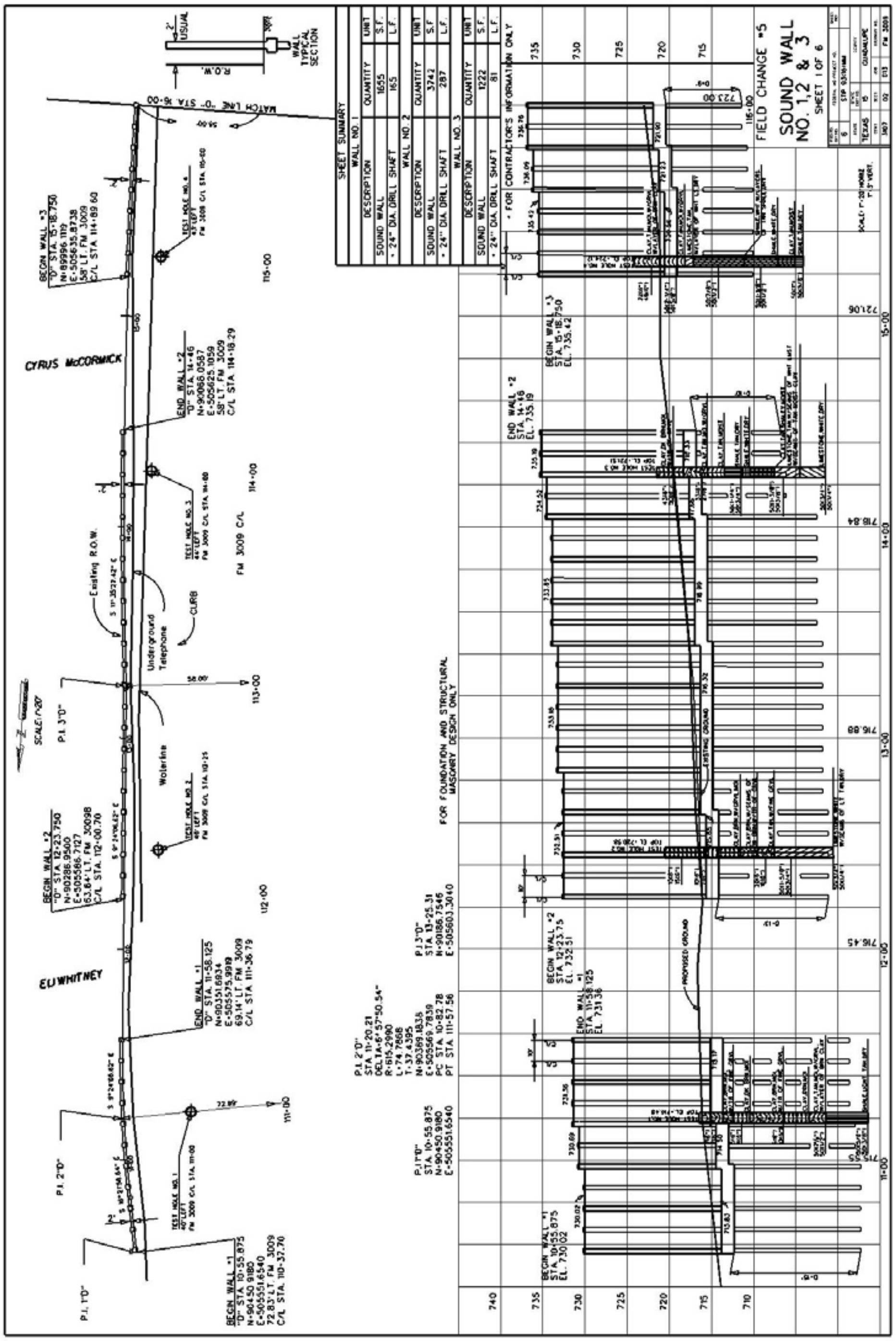

Figure 7.9 TxDOT FM 3009 Concrete Masonry Unit Noise Barrier Sample Drawings— San Antonio District (Sheet 1 of 6)

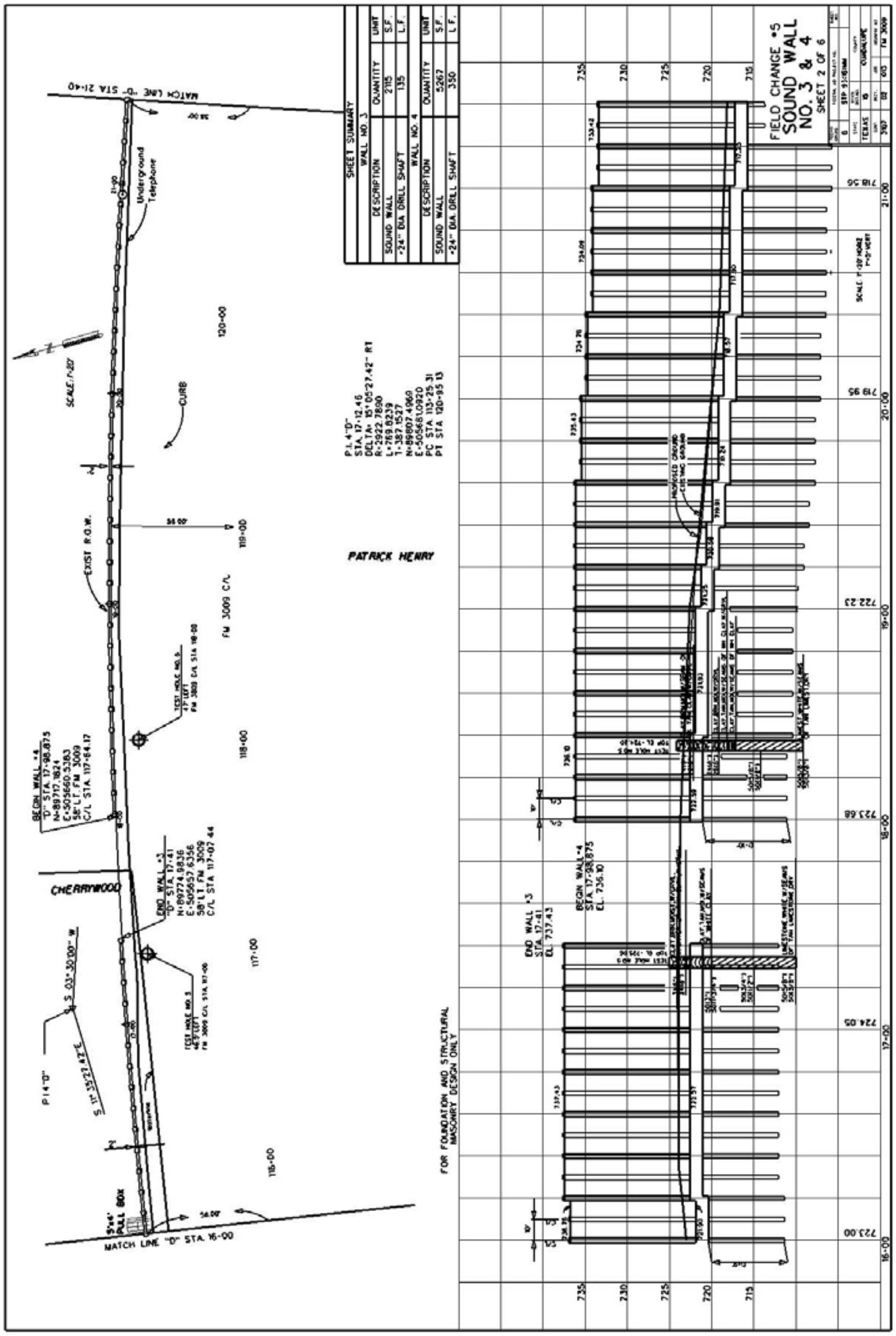

Figure 7.10 TxDOT FM 3009 Concrete Masonry Unit Noise Barrier Sample Drawings—San Antonio District (Sheet 2 of 6)

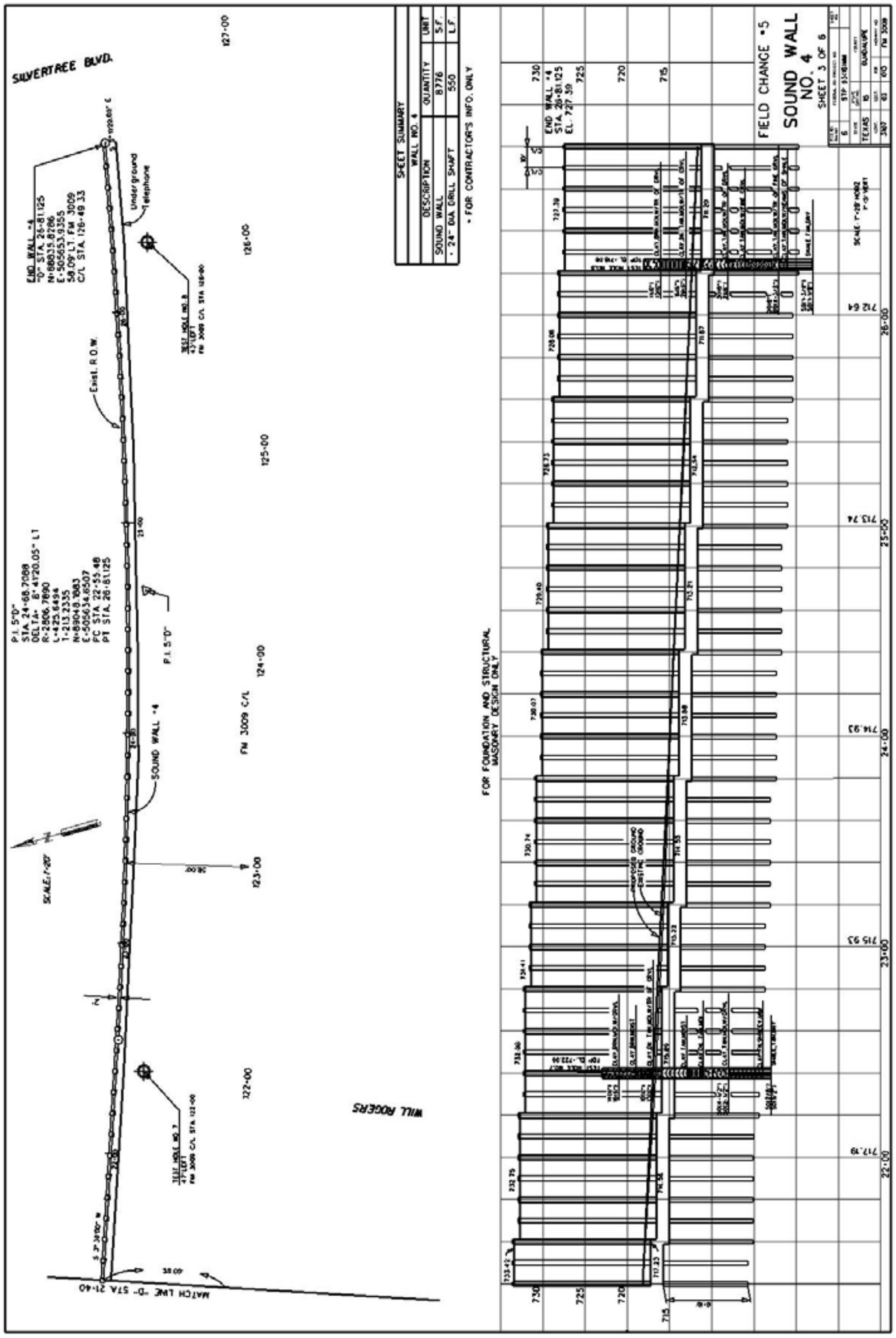

Figure 7.11 TxDOT FM 3009 Concrete Masonry Unit Noise Barrier Sample Drawings—San Antonio District (Sheet 3 of 6)

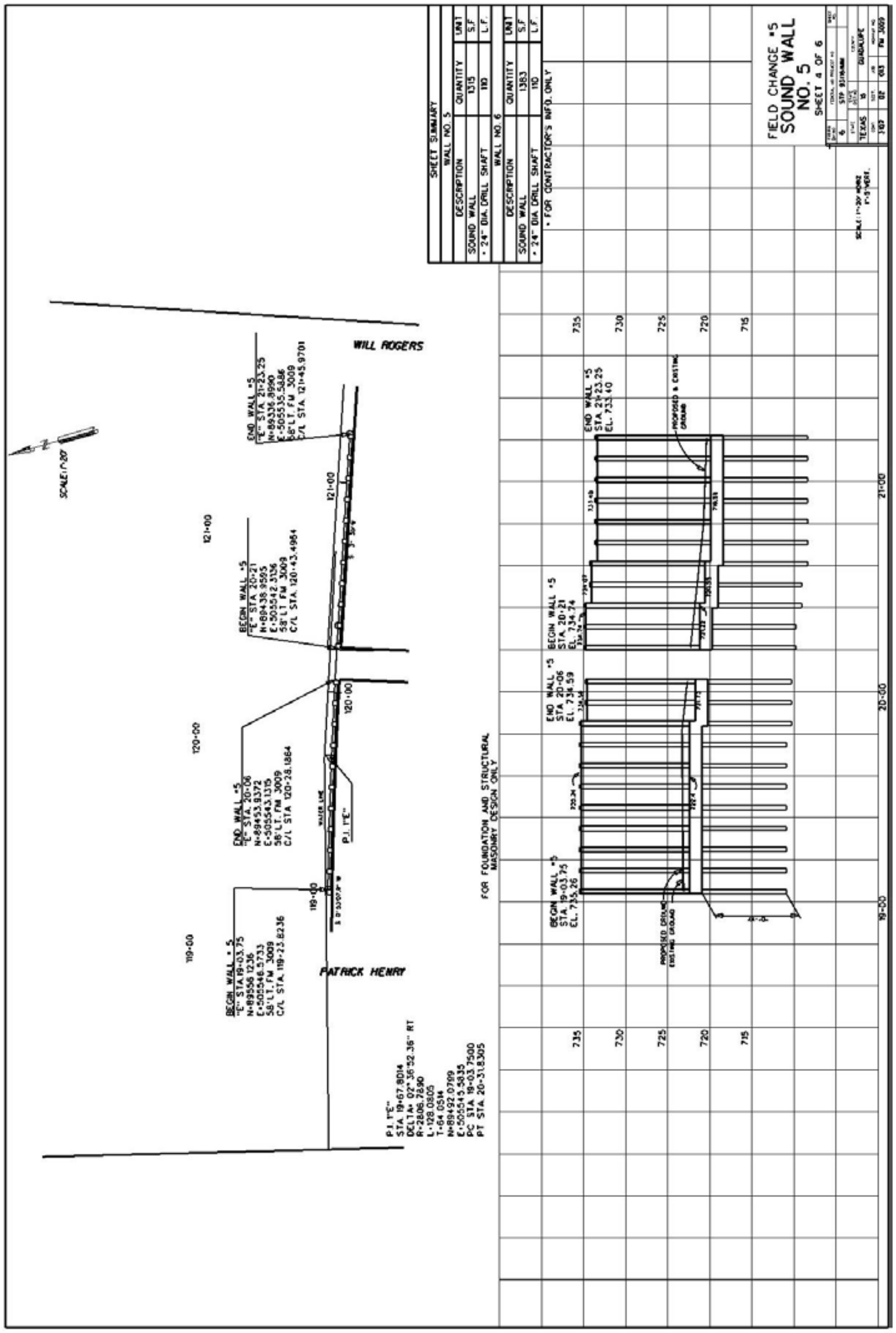

Figure 7.12 TxDOT FM 3009 Concrete Masonry Unit Noise Barrier Sample Drawings—San Antonio District (Sheet 4 of 6)

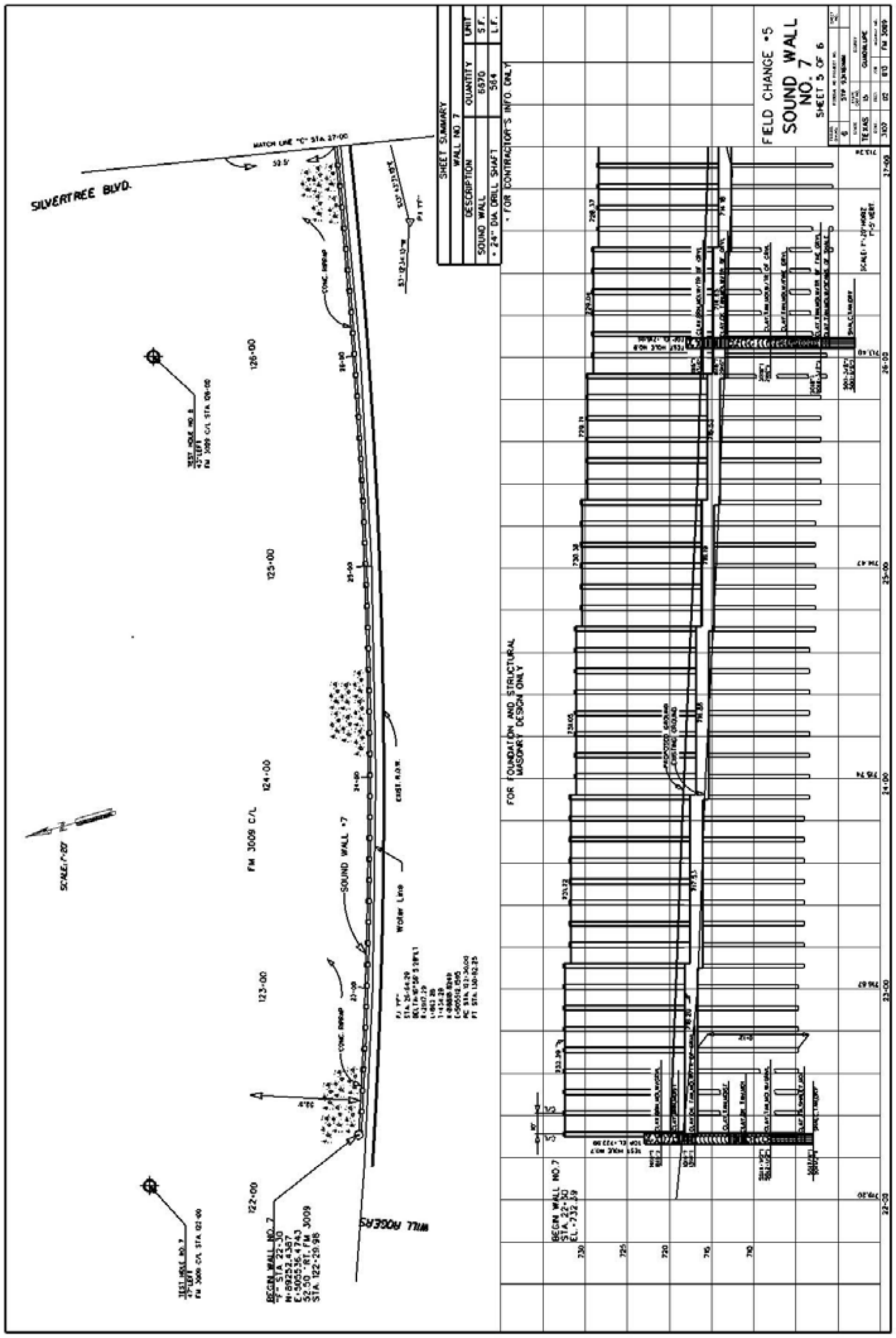

Figure 7.13 TxDOT FM 3009 Concrete Masonry Unit Noise Barrier Sample Drawings—San Antonio District (Sheet 5 of 6)

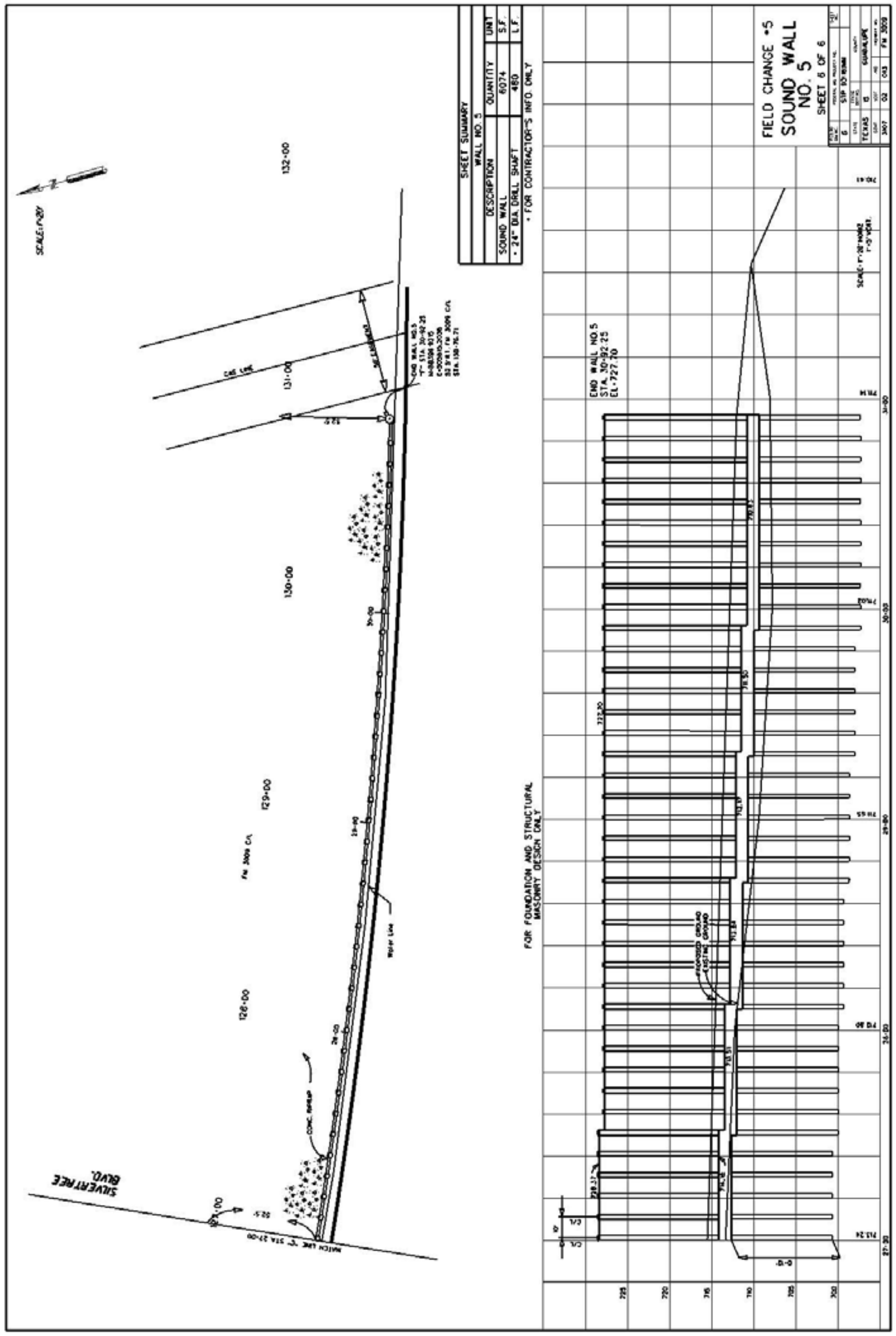

Figure 7.14 TxDOT FM 3009 Concrete Masonry Unit Noise Barrier Sample Drawings—San Antonio District (Sheet 6 of 6)

CHAPTER 8
SUMMARY OF DESIGN REQUIREMENTS FOR SOUND WALLS

General

Design requirements for sound walls can be classified into the following general categories:

- Acoustical requirements;
- Environmental requirements;
- Traffic safety requirements; and
- Structural requirements.

In the remainder of this Chapter, each category of requirements is reviewed and discussed in more detail in synthesized form, drawing on the material presented in previous chapters.

Acoustical Requirements for Sound Walls

The fundamental requirements of a sound wall are acoustical. One requirement is to reduce the noise level perceived by a receptor located away from the roadway (the source of the traffic noise). Another requirement may be to reduce the noise level perceived by a receptor located on the roadway itself. Because these requirements are quite different, they are reviewed separately below. More detailed information on them is given in Chapter 2 of this report.

Acoustical Requirements for Receptors Located Off the Roadway

To be effective, the sound wall must block the line of sight between the source and the receptor. From the viewpoint of the receptor located off the roadway, it is irrelevant whether the sound is absorbed by the wall or reflected back towards the source.

Most conventional wall materials (such as steel, concrete, masonry, or wood) can be used in thicknesses sufficient to block the sound. For all materials except perhaps wood, the thickness that would normally be used in sound walls to achieve structural performance and durability, is sufficient to block sound, and thus to fulfill this acoustical requirement. As discussed later in this chapter, minor openings (such as slight gaps between wall components, or drainage holes) have a negligible effect on the acoustical performance of a noise wall.

Acoustical Requirements for Receptors Located on the Roadway

If the wall must reduce the perceived noise level for receptors located on the roadway, additional acoustical requirements are imposed. The wall can be designed to meet these requirements by reflecting the sound upward, away from the roadway, or by absorbing the sound so that less of it is reflected back to the roadway. While wall texturing may have advantages for aesthetics or graffiti control, it does not affect reflected sound.

Environmental Requirements for Sound Walls

Environmental requirements address the effects of sound walls on their physical and their human surroundings, and their effects on drainage and flood control.

Effect of Sound Walls on Physical Surroundings

Sound walls are perceived by drivers and by receptors. Their effect on drivers depends on the speed of the vehicle, the height of the wall, the distance of the wall from the roadway, and surface texture of the wall. Their effect on receptors depends on the wall height, the distance of the wall from the receptor, and the surface texture and color of the side of the wall facing the receptor. This visual impact can be accentuated if the wall changes the pattern of light and shadow on the receptor's property.

Two design approaches are available: the wall can be designed to be monumental, or to blend with the landscape. Whichever approach is taken, the visual appearance of the sound wall should reflect the historical and archaeological context of the region in which it is placed.

Aesthetic Considerations for Sound Walls

- The wall must be compatible with its natural surroundings in scale, form (shape), and surface texture.
- The wall must be compatible with surrounding structures.
- The wall's appearance must not change over time, unless that change is visually pleasing.
- The wall must conceal, when possible, the marks of vehicular impact.

Drainage and Flood Control Requirements for Sound Walls

Depending on the size and location of the wall, the topography and rainfall characteristics of the area where it is located, and the design practices of the agency responsible for its construction, a formal flood modeling analysis may be required.

The probable effect of a sound wall on drainage depends on its plan length (the greater the length, the greater the effect), and also on its plan location with respect to known characteristics of water flow.

Wall details such as drainage holes have implications for drainage, and should be addressed consistently for all sound walls. Holes are typically placed in sound walls to prevent the walls from acting as dams. Experience in Texas and other states has indicated that the holes should be about 4 inches high. If they are narrower than that, cans and other debris cannot pass through them; if they are wider, children and animals can squeeze through them. Acoustical considerations indicate that as long as the total area of the drainage holes is less than about 3% of the area of the panel, their acoustical effects are negligible. Similar comments also apply to the small gaps that are part of normal construction tolerances in sound walls.

Traffic Safety Requirements for Sound Walls

Sound walls should not decrease the safety of those using the roadway, nor the safety of those adjacent to the roadway.

Requirements for Visibility and Sight Distance

Sound walls must be located so that they do not reduce visibility from vehicle to vehicle, or sight distance from vehicle to intersections, signs, or traffic signals. This requirement can severely restrict acoustical performance, since (as discussed previously) acoustical requirements can generally be met only if the wall blocks the line of sight between the source and the receptor.

Requirements for Effects on Light and Shade

If sound walls create patterns of light and shadow on the roadway, this can be hazardous: because of the time normally required for the human eye to adjust from bright sunlight to shadow, drivers' ability to detect objects on the roadway can be significantly impaired.

In some climates, shadow zones created by sound walls can create areas in which ice can form. Because of the light/dark visual adjustment problems noted above, the ice can be difficult for drivers to detect, thereby increasing its potential hazard.

Finally, sunlight reflecting from sound walls, or from layers of water or ice on the walls, can further impair drivers' vision.

Requirements for Vehicular Impact

Sound walls are not intended to function as vehicular impact barriers. If they are located close enough to the roadway to be impacted by vehicles, however, they must either be placed behind a conventional vehicular barrier, or be mounted on a vehicular barrier. The latter solution is not recommended by TxDOT. Noise barriers associated with vehicular barriers must be crash-tested according to FHWA guidelines.

Requirements for Guidance and Signing

Sound walls must not interfere with the natural placement of signs, nor with the natural cues that drivers use to locate roadway entrances and exits. Signs mounted on noise walls must be clearly visible, and must not project far enough to be a hazard to vehicles.

Requirements for Orientation

If sound walls obstruct landmarks from view, they can impair the ability of drivers to orient themselves. This can confuse drivers, reducing the capacity of the roadway and adversely affecting its safety.

Requirements for Emergency Access

Sound walls placed between the roadway and potential receptors must not restrict emergency access between the roadway and the receptors. Emergency vehicles might need to go from the roadway to the neighborhood, or vice-versa. Fire-fighting vehicles on the roadway might need access to water hydrants located in the neighborhood. Finally, individuals might need access from the roadway to the neighborhood in case of mechanical problems.

Requirements for Defensible Space

Sound walls must not reduce the personal safety of vehicular occupants nor of receptors by making the space around them less defensible. Sound walls should not provide locations for concealment of individuals with criminal intent, nor should they provide access routes along which such individuals could travel, undetected, along the roadway or along the edge of the neighborhood.

Requirements for Safety from Overhead Power Lines

Sound walls must be located far from overhead power lines, to reduce the danger of electrical shock to those near them.

Structural Requirements for Sound Walls

Determination of Primary and Secondary Design Loads

Primary design loads (those which are ordinarily critical for the wall's structural design) normally include wind only. Secondary design loads (which must also be considered, but are usually not critical) normally include loads from gravity, water pressure, loads, and earthquake.

Design of Wall Elements for Given Loads

Although this step might seem trivial, it is not. Structural elements in sound walls are not easily categorized as beam, columns, or walls. Consequently, there may be confusion about which code provisions to apply. In addition, some proprietary sound wall systems use structural configurations or structural materials for which code design provisions are not available. In such cases, design and approval may have to be on the basis of test data or the general provisions of the building code. Transportation department engineers may not have the expertise or computer programs to check a manufacturer's submittal.

Constructability

An efficient structural design, by itself, is not as useful as a less efficient system that can be easily built.

Detailing of Movement and Construction Joints

The sound wall must be provided with joints to accommodate deformations due to structural loads, differential settlement of the underlying soil, and differential shrinkage or expansion of wall materials. The joints must accommodate inter-element movements to prevent spalling, which can have structural as well as aesthetic consequences. Gaps introduced into the walls by joints are rarely significant enough to reduce acoustical performance.

The connection between the foundation (usually a drilled shaft) must be carefully detailed to limit the deformations of the wall under design loads, while permitting simple construction and replacement.

Requirements Imposed by Adjacent Utilities

Influence of Buried Utilities

Buried utilities, if they exist, can restrict the type of foundation that can be used for the sound wall. Either the buried utilities must be re-located, or the foundation must avoid the utilities, or the wall must be of a type not requiring a buried foundation.

Influence of Overhead Utilities

Overhead utilities, if they exist, can limit the maximum height of the sound wall, and also limit how cranes are used in construction. It may be necessary to re-locate overhead utilities, or modify the design of the sound wall.

Access for Future Maintenance

In addition, the presence of the sound wall can restrict future maintenance access to the overhead utilities. Maintenance plans may have to be revised because of the presence of the sound wall.

Soil - Foundation Requirements

Relation between Soil Type and Foundation Type

Although different types of foundations would theoretically be optimum for different types of underlying soil, the use of a single type of foundation has significant design and cost advantages. In addition, new technology (the "auger pile" technique for excavating and placing concrete in a drilled shaft in a single operation) has significantly reduced the costs of drilled shafts in general. Because drilled shafts are highly resistant to differential settlement, and because they greatly reduce the possibility of collapse (as contrasted with foundations involving grade beams only), modern sound wall design has tended to favor the use of drilled shaft foundations on 20- to 24-foot centers, regardless of the underlying soil.

Serviceability Requirements for Sound Walls

Capability for Relatively Simple Replacement

Over time, sound wall posts may lean, and need to be plumbed or replaced. As a result of vehicular impact, posts or the panels between them may be badly damaged. It must be possible to replace posts or panels without much more effort than was originally required to install them.

Resistance to Surface Degradation

Sound walls must retain their surface appearance in spite of natural weathering, and also hazards such as graffiti. Walls must be easy and inexpensive to clean. If necessary, they must accept clear coatings or sealers that increase their resistance to graffiti or their ability to be cleaned.

Resistance to Joint Degradation

Sound walls must be provided with movement joints to accommodate differential movement due to various causes. Any elastomeric sealants used to close these joints must be accessible for replacement.

CHAPTER 9
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

In this report, the current TxDOT design process for highway noise barriers is reviewed (Chapter 1). Design requirements for them are then presented. These include acoustical requirements (Chapter 2), structural requirements (Chapter 3), safety requirements (Chapter 4), and aesthetic requirements (Chapter 5). In Chapter 6, examples are given of different highway noise barriers used in Texas. In Chapter 7, sample plans and specifications are presented. In Chapter 8, design requirements are broadly grouped into acoustical requirements, environmental requirements, traffic safety requirements, and structural requirements; those requirements are again presented in synthesized form, drawing on the material presented in the preceding chapters.

Conclusions and Recommendations for Implementation

A wide range of highway noise barriers has performed satisfactorily in Texas. The information given in this report is intended to help TxDOT designers produce highway noise barriers that are effective from the viewpoints of acoustics, environment, traffic safety and structure.

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