Green Noise Wall Construction and Evaluation

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16. Abstract

This report details the research performed under Phase I of a research study titled "Green Noise Wall Construction and Evaluation" that looks into the feasibility of using green noise barriers as a noise mitigation option in Ohio. This phase included a thorough review of available green noise barriers to assess their advantages and disadvantages. In addition, it included a questionnaire that was sent out to more than three hundred national and international experts in traffic noise analysis and abatement to document their experience with this type of barriers. Based on the outcome of the literature review and responses to the questionnaire, the Deltalok product was determined to be the most likely product to succeed in Ohio. A prototype Deltalok wall, measuring 15 ft in length, 9 ft in width, and 12 ft in height, was constructed in Covington, Ohio (north of Dayton) to evaluate its structural stability and ability to retain moisture. The prototype wall was equipped with various sensors and devices to monitor its earth pressure and deformation characteristics and examine the moisture and temperature distributions within the barrier. The prototype wall was monitored for a period of two months. The data collected from these sensors and the visual inspections allowed for making several recommendations regarding the construction of the Deltalok system and its use as a green noise barrier. Phase I also included a laboratory plant study that allowed for making recommendations regarding the vegetation selection, soil modification, and watering needs of the Deltalok system. It was not possible in this phase to evaluate plant establishment and long-term survival in a natural highway environment since this requires constructing a full scale barrier and actually planting it, as planned in the second phase. Finally, Phase I estimated the anticipated noise reduction from the proposed full scale green noise barrier using the Federal Highway Administration's (FHWA) Traffic Noise Model Version 2.5. The predicted noise reduction at the proposed barrier site was found to exceed ODOT's noise barrier design criteria.

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Abstract

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Chapter 1
Introduction

1.1 Problem Statement

Over the years, considerable research has been performed towards effective and practical noise abatement measures. Some of these techniques include traffic management, use of quieter and noise absorbing pavement surfaces, improving land use and planning, and finally the installation of noise barriers. Generally, the most cost effective and efficient noise abatement option is the use of a noise barrier. As a result, numerous guidelines and specifications have been developed for noise barriers to ensure safety, cost effectiveness and substantial noise reduction. These guidelines include information about determining the need for a noise barrier, design and safety considerations, environmental considerations, potential impact, and implementation procedures.

While constructing an effective noise barrier is a priority in areas where traffic noise impacts are substantial, the needs of the residents in that area must be taken into consideration. In order to gather public opinion on whether a community desires and supports the construction of a noise barrier, the Ohio Department of Transportation (ODOT) holds public information meetings, and surveys the affected public to gauge their support for a noise barrier project and to receive feedback about preferences for the design. However, residents and concerned citizens are limited in the options they are presented with for noise barriers. Typical options for noise barrier structures involve the use of concrete or fiberglass. However, no option exists for a “green” noise barrier at this time.

A green noise barrier is a noise barrier that utilizes soil and vegetation to mitigate traffic noise. This type of barrier is expected to offer many benefits when compared to traditional noise barriers. Among these benefits are: a construction process that is expected to have a lesser impact on the environment; a structure that provides aesthetic beauty to the surrounding area; a structure that can block and absorb a substantial amount of air pollutants from vehicles; and most importantly a structure that offers a competitive noise reduction due to its core that is made of soil and its vegetated surface that can absorb and reflect traffic noise.

In spite of the above-mentioned advantages of green noise barriers, several concerns have been raised regarding their long-term performance and ability to sustain vegetation under adverse weather conditions. Therefore, research is needed to determine whether a green noise barrier is a viable noise mitigation option for Ohio's climate.

1.2 Objectives of the Study

The primary objective of this study is to determine the feasibility of using a green noise barrier as a traffic noise mitigation option in Ohio. To achieve this objective, this study will be conducted in two phases. The first phase is focused on reviewing available green noise products in order to assess their advantages and disadvantages. Key factors to be considered include initial and vegetation costs, ease of construction, structural stability, noise reduction and plant sustainability. This phase also looks into viable plant species through a comprehensive plant study. In addition, it includes constructing a prototype wall, measuring 15 ft in length, 9 ft in width, and 12 ft in height, in order to assess its structural stability and ability to retain moisture. The results of this phase will be evaluated so that recommendations can be made on the construction of a full scale barrier in the second phase. The full scale barrier will be 400 ft in length. A tentative location for this barrier has been selected along the eastbound direction of interstate I-70 in Licking County. The first phase will determine the suitability of constructing the full scale barrier in that location.

Based on the previous discussion, the specific objectives of the first phase of this study are:

- Prepare a synthesis of literature review on subjects pertinent to noise barriers.
- Review available green noise barrier products.
- Summarize the experience of state highway agencies with green noise barriers.
- Construct a prototype green noise barrier and monitor its structural stability and ability to retain moisture.
- Compare the noise reduction and cost/benefit ratio of green noise barriers to conventional noise barriers.
- Make recommendations on the construction of the full scale green noise barrier along interstate I-70 in Licking County.

1.3 Report Organization

This report is organized into eleven chapters. Chapter 2 presents a literature review of subjects pertinent to this study. It provides an overview of sound and traffic noise along with the problems it poses to society and state highway agencies. Chapter 3 contains a thorough review of available green noise barriers and the advantages and disadvantages of each design. Chapter 4 discusses previous green noise barrier attempts along with expert analysis, suggestions and recommendations. Chapter 5 describes the construction process of the prototype wall. Chapters 6 and 7 detail the instrumentation used to monitor the prototype wall. Chapter 8 outlines the vegetation study that was conducted to determine which plant species would be best suited for the barrier. Chapter 9 presents the traffic noise model (TNM) of the full scale green noise barrier site. Chapter 10 compares the estimated cost of the proposed full scale green noise barrier and a traditional concrete barrier. Finally, Chapter 11 provides conclusions and recommendations for the construction of the full scale green noise barrier along interstate I-70 in Licking County based on the experience with the prototype wall and the research performed in Phase I.

Chapter 2
Literature Review

2.1 Introduction

Transportation is a vital part of economic development and prosperity. As our infrastructure develops, the volume of traffic and amount of roadway miles increases which also increases the amount of noise that comes from traffic. This increase of noise has caused noise reduction to become a top priority in preserving the tranquility of surrounding communities.

In order to keep up with the demands of society for quieter communities, there are three techniques to reducing noise (*1*). The first technique is through the control of land use adjacent to highways. Through careful planning, industries and businesses that are not affected by traffic noise can be placed near highways and more sensitive activity categories like hospitals, churches, libraries and residences can be placed further away from the highway. This is a technique that can only be used for developing communities and cannot be implemented for existing communities. The second technique is the practice of mitigating traffic noise through quieter vehicles. Through government standards and consumer demand for quieter vehicles, the level of noise that reaches a home or business can be reduced. When the first two techniques are not possible or fail to have the desired noise reduction results, the final technique is to mitigate traffic noise with individual noise abatement measures. There are many options for individual noise abatement projects like quiet pavements and active noise cancellation. However, for the majority of noise abatement projects the Ohio Department of Transportation (ODOT) is restricted to the implementation of noise barriers.

There are two types of noise abatement projects, Type I and Type II. Type I projects involve the construction of a new highway or the physical alteration of an existing highway by changing the horizontal and/or vertical alignments or by increasing the number of lanes. A traffic noise analysis is required for any project that meets the description of a Type I project. The noise analysis is used to determine the severity of the noise impact and the need for mitigation. The analysis considers all noise sensitive land uses within 500 ft of the edge of pavement of the proposed project. Consideration is limited to exterior areas of frequent human use, except for nonprofit institutions such as places of worship, schools, libraries, and hospitals, which can be considered for interior noise levels. On the other hand, Type II projects (also called “retrofit” noise abatement projects) involve analyzing traffic noise for existing highways where no construction is planned. The implementation of Type II projects is optional and is not required by the Federal Highway Administration (FHWA) regulations. ODOT implements this program with the objective of providing acoustic protection to residential areas where substantial land development predated the existence of any highway. To prioritize noise sensitive areas around the state in a fair and consistent manner, ODOT uses the Noise Abatement Priority Index (NAPI), which takes into consideration the current average daily traffic (ADT), the proximity to the highway, the length of time the impacts have existed, and the density of the development.

To determine if a noise barrier is a feasible and reasonable noise mitigating option for a community, ODOT considers several parameters (*1*). First, the topography of the location adjacent to the roadway is considered. If the land is too steep, noise barriers may not be a viable option for noise reduction. Second, ODOT considers access requirements. Since noise barriers are continuous structures, they may not be suitable for an urban environment with many access points. The next consideration is the presence of intersections. Because noise barriers restrict the vision of traffic, they are not suitable for cross roads. The fourth constraint for the insertion of a noise barrier is whether the noise that causes a disturbance is generated from traffic or another source. For instance, if the noise that is disturbing an area is caused by planes or trains instead of traffic, noise barriers would not be a viable noise mitigating technique. The fifth factor that must be considered is drainage. This not only means the drainage around the barrier that may cause the structure to fail, but also whether the barrier will restrict the runoff from nearby roadways. Finally, ODOT considers the utilities in the area where the proposed noise barrier would be constructed. Major pipelines, power lines and other utility services will prevent the construction of a noise barrier.

Once the study is completed on the physical limitations by ODOT at a potential noise barrier site, there are two final stages in the preconstruction of a noise barrier. These stages are the cost analysis and the investigation of social impacts. To ensure that a noise barrier is feasible, ODOT uses the cost-to-benefit ratio as part of the traffic noise analysis process. This ratio is calculated by dividing the total estimated cost of the noise barrier by the number of benefiting residential units (front row residential units receiving 5 dBA or more noise reduction and other residential units receiving 3 dBA or more noise reduction). If the estimated cost per residence is $35,000 or less, the noise barrier is deemed cost effective. The concepts detailing the measurement units of traffic noise will be covered in subsequent sections. Finally, when a noise barrier is considered as a noise abatement option, ODOT meets with the affected public and provides them with the opportunity to decide whether or not they want a noise barrier, and solicits their feedback about preferences for the design. If a community chooses to go forth with the construction of a noise barrier, they have few choices in terms of materials. Currently the standard options for noise wall material are concrete and fiberglass. However, no options exist for a “green” noise wall at this time.

While there are currently no green noise barrier options that are approved by ODOT, there are available products that have been used in other regions of the United States and other countries. This study reviews available green noise wall products to determine their suitability for Ohio’s environment. In order to better understand the performance of such barriers, a review of sound and traffic noise is necessary.

2.2 Sound

Sound is one of the most complex senses that humans experience every day. In today’s rapidly expanding infrastructure, sound is an important factor in shifting toward a more integrative and natural transportation system. To better understand the sounds emitted from traffic, a basic understanding of the physics of sound is needed. Therefore, the following subsections offer a brief presentation of these concepts.

2.2.1 Sound Source

The source is the key to sound generation. A source is an object that creates and emits vibrations. These vibrations interact with the surrounding air particles causing pressure differences. These changes in pressure propagate longitudinally away from the source. An example of a source of sound is a drum. When a drum is struck by a drum stick the surface of the drum vibrates. As a result, the air particles near the surface of the drum are forced to vibrate.

2.2.2 Sound Waves

In their most basic form, sound waves are changes in pressure and are represented by sine waves (Figure 2.1). When a source vibrates, it causes the surrounding air molecules to move. The air molecules that are moved directly by the source cause a chain reaction forcing the surrounding air molecules to move. This is similar to a spring being compressed and then allowed to uncoil. When pressure changes are gradual, as with weather, the pressure changes do not create sound. In order for sound to be heard by the human ear, pressure changes need to be combined with oscillations, also known as frequencies. The human ear can hear pressure changes when they have a frequency of 20 to 20,000 oscillations per second or hertz, Hz (*2*). The frequency of the sound wave determines the pitch. If the sound wave has a high frequency then the pitch will be high, if the sound wave has a low frequency then the pitch will be low. The final component of sound waves is the amplitude. The amplitude relates to the amount of energy that the sound wave contains, where higher amplitude indicates a higher energy.

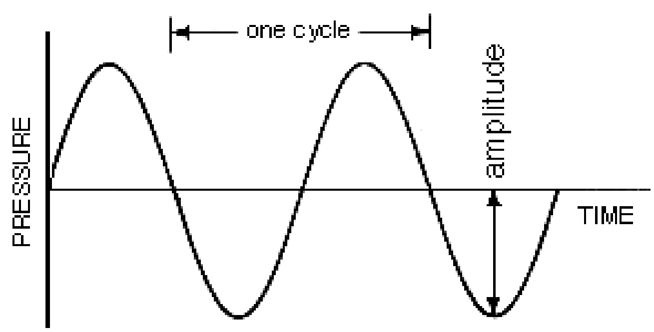


Figure 2.1: Sinusoidal Sound Wave (*3*)

2.2.3 Receptor

The receptor is any person or place that receives sound waves. The important factors that differ between receptors are: sensitivity, environment, and distance from the source. The sensitivity of a receptor varies from one person to another and from place to place. For example, a library is going to be more sensitive to higher sound levels than a manufacturing facility. This is due to the variation in perceived sound levels. If a lawnmower was started in a library, everyone would be able to hear the sound emitted from the lawnmower. However, if the same lawnmower was started in a facility with other noise emitting sources, the lawnmower will not be noticed due to the higher level of sound in that area.

Environment also plays a role in the way sound waves are received. Wind, temperature, ground surface and medium through which sound waves travel all affect sound waves. Wind can either enhance or restrict sound waves depending on the direction of the sound wave and the direction of the wind. If the sound propagates in the same direction as the pressure waves of the wind, the wind can carry the sound waves to further distances making the sound louder. This principle works in reverse if the wind and sound travel in opposite direction because the wind restricts the changes in pressure. Temperature also impacts the way sound waves travel. If the temperature is cold, the sound waves can move through the air with less disturbance and deflection from air molecules. Meanwhile, in warm air, sound waves are deflected by the more active air particles. Therefore, sound waves are perceived to be louder at lower temperatures than at higher temperatures. Along with wind and temperature, distance between the receptor and the source also impacts the perceived sound level. The distance a source is from the receptor impacts the loudness because sound waves lose energy as they travel. Finally, the medium through which the sound travels impacts how loud a sound is perceived. For instance, sound waves travel much faster through water than air. This means that a sound in a humid climate will be louder than the same sound in a dry environment. Therefore, the medium through which the sound waves travel impacts the way sounds are heard by the receptor.

2.2.4 Decibels

The basic unit of sound is the decibel (dB). The decibel is a unit of measure that relates a physical quantity like noise level to a known reference level. It follows a base ten logarithmic scale. This offers many advantages like representing large and small numbers conveniently.

2.3 Noise

When undesirable levels or quantities of sound are emitted from a source, the product is noise. Noise can also be produced by multiple sources, which is the case in traffic noise. Automobiles emit sound form a variety of sources including the engine, brakes, exhaust and the interaction of tires and pavement. When multiple sound waves combine, the result is a sound wave that is not an ideal sinusoidal wave, but a combination of multiple waves, as shown in

Figure 2.2. This combined sound wave is what makes noise mitigation a complex science. Traditional noise barriers are capable of blocking part of this sound wave, but sound waves at lower frequencies can pass through or reverberate off concrete noise barriers. This vital flaw in traditional concrete barriers has led to the research of other noise reduction techniques and materials as will be further discussed in subsequent sections.

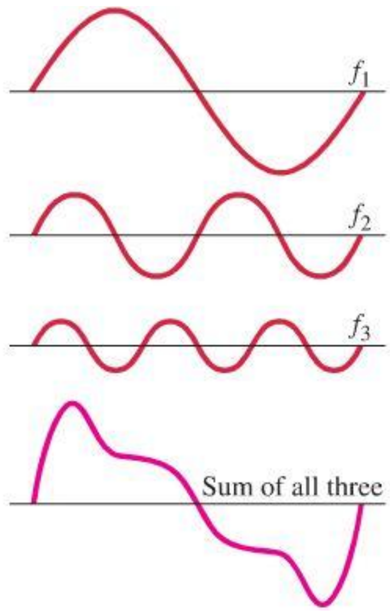


Figure 2.2: Combined Sound Waves (*4*)

2.3.1 A-Weighting

Sound weighting is used to describe the impact of noise on human hearing and represent how humans perceive a given sound. While there are many sound weighting systems, and many overlap (Figure 2.3), A-weighting is the most common. This system represents the response of human hearing to sound waves. It is commonly used to determine the impact of sound levels from transportation and industry on the surrounding environment. As shown in Figure 2.3, if a sound is determined to have a frequency of 200 Hz, the relative response using the A-weighting system would be -10 decibels. This means that at a frequency of 200 Hz, a sound of 100 decibels would actually be perceived as 90 decibels according to the A-weighting scale.

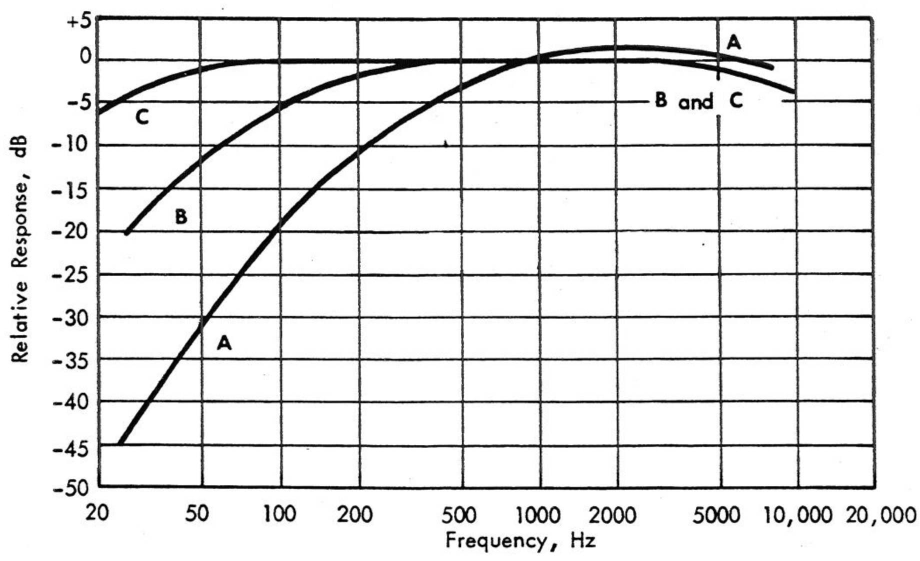


Figure 2.3: A, B, and C-Weighting Scales (*2*)

2.3.2 L_{Aeq} Noise Level

Since sound is not constant and varies over time, the average equivalent sound level for a given time period, L_{Aeq}, is typically used to describe the prevailing noise level. Figure 2.4 demonstrates the concept of the L_{Aeq}. By using the L_{Aeq}, a sound level can be assigned to an area to represent the overall sound level, including any fluctuations. The L_{Aeq} uses the A-weighted scale to determine the average equivalent sound level and presents the results in a way that human sensitivity to these sound levels can be determined.

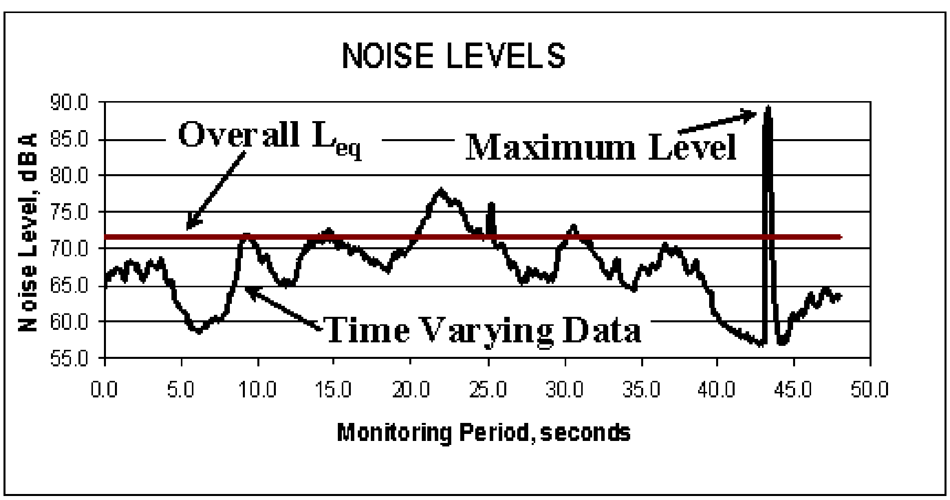


Figure 2.4: L_{Aeq} Noise Level (*5*)

Figure 2.5 relates various sound levels to common indoor and outdoor activities. This figure allows researchers to explain how noise abatement projects will reduce noise levels to the general public. Furthermore, it aids the general public in understanding the impact of increasing and decreasing noise levels. For instance, by looking at this figure, it can be noticed the noise level at a quiet urban environment during the daytime is equivalent to that of a large business office. While the general public may not relate to the prevailing noise level at a quiet urban environment, they will know what the noise is like in a large business office.

It is noted that for residential areas, ODOT considers constructing a noise barrier when the exterior noise level exceeds 67 dBA. Noise abatement actions can also be considered for more sensitive locations such as places of worship, schools, libraries, and hospitals when the interior noise level exceeds 52 dBA.

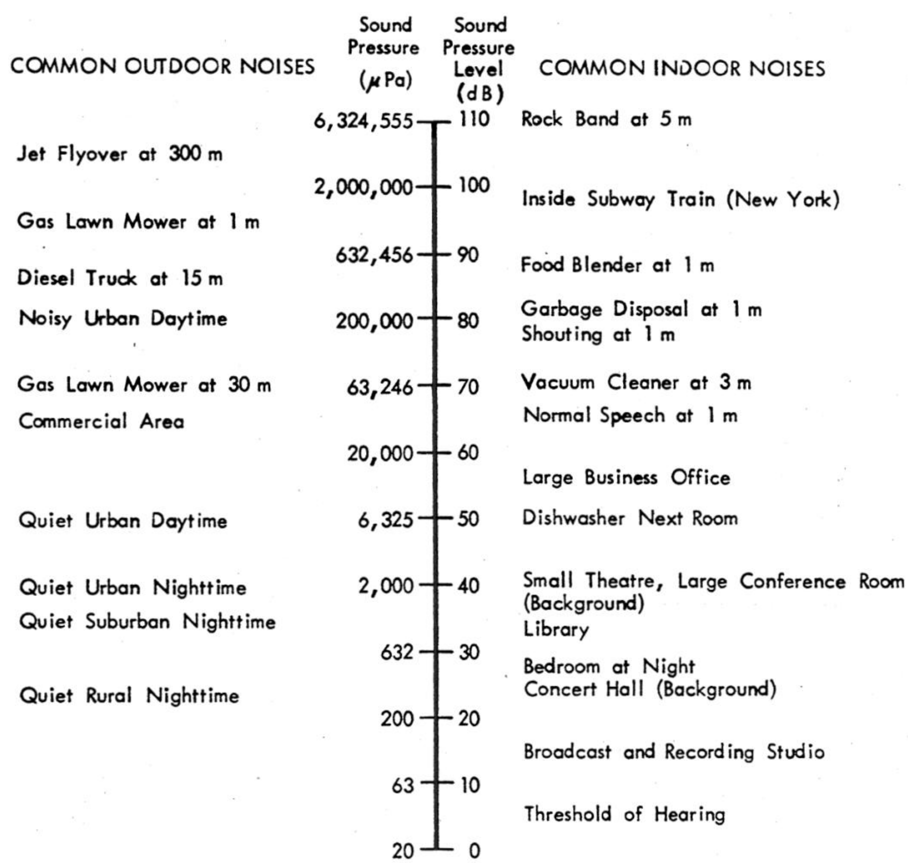


Figure 2.5: Common Indoor and Outdoor Noise Levels (*2*)

2.4 Noise Mitigation Techniques

Noise reduction is becoming increasingly important in traffic design. This is not only due to the increasing number of people driving on major roadways but also due to the rising population living and working in close proximity to these roadways. As previously stated, most of the noise associated with traffic comes from one of four sources: vehicle engine, exhaust, brakes and interaction between tires and pavement. State highway agencies are limited in their abilities to change the design of vehicles and the sound that comes from their engines and exhausts. They can however change the way tires interact with pavement and block sound from reaching surrounding businesses and houses through the use of quieter pavements and the construction of highway noise barriers, among others. The following subsections offer a brief discussion of available noise mitigation techniques. The reader is referred to Reference No. *6* for additional information about these mitigation techniques.

2.4.1 Quiet Pavements

Pavements come in one of two basic compositions, asphalt or concrete. Asphalt pavements are paved with a layer of hot mix asphalt that consists of aggregates and asphalt binder, a by-product of crude oil refining. Concrete pavements, also called Portland cement concrete (PCC) pavements, are made of Portland cement, aggregates and water. The primary considerations in pavement design include the service life, durability and maintenance costs. Additionally, site specific information such as the subsurface soil properties and traffic content are considered. The selection of pavement type and the resulting surface texture have significant influence on the noise generated from tire-pavement interaction.

In asphalt pavements, the surface texture is primarily related to the aggregate gradation and the asphalt binder type and content. Recent efforts to mitigate traffic noise in asphalt pavements has led to the development of many quiet pavements like open graded friction coarse (OGFC) and rubberized asphalt pavements. OGFC is similar to traditional asphalt pavements except that it uses coarser grained aggregates, which increase the void space. This pavement type has better noise reduction properties, but has the disadvantage of reduced durability when compared to traditional asphalt pavements. Rubberized asphalt pavements utilize recycled rubber mixed in with the traditional aggregate in order to reduce the effects of traffic noise. The disadvantage to this design is that the traction is greatly decreased under inclement weather conditions.

Techniques used to mitigate traffic noise in PCC pavements include the use of different texturing methods and the alteration of the mix design. For example, researchers have found that the use of randomized transverse tines may reduce the whining sound of tires more so than uniform transverse tines. Also, longitudinal tines have been reported to produce less traffic noise than transverse tines. In terms of mix design, porous concrete has been used to reduce traffic noise. Porous concrete is a variation of traditional concrete that uses larger aggregates in its mix design. The larger aggregates create a porous surface that allows moisture to penetrate through. These pores also provide noise reduction because they absorb rather than deflect the sound. The disadvantage of this design is that the pores can become clogged and cause water to pool on the surface. Also, porous concrete has a reduced strength when compared to traditional concrete.

2.4.2 Buildings as Noise Barriers

Buildings can provide excellent noise reduction properties. The buildings nearest the roadways act as a noise barrier for other buildings further from the roadway. In general, there is a 3 dBA noise reduction for the first row and a 1.5 dBA noise reduction for each row of buildings or houses after that. This is a significant noise reduction that does not require additional noise barrier structures. The disadvantage of using buildings as noise barriers is that the first row of buildings experiences the full effect of the traffic noise. For residential communities, this first row of houses is a less desirable residence. Therefore, it is recommended that businesses and factories that do not require a peaceful atmosphere be placed nearest the roadway. This fact makes this sound mitigation technique virtually impossible in existing communities. However, when planning the layout of a new community, factories and businesses can be used to shield homes and other noise sensitive facilities from traffic noise. This makes for a more peaceful atmosphere without the additional cost of noise barriers.

2.4.3 Noise Masking

In some cases, noise can be masked rather than blocked. This is the practice of using more appealing sounds to mask traffic noise. Examples of noise masking include fountains and waterfalls. These visually appealing features create a sound that is acoustically pleasing to the general public. Because of the visual and acoustic benefits of these features, noise masking is a popular noise mitigation technique. The disadvantage to noise masking is that it cannot be implemented on a large scale. Therefore, this design technique cannot be utilized by ODOT for large scale noise reduction.

2.4.4 Active Noise Cancellation

Active noise cancellation is a practice that is widely used in fields other than transportation. This is the process of creating sound waves that have equal amplitude and frequency but opposite phase to the sound generated by a noise polluting source. When sound waves that are opposite meet, they cancel each other. An example of this is visually presented in Figure 2.6.

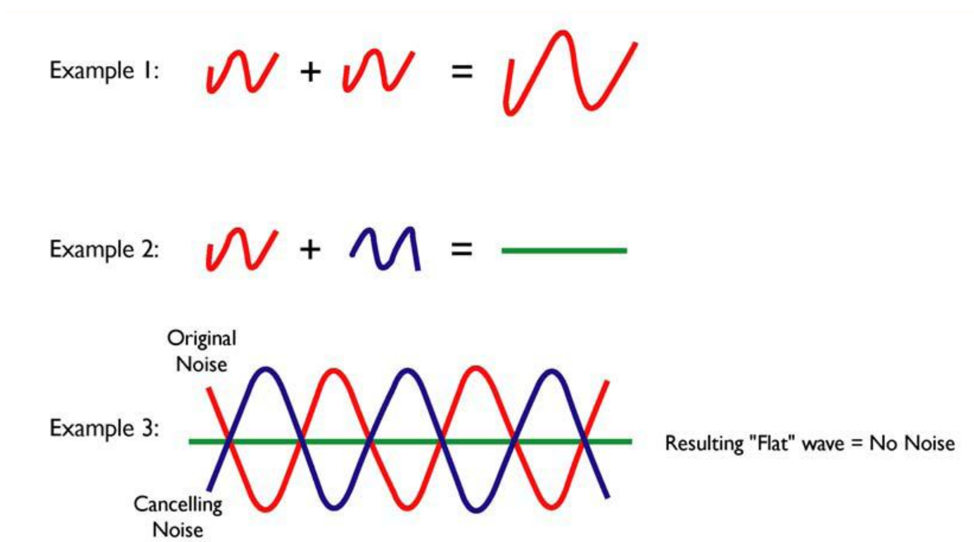


Figure 2.6: Noise Cancellation Diagram (*6*)

This practice has been successfully used in the Heating, Ventilation and Air Conditioning (HVAC) field to eliminate sound created by equipment noise and noise from air moving in duct work. The idea of using noise cancellation for traffic is more complex than noise cancellation in HVAC. This is because traffic noise has a variety of amplitudes, frequencies, and phases compared to HVAC noise that usually have one or two different amplitudes, frequencies and phases. Also, the sound generated by HVAC equipment and air movement is usually in one direction. Traffic noise moves in three dimensions which makes noise cancellation difficult to achieve. While active noise cancellation has recently been used to reduce engine noise it is not suitable for reducing the noise from tire pavement interaction. Since traffic noise is multidimensional this approach is impractical.

2.4.5 Noise Barriers

While the previous noise mitigation techniques offer some noise reduction, they cannot be implemented in every situation. For example, the use of quieter pavements often results in less durable pavement structures that need to be replaced, which costs a great amount of time, money and resources. Therefore, to mitigate traffic noise, state highway agencies often resort to constructing a noise barrier between the highway and the affected community. Noise barriers have a variety of designs ranging from traditional concrete barriers to more natural barriers such as earth berms. The following subsections offer a brief summary of available noise barriers.

2.4.5.1 Concrete Noise Barriers

Concrete noise barriers are the most readily used noise barrier in traffic design. These barriers are used for their simplistic design and construction. Concrete barriers are constructed using precast concrete panels that are manufactured off site and shipped to the project location. Once these panels are delivered to a job site, they are erected between vertical supports. Though the construction of concrete noise barriers is fast, they have many disadvantages. For one, concrete is a valuable material that can be used in other infrastructure projects. Also, it consumes vast amounts of resources during production, which makes the cost of concrete barriers expensive. Furthermore, the noise reduction properties of concrete are relatively poor. While concrete can block most of the sound from reaching the buildings and homes immediately behind the barrier, it reflects the sound rather than absorbing it. The concrete also allows noise at lower frequencies to reverberate through the barrier. The schematic in Figure 2.7 presents the reflection and transmittal performance of a typical concrete barrier. Because noise can be refracted around noise barriers, these noise barriers need to be tall and extend beyond the communities they protect. This increases the amount of concrete that is needed for concrete noise barriers.

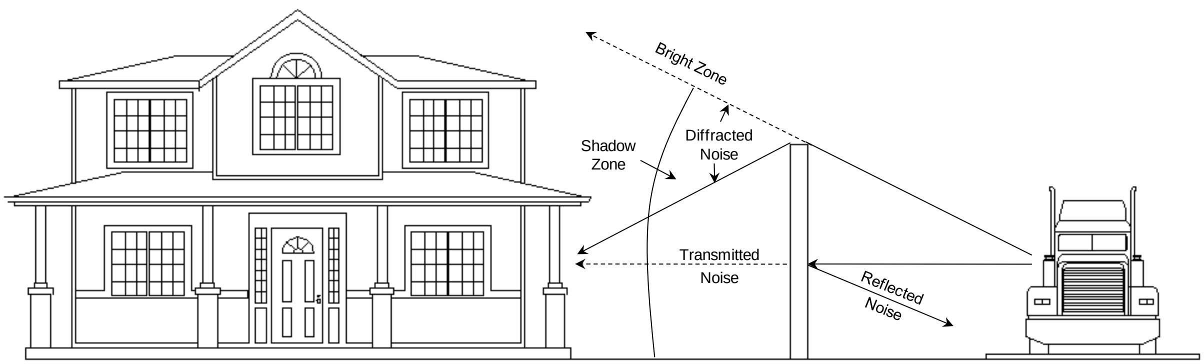


Figure 2.7: Noise Reduction in Concrete Barriers (Based on *6*)

2.4.5.2 Vegetative Screens

Vegetative screens are natural barriers that use plants like bushes and trees to mitigate noise. To achieve the desired noise reduction, this approach to noise abatement requires approximately 100 to 200 ft of tree cover between the highway and the affected community (*6*). Vegetative screens have excellent noise reduction properties because the soft surfaces of the leaves absorb sound while the branches and trunks deflect sound. They are also sustainable because they do not require any man made resources. This reduces the amount of greenhouse gas emissions during construction and can capture greenhouse gas emissions from traffic. Furthermore, vegetative screens are aesthetically appealing because they blend with the natural environment. The disadvantage to vegetative screens is that they require a large amount of space to achieve successful noise reduction. This requires additional right of way to be purchased alongside the roadways which makes vegetation screens an expensive noise barrier technique. It is noted that most of the noise reduction benefits of vegetative screens can be attributed to the 100 to 200 ft distance between the highway and the nearest row of residences.

Vegetative screens offer visual perception benefits that other noise mitigating techniques do not offer. The vegetation provides better aesthetic properties that improve the public perception of this noise mitigating technique. The visual perception of vegetative screens also impacts how the traffic noise is perceived. When people see noise barriers or noise mitigating structures, they know the purpose of the structure and become aware of the noise. When natural vegetation is used to mitigate noise, people see the natural landscape and are less likely to think about traffic noise.

2.4.5.3 Earth Berms

Earth berms are an excellent alternative to traditional noise barriers. These structures use dirt and vegetation to reduce noise pollution. The dirt reduces the amount of noise that is reverberated through the structure. Also, since these structures are covered with vegetation, they absorb sound like the vegetative screens instead of reflecting it like the concrete noise barriers. One additional benefit to earth berms is that they blend with the natural landscape which makes these structures visually appealing. The earth berm noise barrier requires little maintenance which makes the service cost of these structures inexpensive. The cost of these structures can be reduced if soil can be used on site. However, if materials are brought in from an outside source these structures can be equal to or greater in cost to concrete noise barriers. Another disadvantage to earth berms is the size of the structure. For earth berms to be structurally stable, they require a significantly wider base than concrete barriers (Figure 2.8). Earth berms use a side slope of 2:1, which means that a noise barrier with a 12 ft height requires a 48 ft base. Therefore, for a roadway project with noise barriers on both sides of the roadway, there would be an additional 96 ft of right of way that would need to be purchased.

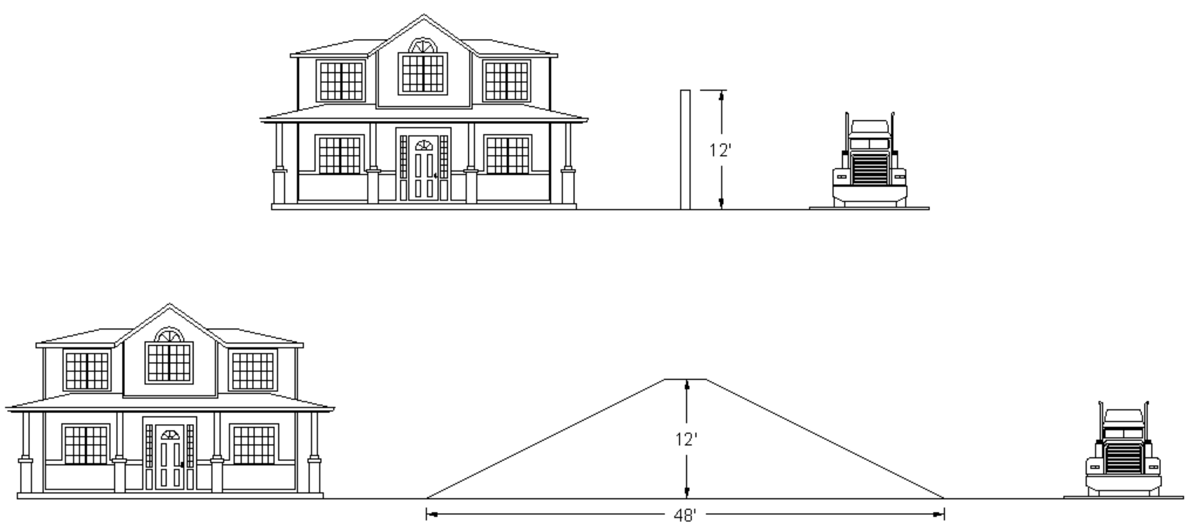


Figure 2.8: Base Width Requirements of a Traditional Concrete Barrier and an Earth Berm

2.4.5.4 Green Noise Barriers

Green noise barriers are free standing barriers that use soil and vegetation to mitigate noise within a confined space. These barriers come in a variety of designs, with the same goal of mitigating traffic noise using various types of vegetation to make the barriers more aesthetically pleasing. Green noise barriers like earth berms and vegetative screens are advantageous to traditional concrete barriers in their ability to blend in with the natural environment. By being more aesthetically pleasing, these barriers improve the public perception to noise mitigation. Green noise barriers also provide equal or better noise reduction when compared to traditional concrete barriers because of their ability to absorb sounds of high as well as low frequencies and deflect sounds in different directions. The width requirement for a green noise barrier is between that of a traditional concrete barrier and an earth berm. Green noise barriers vary in width from 3 ft to 12 ft depending on their design. Therefore, while this barrier may not be suitable for all locations, it might be an acceptable alternative for locations where an earth berm is not a feasible option. Although green noise barriers have smaller base widths than earth berms, they have steeper faces and hence may require additional watering and maintenance in order to ensure vegetation sustainability.

The subsequent chapters provide an overview of available green noise barrier designs and limitations. Chapter 3 offers a brief summary of their construction procedures, advantages and disadvantages. Chapter 4 summarizes the experience of state highway agencies and others with green noise barriers along with their suggestions and recommendations.

2.5 Traffic Noise Analysis

Traffic noise analysis is used to determine the impact of traffic noise on surrounding communities. Traffic noise analysis typically involves: 1. indentifying the potential areas of highway traffic noise impact, 2. determining the existing noise level, 3. predicting the future noise level, 4. evaluating the alternative noise abatement options and 5. evaluating the impact of the proposed noise abatement on the social, economic and environmental aspects (*1*). When these steps are followed, the outcome of the analysis will be consistent and viable for use in traffic noise modeling, which will be covered in subsequent sections.

Highways span vast distances and the locations adjacent to the highway may or may not need noise abatement. For this reason, different activity categories are used to determine whether a given highway segment requires noise abatement actions. This task is complex and can be difficult for small communities with mixed activity categories. Therefore, it is imperative that the activity categories are accurately and precisely documented. These activity categories have different noise requirements and will impact whether the area needs noise abatement actions. The activity categories are defined based on the Noise Abatement Criteria (NAC). The NAC defines the maximum noise level that is allowable for a given location before noise mitigation is required.

ODOT considers noise mitigating when the predicted (design year) noise levels approach the levels shown in Table 2.1 or when the predicted (design year) noise levels exceed existing levels by 10 dBA. Field measurements should be taken at locations that represent each different activity category location to determine whether that location will be impacted by the highway noise. These measurements are taken at three locations: immediately adjacent to the roadway, at the receptor or building that represents that activity category, and at a location between the two points. The measurements are typically taken over a 15 minute time interval with a minimum of 8 samples taken. These are used to determine the hourly equivalent sound level, $L_{eq}(h)$, which is used to determine if noise abatement is required.

Table 2.1: Noise Abatement Criteria (NAC) Hourly A-Weighted Sound Levels (*7*)

Activity Category	$L_{eq}(h)$ in dBA	Activity Category Description
A	57 (Exterior)	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if they are to continue to serve its intended purpose
B	67 (Exterior)	Picnic area, recreation area, playgrounds, active sports areas, parks, residences, motels and hotels, schools, churches, libraries and hospitals
C	72 (Exterior)	Developed lands, properties or activities not included in categories A or B
D	-	Undeveloped land
E	52 (Interior)	Residences, motels, hotels, meeting rooms, schools, churches, libraries, hospitals and auditoriums

Once it is has been found that noise mitigation is necessary, it is imperative to determine whether such action is feasible and reasonable for the given location. In order for a particular mitigation option to be feasible, the proposed option must reduce noise levels by at least 5 dBA with the design goal being 8 dBA. These projects have financial limitations set in place by each state highway agency. ODOT uses the cost/benefit ratio as part of the traffic noise analysis process. This ratio is calculated by dividing the total estimated cost of the noise barrier by the number of benefiting residential units (front row residential units receiving 5 dBA or more noise reduction and other residential units receiving 3 dBA or more noise reduction). If the estimated cost per residence is $35,000 or less, the noise barrier is deemed cost effective.

The final stage of traffic noise analysis is to coordinate with local officials. By consulting with local officials, the social, economic and environmental aspects of the project can be discussed. This stage also provides an opportunity to educate and communicate with the general public that will be affected by the noise abatement. This stage is important in understanding the public perception of the project and the impact the project will have on the surrounding environment.

Chapter 3
Review of Available Green Noise Wall Products

3.1 Introduction

The traditional form of mitigating traffic noise has been the implementation of concrete barriers. These barriers are obtrusive and often cause complaints about their appearance. While society desires more peaceful surroundings, they also desire an aesthetically pleasing environment. This desire has led to the development of green noise barriers. A green noise barrier is an engineered structure that uses soil and vegetation to mitigate traffic noise. These barriers come in a variety of designs, with the same goal of mitigating traffic noise using various types of vegetation to make the barriers more aesthetically pleasing. This chapter summarizes the available green wall products and highlights their advantages and disadvantages. The information in this chapter was obtained from the producers of these products and their websites.

3.2 Living Willow Wall (www.thelivingwall.net)

The living willow wall design originated in Canada and came from the necessity of an all natural, inexpensive and durable noise barrier. The goal of this design was to find a noise barrier that could withstand harsh winters, with temperatures below -20^{o}C and provide protection for the surrounding communities from traffic noise. The living willow wall is composed of a wooden frame and willow trees (Figure 3.1). The construction of the living willow wall starts by digging two 3.3 ft (1 m) deep trenches, 4 ft (1.2 m) apart. The wooden frame is then assembled and placed in the trenches (Figure 3.2). The two sides of the wooden frame are held together using wooden pieces and steel rods. Next, a permeable geotextile is fastened to the backside of the frame over the entire length of the wall and the area between the two sides of the wall is filled with sandy soil to the desired wall height. The geotextile fabric ensures that the soil that is used to fill in the space between the frame stays in place and does not erode under rain or wind.

Irrigation is provided in the living willow wall through perforated hoses installed inside the soil. The irrigation hoses allow watering of the willow trees and reduce the amount of evaporation during watering. The willow trees are planted between the geotextile and the wooden frame. The wooden frame keeps the willow trees from spreading towards the road and restricts bending under heavy winds. Figure 3.3 shows a picture of the living willow wall shortly after construction and Figure 3.4 shows a picture of the wall completely green. As can be seen from the latter, the wooden frame is barely noticeable once the wall is covered with vegetation.

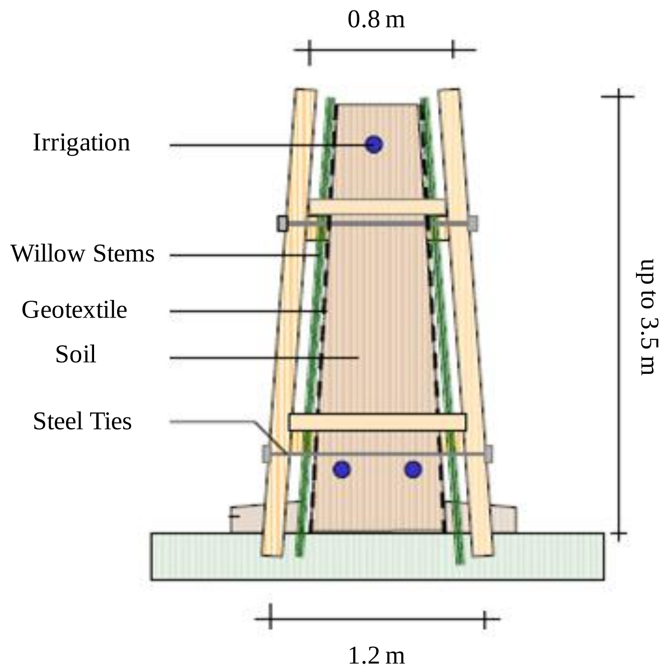


Figure 3.1: Schematic Diagram of the Living Willow Wall (*8*)

Figure 3.2: Construction of the Living Willow Wall (*9*)

Figure 3.3: Living Willow Wall Shortly after Construction (*9*)

Figure 3.4: Living Willow Wall Fully Covered with Vegetation (*9*)

There are many advantages and disadvantages to the living willow wall. One of the advantages is that the living willow wall is composed of a wooden frame and willow trees. Excluding the processing of the wooden frame members and the fasteners used to hold them together, there are very few greenhouse gases emitted during production. Also, since the amount of equipment needed for the installation is minimal, the greenhouse gases emitted during construction are reduced. By using soil and vegetation, the living willow wall is expected to produce comparable if not better traffic noise reduction than a traditional concrete barrier of the same height. Finally, the willow trees can either be grown at nurseries or harvested from existing willow trees. By removing mature willow stems and introducing them into water and soil, these harvested branches can begin to grow into new trees. This technique can make willow trees a rapidly renewable resource which increases the sustainability of the construction of the living willow walls.

Although there are many advantages, the living willow wall has several drawbacks. One of these drawbacks is the use of willow trees. Willow trees thrive in high moisture environments and require continuous watering especially during establishment. Therefore, irrigation might be an issue. Another disadvantage of the living willow wall is the barrier height. The living willow wall design cannot accommodate barrier heights greater than 12 ft (3.6 m), which might preclude its use in many locations. Furthermore, the soil inside the wall may settle, resulting in a reduction in the barrier height and hence its effectiveness to mitigate traffic noise. Finally, although the living willow wall appears to be easy to construct, it is labor intensive and requires skilled labor to harvest and plant the willow trees into the wall.

3.3 PileByg (www.pilebyg.dk)

The PileByg is a Danish company that offers two types of green noise barriers. The first type uses dry willow rods and will be referred to as the dry PileByg, while the second type uses a combination of dry and live willow trees and will be referred to as the living PileByg. The dry PileByg uses two wooden frames to form the noise barrier (Figure 3.5). The wooden frames are fastened to wood posts, which are placed in a concrete foundation. This system of frame and posts provides the structural support of the noise barrier. Dry willow rods are woven through the wooden frame and used as a façade to increase the aesthetics of the noise barrier. The noise mitigation is provided by the core of the wall. This core is made of two 120 mm rock wool layers specially designed to reduce traffic noise. Figures 3.6 through 3.8 show a picture of the dry PileByg structure during construction, a close-up picture of the structure and a picture of the completed structure, respectively.

The construction of the living PileByg is similar to that of the dry PileByg. The main difference is that live willow trees are used on one side of the structure and dry willow rods are used on the other side (Figure 3.9). The willow trees are planted at a depth of 60 cm and secured to a specially designed frame. The living façade is typically placed facing the south and west since the willow trees need light to grow and the dry willow rods are placed on the opposite side that receives less sunlight. Similar to the dry PileByg, the core of the living PileByg consists of two 120 mm rock wool layers to reduce traffic noise. Figure 3.10 shows a picture of the living PileByg during construction. Figures 3.11 and 3.12 show a picture of the dry façade and the living façade of the living PileByg, respectively.

There are many benefits to the PileByg noise barrier design. First, both the dry and living willow branches provide better aesthetics when compared to traditional concrete barriers. The dry willow rods will age and provide a natural look over time. The living willow trees will change with the seasons and blend with the natural environment. Additional plants such as vines could be used with both designs to improve the aesthetics. Finally, the PileByg company claims that these barriers are capable of producing a substantial noise reduction and are expected to have a 30 to 40 year service life.

While the PileByg design offers many benefits, there are also several disadvantages. One drawback is that when the dry willow elements are placed in the ground they require a concrete foundation. This concrete foundation can increase the cost of construction. Also, additional foundations may be required in exposed locations such as banks and slopes. Furthermore, these noise barriers may not provide the required noise reduction to be considered reasonable by state highway agencies.

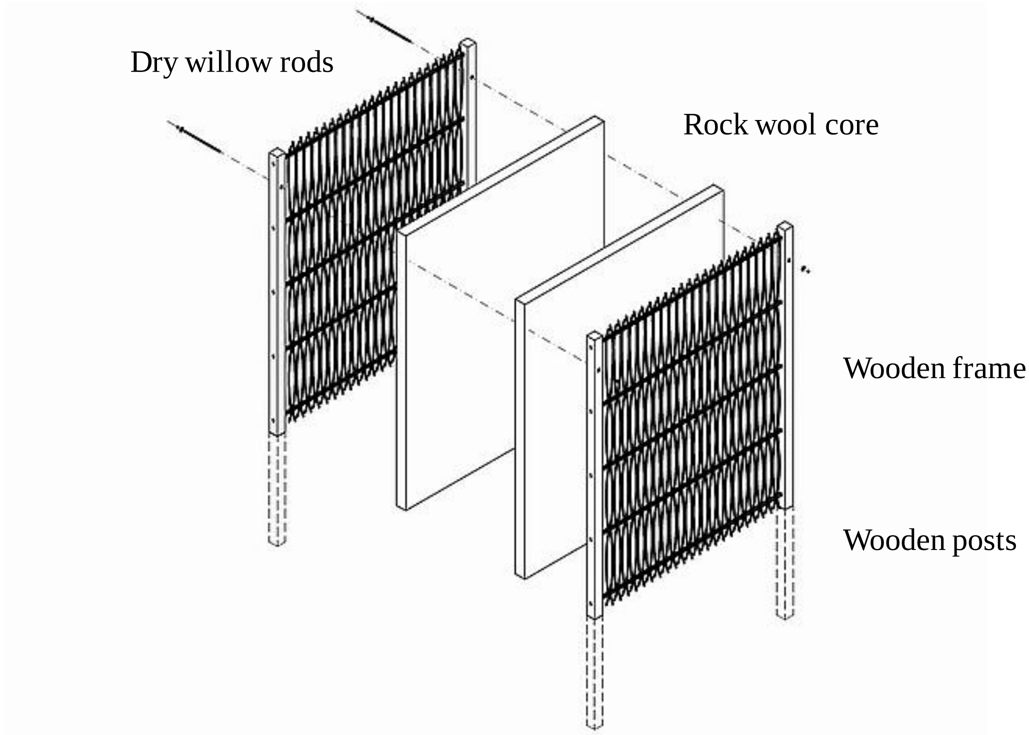


Figure 3.5: Schematic Diagram of the Dry PileByg Structure (*10*)

Figure 3.6: Construction of the Dry PileByg Structure (*10*)

Figure 3.7: Close-Up Picture of the Dry PileByg Structure (*10*)

Figure 3.8: Picture of the Dry PileByg Structure (*10*)

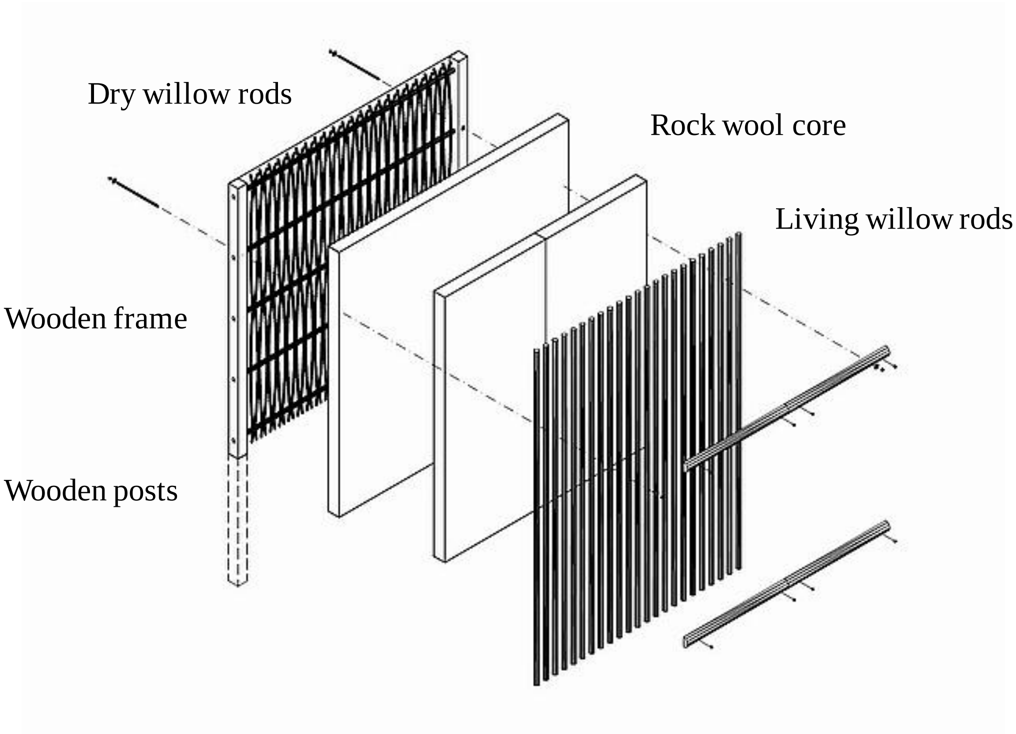


Figure 3.9: Schematic Diagram of the Living PileByg Structure (*10*)

Figure 3.10: Construction of the Living PileByg Structure (*10*)

Figure 3.11: Picture of the Living PileByg Structure, Dry Façade (*10*)

Figure 3.12: Picture of the Living PileByg Structure, Living Façade (*10*)

3.4 Criblock (www.retainingwallsnw.com)

The Criblock wall is composed of concrete grid members stacked together as a crib, with soil and rock backfilled within the crib cell. This structure is produced by a company called Retaining Walls Northwest, Inc. that is based in Bellevue, WA. The Criblock design has been used in a variety of applications, including retaining walls, embankments, and erosion control along river banks. Its producer claims that it can also be used as a free standing wall to reduce traffic noise.

The Criblock wall consists of a combination of concrete headers and stretchers. Stretchers are horizontal concrete members that run parallel with the length of the wall, while headers are run perpendicular to the stretchers (Figure 3.13). Both the headers and stretchers are reinforced with No. 4 steel bars. The construction of a Criblock wall begins with a bottom layer of stretchers that rests on a foundation of concrete or granular material. With the first row of stretchers in place and fastened to the foundation, headers are placed in the grooves near the end of the stretchers. With this row of headers in place, a second row of stretchers are placed on top of the headers but offset by one half of the length of a stretcher. This interlocking design allows for the wall to act as a single unit and ensures the structural integrity. When several layers have been constructed, the wall can be backfilled with soil (Figure 3.14). Finally, with the structure complete and properly backfilled, vegetation can be planted along the surfaces of soil contained by the concrete members (Figure 3.15). If needed, irrigation can be provided by running a water line along the top of the wall.

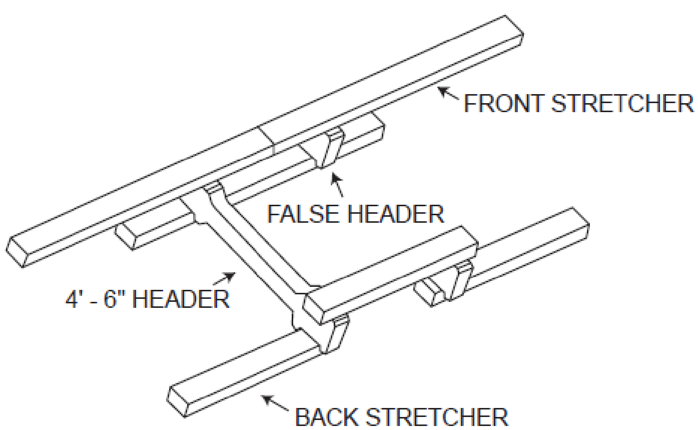


Figure 3.13: Assembly of Stretchers and Headers (*11*)

Figure 3.14: Soil Backfilling in the Criblock Wall (*11*)

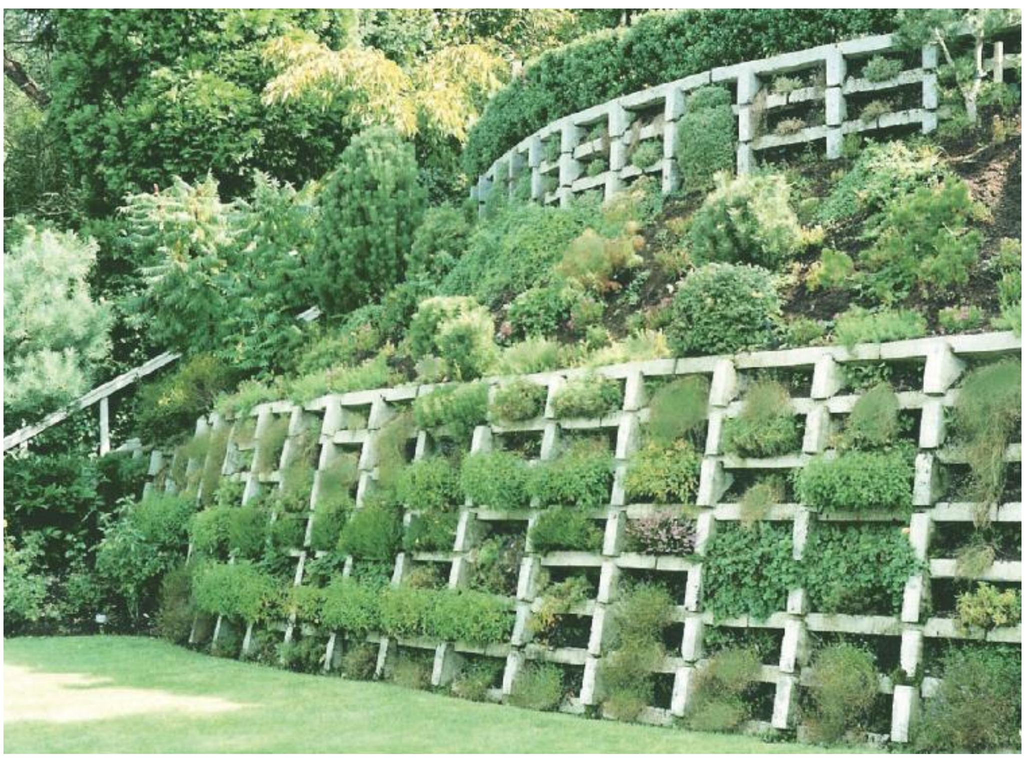


Figure 3.15: Criblock Wall Covered with Vegetation (*11*)

There are many advantages to the Criblock design. One of these advantages is that this design has been proven to be structurally sound and durable in various climates. Another advantage is that the members are precast and only need to be set in place without the need for fasteners or welds, which reduces the construction time. In addition, the Criblock members are relatively small (about four feet long, eight inches high and four inches wide), which eliminates the need for heavy machinery. Furthermore, the mixed surfaces of concrete, soil and vegetation provide excellent noise protection. These surfaces trap, absorb and reflect sound waves, which cause the Criblock walls to perform better than a traditional concrete noise barrier.

In spite of the previous advantages, there are several drawbacks to the Criblock design. First, this system has not been used as a standalone structure, which makes its use as a noise barrier uncertain. When used as a soil retaining structure, the Criblock wall is constructed at a battered 1:4 angle in order to enhance its stability by increasing its resistance to sliding and overturning (Figure 3.16). However, the use of such an angle would not be possible if this product is to be used as a free standing wall. Figure 3.17 presents the suggested designs for the free standing wall by Retaining Walls Northwest. It is not clear from this figure how the concrete members within the free standing Criblock wall can prevent the soil from being eroded from within the structure due to wind and/or rain, leaving the plants without the necessary support and nutrition. It is noted that when this structure is used along river banks, it requires small concrete blocks to be placed between the headers to prevent erosion. Therefore, by using this design as a free standing wall, it may need regular soil replenishment. A further drawback to the Criblock wall is that it depends on concrete and steel for its structural strength. Despite the fact that the quantities of concrete and steel are less than the amounts used in solid concrete walls, they still consume vital resources and large amounts of energy in production. Finally, these walls require small lifts to lift the members into place and backfill the structure during installation. These lifts release greenhouse gases and introduce additional equipment and labor into a construction site.

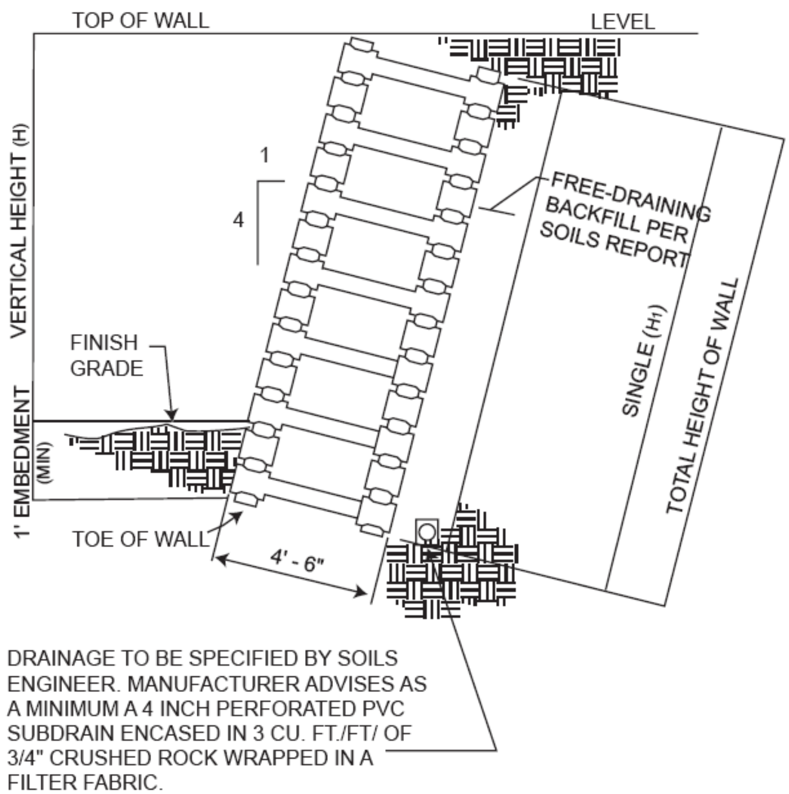


Figure 3.16: Schematic Diagram of a Typical Criblock Design (*11*)

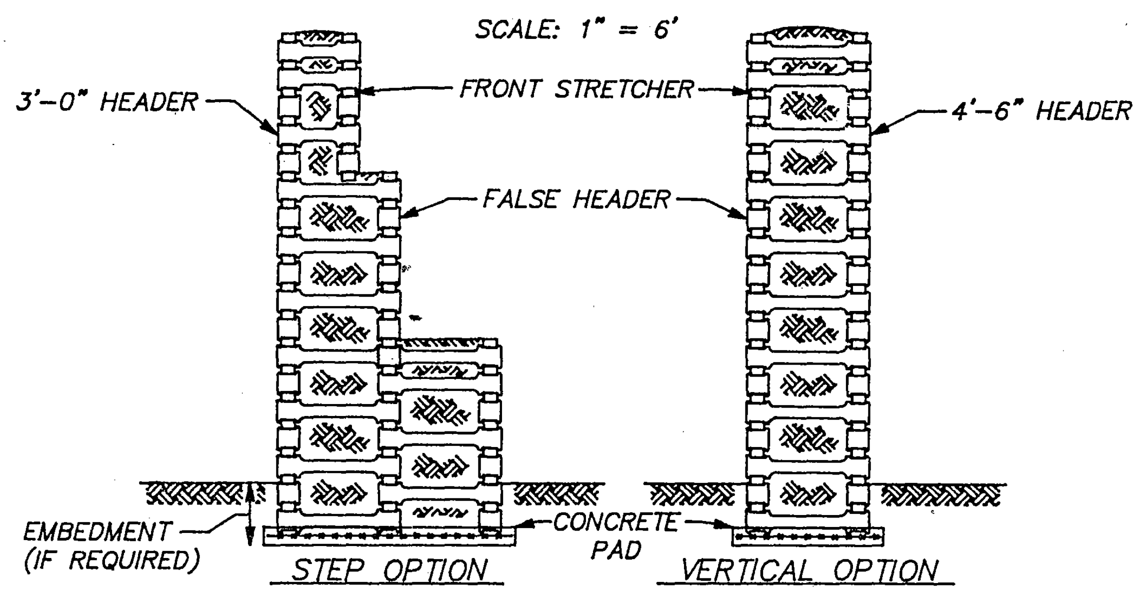


Figure 3.17: Suggested Criblock Designs for a Free Standing Wall

(Provided by the Retaining Walls Northwest, Inc.)

3.5 Timbergrid (www.timbergrid.com)

Timbergrid is a noise reducing technology that is similar in design to the Criblock. The Timbergrid system uses a wooded frame to retain stone, rock or recycled brick and concrete. It has mostly been used as a retaining wall. However, it was also used as a noise barrier.

The Timbergrid structure is typically constructed on a concrete foundation 16 inch deep (Figure 3.18). This foundation will form the support for the wood members to rest on. The width of the members varies depending on the specified height of the structure, which can reach up to 27 ft. The first row of wood panels is perpendicular to the longitudinal face of the wall and is tamped into the concrete. Each subsequent layer of wood panels is placed in an interlocking lattice pattern where alternate layers overlap forming a space that can be filled with gravel, rocks or recycled concrete and bricks. The granular material allows water to drain from the structure which relieves hydrostatic pressure, reducing the forces acting on the members. Within the layers of granular material, planting bags can be placed to allow for the planting of small vegetation. Figure 3.19 shows a picture of the Timbergrid wall with planting bags. Figure 3.20 shows a picture of the Timbergrid wall covered with ivy and vines. The previous figures provide examples of the Timbergrid system as a retaining wall. Figure 3.21 demonstrates the use of the Timbergrid system as a noise barrier.

When used as a noise barrier, the Timbergrid design has many advantages over traditional concrete barriers. This structure provides increased aesthetics since it is made of wood, which is a sustainable material, rather than concrete. The wood also requires less energy in production when compared to concrete and steel, which yields a lower embodied energy. Furthermore, the construction of this product requires a small crew, which reduces labor costs. The Timbergrid design offers unique noise reduction properties. The wood members absorb the sound waves, while the voids created by the backfill material trap and diffuse the sound waves. This causes the noise reduction properties of the Timbergrid system to be greater than a solid concrete noise wall. With the addition of vegetation, these already visually appealing structures take on the appearance of their surroundings increasing the aesthetics. Finally, the Timbergrid Company claims that this product has a sixty year service life, which is considerably longer than other noise barriers. However, this service life is only met with the application of stain or other ultraviolet light protection.

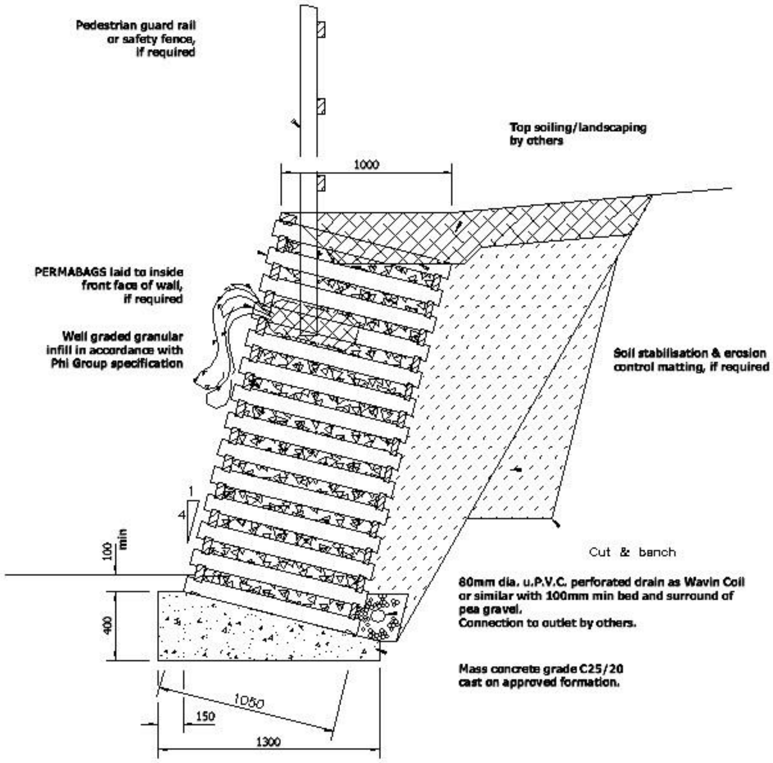


Figure 3.18: Schematic Diagram of a Typical Timbergrid Design (*12*)

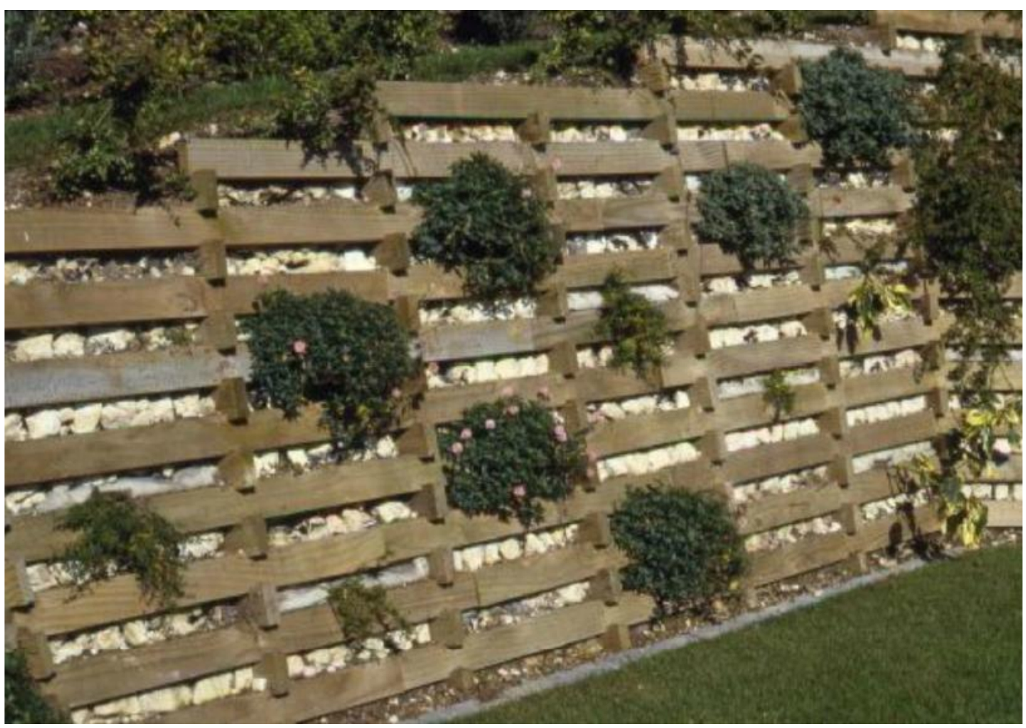


Figure 3.19: Timbergrid Wall with Planting Bags (*12*)

Figure 3.20: Timbergrid Wall Planted with a Mixture of Ivy and Virginia Creeper (*12*)

Figure 3.21: Timbergrid as a Noise Barrier (*12*)

Although there are many advantages to the Timbergrid design, there are several drawbacks. This product needs maintenance to protect the wood. This includes staining, which requires labor and financing. Timbergrid also needs additional planning and design for planting vegetation. The structure is filled with gravel or recycled brick, which are not suitable to grow vegetation. Therefore, planting bags need to be placed in the structure for vegetation to grow. However, since this structure is designed to allow water to drain away, additional watering would be needed to maintain the vegetation. Furthermore, this product has primarily been used as a retaining wall and only selectively as a noise barrier. Therefore, additional testing and analysis is needed to determine how the structure would perform as a green noise barrier.

3.6 Evergreen (www.evergreenwall.com)

Evergreen is a Swiss product that uses a series of precast concrete trays to hold soil and vegetation. The trays have an angled face that helps retain water for the plants to grow. The Evergreen system is constructed by stacking the trays on top of each other until reaching the desired barrier height. The trays are held together by gravity. Figures 3.22 and 3.23 show a schematic and a picture of the Evergreen free standing noise wall system, respectively.

There are many advantages to the Evergreen noise barrier design. Since the concrete trays are precast and shipped to the job site, the construction time and costs are significantly reduced. With the addition of vegetation, the aesthetic properties as well as the public perception of these noise barriers are increased. Finally, the noise mitigating properties are better than those of the traditional concrete noise barriers and can be attributed to two properties of the design. First, the soil absorbs, while the concrete reflects traffic noise. Second, the size of the wall restricts noise from being transmitted through the barrier. Each tray is about 3 to 4 ft thick and there are two trays placed back to back. This results in about 6 to 8 ft thick medium of soil and concrete in which sound waves can be absorbed and deflected before reaching the receptor.

While there are many benefits, there are also many disadvantages to the Evergreen design. Although the trays are designed to prevent erosion from moisture, the open surfaces leave the soil susceptible to erosion from the wind and rain. Also, the vertical construction of this design restricts moisture from reaching the many levels of the barrier. A loss of soil or lack of moisture could lead to the vegetation dying and result in high maintenance costs or a reduction in

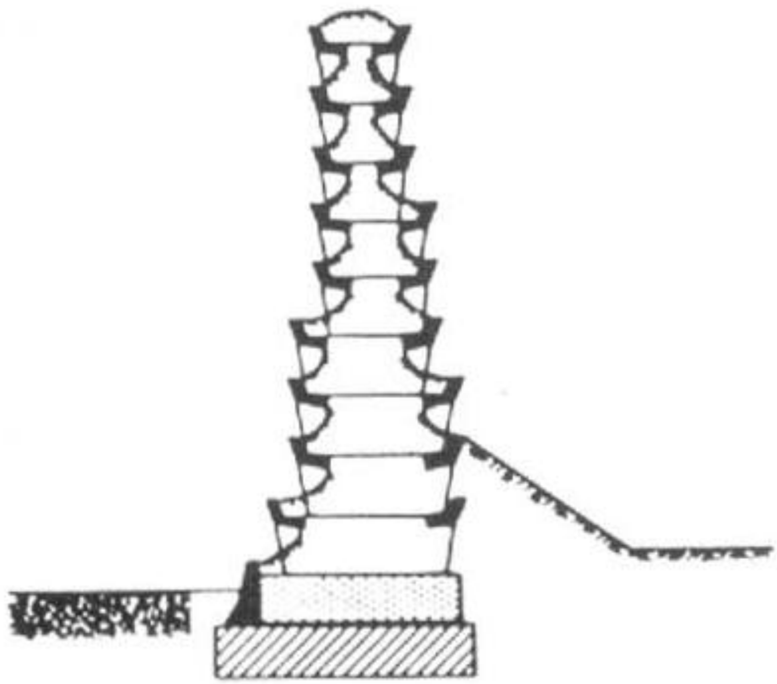


Figure 3.22: Schematic of the Evergreen Free Standing Noise Wall System (*13*)

Figure 3.23: Picture of the Evergreen Free Standing Noise Wall System (*13*)

noise mitigating properties. Furthermore, this design uses large prefabricated concrete units which require large cranes to hoist these units into higher levels. The additional equipment can cause logistic problems on already congested job sites. These barriers also use more concrete than traditional concrete barriers which can greatly increase the cost. Finally, with a larger amount of concrete used for the structure, there is less vegetation on this structure. With less vegetation, the aesthetic properties are reduced when compared to other green noise barriers.

3.7 Recywall

Recywall is a green noise barrier that is green both in its structure and vegetated surface. This design uses structural members that are composed of recycled plastic. The members retain soil and vegetation is planted in the soil.

The construction of Recywall begins with a crushed aggregate foundation underlain by a geogrid. The geogrid provides the aggregate foundation with the ability to resist tensile stresses. The aggregate foundation supports the structure and allows water to drain away from the barrier. A set of vertical supports with notches are placed perpendicular to the length of the wall (Figure 3.24b). Headers are then placed into these notches (Figure 3.24a). This combination of vertical supports and headers create a box like structure in which soil can be placed (Figure 3.25). After several rows of members are in place, the resulting structure is backfilled with soil and compacted. This process is continued until the desired height is reached. The final stage of construction is the planting of vegetation along the structure.

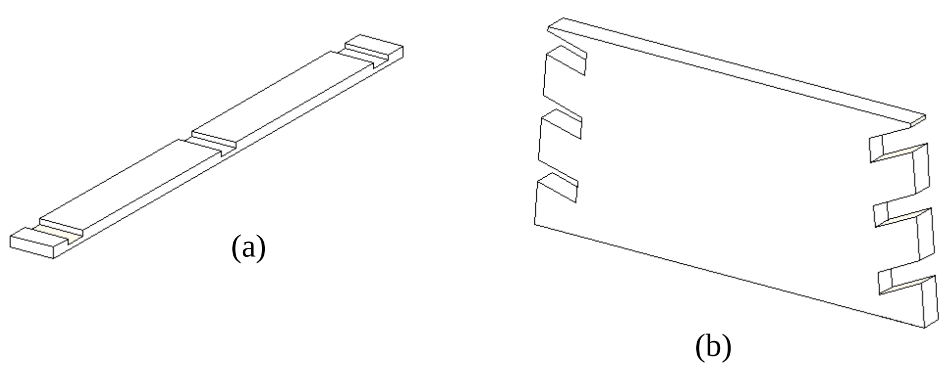


Figure 3.24: Components of the Recywall, a. Headers and b. Vertical Supports (Based on *14*)

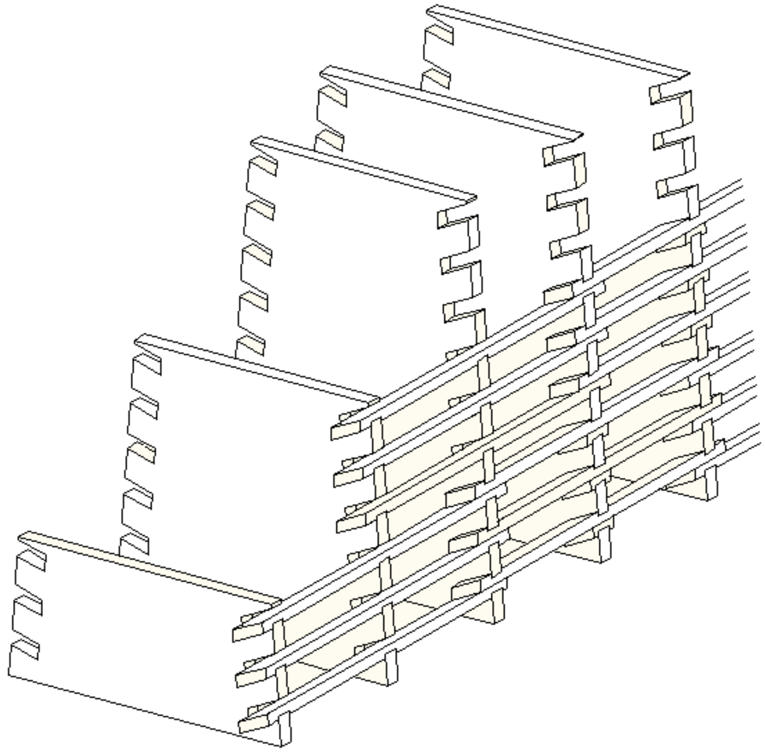


Figure 3.25: Assembling the Recywall System (Based on *14*)

There are many advantages to the Recywall design. This system uses recycled plastic in its structural members, which provides increased sustainable construction practices and reduces the amount of waste that is transported to landfills. These members are relatively light in weight, which allows a small crew to lift the members into place without heavy equipment. The Recywall design is expected to produce better noise reduction properties than traditional concrete barriers, which can be attributed to the soil core and vegetated surface that absorbs sound. Finally, the vegetated surface is expected to provide better aesthetics than traditional concrete noise barriers.

While there are many advantages to the Recywall design, there are also many drawbacks. This barrier is made of plastic, which performs differently at high and low temperatures and can deteriorate when exposed to direct sunlight. This design may also be subject to erosion from wind. Additionally, the vertical design may not allow sufficient moisture to reach the structure. The lack of moisture could reduce the survivability of the vegetation, reducing the aesthetics and noise reduction properties of the barrier.

3.8 Supported Earth Embankment

When there is a desire or need for a noise barrier that reduces noise with a natural appearance, but there is not enough space for an earth berm, a supported earth embankment may be used. Supported earth embankments can come in a variety of forms. In general, these structures use steel or concrete to hold soil and vegetation in place (Figures 3.26 and 3.27). The most common form uses a steel mesh or net with steel or concrete supports to retain soil and vegetation. It is unclear whether additional measures would be required to prevent soil erosion or if the vegetation provides sufficient soil retention.

These structures provide many of the benefits of vegetated noise barriers. They offer the appearance of the natural surroundings and noise reduction with less noise reflection. As can be seen in Figure 3.26, when steel mesh is used, the entire surface can be covered in vegetation with no visible structural support. Society has a reduced awareness of traffic noise when a barrier is fully covered with vegetation. Also, these structures are made using different materials such as concrete, steel or a combination, which means that they can conform to their surroundings.

There are several disadvantages to supported earth embankments. This system uses materials like steel and concrete, which are costly and use large amounts of energy. In this type of structure, concrete is used to hold soil and vegetation or a steel mesh is used to cover the entire structure. These resources are materials that are important in other construction projects. In addition, if concrete is used, the units can be heavy, difficult to assemble and require additional heavy machinery on a job site. Finally, these structures may be susceptible to erosion and lack of moisture to sustain vegetation.

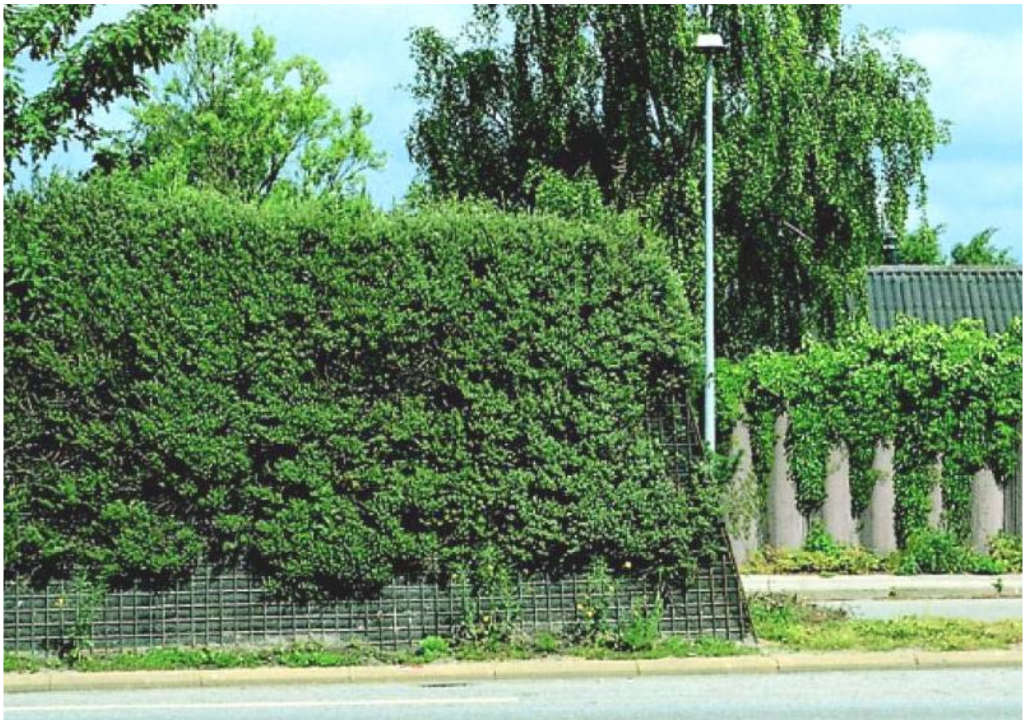


Figure 3.26: Supported Earth Embankment with Steel Mesh (*15*)

Figure 3.27: Supported Earth Embankment with Concrete (*15*)

3.9 Plant Boxes

Plant boxes are a feature that allows growing vegetation adjacent to a noise barrier (Figure 3.28). These boxes are 3 to 4 ft high and are generally made of concrete. They can be implemented during construction or after a noise barrier is already in place. The concrete box can be placed on either side of a traditional noise barrier and is filled with soil. The soil allows vegetation to be planted within the box. The advantage of plant boxes is that they allow almost any type of vegetation to be planted even medium sized trees. The vegetation that is planted increases the aesthetics of existing noise barriers. The drawback to plant boxes is that they add to the cost of a noise barrier. Therefore, while the plant boxes provide the illusion of a green noise barrier, they do not solve the problems associated with traditional noise barriers such as sound reflection and aesthetics.

Figure 3.28: Plant Box (*15*)

3.10 Deltalok (www.Deltalok.com)

The Deltalok is a reinforced earth structure that uses geogrids as reinforcement and the Deltalok ecology bags as facing units. Deltalok standard unit connectors are also used to provide mechanical interlocking to hold the ecology bags in proper position. The Deltalok bags are composed of 100% recyclable polypropylene (Figure 3.29a). These non-woven geotextile bags are designed to be permeable so that water can penetrate the surface and allow vegetation to grow, increasing the aesthetics of the Deltalok structure. The Deltalok connectors are plastic plates with spikes protruding from each face (Figure 3.29b). These spikes penetrate through the bags during construction and provide an interconnection between the Deltalok bags.

(a) (b)

Figure 3.29: Components of the Deltalok System,
a. Deltalok Bags and b. Deltalok Standard Connector (*16*)

The Deltalok design comes from a company that is based in Vancouver, British Columbia in Canada. This system has been used in a variety of applications, including retaining walls, slope stabilization, erosion control, culvert headwalls and streambank protection. Figure 3.30 shows a picture of a Deltalok retaining wall fully covered with vegetation. The Deltalok Company claims that it can also be used as a free standing green noise barrier. Figure 3.31 shows a schematic of the proposed design for the Deltalok green noise barrier.

The construction process of a Deltalok green noise wall is unique in comparison with traditional noise barriers. It starts with digging a 16 to 18 inch deep trench that is backfilled with 4 to 6 inches of granular material. This aggregate base serves as a foundation for the structure and allows water to flow away from underneath the wall. Additional support for the structure can be provided by placing a geotextile fabric under the aggregate basic. Once the foundation is prepared, a geogrid is placed on top of the aggregate layer and a number of Deltalok strandard unit connectors are placed along the perimeter of the wall. The Deltalok bags are then placed on top of the Deltalok connectors so that the longer length of the bag runs parallel to the face of the wall. The subsequent layers of bags are staggered so that the second row of bags is offset from the first row by half a bag. Finally, the space between the bags in each layer is filled with granular material and compacted to form the core of the structure. The previous steps are repeated until reaching the desired height of the structure. Geogrids are placed at predetermined intervals to restrict the lateral movement of the Deltalok bags.

Figure 3.30: Deltalok Retaining Wall Fully Covered with Vegetation (*16*)

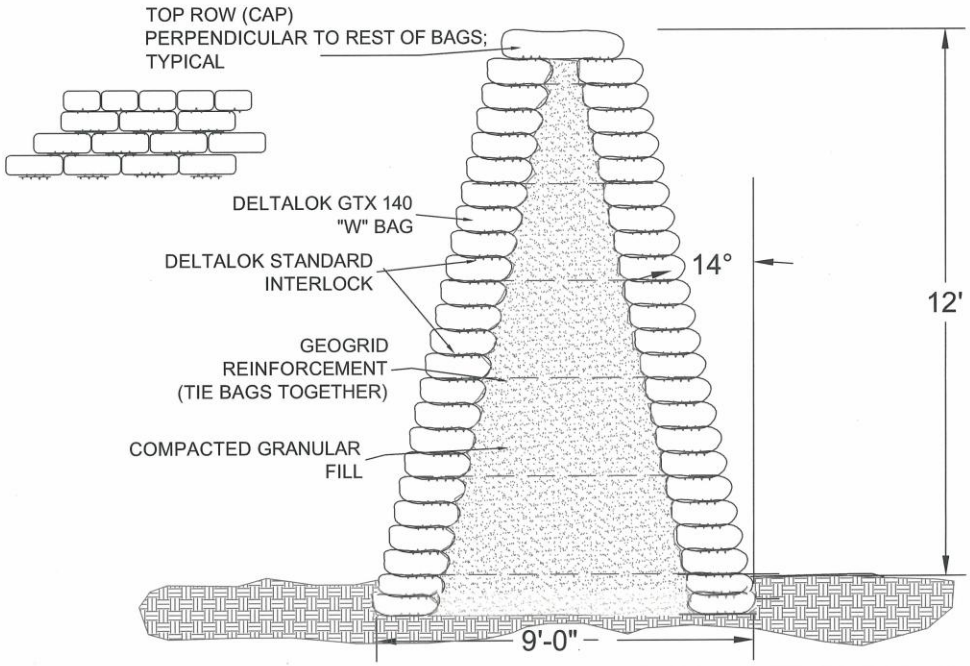


Figure 3.31: Proposed Design for the Deltalok Green Noise Barrier (Provided by Deltalok, Inc.)

The Deltalok design provides many benefits when compared to traditional concrete noise barriers. This design does not use concrete or steel to construct the barrier. Rather, it relies on more sustainable materials that require little energy in production. Since the materials are light and easy to work with, there is no need for very heavy machinery, which reduces the amount of greenhouse gases emitted during construction. This green noise barrier offers the possibility of incorporating different types of vegetation such as grasses, bushes, and small trees. This makes it suitable for different geographic regions and provides continuity with the surrounding environment, increasing the aesthetics and public perception of noise mitigation. Additionally, the Deltalok system uses bags that contain soil to grow vegetation. This design is not expected to completely eliminate erosion. However, it is expected to offer more protection for the soil within the structure from wind and rain. Finally, the Deltalok design is expected to provide substantial traffic noise reduction primarily due to its soil core and to a less extent its vegetation.

In terms of disadvantages, this system has not been used as a free standing wall, which introduces some uncertainty over its performance as a green noise barrier. This structure has a relatively small footprint that may not allow enough rain water to infiltrate into the barrier. Furthermore, it has steep faces that may not allow moisture to be retained within the structure. With insufficient moisture, the structure will require irrigation to sustain vegetation and maintain the aesthetics. Finally, it is expected that there will be some settlement in the soil within the Deltalok bags as well as the backfill material. This will result in a loss of height, which could reduce the noise reduction properties of the noise barrier.

Chapter 4
Past Experience with Green Noise Barriers

4.1 Introduction

Green noise barriers are an innovative solution to noise mitigation. Over the years, state highway agencies have selectively used these structures for noise abatement with varying levels of success. This chapter documents the past experience of state highway agencies with this type of barriers. Special attention was given to states that have similar climate to Ohio. The information presented in this chapter was collected through a detailed questionnaire that was sent to members and friends of Transportation Research Board (TRB) ADC40 (Transportation-Related Noise and Vibration) Committee. Additionally, several green noise barrier producers were asked to provide names and emails of references to their products. A copy of this questionnaire is available in Appendix A. The questionnaire included four sections: general information about the green noise barrier, the preconstruction stage, the construction process and the post-construction stage. The responses to the questionnaire offered valuable information about the performance of green noise barriers and provided insight into the factors that need to be taken into considerations before constructing a green noise barrier.

4.2 The New Hampshire Experience

The New Hampshire Department of Transportation (NHDOT) constructed three green noise barriers in the early 1990s. The first barrier was constructed in 1992 in the City of Manchester along interstate I-93. The other two barriers were constructed shortly thereafter in the City of Nashua. This region of New Hampshire is generally moist with significant rain during the spring months. Summer temperatures range from 60 to 90^{o}F and winters have considerable snow accumulation with temperatures below freezing at night and between 30 and 40^{o}F during the day. NHDOT decided to construct the three green noise barriers with the goal of providing a more natural and aesthetically pleasing transportation system. Aesthetics were considered to be a high priority since New Hampshire is a favorite tourist destination. It was hoped that a green noise barrier would blend in with the surroundings and enhance the driving experience. All three barriers were constructed using the Evergreen concrete planter design. The performance of the three barriers was relatively the same. Therefore, this section will focus on the first barrier that was constructed in Manchester.

The Manchester green noise barrier measured 1700 ft in length and ranged from 8 to 24 ft in height. The barrier height was determined using traffic noise analysis ensuring that the barrier would provide a desired noise reduction between 8 and 10 dBA. The barrier was oriented in the north-south direction. It was planted with a combination of shrubs, vines and small plants (including Memorial Rose, Sweet Fern, Trumpet Creeper, Virginia Creeper, Penngift Crownvetch and Sweet Pea). Vegetation was selected by NHDOT Roadside Development Section based on their experience with landscaping and knowledge of New Hampshire's climate. This vegetation was chosen based on survivability and aesthetic properties. A mixture of vegetation was selected in order to prevent a monoculture from forming and reduce the possibility of a mass die off.

The construction of the Manchester green noise barrier began in the spring of 1992 and continued for one construction season. A number of contractors with previous experience in constructing noise barriers bid on the project. The successful bidder was responsible for the design and construction of the barrier with input from the Evergreen Company. The NHDOT Construction Bureau oversaw the construction process, which proceeded as described in the previous chapter. The NHDOT noted that the major difficulty with the construction process was the erection of the barrier at the upper levels where relatively large cranes were needed to lift the concrete trays into position. The total cost of construction was $950,000, which included the cost of labor, structural materials and vegetation. This figure was higher than anticipated. However, it was acceptable provided that the barrier was successful.

Once the barrier was completed, the wall was monitored periodically by visual inspection. For the first two years, the Evergreen system was found to be structurally sound and capable of sustaining vegetation. The shrubs and small plants were initially green so there was no establishment period, but the vines took longer to establish. The Evergreen system also performed as intended by providing substantial noise reduction (prior to construction the prevailing noise level was found to be about 75 dBA, which was reduced to about 65 dBA after construction). However, after that period it faced problems with the vegetation because of lack of moisture. It was determined that the Evergreen design did not allow sufficient precipitation to reach vegetation. As a result, an irrigation system was added to the barrier. The irrigation system was connected to a local water supply and regulated by a timer.

One year the irrigation system was not properly drained before winter and the freezing temperatures resulted in cracked pipes. After the pipes cracked, the irrigation system could no longer be used and was never repaired. Without adequate irrigation, the Evergreen system was not capable of sustaining the vegetation. The barrier was affected by the lack of moisture, especially during the summer and winter months. The barrier was replanted twice between 1992 and 2007. However, the new vegetation either failed to take root or died. Without vegetation to bind the soil together, the soil lacked cohesion and was subject to erosion. In addition, some bushes inside the structure became too large to be retained and fell out of the barrier. The combination of soil erosion and bushes falling from the structure resulted in several holes approximately 1 ft by 1 ft in the wall. These holes did not affect the structural stability of the Evergreen system. However, the noise reduction was slightly reduced. Attempts were made to replace eroded soil, but without vegetation the erosion persisted.

In subsequent years, it was extremely difficult to maintain vegetation due to the lack of moisture and weeds became prevalent. This reduced the aesthetics of the barrier and caused nearby residents to complain about the structure. In order to improve the aesthetics and quell complaints, NHDOT planted several trees and shrubs such as White Spruce, Marshall Seedless Ash and Pin Oak in front of the wall. Figures 4.1 and 4.2 show front and back view pictures, respectively, of the Manchester green noise barrier taken in May 2011. As can be seen in these pictures, the wall is mostly covered with weeds on the front side and very little vegetation on the back side.

In summary, the Evergreen system was found to be structurally stable and effective in mitigating traffic noise. However, it was not capable of sustaining vegetation and failed to produce the desired aesthetics. Furthermore, it was expensive to construct and maintain. The NHDOT indicated that they do not recommend the Evergreen system as a green noise barrier and would rather use concrete posts and pressure treated wood panels, which is the traditional design for noise mitigation in New Hampshire.

Figure 4.1: Front View of the Manchester Green Noise Barrier (Courtesy of the NHDOT)

Figure 4.2: Back View of the Manchester Green Noise Barrier, A Small Hole in the Wall Can Be Noticed in the Right Side of the Picture (Courtesy of the NHDOT)

4.3 The Colorado Experience

The Colorado Department of Transportation (CDOT) constructed a green noise barrier in 1994 in Silver Plume, Colorado and is still standing. The Silver Plume green noise barrier was constructed under the Colorado Type II noise barrier program. It was positioned along the westbound on-ramp of the I-70 interchange at Silver Plume and situated atop a slight embankment within the right-of-way clear zone. The barrier sits at an elevation of slightly more than 9000 ft in a mountain valley approaching the continental divide. The average temperature during the winter is about 16^{o}F and it ranges between 40 to 90^{o}F during the summer. The climate is relatively dry with an average humidity of 20% and 5 to 8 inches of moisture, almost exclusively in the form of snow. The valley can further be characterized as windy with about 10 mph of sustained breeze and 60 mph wind gusts being not uncommon.

Figure 4.3 shows a recent picture of the Silver Plume noise barrier. This barrier was constructed using recycled plastic, forming a series of tiered, pocketed soil bins designed for vegetation. The barrier is oriented in an east-west direction with a slight curvature. The south side faces the interstate and receives maximum sunlight, while the north side faces the town and receives very little direct sunlight. From the description provided, it seems that this noise barrier utilized a similar technology to that of the Recywall. This design was thought to be suitable to the heavy tourist travel on the interstate through this region. CDOT worked with local agencies to make the wall unique and attractive to local residents and highway travelers.

The 1200 ft long barrier varies from 9 to 14 ft in height and runs parallel to the westbound shoulder of the interstate and the entrance ramp west of the town center. The variable height compensated for changing ground elevation to provide a consistent shielding height to residents from a climbing roadway. The overall dimensions were determined to best provide 5 dBA target reductions (old CDOT optimization standard) to village residential areas from interstate traffic noise.

No information is available about the construction or vegetation selection process of the Silver Plume noise barrier. However, the responder to the questionnaire indicated that the construction was likely performed by a CDOT approved contractor and that native plant species for the specific climatic zone were used, which is the current practice of CDOT. It was also noted that plant cover was never established on the wall due to the harsh mountain environment. Several other factors might have also led to the vegetation failure: the soil pockets were not irrigated, irregular natural precipitation, and exposure to winter deicing salt and sand. As a result, the barrier failed to achieve the anticipated aesthetic results.

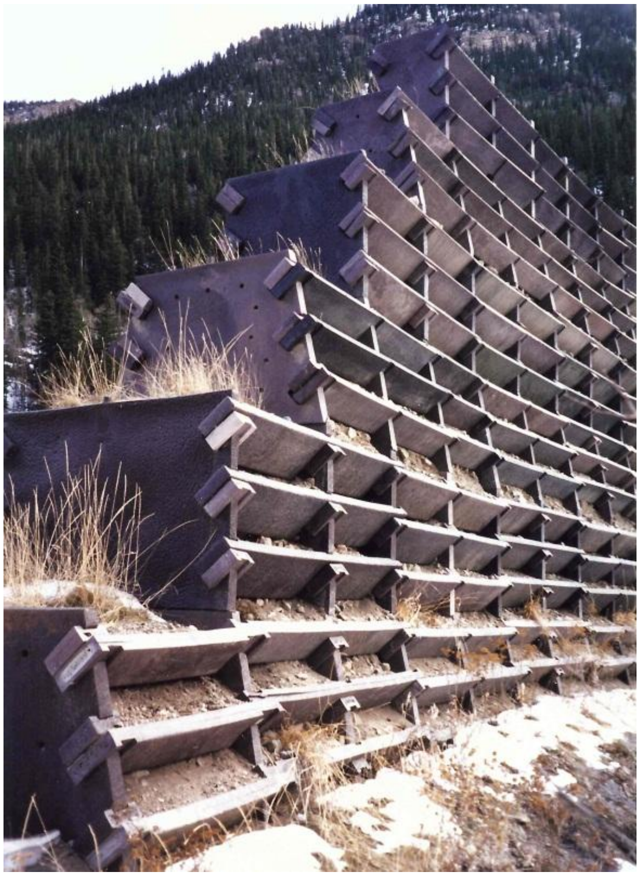


Figure 4.3: Silver Plume Noise Barrier in Colorado (Courtesy of the CDOT)

A reevaluation was conducted in 2005 to determine the structural stability and acoustic performance of the barrier. Based on this reevaluation, it was noticed that the overall structural integrity is good and the acoustic properties remain consistent with the design. The wall material was found to be in fair to good condition with some damage from winter snowplowing operations and about 80% of the pocketed bins to be viable. At the time of the reevaluation, the noise level behind the wall at the nearest residence averaged 63 to 66 dBA, as compared to 66 to 70 dBA before construction. It should be noted that traffic volume has double from 1993 to 2005 and that traffic noise has most likely risen as a result. Therefore, it can be assumed that immediately after construction the noise level was lower than the 63 to 66 dBA noise level at the time of the reevaluation.

In summary, the Silver Plume noise barrier is a stable structure and a successful noise abatement measure. This barrier is still standing after 17 years of service and is expected to reach the 20 to 25 year design service life for noise barriers in Colorado. Also, this barrier continues to provide substantial noise reduction. However, it failed to achieve the desired properties of a green barrier. The vegetation never established and the aesthetics were not what was expected by CDOT.

The CDOT had the following recommendations based on their experience with green noise barriers. If they were to reattempt the project, they would not have selected a high-altitude location for the green noise wall. Additionally, if they were to construct another green noise wall, they would require an automated drip irrigation system to water the vegetation. Plants would be selected to best meet the harsh semi-arid, sub-alpine climate and regular monitoring of plant survival and replanting would be instituted for a two year period. They also recommended implementing a maintenance program for debris removal that continued to accumulate on the sides of the wall. Finally, lower tier bins would not be planted to avoid contamination from deicing salt and sand from winter maintenance operations.

4.4 The Wisconsin Experience

The Wisconsin Department of Transportation (WisDOT) constructed a green noise barrier in 1994 in Milwaukee, Wisconsin. The barrier was situated along the southbound direction of interstate I-94, north of College Avenue (Figure 4.4). The decision to build a green noise barrier came from the increased demand by the general public for alternatives to traditional noise barriers. Many residents complained about the aesthetic properties of concrete and steel noise barrier, claiming they resembled prison walls or industrial warehouses. Efforts to improve the aesthetics added to the cost of existing noise barrier projects. As a result, WisDOT began investigating available living noise barrier products that might be able to increase aesthetics without increasing cost.

The investigation was part of a formal research study led by WisDOT in collaboration with Howard, Needles, Tammen and Bergendoff (HNTB). This study was conducted in two stages. The first stage focused on determining whether a "living" noise barrier is maintainable, cost effective and aesthetically pleasing when compared to the standard post and panel type noise barrier. This involved evaluating available living noise barriers, consulting with other highway agencies regarding their experience with living noise barriers, identifying suitable types of vegetation, and determining if a prototype living noise barrier would be feasible. The second stage involved proceeding with the construction of the actual living noise barrier depending on the outcome of the feasibility study. The first stage concluded in the summer of 1993 and determined that a prototype living noise barrier project would be feasible. It also recommended using the Recywall design that uses recycled plastic.

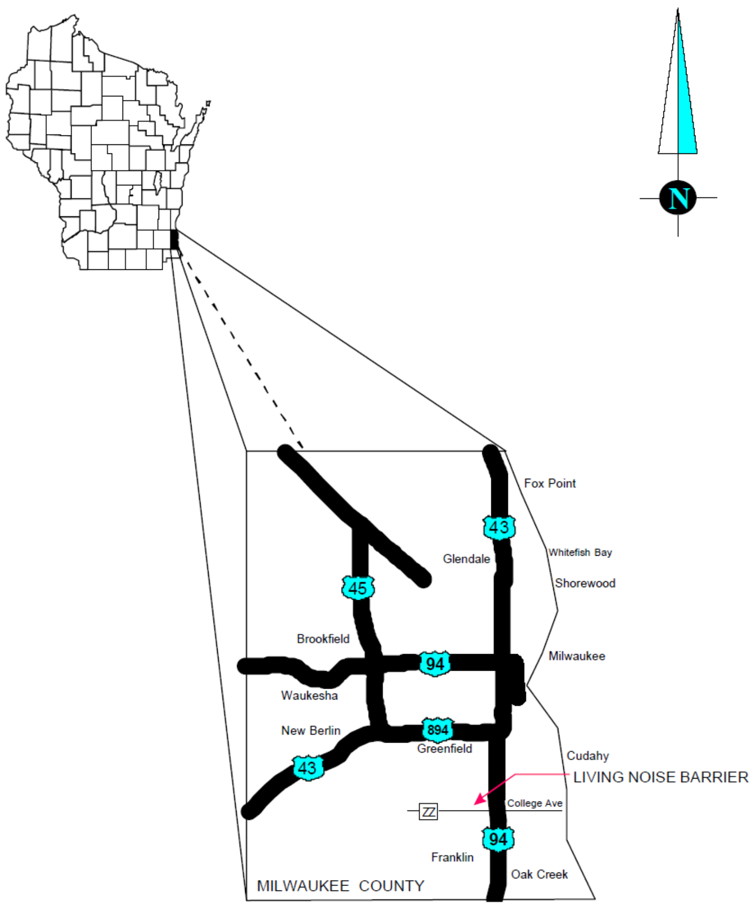


Figure 4.4: Location of Wisconsin Recywall (*14*)

Once the decision to proceed with the prototype wall was made, HNTB staff prepared plans and specifications of the structure including foundation design, barrier profile, horizontal alignments and planting plans. The manufacturer of Recywall, Sanders Enterprises, Inc. (SEI), prepared the design and shop drawings for the plastic structure. The initial design called for a structure that is 520 ft long and 9 ft wide. The barrier height was designed using the FHWA

STAMINA traffic noise model, with the objective of producing a noise reduction of 8 dBA. The maximum barrier height was found to be 21 ft. The manufacturer's final design had several variations from the initial design. The base of the structure was reduced from 9 ft to 7 ft in order to save on materials and cost. This resulted in the side slope being increased from 1:5.25 to 1:7 to reach the required heights. WisDOT expressed concern over the steep faces and the ability of the structure to collect rainfall, but the manufacturer was unwilling to revise the design of the structure without substantial additional cost to WisDOT. The WisDOT decided to proceed with the final design due to lack of funding.

The actual construction of the Wisconsin green noise barrier began in April of 1994. The foundation was composed of a geogrid and an 18 inch crushed limestone base layer. The plastic frame was constructed as specified by the manufacturer. The soil was originally designed to be a mixture of topsoil, sand, and peat moss in a 1:1:1 ratio by volume. This was changed to 70% and 30% mixture of topsoil and peat, respectively. The soil was loaded into the plastic frame using a backhoe (Figure 4.5). A jumping jack compactor was initially used, but caused the plastic frame to bow outwards. As a result, the contractor used a plate compactor at a low intensity to compact the backfilled material (Figure 4.6). The structure was completed in June of 1994. It was planted with a variety of vegetation including evergreens, shrubs, vines, roses, ground covers and perennials. The total cost of the structure was $395,000, which included $285,902 for the structure and $109,981 for the vegetation.

Several problems with the structure were noted during construction and shortly after completion. The first problem was a bulge that appeared in the upper third portion of the wall on the northeastern end of the structure. This bulge was noticed after initial watering of the vegetation. Measurements were taken and determined the bulge to be 8 inches outwards. However, it was decided that the bulge had ceased expanding and had not compromised the structure. Therefore, no corrective actions were implemented. The second problem that was observed was a loss of soil from within the structure (Figure 4.7). The soil that had fallen from the structure caused a domino effect in which soils for the higher levels of the structure would also be lost. This occurred until the cells were emptied. The corrective action that was taken to fix this problem was to refill the cells where soil loss persisted. In order to prevent the soil loss problem, vegetation was planted in the cells so that the roots could bind the soil together and provided stability. This effort was unsuccessful and many of the plants either died or fell from the cells along with the soil. The decision to permanently end the loss of soil and vegetation did not occur until April of 1995, in which extensions were added to the members. These members were successful in preventing the soil and vegetation from falling from the structure.

Figure 4.5: Filling the Recywall with Soil (*14*)

Figure 4.6: Soil Compaction in the Recywall (*14*)

Figure 4.7: Soil Loss in Plating Cells (*14*)

The project was monitored for two years and was found to have many defects in addition to the previously mentioned bulging and soil loss. These problems included excessive deflection and shearing in the vertical and horizontal supports and the overall structure was found to be leaning (Figure 4.8). Upon further investigation, it was found that some plastic connections contained very large air voids due to factory defects (Figure 4.9). Later analysis revealed that the recycled plastic was not a suitable structural component to handle the forces that were applied. The soil loss was solved through the addition of the extensions, but the vegetation faced many difficulties. Nearly 5,000 of the initial 13,000 plants did not survive the first growing season. Also in the first year, 2,400 of these plants needed replacement after soil loss caused them to fall from the structure. Once the soil loss problem was resolved, water became the main issue. No irrigation system was implemented because it was not cost effective due to the lack of a nearby water source. Since the structure was tall and narrow, little rainfall reached the structure. When rain did reach the structure, it only reached the upper portion of the wall. Additionally, weeds became prolific and proved to be better at growing under adverse conditions. These weeds influenced the aesthetics and public perception of the noise barrier. These problems persisted until August 1996 when the top 6 to 8 ft of a 100 ft section collapsed (Figure 4.10). This was followed by an additional 100 ft section collapsing two weeks later.

Figure 4.8: Excessive Deformation in the Horizontal and Vertical Supports (*14*)

Figure 4.9: Large Air Voids in Plastic Connections Due to Factory Defects (*14*)

Figure 4.10 Collapse of the Wisconsin Recywall (*14*)

Following an investigation, several contributing factors were identified as potential causes of failure. In addition to the previously mentioned manufacturing defects, high temperatures from the sun are believed to have weakened the plastic framework. The continued loss of soil reduced the support strength of the structure. This is because the Recywall relies on the soil to support the horizontal and vertical members. A lack of moisture resulted in shrinkage and consolidation within the core of the structure contributing to the reduced support for the horizontal and vertical members. The structure was removed in September 1996 and the soil was formed into a small earth berm with the surviving vegetation planted along the berm.

WisDOT came to the following conclusions and recommendations from their experience with this project. The geometric design of the Recywall is not capable of capturing sufficient rainfall for healthy plant growth. The steep side slopes prohibited moisture from entering the plant cells. Also, the plastic framework was not properly designed to hold the soil core in place. Without the ability to provide adequate support, large amounts of soil were lost from within the structure, which might have contributed to the collapse of the structure. Several plant species like Sedum, Phlox, Fragrant Sumac, Alpine Current, Englemann Ivy, Lamium, Artemesia and Daylily performed well. However, the majority of the plant species were unable to survive the harsh weather conditions. WisDOT also noted that weeds could not be controlled without extensive manpower and that weed growth reduced the aesthetics of the noise barrier. Finally, the cost of this barrier was found to be 146% greater than that of a traditional noise barrier. Therefore, it was concluded that a green noise barrier is not a feasible option for Wisconsin.

4.5 The Ontario Experience

Many green noise barriers have been constructed in the Province of Ontario, Canada using the Living Willow Wall design. Several individuals involved with these barriers were contacted by the research team. The responses of these individuals to the questionnaire revealed that most of the barriers were constructed very recently. Hence, these barriers could not provide beneficial knowledge of the long term performance of this design. Additionally, none of these barriers were constructed along a major highway. Therefore, their performance may not necessarily reflect how these barriers would perform along a major highway.

An example Living Willow Wall that was used along two major arterial roads was that constructed in the Town of Whitby, Ontario in 2005. This barrier was constructed at the intersection of Taunton road and Anderson road. Taunton road runs in the Southwest-Northeast direction, while Anderson road runs in the Northwest-Southeast direction. This region of Canada sees average temperatures of 25^{o}F in the winter and 75^{o}F in the summer, with an average annual precipitation of 30 to 40 inches. The Living Willow Wall design was ultimately chosen because of its combination of noise reduction and aesthetics.

The Whitby Living Willow Wall was 4 ft wide, 6 ft high and was designed to provide the optimal sound protection for the surrounding residences. This barrier used a wooden frame and willow branches to retain soil. The barrier was oriented in both the north-south and east-west directions, which caused different amounts of sunlight to reach the faces. However, the responder to the questionnaire indicated that the orientation did not affect the performance of the vegetation.

The wall design and construction was the responsibility of The Living Wall Company. The construction process lasted two days and is detailed in the previous chapter. Willow branches require large amounts of moisture especially during the establishment period. Due to this fact, a self watering irrigation system was installed within the barrier. The final cost of the construction including vegetation, labor, materials and irrigation system was about $33,000.

After completion, the barrier was monitored by visual inspection. The barrier has proven to be structurally sound and is still standing today. The vegetation took 6 months to establish, but required minimal maintenance (trimming the vegetation) once established. The noise levels were found to be considerably lower after construction but exact levels were not provided.

In summary, a large number of Living Willow Walls have been constructed in Ontario. All of these barriers were constructed along less traveled roads such as transit yards, residential developments, etc. Based on the responses to the questionnaire, all the respondents were pleased with the overall performance of the barriers. Furthermore, very few issues were raised regarding the structural stability and the aesthetics of the barriers.

The Ontario Ministry of Transportation was also contacted and provided information on why these barriers have not been used along major highways. They expressed concern over the service life of green noise barriers in comparison to conventional noise barriers. They believed that the vegetation may die off from adverse weather conditions and the use of deicing salt during winter. In order to reduce the effects of deicing salt, they recommended placing these barriers 50 ft away from the road, which implies that additional right of way needs to be purchased. Additionally, they pointed out that these structures require more maintenance than traditional barrier such as trimming, weed removal and replanting (if necessary), and that funding for such activities might be more difficult to obtain than initial (capital) construction. Finally, with regard to the Living Willow Wall they indicated that this design fails to meet the height requirements demanded for most noise mitigation projects. Many noise barriers need to be more than 12 ft high to provide adequate noise reduction, which is greater than the maximum height of the Living Willow Wall. This problem is only intensified by the possibility of settlement within the barrier that may reduce the height and noise reduction properties.

4.6 Green Noise Barrier Recommendation

The primary objective of reviewing available green noise barrier products and conducting the questionnaire was to identify a product that would be suitable for Ohio. In order for this product to be viable it shall sustain vegetation during its intended service life, provide comparable if not better acoustic protection than conventional noise barriers, and maintain structural integrity with minimal settlement and material defects.

While many green noise barriers have been successful in various geographic regions, the majority of these successes have been in moderate climates where there is little temperature change and abundant moisture. Ohio has a widely contrasting climate with harsh winters, occasional dry summers and monthly average temperatures ranging from 15^{o}F to 85^{o}F. Additionally, the state receives an average of 37 inches of precipitation annually. Therefore, the selected design needed to provide the best chance of enduring Ohio's climate.

Based on the outcome of the literature review and responses to the questionnaire, several concerns have been raised regarding some of the green noise barrier products presented in Chapters 3 and 4. Main concerns include the ability of the green noise barrier product to capture and retain moisture, the ability of the barrier to incorporate suitable vegetation for the prevailing environment, the ability of the barrier to resist erosion and the height limitations of the barrier.

Green noise barriers typically have a relatively small footprint with a base width of about 3 to 12 ft. This width does not enable these barriers to capture enough moisture to sustain vegetation. In addition, these barriers have large surface areas that are exposed to sun and wind, increasing the rate of evaporation of the moisture within the barrier. Therefore, unless the barrier is located in a very moist environment during the summer and the winter, an irrigation system is needed to sustain vegetation.

Some types of vegetation require more moisture than others. For example, willow trees thrive in high moisture environments and require continuous watering especially during establishment. Meanwhile, prairie grass can survive dryer environmental conditions. Therefore, being able to incorporate vegetation that is resilient to adverse conditions can reduce the amount of irrigation and maintenance costs. Due to the occasional lack of moisture in Ohio, it is imperative to select a green noise barrier that has the ability to incorporate vegetation that can survive with little moisture.

Another concern was the erosion of soil from within the green noise barrier. Many of the designs were reported to be susceptible to erosion, which could lead to a loss of vegetation and a reduction in noise mitigation. This loss of soil could also increase maintenance costs and decrease the aesthetics of the structures. As a result, the selected design would need to resist erosion from both wind and rain.

The final concern associated with green noise barriers are the height limitations. Some of the green noise barrier products were limited in height, which makes them not suitable for many locations. Most noise barriers require at least 12 ft of height to provide sufficient noise mitigation and be considered feasible. Therefore, if a particular design cannot accommodate a barrier height greater than 12 ft it may not be a practical alternative to traditional concrete barriers.

After reviewing the available products and analyzing their advantages and disadvantages, the Deltalok product seems to be the most viable. The Deltalok design alleviates most of the concerns commonly associated with green noise barriers. The Deltalok barrier has a large mass when compared to other designs, which allows more moisture to be retained within the structure. This large mass will also aid in retaining heat during Ohio's winter months increasing the vegetation survivability. The Deltalok design allows for the use of a wide variety of vegetation including small trees, bushes, plants and most importantly, grasses. Grass is one of the most resilient types of vegetation and is favorable for location with little moisture. In addition, the Deltalok bags promise to minimize erosion from the structure. These bags allow moisture to infiltrate but restrict the soil from being removed by water. Furthermore, since the soil is retained in the bags, erosion from wind is minimized. Finally, the Deltalok design can accommodate heights greater than 12 ft, which makes this structure suitable for many noise mitigating applications.

While the Deltalok design addresses many of the concerns associated with other green noise barriers, this design has several limitations. As mentioned in Chapter 3, this design has a steep face that may not allow the barrier to capture and retain enough moisture to sustain vegetation. Furthermore, it has not been used as a free standing wall, which introduces some uncertainty over its structural performance. To evaluate these concerns, a prototype Deltalok wall was constructed and monitored as discussed in the following chapters.

Chapter 5
Construction of the Prototype Wall

5.1 Introduction

Before a full scale green noise wall is constructed, a prototype wall was built and instrumented with various sensors and devices to monitor its structural stability and ability to retain moisture. As discussed in the following chapters, data collected from these sensors and devices was used to validate the structural design and make recommendations regarding the irrigation of the full scale wall.

The prototype wall was constructed in Covington, Ohio (north of Dayton) in Miami County. The wall construction took place in March 2011 after the soil has defrosted. The material and equipment was provided by TJ Sales & Consulting, an authorized Deltalok distributor. Along with the material and equipment, TJ Sales & Consulting also provided three fulltime crew members who worked for two days to construct the prototype wall. Upon completion, the prototype wall measured 15 ft in length, 9 ft in width, and 12 ft in height.

5.2 Wall Materials

The prototype wall was constructed from Deltalok products that were provided by TJ Sales & Consulting. The primary component of the Deltalok system is the Deltalok GTX bags (Figure 5.1). The GTX bags have an unfilled dimension of 35 inches by 15 inches. These bags would provide the structural support and surface for plants to grow. The open end of these bags would be securely tied using zip ties. The Deltalok standard units were used to provide a connection between the layers of Deltalok bags. The Deltalok standard unit was preferred over the Deltalok engineered unit due to the application and structural design. The standard unit is a 100% recyclable plate that has 3 spikes protruding from the top and 8 spikes protruding from the bottom (Figures 5.2 and 5.3, respectively). These plates are placed at the point where two bags meet with a subsequent layer placed on top linking three bags together to act as a single unit. The engineered units differ in that they have additional hooks on the side of the plate that allow for connection to high density polyethylene (HDPE) geogrids. However, for this project it was determined that STRATAGRID 200, a polyester geogrid, would provide adequate reinforcement and therefore the Deltalok standard unit was utilized.

Figure 5.1: Deltalok GTX Bag

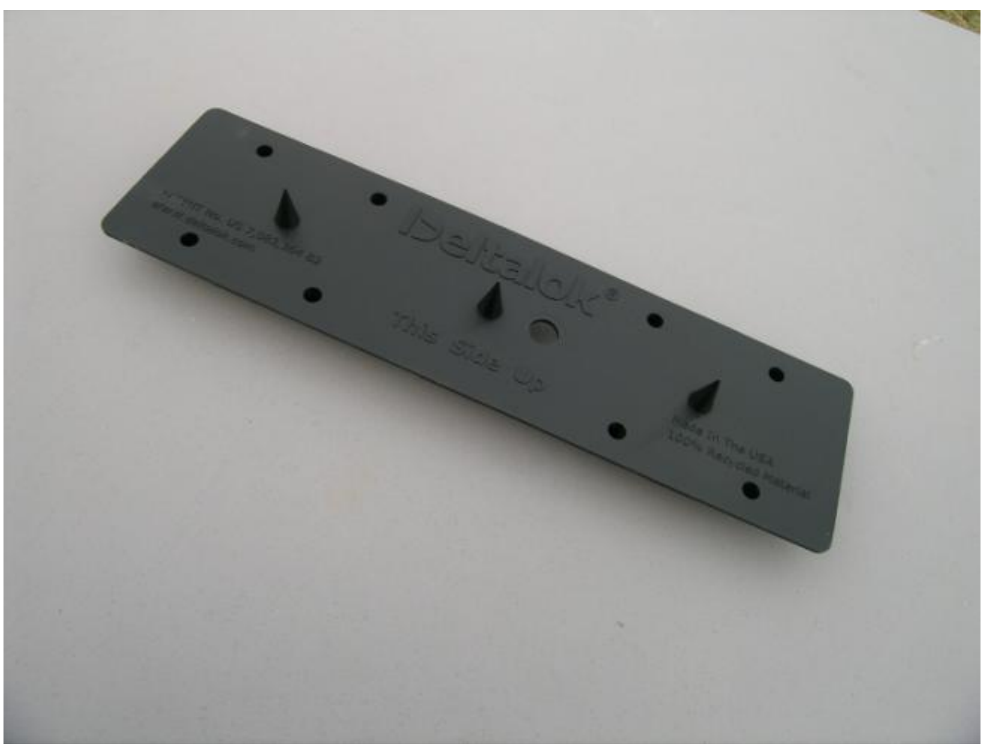


Figure 5.2: Top View of Deltalok Standard Unit

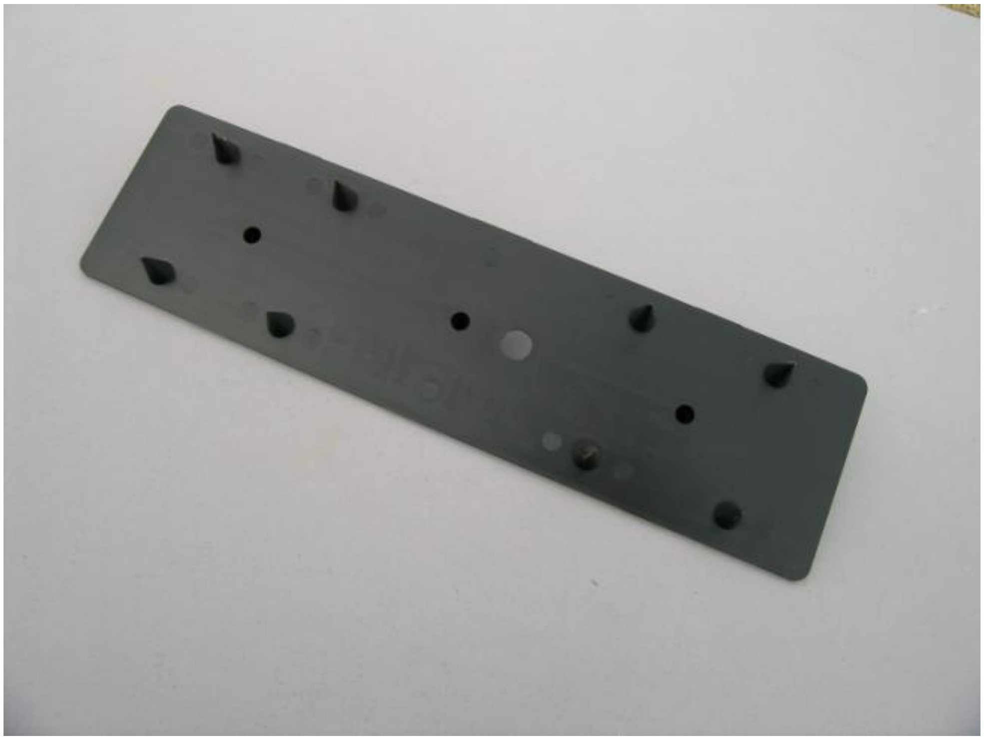


Figure 5.3: Bottom View of Deltalok Standard Unit

5.3 Filling the Deltalok Bags

The Deltalok bags were filled with a mixture of 25% top soil and 75% sand. The top soil would provide a medium in which vegetation could grow while the sand would provide voids in which moisture could infiltrate to all levels of the structure. In order to expedite the filling of the bags, multiple bags would be filled simultaneously. A wooden frame was constructed with 24 holes cut in a sheet of plywood; thus, allowing to fill 24 bags at once. The open end of the bags were placed in the holes of the wooden frame and secured. With the bags in place, a skid steer was used to load soil onto the frame (Figure 5.4). Workers pushed the mounded soil into the bags ensuring that the bags are equally filled (Figure 5.5). The bags were then removed from the frame and tied off using zip ties (Figure 5.6). Once the bags were filled and tied, they were stacked on pallets and placed inside a warehouse to protect them from rain (Figure 5.7). This process would provide bags that were equally filled and approximately the same shape. This step would also reduce the stacking time, leveling process and reduce the settlement that would occur in the structure. The final bag weight was between 90 and 100 pounds. Each bag was about 11 inches wide, 28 inches long and 5.5 inches high.

Figure 5.4: Filling the Deltalok Bags

Figure 5.5: Pushing the Soil into the Bags

Figure 5.6: Closing the Bags using Zip Ties

Figure 5.7: Bag Stacking and Storage

5.4 Foundation Preparation

With the bags prepared, the second step of construction was preparing the foundation. Soil was excavated to a depth of 8 to 12 inches. Once the hole was dug, a geotextile fabric was placed at the bottom of the excavation to minimize lateral deformation at the bottom of the wall. Six inches of dense graded gravel (ODOT Item 304) was then placed on top of the geotextile and was compacted and leveled to provide structural support (Figure 5.8).

The first layer of geogrid was placed on the level surface of the base course (Figure 5.9). Deltalok connectors were placed on top of the geogrid which served as a link between the Deltalok bags and the stable foundation. Two layers of Deltalok bags filled with gravel were placed around the perimeter of the prototype wall. These bags were filled with gravel to allow water to drain away from the structure releasing any hydrostatic pressure. The bags were then stepped on by the crew members to ensure a secure link between the Deltalok bags and the Deltalok units (Figure 5.10). The center area, between the Deltalok bag perimeters, was backfilled with ODOT Item 304 and compacted. This brought the foundation height to the natural ground level. With the foundation at ground level, the assembly of the structure could begin.

Figure 5.8: Geotextile Fabric and Base Course

Figure 5.9: First Layer of Geogrid and Two Rows of Deltalok Bags Containing Gravel

5.5 Assembly of the Structure

The third stage of construction was assembling the Deltalok bags. The Deltalok bags were placed on top of the connectors that were attached to the foundation with the longer side of the bag running parallel to the face of the wall. In preparation for the following row of bags, another Deltalok standard unit was placed on top of these bags at the point where two bags met. In the following row, a bag would be placed directly above the standard unit. This process would be repeated providing linkage between layers of Deltalok bags. To ensure the bags were secured to the connectors, workers stood on top of the bags after each row was placed (Figure 5.10). After workers had constructed two layers of Deltalok bags, a backhoe would fill the central portion of the barrier. The backfill would compose the core of the wall and had a specified composition (Figure 5.11). The composition of this granular material was 25% top soil and 75% ODOT Item 304. This core was compacted by walk-behind vibrating plate compactor every two layers of Deltalok bags (Figure 5.12). The compaction was done at this interval because of the difficulty in compacting more than 11 inches of soil using a plate compactor. During construction, special attention was paid to the compaction of the backfill material since proper compaction would reduce the amount of settlement once the barrier was complete. However, less room was available for compaction towards to the top of the wall (Figure 5.13). Therefore, it was harder to control the compaction at that location.

During the construction, geogrid was placed every four layers of Deltalok bags. The geogrid was placed after compaction and before the placement of the Deltalok standard units. The geogrid was aligned so that the ultimate strength direction was perpendicular to the wall face. The placement of the geogrid was determined by Deltalok and checked by the research team assuming active lateral earth pressure. As discussed in the next chapter, the tensile forces in the geogrid were found to be lower than the long term design and ultimate tensile strengths of the geogrid.

5.6 Wall Height and Angle

During construction, several checks were made to ensure the structure was constructed properly. As the rows of bags were placed on the barrier, a laser level was used to ensure that all bags had the same height (Figure 5.14). Any variations in height were accounted for in subsequent rows of bags by tightening the zip tie to increase the bag height and thus increase the level at the location where the bag will be placed. The use of the laser level made certain that the top of the bags had the same level and the structure was not leaning.

The slope of the wall was checked using an “A” frame and a simple right angle triangle jig with a level attached to its side (Figures 5.16 and 5.17, respectively). Both instruments allowed the slope of the bags to be constant throughout the layers.

Figure 5.10: Stepping on the Bags to Engage the Deltalok Units

Figure 5.11: Wall Backfill

Figure 5.12: Backfill Compaction

Figure 5.13: Construction at Higher Height Levels

Figure 5.14: Laser Level

Figure 5.15: Checking the Wall Height

Figure 5.16: Checking Angle with A-Frame

Figure 5.17: Checking Angle with Triangle Jig

5.7 Completed Structure

The completed structure stood twelve 12 ft high, 9 ft wide and 15 ft long (Figure 5.18). All faces had a slope angle of about 76^o from the horizontal (about 14^o from the vertical). The wall was aligned in the east-west direction, with its southern face receiving the highest exposure to sunlight and its northern face being on the shady side of the wall. The prototype wall was constructed using 475 Deltalok bags. To reach the target height, twenty six (26) rows of Deltalok bags were needed (12 ft wall height x 12 inch per ft / 5.5 inch per bag ≈ 26 rows of bags), not including the first two rows of bags that were filled with gravel.

Figure 5.18: Completed Prototype Wall

The prototype wall was monitored for two months. During this period, the performance of the prototype wall was evaluated for geotechnical stability and structural integrity. In addition, soil temperature and moisture content data was collected and utilized in the design of an irrigation system for the full scale green noise wall. As such, the prototype wall was an important component of the research process. It provided valuable information that helped predict how the full scale green noise barrier will perform.

Chapter 6
Structural Stability of the Prototype Deltalok Wall

6.1 Introduction

The Deltalok product is a reinforced earth structure that uses geogrid as reinforcement and Deltalok ecology bags as facing units. The prototype Deltalok wall discussed in the previous chapter measured 15 ft in length, 9 ft in width and 12 ft in height. All faces had a slope angle of about 76^{o} from the horizontal (14^{o} from the vertical). The Deltalok bags were held together by Deltalok standard unit connectors, which are plastic plates with spikes protruding from each side that penetrate through the bags, and provide connection with the geogrid. These geogrids were placed every four rows of Deltalok bags (or approximately every 22 inches) and were used to resist tensile forces within the wall.

The prototype wall was equipped with various sensors to monitor its external and internal stabilities. The external stability includes the bearing capacity, overturning and sliding failure modes as well as excessive settlement or tilt in the structure. The internal stability refers to the tensile failure of the geogrid reinforcement or pullout of geogrid from between the Deltalok bags. The former was monitored using an earth pressure cell placed at the center of the base of the wall and a number of survey points located on the exterior of the wall. The latter was monitored using vibrating wire displacement transducers (crackmeters) located at the center of the longitudinal face of the wall and connected to the geogrid within the core of the structure.

6.2 Material Description

This section covers the properties and characteristics of the materials that were involved in the construction of the prototype wall. These materials include the subsurface soil, the geogrid reinforcement, the bagfill and the backfill soils. The properties of these materials were used in the analysis of the structural stability of the prototype wall, as will be discussed in the following sections.

6.2.1 Subsurface Soil

A subsurface soil investigation was performed by the Ohio Department of Transportation (ODOT) Office of Geotechnical Engineering (OGE) prior to construction. The soil boring was conducted to a depth of 25 ft. The subsurface soil investigation results revealed very stiff ($2 \leq q_u \leq 4$ ton per ft^2) to hard ($q_u > 4$ ton per ft^2) cohesive soil underneath the wall, where q_u is the unconfined compressive strength of the soil. Therefore, the soil was determined to be stable for the construction of the prototype wall.

6.2.2 Geogrid Reinforcement

The wall contained eight layers of geogrid reinforcement. STRATAGRID 200, a polyester geogrid, was used in the wall. The STRATAGRID 200 is a uniaxial geogrid with an ultimate tensile strength of 3,600 lb/ft in the longitudinal (strong) direction and 1,600 lb/ft in the transverse (cross-roll) direction. Assuming a design life of 40 years, the long-term design strength (LTDS) of STRATAGRID 200 is 1881 lb/ft for the longitudinal direction and 726 lb/ft for the transverse direction. The LTDS accounts for creep loading, durability reduction and installation damage.

6.2.3 Bagfill and Backfill Soils

The Deltalok bags were filled with a mixture of 25% top soil and 75% sand, while the core of the wall was constructed using a mixture of 25% top soil and 75% ODOT Item 304. Table 1 presents the bagfill and backfill soil properties. Figure 1 shows their particle size distributions. As can be seen from Table 1, the bagfill soil had 91.4% passing Sieve No. 4, 86.8% passing Sieve No. 10 and 34.9% passing Sieve No. 200. Meanwhile, the backfill soil had 40.8% passing Sieve No. 4, 33.4% passing Sieve No. 10 and 19.7% passing Sieve No. 200. Additionally, both soils were found to have low plasticity, as indicated from their liquid limits and plasticity indexes. The AASHTO and Unified Soil Classification (USC) systems were used to classify the bagfill and backfill soils. Based on the AASHTO classification system, the bagfill soil can be classified as A-2-4 and the backfill soil can be classified as A-1-b. Meanwhile, based on the USC system, the bagfill soil can be classified as SC-SM (silty clayey sand) and the backfill soil can be classified as GM (silty gravel with sand).

Table 6.1: Bagfill and Backfill Soil Properties

		Percent Passing (%)	
Sieve No.	Sieve Opening (mm)	Bagfill Soil	Backfill Soil
1"	25.4	100.0	91.7
3/4"	19.05	100.0	83.2
1/2"	12.7	100.0	65.8
3/8"	9.525	100.0	57.2
4	4.75	91.4	40.8
10	2	86.8	33.4
20	0.85	72.9	28.9
30	0.60	64.6	27.2
40	0.425	56.4	25.9
60	0.250	45.3	24.2
140	0.106	36.4	21.0
200	0.075	34.9	19.7
Liquid Limit, LL		19.6	21.2
Plastic Limit, PL		17.6	16.2
Plasticity Index, PI = LL - PL		2.0	5.0
AASHTO Classification		A-1-b	A-2-4
Unified Soil Classification		GM	SC-SM

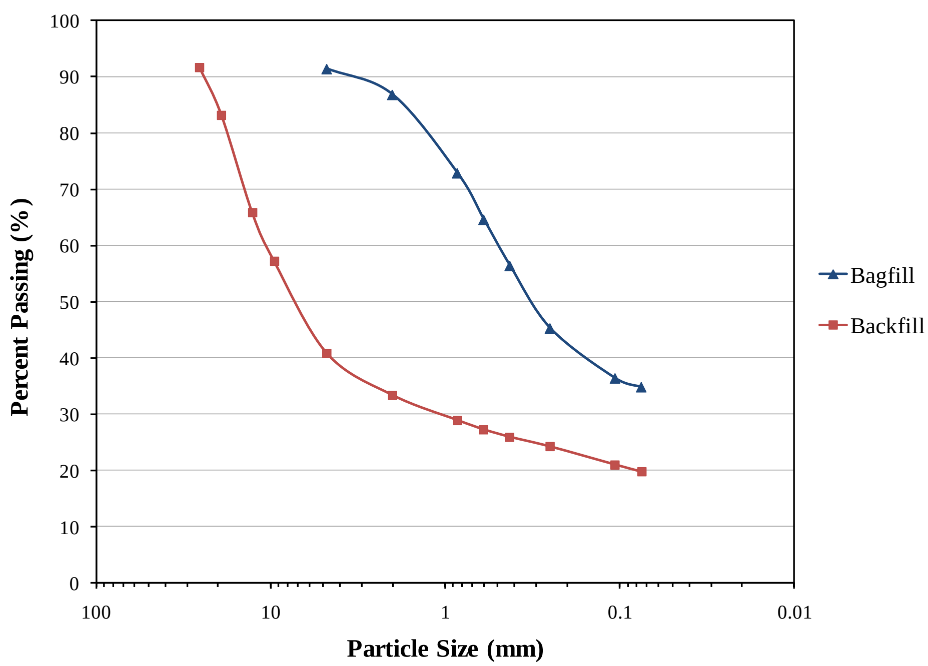


Figure 6.1: Particle Size Distribution

6.3 Instrumentation Plan

The earth pressure and deformation characteristics of the prototype wall were monitored for a period of two months after construction. The instrumentation plan included an earth pressure cell placed at the center of the prototype wall to measure vertical pressure, four vibrating wire displacement transducers (or crackmeters) mounted on the geogrid at various heights within the wall to measure geogrid deformation and a number of survey points located on the exterior of the wall to monitor wall deformation.

6.3.1 Earth Pressure Cell

Earth pressure cells are designed to measure the total pressure in earth fills and embankments. In this application, the total vertical pressure is resulted from the combined weight of the soil and water within the structure. A single vibrating wire pressure cell was used in the prototype wall and was located at the center of the base of the wall (Figure 6.2). The pressure cell used in the prototype wall was the GeoKon Earth Pressure Cell (Model 4800). It had a pressure range of 25 psi (170 kPa) and an accuracy of plus or minus 0.5% (0.125 psi or 0.85 kPa). A thin layer of fine-grained soil was placed around the pressure cell to reduce the effect of point loading from gravel particles. This sensor consists of two 9 inch diameter stainless steel plates welded together. The space between is filled with hydraulic fluid. The weight of the structure presses the plates together, increasing the pressure of the fluid between the two plates which is transferred to the vibrating wire. This wire converts the pressure into an electrical signal which can be read by a readout device. The advantage of the vibrating wire design is an increased life span and more accurate results.

Figure 6.2: Earth Pressure Cell

6.3.2 Vibrating Wire Displacement Transducers

Vibrating wire displacement transducers (crackmeters) were used to measure deformation in the geogrid. A total of four displacement transducers were used in the prototype wall. They were located at the center of the longitudinal face of the wall and connected to the geogrid using special clamps. The location of the displacement transducers is shown in Figure 6.3. As can be seen from this figure, the first displacement transducer was placed two layers of Deltalok bags above the foundation. Each subsequent transducer was located directly above the previous sensor with four layers of Delatlok bags between.

GeoKon Crackmeter (Model 4420) was selected for its durability and accuracy. This transducer had an unstretched length of 354 mm (13.9 inches) and a range of 50 mm, with an accuracy of 0.1% (0.05 mm). Figure 6.4 shows a picture of one of the displacement transducers. This design uses a metal rod connected to a spring within a housing. As tension is applied to the rod, the spring is elongated and is sensed by the vibrating wire. The tension in the wire is directly proportional to the extension which yields accurate strain measurements.

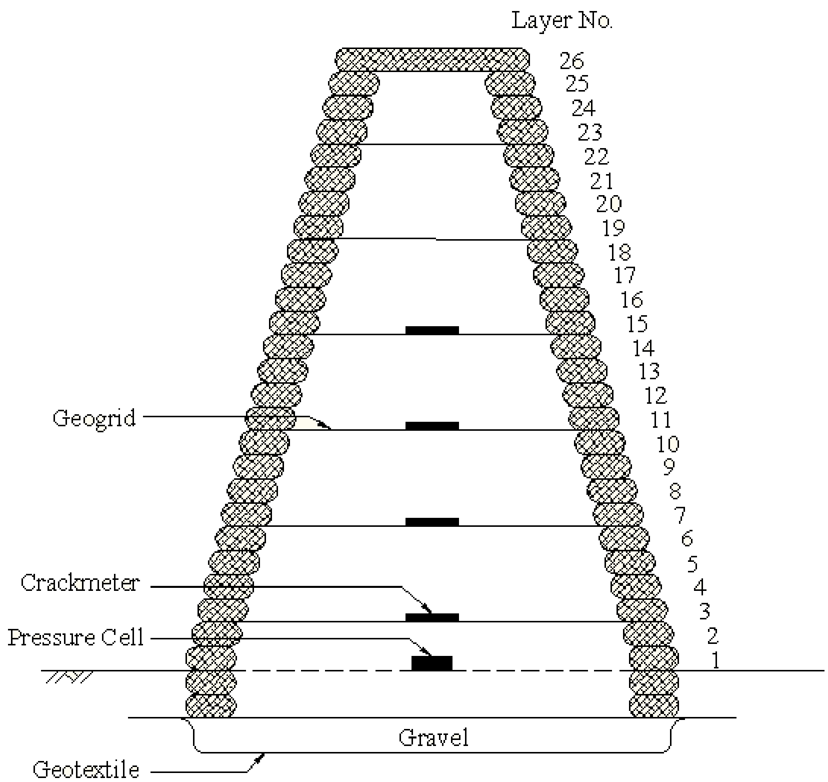


Figure 6.3: Location of Displacement Transducers

Figure 6.4: Vibrating Wire Displacement Transducer (Crackmeter)

6.3.3 Data Acquisition

The data from the pressure cell and the displacement transducers was retrieved by a readout device specially designed for vibrating wire sensors. The readout device used in this study was the GeoKon Readout Device (Model GK-403). This unit provides instant measurements from the sensors which are read from an LCD screen. The unit has the ability to download these readings into a spreadsheet which can be used for further analysis. Additionally, the readings are provided with the temperature so that corrections can be made on the data collected.

A baseline reading was recorded in the field for both the pressure cell and displacement transducers. These reading were obtained before the backfill material was placed on top of the sensors. The baseline reading for the pressure cell was used to establish a zero reading that will be used in calculating the vertical pressure. For the displacement transducers, this zero reading was used to determine a reference (initial) length for the displacement transducer.

6.3.4 Survey Points

A total of 21 survey points were placed on the exterior of the prototype wall to monitor wall deformation. Each survey point consisted of a 12 inch threaded metal rod (3/8” diameter), six washers, and two nuts (Figure 6.5). These survey points were placed in the center of the bags at different locations within the structure. A set of three washers were placed on the outside of the bags and nuts were used to secure the rods to the bags (Figure 6.6). The washers were used to prevent the nuts from piercing through the bags when the nuts were tightened. The approximate and final locations of each survey point can be seen in Figures 6.7 and 6.8, respectively.

A total station was used to determine the initial position of each survey point immediately after construction and to monitor their movement in subsequent evaluations. The procedure for evaluating the location of the survey points was as follows. Two reference points that would not move were established near the wall. The total station was placed at a point facing two sides of the wall where the two reference points were visible. From this location, the positions (elevations, angles and distances) of the survey points could be determined. The total station was then moved to the opposite corner of the wall so that the two reference points are visible, and the same procedure was followed to obtain the position of the survey points on the other two faces.

Figure 6.5: Survey Point (Before Installation)

Figure 6.6: Survey Point (After Installation)

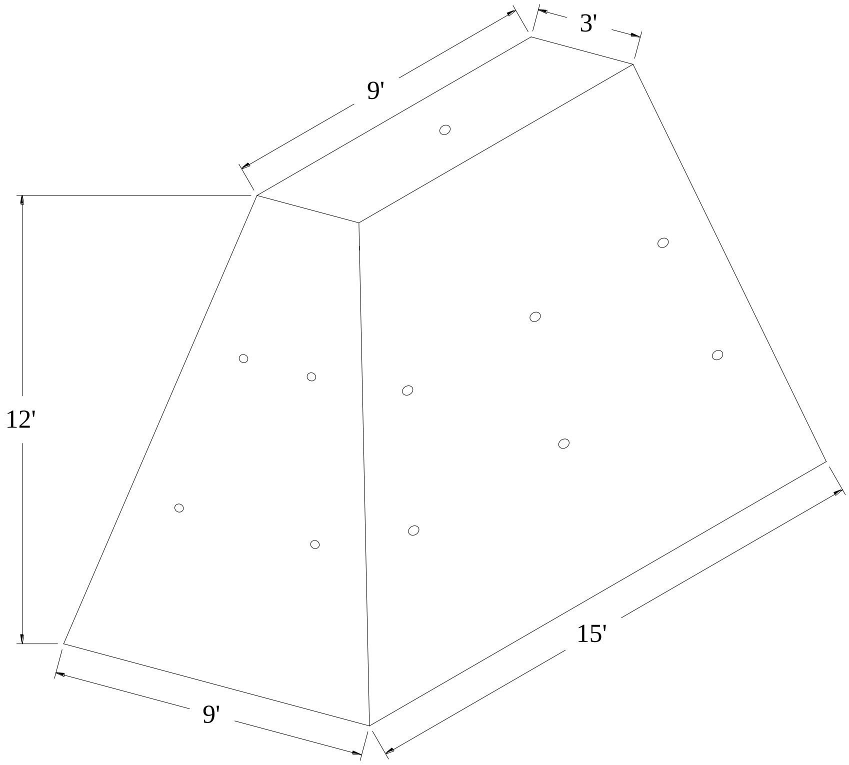


Figure 6.7: Approximate Location of Survey Points

Figure 6.8: Final Location of Survey Points

6.4 Results and Analysis

The monitoring of the prototype wall lasted two months and was based on data collection and visual inspection. This section discusses the results of the data collection. Due to the relatively short period of time in which the data was collected, this evaluation is considered preliminary and is not necessarily indicative of the long term performance of the Deltalok product.

6.4.1 Vertical Pressure

Table 6.2 presents the earth pressure readings and the corresponding temperatures obtained prior to construction, at the end of construction, 1 month and 2 months after construction. These readings were used to calculate the total vertical pressure, P, based on the formula provided by the GeoKon Company:

$$P = G(R_o - R_1) + K(T_1 - T_o) - (S_1 - S_o) \quad (1)$$

where P is the total vertical earth pressure in psi, G is the linear gage factor and is equal to 0.007385 psi/digit, R_o is the zero reading of the pressure cell prior to construction, R_1 is the gage reading, K is the thermal factor and is equal to 0.010864 psi/^{o}C, T_o is the temperature reading before construction in ^{o}C, T_1 is the temperature reading in ^{o}C, S_o is the barometric pressure prior to construction in mbar and S_1 is the barometric pressure at the time of measurement. The barometric pressure has minimal effect on the pressure value and therefore can be eliminated.

Table 6.2: Vertical Earth Pressure at the Center of the Base of the Wall

	Readings		Vertical Pressure (Linear) (psi)
	Pressure (digit)	Temperature (^{o}C)	
Zero Reading in the Field	9702	9	0.0
End of Construction	8899.5	5.9	5.9
1 Month After Construction	8845.2	6.8	6.3
2 Months After Construction	8859.2	11.5	6.3

As can be seen from Table 6.2, the total vertical earth pressure at the center of the base of the wall immediately after the end of construction is equal to 5.9 psi. This value is less than that estimated from the at-rest vertical pressure, $\sigma_v = \gamma h$, where γ is the unit weight of the soil and h is the height of the barrier. Assuming a unit weight of soil of 120 lb/ft^3 and a barrier height of 12 ft, the estimated vertical pressure at the center of the base of the wall is 120 lb/ft^3 x 12 ft x (1 ft / 12 inch)^2 = 10 psi. This implies that the vertical load is not uniformly distributed at the base of the wall and the outer portion of the base is carrying a greater portion of the load than the middle. This can be attributed to two factors. The first is the effect of soil arching, which is common in earth embankments, due to the shape of the prototype wall. The second is the transfer of the vertical load to the sides of the wall through the geogrid reinforcement. In order to better understand this phenomenon, it is recommended that more pressure cells be used in the second phase of this study. It can also be observed from Table 6.2 the total vertical pressure slightly increased over time. This could be due to the increase in moisture content within the wall and due to the deformation of the structure, as will be discussed in the following sections.

6.4.2 Geogrid Deformation

The deformation of the geogrid was monitored by vibrating wire displacement transducers located at lower half of the barrier, as previously discussed in Section 6.1. The values recorded from the displacement transducers can be seen in Table 6.3. These readings were obtained prior to construction, at the end of construction, 1 month and 2 months after construction. These readings were used to calculate the deformation of the geogrid, D, based on the formula provided by the GeoKon Company (Equation 2). The deformation values obtained from this equation are presented in Table 6.4. As can be seen from this table, all deformation values were positive, which implies stretch in the geogrid (or tensile deformation).

$$D = G(R_1 - R_o) \tag{2}$$

where D is the deformation of the geogrid in inches, G is the linear gage factor in inch/digit, R_o is the initial (zero) reading from the displacement transducer prior to construction and R_1 is the reading from the displacement transducer after construction.

Table 6.3: Displacement Readings from Vibrating Wire Displacement Transducer

Disp. Transducer	Height (Above Ground)	Linear Gage Factor, G	Displacement Readings			
			Zero Reading	End of Construction	1 Month	2 Months
#	(inch)	(inch/digit)	(digit)	(digit)	(digit)	(digit)
1	11	0.0003885	2537.6	2658.0	2769.0	3001.9
2	33	0.0003890	3437.0	3874.5	4157.2	4646.4
3	55	0.0003901	2763.7	2891.9	3452.7	3629.2
4	77	0.0003895	3220.0	3297.7	3650.4	3650.4

Table 6.4: Geogrid Deformation

Disp. Transducer	Height (Above Ground)	Geogrid Deformation			
		Zero Reading	End of Construction	1 Month	2 Months
#	(inch)	(inch)	(inch)	(inch)	(inch)
1	11	0.0	0.047	0.090	0.180
2	33	0.0	0.170	0.280	0.470
3	55	0.0	0.050	0.269	0.338
4	77	0.0	0.030	0.168	0.168

The strain in the geogrid was calculated by dividing the geogrid deformation by the initial length of the displacement transducer prior to loading. Table 6.5 presents the strain in the geogrid, expressed as a percentage. Figure 6.9 shows the strain in the geogrid versus height above ground. The strain at the top of the wall was given a zero strain value. As can be noticed from both Table 6.5 and Figure 6.9, the measured strain in the geogrid varied nonlinearly with wall height and increased over time. The maximum strain was obtained at a height of 33 inch.

Table 6.5: Geogrid Strain

Disp. Transducer	Height (Above Ground)	Geogrid Strain			
		Zero Reading	End of Construction	1 Month	2 Months
#	(inch)	(%)	(%)	(%)	(%)
1	11	0.0	0.3	0.6	1.3
2	33	0.0	1.2	2.0	3.4
3	55	0.0	0.4	1.9	2.4
4	77	0.0	0.2	1.2	1.2

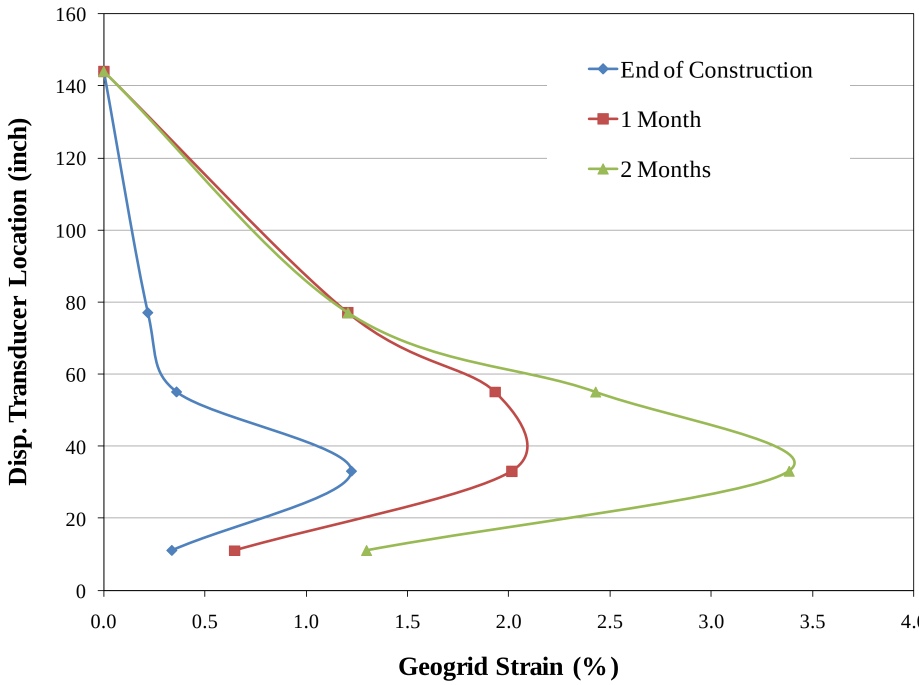


Figure 6.9: Geogrid Strain versus Height Above Ground

The load in the geogrid was estimated from load versus strain curves established in the laboratory for STRATAGRID200. Figure 6.10 shows the experimental setup for the laboratory testing of the geogrid. As can be seen in this figure, the laboratory testing procedure involved a simple test setup with a single load cell to measure the force and a gear box to apply the deformation until failure. The geogrid specimens were glued to the loading fixtures in order to prevent slippage. Each specimen consisted of a single strand of geogrid measuring 5.25 inches in length. Figure 6.11 presents the experimental test results obtained at 0.01 inch/min, 0.10 inch/min, and 0.50 inch/min. From this figure it can be noticed that the load versus strain curves are nonlinear and are dependent on the loading rate. The higher is the loading rate, the higher is the tensile strength of the geogrid and the lower is the tensile strain at failure. It is noted that the geogrid strain observed in the field was less than 4% (Table 6.5); and therefore only the portion of the curves in Figure 6.11 relative to this data was considered. At that strain level, there was minimal difference between all three loading curves.

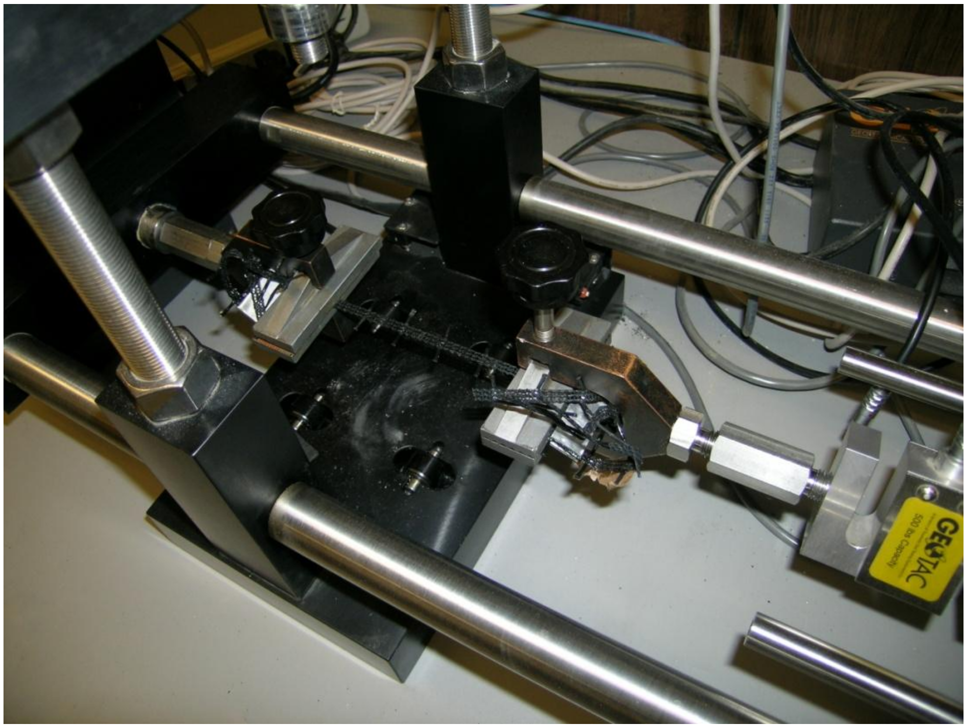


Figure 6.10: Laboratory Testing of Geogrid

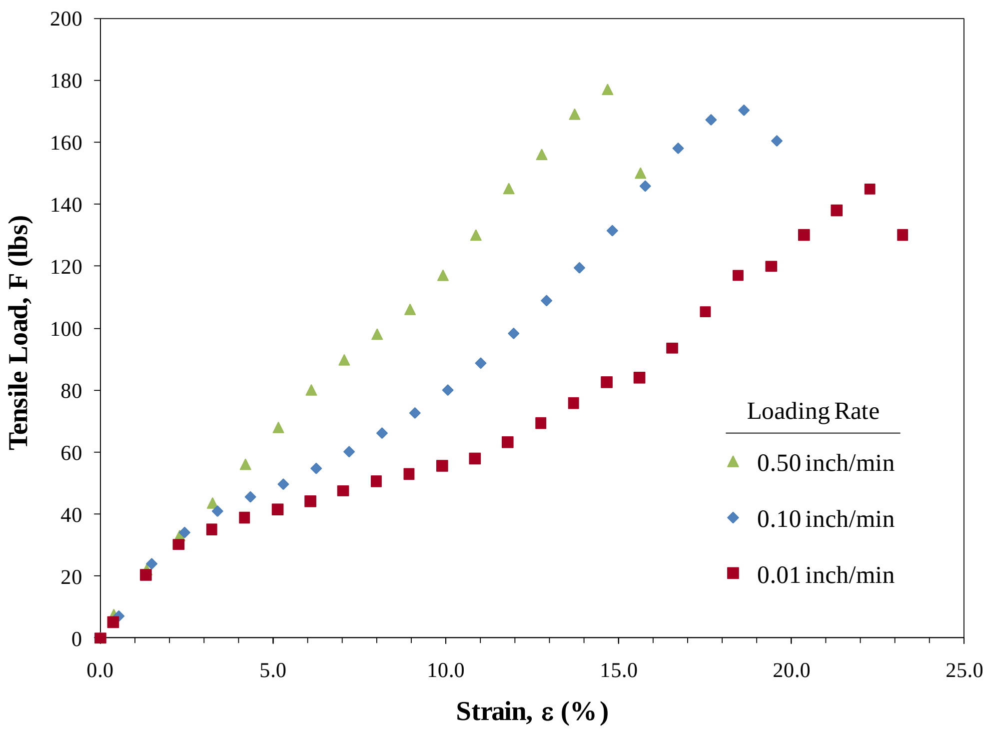


Figure 6.11: Force versus Strain Curves for STRATAGRID200 at Different Loading Rates

Figure 6.12 shows the load versus strain regression model at 0.50 inch/min. This loading rate was selected because it provides the highest load estimates. As can be seen from this figure, the best fit curve for the data was a third degree polynomial model (cubic curve) with an R^2 value equal to 1. This formula was used to obtain the load acting on the geogrid in the prototype wall. Since the laboratory tests were conducted on a single strand of geogrid, the load values obtained from this formula were multiplied by the number of strands per foot, which is 13.8, to obtain the load per linear foot of the geogrid width. The resulting load values are provided in Table 6.6.

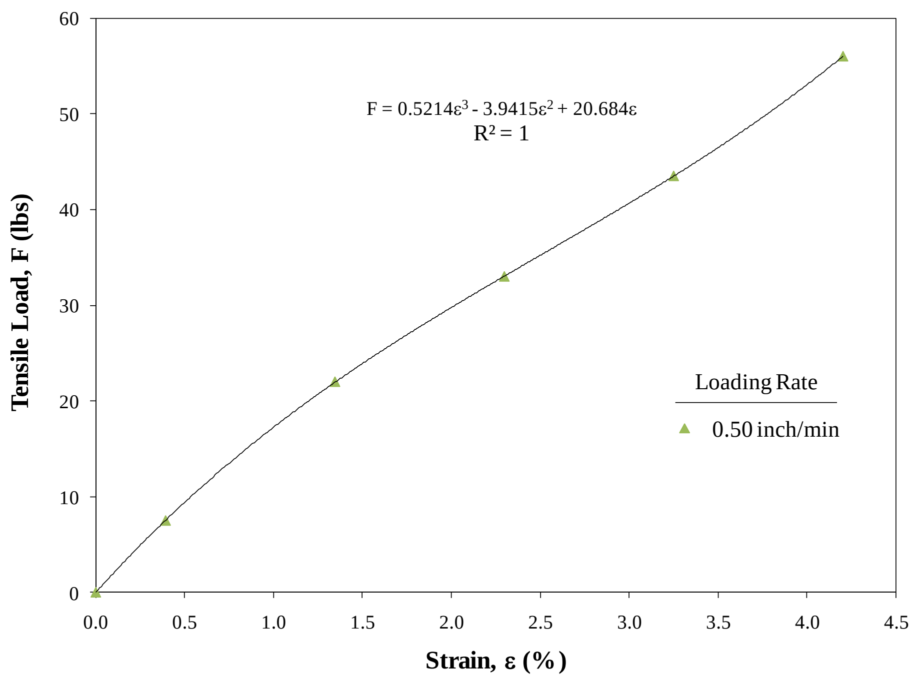


Figure 6.12: Load versus Strain Regression Model at 0.50 inch/min

Table 6.6: Geogrid Load in the Prototype Wall

Disp. Transducer	Height (Above Ground)	Geogrid Load			
		Zero Reading	End of Construction	1 Month	2 Months
#	(inch)	(lb/ft)	(lb/ft)	(lb/ft)	(lb/ft)
1	11	0.0	90.1	163.7	294.3
2	33	0.0	280.9	413.0	621.5
3	55	0.0	95.9	400.3	475.2
4	77	0.0	59.6	277.6	277.6

Tables 6.7 and 6.8 present the ultimate strength to load ratio and the design strength to load ratio, respectively. Since the ultimate strength is higher than the design strength, the latter will be used as the basis for the analysis. Low design strength to load ratio implies a low factor of safety. Therefore, the most probable location for geogrid failure is at a height of 33 inches, in the bottom quarter of the wall. This is the most critical location based on readings obtained immediately after construction as well as 1 month and 2 months after construction. The minimum design strength to load ratio was obtained 2 months after construction and was equal to 3.1. This high ratio implies that the structure is internally stable in the transverse direction. There is more concern about the internal stability of the prototype wall in the longitudinal direction due to the relatively low strength for the geogrid in that direction and the short length of the prototype wall. A full scale barrier would have a plane strain response reducing the effects of the longitudinal forces in the geogrid near the middle of the wall. Towards the end, additional reinforcement might be needed to increase the resistance of the wall to longitudinal deformation.

Table 6.7: Ultimate Strength to Load Ratio

Disp. Transducer	Height (Above Ground)	Ultimate Strength to Load Ratio			
		Zero Reading	End of Construction	1 Month	2 Months
#	(inch)	(unitless)	(unitless)	(unitless)	(unitless)
1	11	N/A	40.0	22.0	12.2
2	33	N/A	12.8	8.7	**5.8**
3	55	N/A	37.5	9.0	7.6
4	77	N/A	60.4	13.0	13.0

Table 6.8: Design Strength to Load Ratio

Disp. Transducer	Height (Above Ground)	Design Strength to Load Ratio			
		Zero Reading	End of Construction	1 Month	2 Months
#	(inch)	(unitless)	(unitless)	(unitless)	(unitless)
1	11	N/A	21.1	11.6	6.4
2	33	N/A	6.8	4.6	**3.1**
3	55	N/A	19.8	4.7	4.0
4	77	N/A	31.8	6.8	6.8

6.4.3 Wall Deformation

As discussed earlier in Section 6.3.4, the prototype wall was monitored for deformation by a total of 21 survey points. These points were placed on the barrier in the approximate locations shown in Figure 6.13. The letters N, S, E, W refer to the north, south, east and west directions, respectively, while U and L represent upper and lower levels of survey points. The east direction was established as the positive X direction, the north direction was established as the positive Y direction, and the wall elevation was established as the positive Z direction.

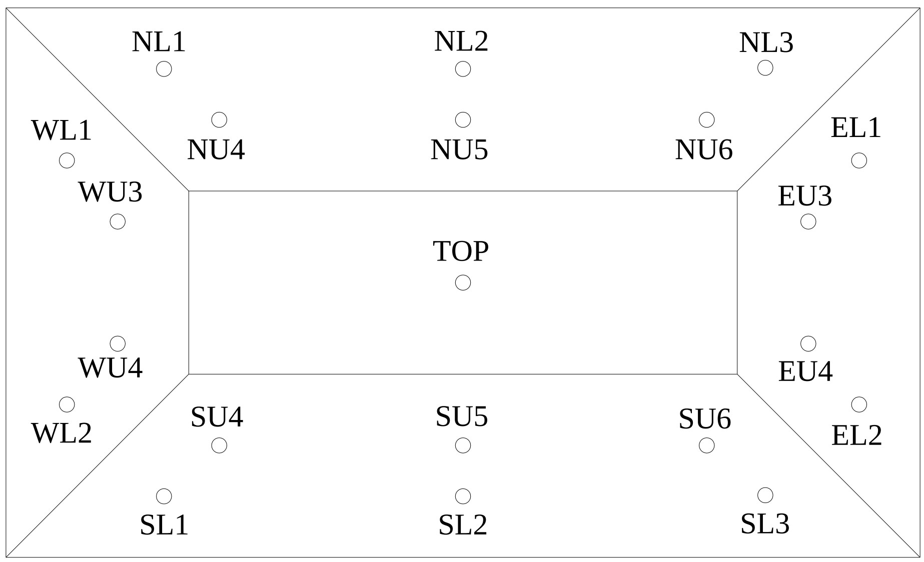


Figure 6.13: Approximate Location of Survey Points

A total station was used to determine the initial position of each survey point immediately after construction and to monitor their movement in subsequent evaluations. These values were used to determine the deformation of the wall one month and two months after construction (Table 6.9). From this table, it can be noticed that the prototype wall continued to deform two months after construction. Based on the two-month displacements, it can be noticed that the greatest vertical movement took place at the top of the wall, followed by the upper level of survey points, then the lower level of survey points. This is expected since the survey point at the top of the wall would respond to deformation at all levels within the wall. Meanwhile, the survey points at the lower level of the wall would only respond to deformation in the bottom third of the wall. The total settlement in the prototype barrier (vertical displacement at the top of the wall) was equal to 4.98 inches (about one row of Deltalok bags). From this table, it can also be noticed that two months after construction the vertical deformation in the north and east faces was greater than that in the south and west faces, which indicates that the barrier may be shifting or tilting toward the north and east directions. This observation is consistent with the displacement values in the X and Y directions, which indicate the wall is tilting toward the north and east directions.

Table 6.9: Displacement Data of Survey Points

	1 Month			2 Months		
Point	ΔX (East)	ΔY (North)	ΔZ (Elev.)	ΔX (East)	ΔY (North)	ΔZ (Elev.)
#	(inch)	(inch)	(inch)	(inch)	(inch)	(inch)
NL1	-0.06	-0.12	-0.24	-0.42	-0.54	-2.70
NL2	0.06	0.06	-0.30	0.48	0.06	-3.36
NL3	0.30	0.00	-0.30	0.72	0.06	-2.22
NU4	-0.18	-0.12	-1.14	0.42	0.66	-4.92
NU5	0.06	-0.30	-1.02	0.72	0.54	-6.06
NU6	0.24	-0.36	-1.20	0.84	0.42	-5.46
WL1	-0.18	-0.54	-0.60	-0.96	-0.78	-1.68
WL2	-0.06	-0.30	-0.66	-0.78	-0.96	-1.38
WU3	0.06	-0.36	-0.96	0.66	0.24	-3.36
WU4	0.06	-0.30	-0.96	0.42	0.36	-2.58
SL1	-0.48	-0.12	-0.60	-0.42	0.12	-1.08
SL2	-0.06	-0.24	-0.72	0.00	0.36	-1.20
SL3	0.24	-0.18	-0.72	0.18	0.90	-1.20
SU4	-0.06	-0.24	-1.14	0.60	1.50	-2.58
SU5	0.12	-0.30	-1.32	0.30	1.62	-3.30
SU6	0.18	-0.18	-1.26	0.24	1.74	-2.88
EL1	0.48	0.06	-0.48	1.68	0.72	-2.58
EL2	0.36	-0.18	-0.72	1.08	-0.06	-1.68
EU3	0.18	-0.18	-1.20	0.42	1.44	-4.38
EU4	0.12	-0.12	-1.20	0.36	1.56	-3.54
Top	--	--	-1.50	--	--	-4.98

6.5 Conclusions

This chapter documented the instrumentation, data collection and analysis of the prototype Deltalok wall in order to determine its viability as a green noise barrier. The analysis was based on the data collected during the periodic site visits that lasted two months and visual inspection. Due to the relatively short period of time in which the wall was monitored, this evaluation is considered preliminary.

Based on the outcome of the field evaluations and visual inspections, the following conclusions can be made about the stability of the Deltalok design:

- The total vertical pressure from the barrier acting at the center of the foundation was less than that estimated from the at-rest vertical pressure. This indicates that the vertical load is not uniformly distributed at the base of the wall and the outer portion of the base is carrying a greater portion of the load than the middle. This can be attributed to effect of soil arching and the transfer of the vertical load to the sides of the wall through the geogrid reinforcement. In order to better understand this phenomenon, it is recommended that more pressure cells be used in the second phase of this study.
- The data from the vibrating wire displacement transducers was used to calculate the deformation, strain and load in the geogrid. The maximum geogrid strain occurred 33 inches (6 rows of Deltalok bags) above ground and was equal to 3.4%. This strain corresponded to 621.5 lb/ft load in the geogrid. This load was found to be significantly lower than the long-term and ultimate tensile strengths of STRATAGRID200, which implies that the prototype wall is internally stable in the transverse direction. This conclusion is for a 12 ft barrier, additional reinforcement might be needed for Deltalok structures of greater height. Additionally, a full scale barrier would have a plane strain response reducing the effects of the longitudinal forces in the geogrid near the middle of the wall. Therefore, additional reinforcement might be needed towards the end of the structure to increase its resistance to longitudinal deformation.
- The total vertical settlement in the prototype wall was found to be 4.98 inches or about one layer of Deltalok bags. The prototype wall is expected to continue to settle. Therefore, to account for the effect of settlement on the reduction in acoustic performance of the Deltalok wall, it is recommended to construct the barrier using two additional layers of Deltalok bags. The settlement of the Deltalok structure can be minimized through the use of additional

layers of geogrid and by ensuring proper compaction of backfill materials during the construction of the structure.

- Finally, although the analysis took place over a relatively short period of time, the results indicate that the Deltalok green noise barrier is a stable structure. Thus far, it appears that this product may be a viable option for noise mitigation. However, additional evaluations may be needed to determine the long-term performance of the wall.

Chapter 7
Moisture and Temperature of the Prototype Wall

7.1 Introduction

The ability to sustain vegetation is one of the most important aspects of a green noise barrier. The vegetation provides the barrier with the aesthetic properties that are lacking in traditional noise barriers. In order to sustain vegetation, the barrier must be capable of retaining moisture and providing a suitable temperature in which the vegetation can grow. Increased respiration will occur if the barrier becomes too hot, while plant growth will be restricted if the barrier becomes too cold. Therefore, the prototype wall was monitored to determine the moisture and temperature distributions within the barrier.

This chapter documents the instrumentation, monitoring and analysis of the moisture and temperature data to determine the barrier’s ability to retain moisture and the type of plants best suited for the green noise barrier. The analysis was based on the data collection from the instrumentation and visual inspection that lasted for two months. This will be a preliminary evaluation due to the short period of time in which the data was collected.

7.2 Instrumentation Plan

The prototype Deltalok wall was equipped with eight moisture and eight temperature sensors that were embedded in the Deltalok bags. The moisture and temperature sensors were installed in separate, but adjacent bags so that readings from one sensor would not interfere with readings from the other. As can be seen in Figure 7.1, two sets of four moisture and four temperature sensors were installed in the prototype Deltalok wall. One set was installed on the north side and the other was installed on the south side. Each set was connected to a solar powered data logger capable of storing the data for later retrieval. The sensors were located in the first, ninth, seventeenth, and twenty fifth rows of Deltalok bags. By placing these sensors at multiple heights, the research team could evaluate the distribution of moisture and temperature within the barrier.

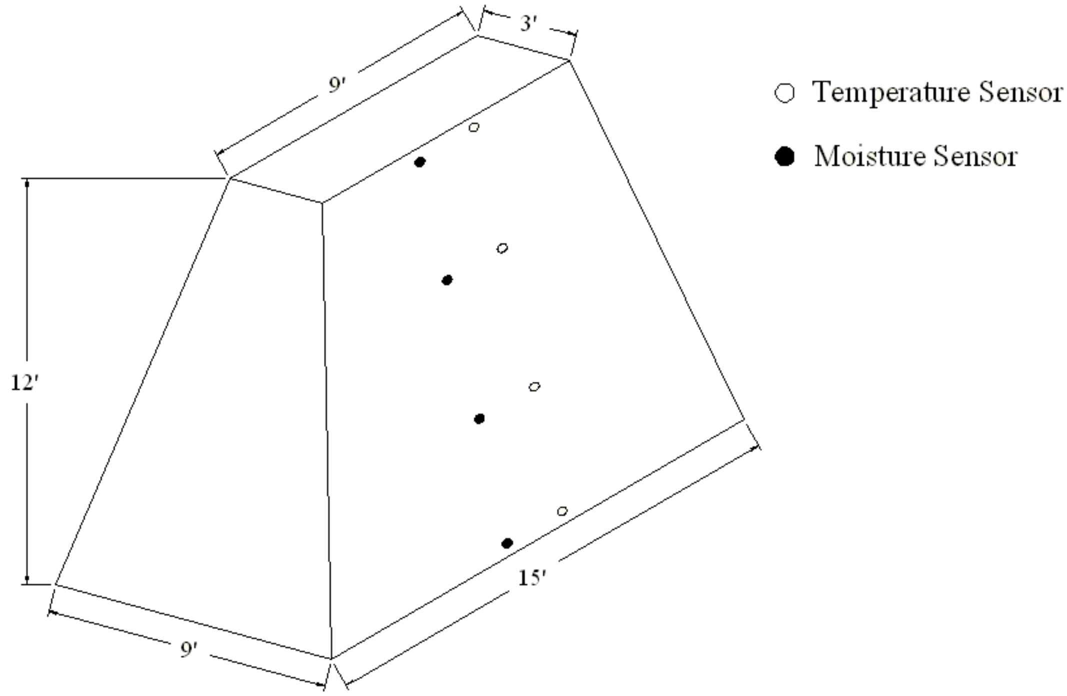


Figure 7.1: Location of Temperature and Moisture Sensors

7.2.1 Moisture Sensors

The prototype wall was instrumented with Decagon Model S-SCM-M005 (EC-5) moisture sensors (Figure 7.2). This sensor measures the volumetric water content within a cylindrical region of soil around the sensor measuring 181 cm^3. It has an accuracy of plus or minus 3%. This sensor determines the volumetric water content (VWC) by measuring the dielectric constant of soil using capacitance/frequency domain technology. Since electricity acts differently in air than water, this technology emits electrical signals to measure differences in the resistance of these signals. This model uses a 70 MHz frequency, which minimizes salinity and textural effects, making the EC-5 sensor accurate in almost any soil or soil-less media.

7.2.2 Temperature Sensors

The prototype wall was instrumented with Onset Model S-TMB-006 temperature sensors. This sensor measures temperatures ranging from -40 to 100^{o}C, with an accuracy of plus or minus 0.03^{o}C. Similar to the moisture sensors, the temperature sensors were inserted into the Deltalok bags prior to construction.

Figure7.2: Decagon Model S-SCM-M005 (EC-5) Moisture Sensor.

Figure 7.3: Onset Model S-TMB-006 Temperature Sensor

7.2.3 Data Collection

Two Onset HOBO U30 data loggers were used to collect the data from the moisture and temperature sensors (Figures 7.4 and 7.5). The data loggers were fastened to steel poles driven into the ground. A solar panel was attached to each data logger and served as the power source.

Figure 7.4: Onset HOBO U30 Data Logger

Figure 7.5: Location of Data Loggers

7.3 Results and Analysis

After the completion of the construction, the barrier was watered with a soaker hose until saturation. This was done to test that the moisture sensors were working properly and to start monitoring from a known moisture level rather than relying on natural precipitation data. The monitoring began immediately after construction; however, the data presented in this section focused on that collected after saturation by the soaker hose (from April 10, 2011 to May 12, 2011).

7.3.1 Temperature

Figures 7.6 and 7.7 present the data obtained by the temperature sensors on the north and south sides, respectively, along with the high and low air temperatures for the Dayton area obtained from the national weather services. In comparing the two figures, several observations can be made. The temperature readings gathered from the south side were higher than those taken from the north side. Additionally, the south side saw more fluctuation in temperature than the north side. This was expected because the south side received direct sunlight, which raised the temperature of the soil within the Deltalok bags during the day. The increases in temperature were lost quickly at night, causing the noticeable fluctuations.

By comparing the temperature readings on the same side, it can be noticed that the temperature at the top of the barrier was greater than the temperature on the lower parts of the barrier. This was true for sensors on both the north and south sides. This variation is caused by the bottom of the barrier being in contact with the ground, which reduces its temperature. Meanwhile, the top of the barrier is exposed to direct sunlight, which increases its temperature. Since this data was collected in the months of April and May, wind did not significantly impact the temperature distribution within the barrier. However, it is expected that the top of the barrier will have a lower temperature in the winter months because it is exposed to wind and does not have a large mass to retain heat. In contrast, the top of the barrier is expected to be warmer in the summer months because of the exposure to sun.

By comparing the temperature readings on the north and south sides of the barrier with the high and low air temperatures, it can be noticed that the temperature within the barrier was

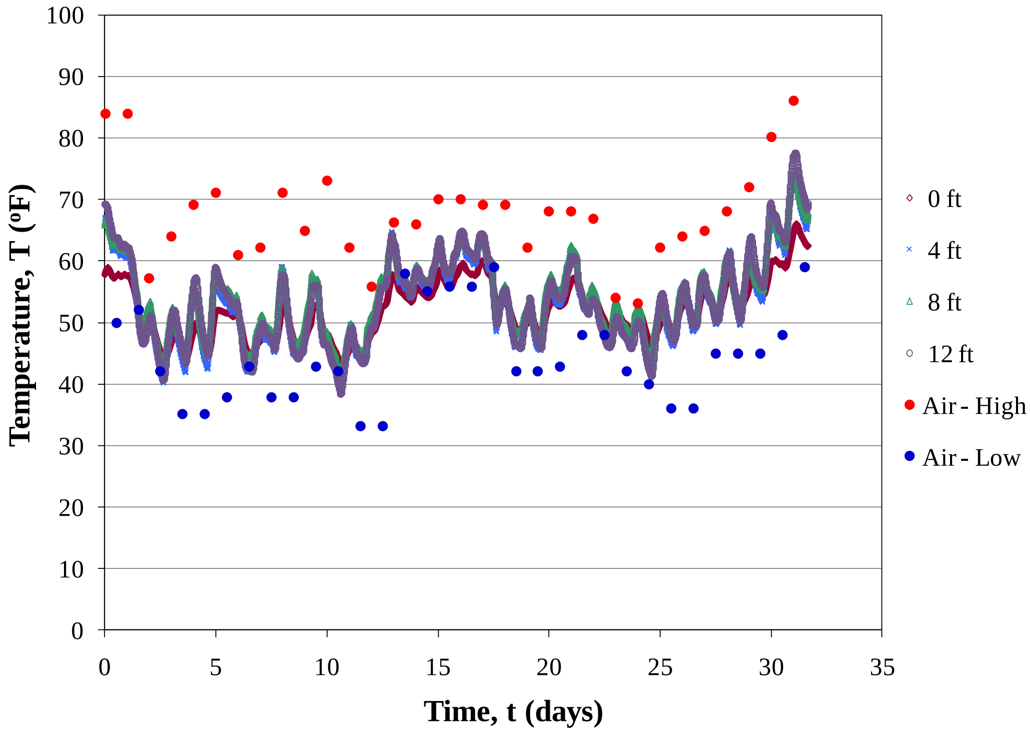


Figure 7.6: North Side Temperature Readings

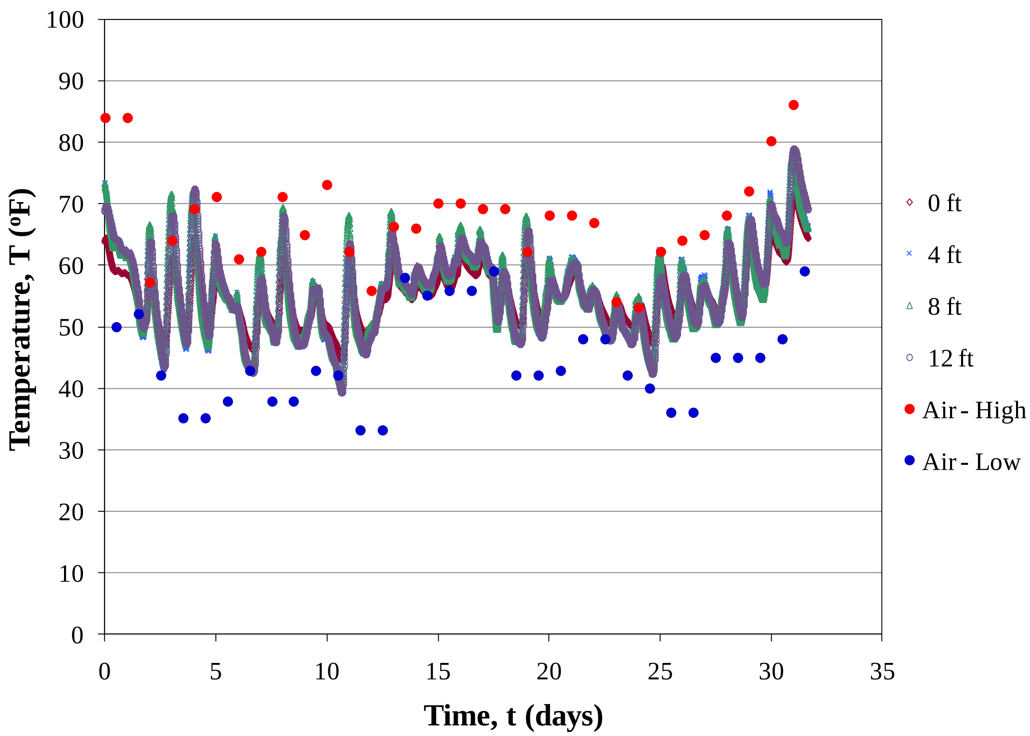


Figure 7.7: South Side Temperature Readings

lower than the high air temperature during the day and higher than the low air temperature during the night. In other words, the temperature variations within the green noise barrier were less than the variations in air temperature. This indicates that the Deltalok structure did not gain large amounts of heat during the day and was capable of retaining some of that heat during the night. It is noted that the temperature readings were obtained during the months of April and May. During this period, the weather was mostly cloudy in Dayton. Therefore, this data is not necessarily representative of the temperature distribution within the barrier in other months during the year.

7.3.2 Moisture

Figures 7.8 and 7.9 present the data obtained by the moisture sensors on the north and south sides, respectively. After the barrier was saturated by the soaker hose, it became obvious that two of the sensors were not working properly. As can be seen from Figure 7.8, the sensors at locations 0 ft and 4 ft above ground failed to record the changes in moisture content represented by the other sensors. The failure can be validated by observing the trends in Figure 7.9. This failure could be due to excessive soil compaction or debris becoming wedged between the prongs of the sensor disrupting the readings.

By comparing the data collected from the north and south sensors, it can be noticed that the moisture content never reached the levels expected for a saturated soil. The maximum level within the barrier was 30% and the average VWC of saturated soils is generally 40-60% depending on the soil. This suggests that the soil used within the Deltalok bags may not have sufficient voids to retain water or could contain large voids allowing water to escape quickly. This can be supported by the observation that all trends lost 30 to 40% of their moisture content within one week after the soaker hose was turned off. Additionally, it can be noticed that the south side had higher moisture content than the north side. This can be attributed to the general direction of rain storms in Ohio. It is important to note that Ohio had record levels of precipitation during the monitoring period. The region where the barrier was constructed saw 8.72 inches of rain in April and 6.06 inches of rain in May (Figure 7.10). Finally, by comparing the trends on the sensors that properly recorded the moisture content, it can be noticed that the top of the wall failed to retain as much moisture as the lower portions of the wall. This is expected because the top of the barrier has less soil to retain moisture and is more prone to evaporation due to exposure to wind and sun.

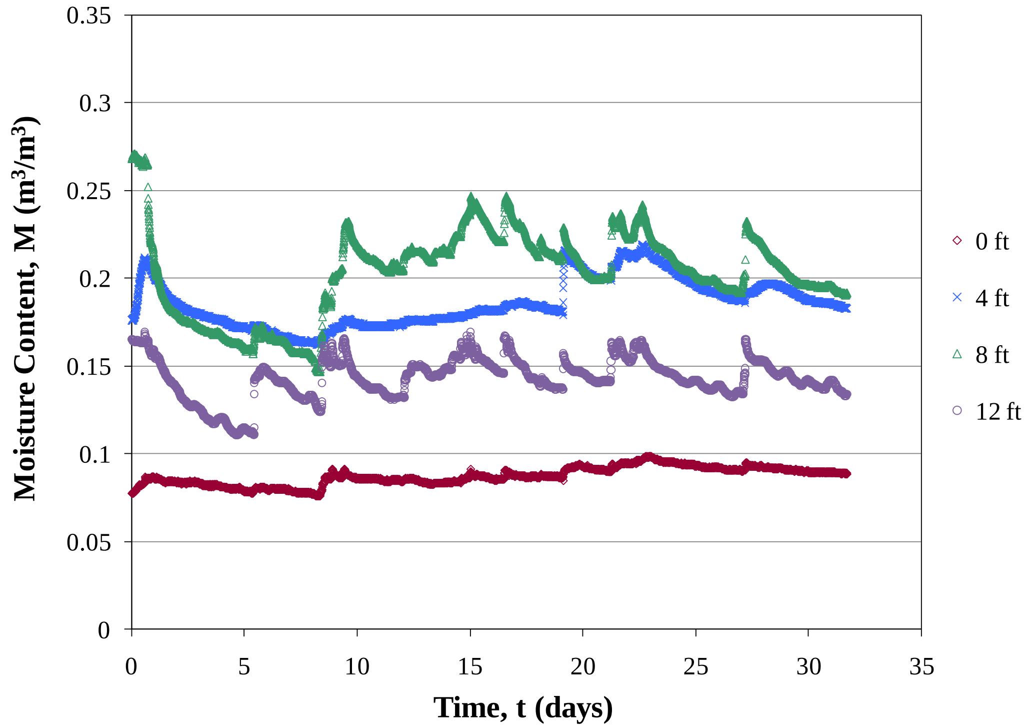


Figure 7.8: North Facing Moisture Readings

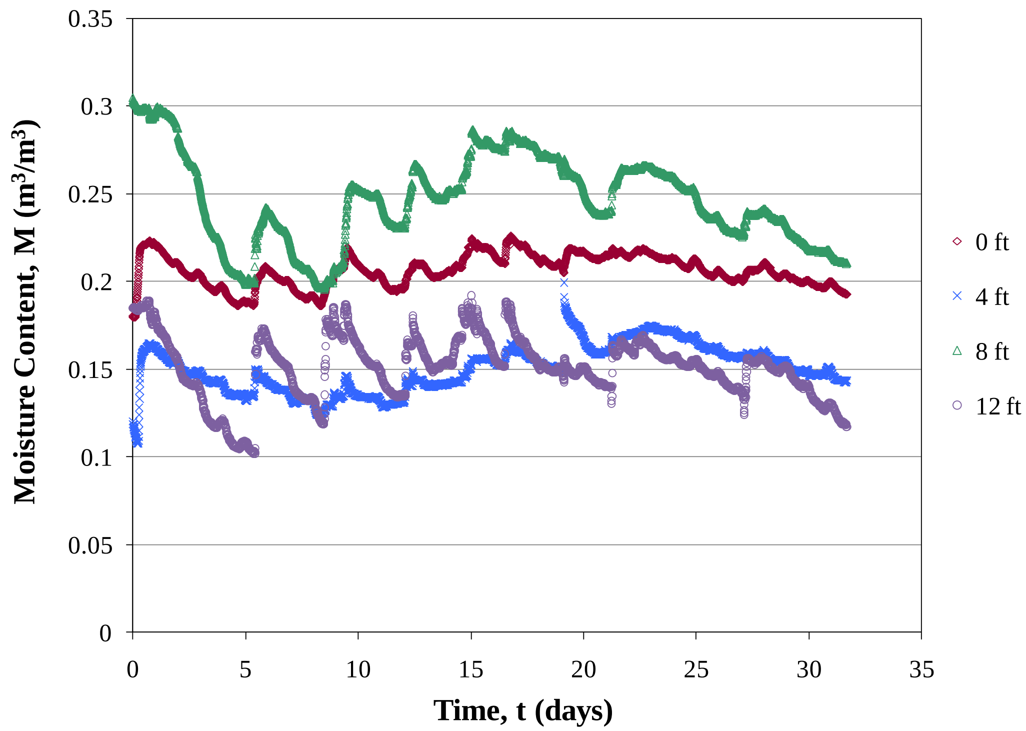


Figure 7.9: South Facing Moisture Readings

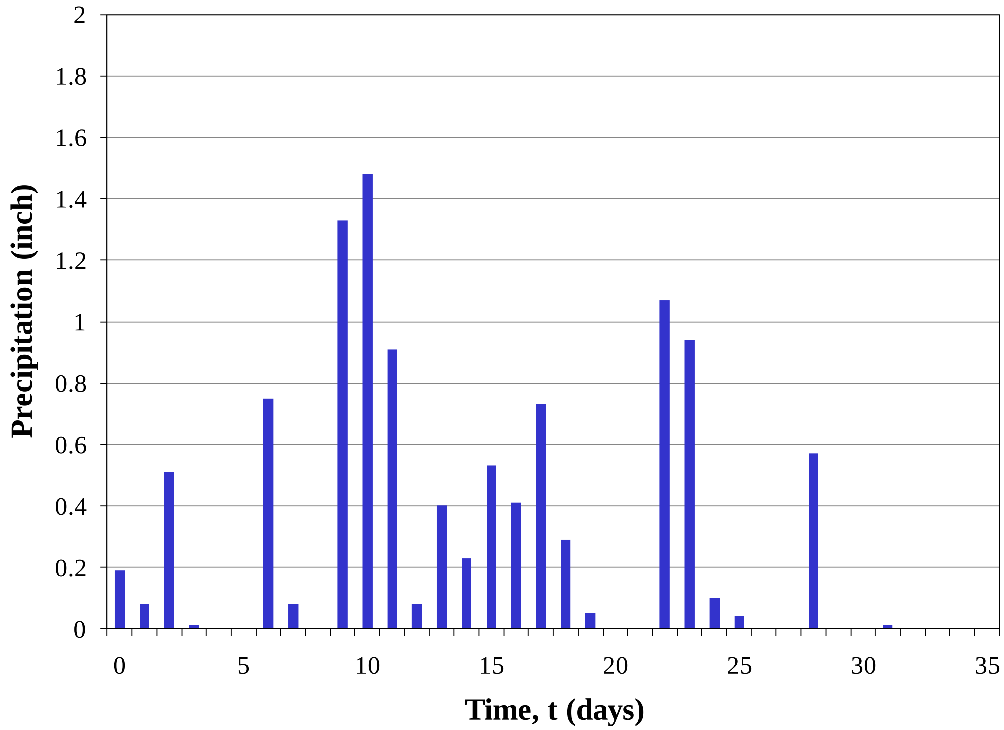


Figure 7.10: Daily Precipitation Data for Dayton from April 10, 2011 to May 12, 2011

7.4 Conclusions

This chapter documented the moisture and temperature distribution within the prototype Deltalok wall during the period from April 10, 2011 to May 12, 2011. The data was collected over a period during which record rainfalls were experienced in Ohio. Due to the short period of time and the record precipitation, additional analysis may be needed to determine the long term moisture retention within the Deltalok green noise barrier especially during the summer.

Based on the data trends and observations, the following conclusions can be made about the moisture and temperature distributions within the Deltalok wall:

- The temperature varied within the barrier from the day to night. The barrier gained heat from the sun during the day and lost that heat at night.
- The temperature was greater on the south side than on the north side of the barrier due to exposure to sunlight. The presence of vegetation is expected to shield the black Deltalok bags from direct sunlight and reduce the temperature within the bags.
- Little variation in temperature was observed with barrier height. This variation is expected to increase the winter and the summer months. In the winter, the temperature is expected to be

lower in the top part of the barrier than the lower part because of the exposure to wind. In contrast, the bottom of the barrier is expected to have a lower temperature in the summer months due to cooling from the ground.

- The temperature within the barrier was lower than the high air temperature during the day and higher than the low air temperature during the night. This indicates that the Deltalok structure did not gain large amounts of heat during the day and was capable of retaining some of that heat during the night.
- The moisture was greater on the south side of the barrier than on the north side. The variation in moisture content was caused by the direction of rain storms in Ohio.
- The moisture level at the top of the barrier was lower than the bottom of the barrier. This was expected because the top of the barrier has less soil to retain moisture and is more prone to evaporation due to exposure to wind and sun.

Chapter 8
Plant Study

8.1 Introduction

The first step in plant selection is to define specific goals for what the vegetation should accomplish functionally and aesthetically. Functionally, the main goal of the vegetation is to provide visual and protective cover to the structure. The plant cover is not expected to play a large role in noise mitigation, as this function is performed by the physical design of the wall and the properties of the building materials. Vegetation will function to reduce the impact of the environment on the wall. Specifically this involves intercepting certain wavelengths of solar energy, which cools the surface and helps protect the cloth material from potential sun damage. Furthermore, if the bag material tears or eventually begin to disintegrate, roots from the plants will help hold the soil in place and prevent erosion. With the ability of the vegetative cover to intercept photosynthetic energy, another function of the plant cover is to compete with weeds and invasive plants. It is likely that the soil used in the stacked bags will contain viable weed seeds. In addition, seeds of many weed species will spread to the wall, even to the highest levels, by wind and animals. Nevertheless, the vegetative cover on the noise barrier will serve to restrict the ability of these species to fully establish and survive.

The other main consideration for plant selection is aesthetics. Vegetation improves the quality of urban life with pleasant aesthetics, shade, landscape beauty, and other benefits. Considerable research has been conducted to identify visual characteristics of landscapes that determine aesthetic preferences, especially those associated with scenic preferences for natural settings. In general, vegetation that has been planted along highways includes grassy vegetation and some wildflowers. Areas that are weedy and unkempt give the roadway a neglected appearance. Meanwhile, mowed vegetation generally lends a roadway an appearance of cleanliness and neatness. Above all, the preferred landscapes include orderly, ‘well managed’ combinations of natural elements rather than a sense of wildness. The feature of vegetation that is most difficult to manage is year-round visual appeal. This is because no plant maintains the same high level of attractiveness throughout the year. Even lawn grasses lose their color and integrity during winter. Similarly, common roadside vegetation is mostly brown in winter and dry summer months. However, given the newness of the idea of a vegetated wall, the standards for visual concerns are likely higher than for other roadway corridors. Therefore, it is critical that the aesthetics of the green noise barrier achieve an acceptable level of appearance. Design alternatives should consider the minimum standards for these issues and the maintenance required to meet the public's expectations for the appearance of the roadside.

8.2 Plant Selection

Plants chosen for the wall must be adapted to the climate of central Ohio. The United States Department of Agriculture has developed a map of winter minimum temperatures to designate plant hardiness zones based on similar winter conditions. The horticulture and plant nursery industries have used this hardiness zone system to make recommendations of plants to grow across North America. The hardiness zone for Columbus is 5b, meaning that plants must tolerate winter temperatures from -15°F to -10°F. For plant longevity, only plants rated as hardy in this zone will be considered for selection.

The plants for the green noise wall were selected according to the following criteria pertaining to the conditions anticipated for the green noise wall:

- *Available moisture/water requirements.* Water availability was a limiting factor in determining what species could be used. The high percentage of sand in the mix used to fill the Deltalok bags presented a challenge in maintaining the moisture level. This is especially true during the establishment period, but also after plants are germinated in the case of seeds or rooted in the case of live stakes or plugs. It will not be possible to achieve proper establishment without irrigation and irrigation will be needed if dry periods occur or persist after establishment.
- *Exposure/light requirements.* The two sides of the barrier will have markedly different conditions. The north side will receive less intense light during the hottest part of the day. The south exposure will have longer light exposure and reach higher temperatures.
- *Soil requirements.* The soil mix used to fill the bags (approximately 70% sand/30% top soil) limits the water and nutrient holding capacity. Without these resources, growth of species adapted to mesic or riparian environments will be inhibited. Species selected should be adapted to poor soils, relatively low fertility and dry conditions.

- *Plant growth habit.* Species selected should be low to medium height so neighboring plants are not shaded. A spreading habit would be beneficial to allow good coverage, both to cover the bag surface for aesthetic purposes and also to fill in open space to minimize weed growth.
- *Root development and morphology.* Selected species should be fibrous rooted rather than having a deep tap root. Species having these attributes should be more likely to establish effectively, not require moisture beyond the capacity of the planned irrigation system, live longer and also should not have a negative effect on the integrity of the bags or the structure.
- *Sustainability (plant longevity and maintenance).* Species selected should not require intensive maintenance (pruning, deadheading, frequent fertilization). Perennial species or species capable of self sowing should be considered over short lived plants.
- *Salt sensitivity.* Although the proposed wall is not immediately adjacent to the road, it may be subject to salt spray during winter. Plants that are tolerant to high salinity would be better choices than those that are sensitive to high salt conditions.
- *Availability of seeds or cuttings in quantities needed.* Species selected must be available in quantities needed at the optimum time for planting, or can be collected and produced from wild sources in quantities at the proper time for vegetating the barrier.
- *Timing of planting.* Planting, whether accomplished by hydroseeding or live planting, must be scheduled at a time when optimum growth conditions for establishment prevail. The best time will be determined by time of wall construction, favorable environmental conditions (likely mid spring or early fall), and availability of plant propagules at the scheduled planting time.

Plant selection must also consider temporal dynamics in color, texture, structure, lines, and depth. Plants that remain green through winter provide a visual element during times when the landscape is generally shades of grey. Species with persistent dense green color provide protective habitat for birds and other animals and give a background for contrasting red or yellow twigged, bare-stemmed winter shrubbery. For the wall, persistent green can come from evergreen conifer shrubs as well as some broad-leafed shrubs and hardy perennial plants. Contrasting red or yellow can come from species like red-twig dogwood and yellow-stem dogwood. Other species that provide winter color include winterberry (*Ilex verticillata*), which has red or orange berries. There is a yellow-berried form of American holly (*Ilex opaca* f. xanthocarpa), which may be too tall for these purposes, but some low growing cultivars might be available. Some varieties of creeping evergreens and small woodland evergreen plants are available for our hardiness zone, but many of these are considered invasive. These include *Euonymous* spp, English ivy (*Hedera helix*), periwinkle (*Vinca minor*), and *Mehonia* spp. Other species, such as bearberry (*Arctostaphylos uva-ursi*) would provide attractive cover but are likely to have specific soil nutrient requirements that are outside the norm for other plants that might be used. Plants like helleborus (*Helleborus* spp.) and ferns (numerous genera) remain green through winter even beneath snow and could provide visual relief in a mid-winter thaw as well as nice contrast for early spring vegetation. Groundcovers with fleshy leaves often remain evergreen, including *Liriope* spp. and *Sedum* spp. but would likely be shaded out by taller species during summer.

It is also important to note that plant communities are inherently dynamic due to complex interactions within and among species that determine the short and long-term survival of any given species in a mix. As a result, species composition is expected to change over time. Differences in survival are also expected among species due to different microsite conditions along the wall, especially north- versus south-facing slopes, and also upper versus lower height zones, and possibly species rooted in cracks between bags versus those rooted in the exposed face of the bags. With conditions varying at these microsites within a growing season and over time as the plant community develops, some species will provide cover at one time but fail to survive under a new set of conditions at some locations on the wall. Other species might be weak initially at some parts of the wall, but – if not totally suppressed – increase in importance over time.

8.3 Plant Species Mix Options

The original vegetation plan called for planting four different mixes in 100-ft sections along the wall, with the goal of testing the resilience of various species that differ in their native habitat and growth form. As a standard ‘control’ treatment, these mixes will include one of ODOT’s plant mixes that contain hardy grasses and forbs that would commonly be used along steep road cuts. Another mix of interest is one containing native prairie species, including grasses and forbs. Additionally, two mixes containing mostly woody vines plus spreading forbs will be considered. One of these will consist of native plant species and one of adapted introduced species.

8.4 Laboratory and Green House Studies

Several studies were conducted during Phase I to make recommendations on the species to be included in the mixes and to identify commercial sources of propagules (a plant material that is used for the purpose of plant propagation). These studies focused on the effect of hydroseeding on seed germination and establishment.

8.4.1 Hydroseeding Products and Seed Germination

The hydroseeding (hydraulic seeding) planting process uses a slurry that contains seeds, mulch, fertilizer and a tackifier. The slurry is transported to the site in a tank and sprayed in a uniform layer over prepared ground. The nutrient rich slurry helps promote early establishment and fast seedling growth. The mulch helps keep the soil from drying and protects seeds during germination and seedlings during early growth. The tackifer functions like a glue, holding the mulch and seeds in place and preventing washing off by rainfall. Areas that are difficult or impossible to dry seed, such as hillsides, can be planted effectively with hydroseeding.

Most research on hyrdoseeding has used grasses or some forbs. However, there is less research, but more experience with pasture mixes, native grasses, wildflowers, roadside mixes and erosion control mixes. Although ODOT recommends hydroseeding (see Table 659.12 of ODOT Construction and Material Specifications), no optimization of hydroseeding slurry components has been conducted for seeds of different plant species. Among the producers of hydroseed compounds that were consulted, none have performed tests to determine whether the compounds they use affect germination of our species of interest. Therefore, research is needed to determine which hydroseeding compounds are suitable for application on the green noise wall.

This study was conducted to evaluate the effect of hydroseeding slurry components on the seed germination of native grass and forb species that might be used on the green noise wall. Hydroseeding compounds include natural and synthetic colloidal compounds that act to adhere seeds to surfaces (tackifiers) and help retain water in the soil after mixes are applied (hydroretentors). Some also include materials that act as a mulch. Colloidal compounds for hydroseeding have been optimized for forage grass mixes, but not for many of the species of interest. Compounds that inhibit germination should not be considered for use in hyrdoseeding. Companies that produce these compounds were contacted to determine which commercially available products would be most suitable for use on the steep slope conditions dictated by the

Deltalok design. Samples of appropriate products were procured, along with the recommended application rates. Experimental treatments included a range of natural and synthetic colloidal compounds and hydroretentors, including alginage, xanthane, guar, karaya gum, maize-derived hydroretentors and various synthetic polymers (Table 8.1).

Table 8.1: Hydroseeding Compounds

Class	Compound	Company
Tackfier	KelGel	Cambrian Products
	Hytac II	EasyLawn
	Finn Hydro-Stik	FinnCorp
	Finn E-Tack	FinnCorp
	DirtGlue	DirtGlue Enterprises
	Hydro-Pam	Watersorb
	Poly Tack(organic polyacrylamide)	Central Fiber
	TacPac GT(guar gum)	Central Fiber
	Tacking Agent 3	Profile Products
	ConTack Organic	Profile Products
	ConTack AT	Profile Products
Hydroretentor	Hygel	EasyLawn
	Finn Hydro-Gel B	FinnCorp
	Finn Stik Plus	FinnCorp
	Watersorb	Watersorb
	Aqua Gel C	Profile Products
	Aqua Gel D	Profile Products

8.4.1.1 Germination Test

Standard petri dish seed germination assays were performed, with two concentrations tested for each of the hydroseeding compounds. Concentrations were based on recommended application rates calculated by area covered. Application rates recommended by manufacturers varied widely (Table 8.2). Amounts equivalent to field rates to cover the area of 50 petri-dishes were used, to allow more volume than needed for the 36 dishes needed to test each compound. Since the recommended application rates are always expressed in terms of area (volume of water used for application is variable), water volume was adjusted to allow for best distribution of compounds over the surface of the area to be covered. In most cases, a 1X rate equivalent to the recommended application rate for that compound, and a 0.5X rate equivalent to half the recommended rate, were used. These concentrations were chosen for ease of application, since concentrations (especially of hydroretentors) greater than 1X were very viscous and/or "clumpy". This characteristic made uniform application to plate surfaces very difficult.

For each species, three replications (each replication was one petri-dish) were tested with the two concentrations of a compound. Depending on seed size, either 25 larger seeds or 50 smaller seeds were used per replication. Three replications using distilled water as a control were also prepared for each set of compounds tested. Not all compounds were tested at the same time. Each set of compounds tested was designated a "series", and included two or more compounds at two rates. Each series also included water controls, and germination rates were expressed as a percent of control for each species.

Table 8.2: Recommended Application Rates of Hydroseeding Compounds

Compound	**1X Application Rate**
KelGel	10 gal/A
Hytac II	3 lb/A
Finn Hydro-Stik	60 lb/A
Finn E-Tack	6 lb/A
DirtGlue	6 oz/yd^3
Poly Tack (organic polyacrylamide)	6 lb/A
TacPac GT(guar gum)	20 lb/A
Tacking Agent 3	60 lb/A
ConTack Organic	60 lb/A
ConTack AT	150 lb/A
Hygel	1 lb/4000 ft^2
Finn Hydro-Gel B	2.5 lb/10000 ft^2
Finn Stik Plus	120 lb/A
Aqua Gel C	10 lb/A
Aqua Gel D	10 lb/A
Watersorb	.5 lb/1000 ft^2

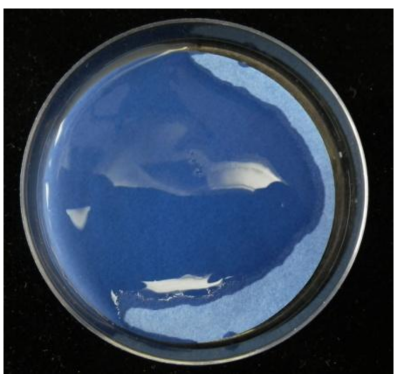
Seeds for germination tests to test hydroseeding compounds were selected after consultation with Mr. Mark Fiely of Ernst Seeds (one of the largest seed distributors in eastern United States). Ernst Seeds donated seeds of seven grasses and fourteen forbs considered to be potentially useful for the project. Twelve species (6 grasses, 6 forbs) were selected to use in the hydroseeding compound tests (Table 8.3). Species were selected to represent differing seed sizes, since seed size may affect the way seeds adhere to bags when applied via hydroseeding. Species were also chosen for ease and speed of germination (no lengthy pre-germination treatments needed) to allow for rapid evaluation of germination tests. One grass, *Tridens flavus* was used for series 1, 2 & 3, but was replaced with another grass, *Panicum virgatum*, for series 4 and 5, due to low germination rate. Aliquots of seeds were pre-counted. If a treatment of gibberellic acid was required to ensure good germination, the aliquots were soaked for 8 to 16 hours in a solution of 500 ppm gibberellic acid (GA3) and rinsed with distilled water prior to placing in petri dishes.

Table 8.3: Species used in Hydroseeding Compounds Germination Tests

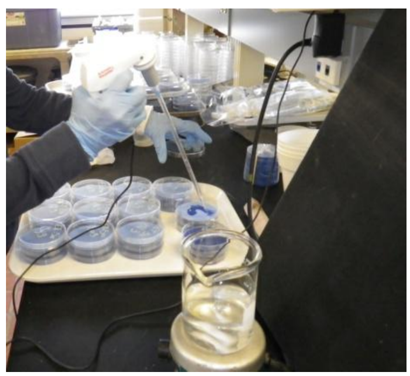
Species	Common name	Type	Seed size	Seed Treatment
Agrostis perennans	Autumn Bentgrass	Grass	Small	
Elymus canadensis	Canada Wild Rye	Grass	Large	
Elymus virginicus	Virginia Wild Rye	Grass	Large	
Panicum clandestinum	Deertongue	Grass	medium	
Sorghastrum nutans	Indiangrass	Grass	Large	
Tridens flavus	Purple Top	Grass	medium	
Aster laevis	Smooth Aster	Forb	medium	Gibberellic acid
Chamaecrista fasciculate	Partridge Pea	Forb	Large	Scarify
Coreopsis lanceolata	Lanceleaf coreopsis	Forb	Large	
Monarda fistulosa	Wild bergamot	Forb	medium	Gibberellic acid
Ratibida pinnata	Gray coneflower	Forb	medium	Gibberellic acid
Rudbeckia hirta	Black Eyed Susan	Forb	Small	Gibberellic acid
Solidago juncea	Early Goldenrod	Forb	Small	Gibberellic acid

The germination test procedure is presented in Figure 8.1. An appropriate amount of each compound was mixed with 250 mL of distilled water, with constant agitation. Each dish was fitted with a disk of standard germination paper. Each replication (petri-dish) received 5 mL of the solution delivered on the surface through a pipet as uniformly as possible. After plates were prepared, a pre-counted aliquot of seeds of one species was added to the dish and seed spacing was adjusted with forceps so that no seeds were touching each other or the sides of the petri-dish. Dishes were covered, placed on trays and enclosed in Ziploc plastic bags to assure adequate moisture retention for seed germination. Trays were placed in germination chambers programmed for alternating temperatures of 15/25^{o}C for 12 hour periods, with light during the high temperature period.

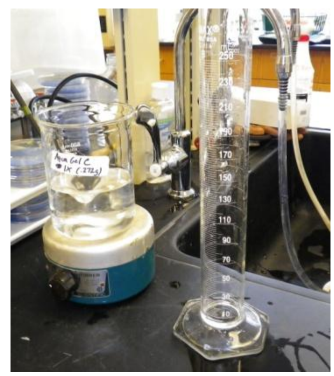
Germinated seeds were counted at 3, 5, 7, 10, 12 and 14 days. Plates were checked periodically between counts to be sure the seed environment stayed moist, and distilled water was added if necessary. At 14 days, ungerminated seeds were counted and the total number of seeds for each petri-dish (replication) was calculated. Germination percentages, relative to controls, were analyzed by ANOVA in SAS. Each species was analyzed separately. Few compounds had an adverse effect on germination. In some cases, compounds enhanced germination of some species. Tables 8.4 and 8.5 below show the results for tackifiers and hyrdoretentors, respectively, for the 1X and 0.5X application rates of the compounds. The non-treated controls had germination percentages ranging from 0.27 to 0.94. With values as low as 0.27, it is often difficult to make firm conclusions about effects on germination. In this case, most of the significant differences for low germination species occurred where germination was higher with the tackifier than the control. Where germination was lower (e.g. for compound ConTack AT and Hytac II), the difference was only 0.01. While this difference is statistically significant, it is not biologically meaningful.



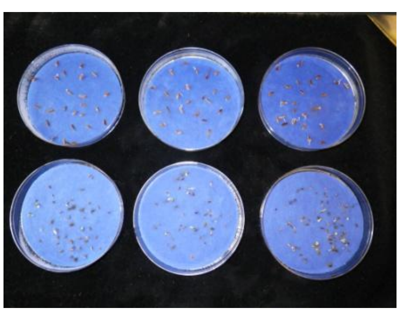
Tackifier in petri dish.



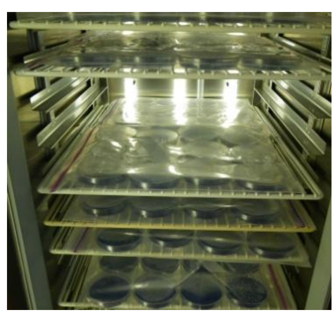
Metering out compounds.



Mixing compounds.



Dishes with seeds.



Germination chamber.

Counting germination.

Figure 8.1: Germination Test Procedure

Table 8.4: Effect of Tackifier on Germination of 6 Grass and 6 Forb Plant Species using 0.5X and 1X Concentrations

(Highlighted Cells Signify Difference from the Non-Treated Control at the 0.05 Level of Significance)

Species[1]	**Control**	**KelGel**		**Tacking Agent 3**		**ConTack AT**		**ConTack Organic**		**Hytac II**		**Finn Hydro-Stik**		**Finn E-Tack**		**Poly Tack**		**Tac Pac GT**		**Dirt Glue**	
		0.5	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**	**1**
AP	0.94	0.97	0.99	0.98	0.97	0.94	0.92	0.96	0.97	0.94	0.90	0.97	0.93	0.96	1	0.93	0.89	**0.97**	**0.99**	**0.96**	**0.96**
EC	0.82	0.68	0.75	0.58	0.71	0.83	0.84	0.86	0.84	0.87	0.83	0.88	0.85	0.85	0.9	0.93	0.89	0.87	0.82	0.80	0.85
EV	0.97	0.97	0.96	0.95	0.96	0.95	0.97	0.99	0.99	0.97	0.98	0.97	0.96	0.97	1	1	0.99	0.99	1	0.99	0.97
PC	0.27	**0.32**	**0.34**	0.48	0.26	**0.48**	**0.29**	0.34	0.37	**0.68**	**0.26**	0.26	0.20	0.22	0.25	0.28	0.29	0.25	0.27	0.26	0.12
SN	0.77	0.68	0.77	0.77	0.78	0.78	0.83	0.77	0.85	0.77	0.67	0.68	0.80	0.72	0.72	0.76	0.67	0.73	0.71	0.76	0.61
PV	0.28	0.00	0.01	0.03	0.01	0.00	0.00	0.01	0.01	.	0.02	0.73	0.72	0.62	0.68	0.71	0.69	0.76	0.75	0.82	0.70
AL	0.57	0.50	0.56	0.57	0.55	0.64	0.59	0.61	0.56	0.59	0.70	0.56	0.55	0.54	0.51	**0.49**	**0.60**	0.54	0.54	0.50	0.52
CF	0.59	0.64	0.61	0.50	0.65	0.54	0.57	0.56	0.56	0.46	0.52	0.57	0.40	0.66	0.65	0.64	0.59	0.51	0.50	0.45	0.45
CL	0.66	**0.61**	**0.53**	**0.61**	**0.53**	0.69	0.58	0.80	0.72	0.53	0.60	0.67	0.56	0.50	0.57	0.53	0.44	0.58	0.69	0.72	0.61
MF	0.7	0.61	0.73	0.69	0.54	**0.64**	**0.55**	**0.67**	**0.62**	0.57	0.64	0.71	0.67	0.67	0.65	**0.60**	**0.75**	0.72	0.65	0.66	0.65
RP	0.81	0.80	0.76	0.86	0.84	0.84	0.77	0.74	0.82	0.76	0.78	0.78	0.79	0.77	0.75	0.75	0.78	0.72	0.79	0.79	0.75
SJ	0.74	0.75	0.72	0.65	0.60	0.69	0.74	**0.67**	**0.80**	0.67	0.77	0.67	0.63	0.68	0.59	0.72	0.69	0.69	0.67	0.60	0.65

[1]The six grasses are: AP= Agrostis perennans (Autumn bentgrass) , EC= Elymus canadensis (Canada Wild Rye), EV= Elymus virginicus (Virginia wild rye), PC=Panicum clandestinum (Deer tongue), SN = Sorghastrum nutans (Indiangrass), PV = Panicum virgatum (switchgrass). The six forbs are: AL = Aster laevis (Smooth aster) + 500 ppm GA for 24 hr, CF = Chamaecrista fasciculate (Partridge pea) seeds scarified, CL = Coreopsis lanceolata (Lanceleaf coreopsis), MF = Monarda fistulosa (Wild bergamot) + 500 ppm GA for 24 hr, RP = Ratibida pinnata (Gray coneflower) + 500 ppm GA for 24 hr, SJ = Solidago juncea (Early goldenrod) + 500 ppm GA for 24 hr.

Table 8.5: Effect of Hydroretentor on Germination of 6 Grass and 6 Forb Plant Species using 0.5X and 1X Concentrations (Highlighted Cells Signify Difference from the Non-Treated Control at the 0.05 Level of Significance)

Species[1]	**Control**	**Aqua Gel C**		**Aqua Gel D**		**Hygel**		**Finn Hydro-Gel B**		**Finn Stik Plus**		**Watersorb**	
		0.5	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**	**1**
AP	0.94	0.93	0.96	0.95	0.94	0.96	0.94	0.91	0.97	0.92	0.95	0.88	0.92
EC	0.82	**0.94**	**0.88**	0.75	0.82	0.73	0.63	0.81	0.84	0.88	0.85	0.81	0.83
EV	0.97	0.95	0.95	0.99	0.96	0.96	0.95	0.97	0.97	**1**	**0.99**	0.96	1
PC	0.27	0.27	0.32	0.35	0.29	**0.27**	**0.19**	0.24	0.17	0.15	0.12	**0.28**	**0.14**
SN	0.77	**0.68**	**0.80**	**0.80**	**0.65**	0.83	0.77	0.81	0.79	0.72	0.72	0.69	0.72
PV	0.28	0.01	0.00	.	.	.	.	0.69	0.70	0.65	0.65	0.80	0.78
AL	0.57	0.73	0.61	0.66	0.65	0.50	0.72	0.48	0.45	**0.55**	**0.48**	**0.60**	**0.51**
CF	0.59	0.57	0.59	**0.64**	**0.60**	0.47	0.58	0.55	0.63	0.49	0.65	0.65	0.59
CL	0.66	0.63	0.76	0.68	0.76	0.67	0.59	0.58	0.61	0.55	0.59	0.54	0.73
MF	0.7	0.68	0.59	0.60	0.70	**0.57**	**0.76**	0.64	0.61	0.63	0.65	0.59	0.61
RP	0.81	**0.73**	**0.82**	**0.77**	**0.84**	0.79	0.82	0.81	0.73	0.79	0.81	0.78	0.80
SJ	0.74	0.75	0.68	0.70	0.64	0.71	0.67	**0.58**	**0.74**	0.62	0.65	0.70	0.69

[1]The six grasses are: AP= Agrostis perennans (Autumn bentgrass) , EC= Elymus canadensis (Canada Wild Rye), EV= Elymus virginicus (Virginia wild rye), PC=Panicum clandestinum (Deer tongue), SN = Sorghastrum nutans (Indiangrass), PV = Panicum virgatum (switchgrass) . The six forbs are: AL = Aster laevis (Smooth aster) + 500 ppm GA for 24 hr, CF = Chamaecrista fasciculate (Partridge pea) seeds scarified, CL = Coreopsis lanceolata (Lanceleaf coreopsis), MF = Monarda fistulosa (Wild bergamot) + 500 ppm GA for 24 hr, RP = Ratibida pinnata (Gray coneflower) + 500 ppm GA for 24 hr, SJ = Solidago juncea (Early goldenrod) + 500 ppm GA for 24 hr.

None of the tackifiers reduced germination of any of the grass or forb species to an extent that would raise a concern about using that product. The increased germination for some products is an issue of interest, but these probably represent either normal experimental error or hormonal stimulation, which is commonly seen in germination responses in the presence of chemicals at low doses. Likewise, none of the hyrdoretentors reduced germination sufficiently to elicit concern. However, these products were difficult to work with, so the true effect in a hydroseeding situation is difficult to predict. These compounds were examined separately from the hydroseeding mix because they seemed to interfere with germination. Other hydroseeding components such as mulch are not expected to have a significant impact on the germination process. Therefore, it is concluded that none of the grass or forb species of interest are negatively affected by standard hydroseeding compounds. This, of course, is not a comprehensive evaluation of species, but it covers a range of general, biological characteristics, and seed traits – especially seed size. Results suggest that the compounds tested could be used on a wide range of species with no predictable loss of germinability or seedling viability. Therefore, ease of use and preferences of the hydroseed contractor chosen for Phase II of the green noise wall project should be the main considerations for compounds included in the seeding mixes.

8.4.1.2 Seedling Establishment Test

To determine the best methods for evaluating seedling establishment, TJ Sales & Consulting (authorized Deltalok distributor) was consulted about methods used for filling and handling Deltalok bags. Sand (river run sand, pH neutral) was mixed with soil at a volume/volume ratio of approximately 70% sand and 30% soil. Soil used is as dry as possible to allow easier handling because of lighter weight. For these experiments, small versions of the Deltalok bags (mini bags) were used. Full size Deltalok bags (15 x 35 in) were deconstructed, and the fabric cut and sewn into smaller bags (6.5 in x 15 in, or 4 x 9 in, before closing) using a household sewing machine. The smaller mini bags (4 x 9 in) had seams on one side and one open end in an orientation identical to the full sized bags.

Figure 8.2: Example Mini Bag Made of About 1/3 of a Standard Deltalok Bag

An experiment was conducted in the greenhouse to determine early establishment success of seeds in a mix applied to Deltalok bags. Mini bags were filled with a typical sand/soil mix and saturated with water. A mix containing water, colloidal tackifier and seeds was applied. Seeds of several species, representing a range of size, shape, and morphology, were used. Bags with soil and seed attached were watered by an automated irrigation system in the greenhouse. Germination success was evaluated on regular basis based on seed germination and root penetration of the bag. Seeds that germinate but do not penetrate the bag might have questionable success in seed mixes.

In one experiment, mini bags were filled with a 70% sand/30% soil mix (50% Wooster silt loam and 50% Promix, a soilless growing medium containing peat and perlite). Tacking Agent 3 (tackifer, Profile Products) was mixed with water at a concentration equivalent to the recommended rate for that product based on area of application. This particular tackifier was chosen for ease of handling and because preliminary observations of germination tests did not indicate any negative effect on germination

Three species each of grass and forbs with rapid germination rates were used. Amount of seed to apply was calculated based on Ernst Seeds catalog recommendations, doubled, and measured by weighing. Tackifier and seeds were added to water and mixed on a stir plate. Mini bags were placed on a greenhouse bench and saturated using a hose prior to application of seed mixture. Bags were "painted" with the mixture using an inexpensive paint brush (chip brush). Half of the bags were placed in fiberglass trays with water covering the bottom of the trays to a depth of approximately 1 inch to keep soil mix constantly moist. The other bags were watered as necessary (at least daily) with a hose to maintain moisture. Germination was observed every three days, but very little germination occurred. The seed volume was too low and not enough seeds were applied to obtain results of germination in the small surface area of the mini bags. Figure 8.2 shows an example mini-bag made of about 1/3 of a standard Deltalok bag. The mini bag was divided into four sections (bottom to top) seeded in the outside with large and small seeded grass, followed by a small and large seeded forb. This picture was taken two weeks after the bag sat in a water lined tray. Note the relative lack of germination by any of the species. Results suggest the mulch component of hydroseeding mixtures is essential.

In another experiment, fabric from bags was cut in flat pieces to fit the surface of a growing tray (13 x 18 cm) with drainage holes. Trays were filled with 70% sand 30% soil mix (50% Wooster silt loam and 50% Promix, a soilless growing medium containing peat and perlite) and saturated by watering with a hose. Four replications were used, and the same tackifier/seed mix used in previously described preliminary mini bag experiments was applied. Three species each of grass and forbs with rapid germination rates were used. Amount of seed to apply was calculated based on Ernst Seeds catalog recommendations, doubled, and measured by weighing. Tackifier and seeds were added to water and mixed on a stir plate. Applications were made as before to either the top surface of a wet fabric on the soil surface, or a piece of bag fabric was wet in water, then smoothed on the surface with the seeds on the surface in contact with the soil and slight even pressure applied to ensure good contact with the sand/soil mix prior to application of tackifier/seed mix applied with a brush. Germination was observed at one and two weeks, but very little germination occurred. The seed volume may have been too low to observe results of germination in a very small area.

In another experiment to test placement of seeds, fabric from bags was cut in flat pieces to fit the surface of a standard 1020 growing tray with drainage holes. Trays were filled with the same medium as above and saturated by watering with a hose. Four replications were used, and the same tackifer/seed mix used in previously described preliminary mini bag experiments was applied. Applications were made as before to either the top surface of a wet fabric on the soil surface, or a piece of bag fabric was wet in water, then smoothed on the surface with the seeds on the surface in contact with the soil and light, even pressure applied to ensure good contact with the sand/soil mix prior to application of tackifier/seed mix applied with a brush. The surface of each tray was divided in half, and each half sowed with 25 or 50 seeds of 4 species, separated, 2 grass and 2 forbs, either on the top surface or the bottom surface. For half the bottom-sowed seeds, tackifier/seed mixture was applied to a sheet of blank newsprint positioned under the fabric. The other bottom-sowed seeds were applied to the underside of bag fabric that was wet with water prior to application. Germination was observed after one and two weeks. Germination of grass species was adequate on both surfaces, but slightly better on the bottom surface either with or without newsprint. Germination of forbs occurred on both surfaces, but seedlings were not able to penetrate from the bottom of the bags with or without newsprint. Figure 8.3 shows the emergence of grasses and forbs on Deltalok bag sections in tray studies. Results showed that root penetration of the bag material was possible for a range of species, especially those with small seeds.

Figure 8.3: Emergence of Grasses and Forbs on Deltalok Bag Sections in Tray Studies

Another mini bag experiment was done using 4 x 9 inch mini bags. To more accurately represent the soil mix used in actual practice, a sand/soil mix was prepared using washed sand (Quickcrete All-Purpose sand, washed, graded all-purpose sand) mixed with Wooster silt loam in a 70%/30% weight /weight ratio. Sand and soil were weighed and mixed on a concrete floor with a shovel until the mix was uniform. One mini bag was filled to the appropriate volume to allow easy closure with a zip tie, and that volume of soil weighed (7 lbs). Aliquots of sand/soil mix were weighed for each mini bag. Finn Hydro Stik (tackifier) and Finn Hydro Gel B (hydroretentor) were mixed with water at concentrations equivalent to the recommended rate for those products based on area of application. These compounds were chosen for ease of handling and because they showed no negative impact on germination in the germination tests. Treatments were a factorial combination of seed location (outside or inside of bag) and hydroseeding compound (tackifier only or tackifier plus hydroretentor) with three replications, one bag per replication.

Bags were marked in four zones for application of seeds of four different plant species. Two grasses (*Agrostis perennans* and *Elymus virginicus*) and two forbs (*Monarda fistulosa* and *Coreopsis lanceolata*) were used, one large and one small-seeded species for each type. Each species was assigned a zone in random order. For seeds placed on the outside of bags, bags were filled with sand/soil mixture, seeds were placed on the bag after treatment with the hydroseeding compound(s) and then bags were watered. For seeds placed inside the bags, seeds were placed on germination paper treated with the hydroseeding compound(s) and then placed inside the bag before the bag was filled with sand/soil mixture, then watered. Bags were placed in trays of water in the greenhouse to keep them moist, and germination counted periodically. At the end of the study, number of seedlings rooting into the bag (for seeds placed on the surface) and the number of seedlings not able to emerge through the bag (for seeds placed inside the bag) were counted.

As shown in Figure 8.4, many seeds germinated within the bag but the epicotyls were unable to penetrate the fabric, resulting in a high level of establishment failure. The germination percentage did not depend on the type of hydroseeding compound used, but on the characteristics of the species of seeds. The grass species had better germination compared to the forb species. This is likely due to the high matric potential of grass seeds and their ability to tolerate the surface conditions. Since the growing point of grasses is the intercalary meristem and root tips, the seeds can remain stable on the fabric surface while cell division is taking place to put out the leaf tip from one end and root primordial from the other end. In contrast, forb seeds contain the terminal meristem attached to cotyledons, in such a way that as the root emerges and pushes against the fabric surface, the seed/seedling supplies the opposing force, which is not secure. Therefore, germinating radicles pushing on the fabric can cause the seed to move or become detached, or can result in displacement of the root tip from the frabric surface in such a way that contact cannot be reestablished. The small-seeded grass (*Agrostis perennan* - bentgrass) had the best germination inside and outside of the bag.

Figure 8.4: Mini Bag Dissected to Examine Germination

Neither of the forbs emerged through the bag due to blockage by the fabric and inability of forb meristems to penetrate the fabric (Figure 8.5). This suggests that sowing seeds inside the bag is likely to be unsuccessful if forbs are used. The growing points of a forb are the terminal bud and the root tip. Leaf primordial is initiated from the bud, which contains stem and leaf initials. As a result, the diameter of the terminal bud is such that emergence is restricted by the tightly woven fabric. For grasses, the growing point from a seed is essentially in the seed, which remains underground, or in this case within the bag. The tip of the grass is sharp and pointed and able to penetrate small openings. If inside sowing is chosen, a workable method to prepare the large number of bags for the green noise wall will need to be developed. It may be advantageous to include a mulch in the hydroseeding mix, or choose a hydroseeding compound that already includes a mulch, to aid germination of some species.

Figure 8.5: Forbs Seedlings Unable to Penetrate the Fabric

Data was analyzed with ANOVA in SAS to validate the visual observations. For *Agrostis Perennans* (AP) and *Monarda Fistulosa* (MF), percent germination did not differ inside vs. outside the bag (P <0.05) as shown in the table below. However, *Elymus Virginicus* (EV) and *Coreopsis Lanceolata* (CL) had higher germination inside the bag (there was no germination on the outside of the bag) (P <0.05). For seeds placed on the bag surface, rooting was best for the small-seeded grass (AP), but there was some rooting for the small-seeded forb (MF) (P <0.05). Neither large-seeded species rooted into the bag. For seeds placed inside bag, grasses had better emergence than the forbs (no forbs emerged), but the small grass (AP) had higher emergence than the large grass (EV) (P <0.05).

Table 8.6: Large and Small Seeded Grass and Forb Germination when Seeded Inside versus Outside the Deltalok Bags. Data are Germination Percentages Relative to Controls.

	Grasses		Forbs	
	Agrostis perennans (small seed)	*Elymus virginicus* (large seed)	*Monarda fistulosa* (small seed)	*Coreopsis lanceolata* (large seed)
	------------------------------- %	----------------------------------		
Seeds in bag	0.51	0.45	0.26	0.22
Seeds outside bag	0.37	0.00	0.16	0.00
TOTAL	0.44	0.23	0.21	0.11

8.5 Conclusions of Laboratory and Green House Studies

The following conclusion can be made from the germination and emergence tests:

- The standard tackifiers and hyrdoretentors are safe to use with the native prairie species. Therefore, no changes are recommended to the standard hydroseeding procedure currently used by ODOT.
- Hydroseeding of forb mixes should be done on the outside of the bag to ensure successful emergence.
- Hydroseeding of grass mixes could be done on the inside or the outside surface of the Deltalok bag. No distinct advantage was observed for placing the grass seeds on the inside of the bags. Therefore, with the added cost of materials and time, seeding inside the bags makes little sense.

8.6 Recommendations for Plant Mixes

Based on the outcome of the laboratory and green house studies and consultation with several plant experts, it is recommended that ODOT considers the following four options for vegetation on the noise barrier. The seeding rates were calculated based on an area of 9600 sq ft per treated area (100 ft length x 12 ft height x 2 sides x 4 surface factor):

- Mix One: a standard grass mix that ODOT would normally apply through hydroseeding to a road-cut. This will function as a sort of control treatment.
- Mix Two: grasses and native prairie forb species. There are several options for this. ODOT describes some native grass and wildflower mixes that would be acceptable (659.09). Alternatively, Ernst Seeds has two excellent options shown below with the estimated cost for the project.

Native Steep Slope Mix with Annual Ryegrass ERNMX-181
Seeding Rate 30 lb per acre or 1 lb per 1,000 sq ft
Need 9.6lbs
24% Little Bluestem (Schizachyrium scoparium)
20% Annual Ryegrass (Lolium multiflorum (L. perenne var. italicum))
12% Canada Wild Rye (Elymus canadensis)
11% Indiangrass (Sorghastrum nutans, 'Prairie View')

8% Virginia Wild Rye (Elymus virginicus)

4% Switchgrass (Panicum virgatum)

3% Autumn Bentgrass (Agrostis perennans,)

3% Rough Bentgrass (Agrostis scabra)

3% Purple Top (Tridens flavus)

2% Partridge Pea (Chamaecrista fasciculata (Cassia f.))

2% Wild Bergamot (Monarda fistulosa)

2% Tall White Beard Tongue (Penstemon digitalis)

2% Black Eyed Susan (Rudbeckia hirta)

2% Lance Leaved Coreopsis (Coreopsis lanceolata)

1% Marsh (Dense) Blazing Star (Liatris spicata)

1% Purple Coneflower (Echinacea purpurea)

Northeastern US Roadside Native Mix ERNMX-105

Seeding Rate 15 lb/acre or 1/3 - 1/2 lb per 1,000 sq ft

Need 4.8 lbs

32% Little Bluestem (Schizachyrium scoparium)

10% Indiangrass (Sorghastrum nutans)

10% Virginia Wild Rye (Elymus virginicus)

5% Canada Wild Rye (Elymus canadensis)

5% Black Eyed Susan (Rudbeckia hirta)

5% Tall White Beard Tongue (Penstemon digitalis)

5% Partridge Pea (Chamaecrista fasciculata (Cassia f.))

4% Wild Senna (Senna hebecarpa (Cassia h.))

4% Golden Alexanders (Zizia aurea)

3% Grass Leaved Goldenrod (Euthamia graminifolia (Solidago g.))

2% Nodding Onion (Allium cernuum)

2% Blue False Indigo (Baptisia australis)

2% Flat Topped White Aster (Aster umbellatus)

2% Maryland Senna (Senna marilandica (Cassia m.))

2% Marsh (Dense) Blazing Star (Liatris spicata)

2% Ohio Spiderwort (Tradescantia ohiensis)

2% Wild Bergamot (Monarda fistulosa)

1% Zigzag Aster (Aster prenanthoides)

1% New England Aster (Aster novae-angliae))

1% Early Goldenrod (Solidago juncea)

- Mix Three: a combination of herbaceous species (Mix One) plus selected woody species. Mix Three is underlaid with hydroseeded grasses from Mix One seeded at 2/3 the normal seeding rate.
- Mix Four: similar to Mix Three, is underlaid with hydroseeded grasses and forbs from Mix Two, seeded at 2/3 the normal seeding rate. The woody species will be the same for Mix Three and Mix Four.

Options for the woody species for Mix Three and Mix Four:

<u>Vines</u>

Virginia creeper *Parthenocissus cinquefolia*

Bearberry *Arctosaphylos uva-ursi*

Boston ivy *Parthenocissus tricuspidata*

Running serviceberry *Amelanchier stolonifera*

Virgin’s bower *Clematis virginiana*

<u>Shrubs</u>

Red twig dogwood *Cornus sericea*

Grey dogwood *Cornus racemosa*

Silky dogwood *Cornus amomum*

Sanbar willow *Salix exigua* subspp interior

Fragrant sumac *Rhus aromatica* cv ‘grow low’

Northern bayberry *Myrica pensylvanica*

These mixes were selected to provide visual interest and to evaluate a range of adapted species. Mix 1 is a grass mix that ODOT would normally apply through hydroseeding to function as a control treatment. Mix 2 includes grasses and native prairie forb species. There are several options for Mix 2. ODOT describes some native grass and wildflower mixes that would be acceptable (659.09). Alternatively, Ernst Seeds Company has two excellent options. Mixes 3 and 4 are a combination of herbaceous species plus some selected woody species. The woody species are the same for Mix 3 and Mix 4. The difference is that Mix 3 is underlaid with hydroseeded grasses from Mix 1 (seeded at 2/3 the normal seeding rate), while Mix 4 is underlaid with hydroseeded grasses and forbs from Mix 2 (seeded at 2/3 the normal seeding rate).

Several options are available for the woody species for Mix 3 and Mix 4. For visual appeal it is recommended that many different woody species, especially vines that could have interesting visual effects. Desirable species of native vines are not available in the nursery trade as rooted cuttings or plugs in large quantities. It is recommended to use live stakes, which would have to be planted during construction of the wall. Live stakes are dormant cuttings that can be placed between Deltalok bags during construction. Live stakes of some native woody plant species are available from nurseries. If provided sufficient time, commercial nurseries will propagate these species to provide quantities needed.

Rooted cuttings or plugs should be planted in early fall to allow root establishment before frost, or in early spring. Live stakes must be planted in early fall or in late winter before growth starts in spring. This should be done during construction of the wall. The grass and grass+forb mixes should be hydroseeded immediately thereafter. Planting time is critical. Mid-summer planting must be avoided. A planting density of 3 feet apart will require 2133 plants to cover 2 sections of the wall. Species available as live stakes have a larger final size and could be spaced 5 feet apart, requiring 400 plants for two sections of wall.

8.7 Soil Evaluation

The soil source pile that was identified at the green noise wall test site for use in the sand/soil mix was evaluated to ensure its suitability. The pile is on Humphries Road, south of US Rt 40 in Reynoldsburg, OH, approximately 1.5 miles from the proposed green noise wall site in Pataskala. Source of soil in the pile is unknown, but is probably topsoil removed from sites of nearby buildings or excavation projects. Soil pile is approximately 150 ft long, 75 feet wide, and 4 feet deep at deepest point.

Soil sampling was done on March 29, 2011 after several days of relatively dry weather. Upon arrival at the site, it was determined that there was too much debris present to use the originally described source pile. However, there was an adjacent pile approximately 50 feet away that was adequate in size, approximately 250 feet long by 50 feet wide, to provide the volume of soil needed for the green noise wall. From the alternate pile, samples were taken at 24 sites, along two transects 20 feet apart on 20 foot centers. Four cores were sampled at a depth of 10 inches from each site and were combined in a plastic bag to prepare a composite sample from each site. Samples were transported to the lab and refrigerated for 6 days. To prepare for analysis, samples were placed on lab bench and allowed to dry at room temperature for approximately four to five days, breaking up clumps daily. Samples were dried uniformly by manually turning soil in the bags every day, and then sieved through a No. 10 sieve (20 mm openings). When dry enough to use in greenhouse studies (adequate moisture for plant growth, but not saturated, a two cup (472 mL) aliquot of each soil sample was placed in 4.75 inch (120 cm) x 6.5 inch (165 cm) plant growing trays lined with capillary matting. Samples were placed in the greenhouse, bottom irrigated as needed for consistent soil moisture, and maintained at ambient greenhouse conditions (natural daylength, day temp 80-85˚F, night temp 70-75˚F). Emerging seedlings were observed after 15, 25, and 35 days to determine whether any weed species of concern were present in the soil. No invasive plant species or species that prove detrimental to green noise wall integrity or maintenance were found.

The remaining volume of the samples was uniformly air dried by manually turning soil in the bags every day, and then sieved through a No. 10 sieve (20 mm openings). A 50 g aliquot of each sample was placed in a new coin envelope and submitted to the STAR lab (Service Testing and Research Lab) at the OARDC, Wooster, for analysis of pH, Lime Test Index, available phosphorus (P), exchangeable potassium(K), calcium (Ca), magnesium (Mg), and cation exchange capacity (CEC). The chemical test results are presented in Table 8.7. Data was compared to standard levels for adequate plant growth to determine whether the source pile is suitable for the sand/soil mix for the green noise wall.

Table 8.7: Results of Soil Sample Analysis for Topsoil Piles Near the Proposed Noise Wall Site. Bray P-1 was used for P Analysis and Ammonium Acetate Extract for Other Nutrients

ID	**pH**	**LTI**	**P**	**K**	**Ca**	**Mg**	**CEC**	Ca	Mg	K
			----------------- µg/g -------------------				meq/100g	% Base Saturation		
1	7.22	70.0	34.0	292.1	2634.0	433.7	17.5	75.1	20.6	4.3
2	7.31	70.0	45.3	308.2	2727.6	467.8	18.3	74.4	21.3	4.3
3	7.00	70.0	36.4	294.1	2642.7	484.1	18.0	73.4	22.4	4.2
4	6.78	69.9	25.3	219.1	2683.4	504.6	18.3	73.3	23.0	3.1
5	7.24	70.0	21.8	183.5	2724.8	477.2	18.1	75.4	22.0	2.6
6	7.27	70.0	38.9	286.2	2721.8	483.8	18.4	74.1	21.9	4.0
7	7.00	70.0	25.9	246.5	2692.5	471.8	18.0	74.7	21.8	3.5
8	6.73	70.0	16.9	175.7	2582.4	482.5	17.4	74.3	23.1	2.6
9	7.26	70.0	19.4	147.2	2595.3	435.0	17.0	76.4	21.3	2.2
10	7.61	70.0	18.1	137.3	2673.7	412.0	17.2	77.9	20.0	2.1
11	7.49	70.0	20.8	163.1	2646.2	400.2	17.0	77.9	19.6	2.5
12	7.23	70.0	20.4	139.3	2792.4	496.9	18.5	75.6	22.4	1.9
13	7.36	70.0	21.9	143.6	2755.7	461.9	18.0	76.6	21.4	2.0
14	7.34	70.0	20.5	148.4	2723.7	439.1	17.7	77.1	20.7	2.2
15	7.04	70.0	17.7	114.2	2597.4	472.7	17.2	75.4	22.9	1.7
16	7.17	70.0	13.6	94.7	2535.6	460.6	16.8	75.6	22.9	1.4
17	6.83	70.0	13.5	97.3	2542.1	460.7	16.8	75.7	22.9	1.5
18	6.99	70.0	13.0	103.9	2687.3	453.4	17.5	76.9	21.6	1.5
19	7.32	70.0	15.7	102.0	2761.1	414.3	17.5	78.8	19.7	1.5
20	6.86	70.0	13.0	94.1	2627.3	467.9	17.3	76.0	22.6	1.4
21	6.81	70.0	12.4	99.4	2599.8	471.0	17.2	75.7	22.8	1.5
22	6.99	70.0	17.3	159.2	2593.2	457.8	17.2	75.4	22.2	2.4
23	7.19	70.0	25.4	225.8	2586.6	438.7	17.2	75.3	21.3	3.4
24	7.25	70.0	32.9	284.1	2669.6	452.6	17.8	74.8	21.1	4.1
Avg	7.1	70	23	177	2658	458	17.6	75.7	21.7	2.6

The most remarkable feature of the soil samples is their uniformity in pH in spite of unknown and possibly variable sources of the soil piles. The soil pH ranges from 6.73 to 7.61. This is well in the range of tolerance for many plants that will be useful for the wall. The exceptions will be ericaceous species, which are sun-loving plants that grow in acid soils (e.g., rhododendrons, azaleas, cranberries, blueberries). The soil test results do not support the addition of lime to this particular topsoil for the wall. The Ca:Mg ratio is about 3.5, which is well in the acceptable range. The P level ranges from 12.4 to 45.3 μg/g, which is rather high. The optimum level is between about 15 and 40 μg/g. Only five of the samples were below this range. Phosphorus is tightly bound and does not move readily in soil. It might be lost from the wall mostly in plant uptake and the minimal amount of erosion that is likely to occur. In topsoil, adding 100 units of P will raise the soil test P level by about 10 units. Since sand will be a large component of the medium and P in the topsoil will be so tightly bound and minimally available, some P should probably be added. If seeding is done in springtime, a dose of starter P should also be added. The K level of the topsoil ranged from 94.1 to 308.2. Optimum levels for most species are from 100 to 200 μg/g. Potassium is absorbed tightly on clay particles and does not move readily in soil. It, too, would be lost mostly by plant uptake. The Mg:P ratio should be >2:1, and in this case it is >8:1, so there appears to be no need to adjust this balance.

A number of assumptions are required for determining nutrient additions. Additions of P and K should be made to meet requirements of plant removal and to maintain a desirable reservoir in the soil. Since the topsoil is to be mixed with sand, which holds few nutrients, the nutrient storage capacity is expected to be low and limited to that in the topsoil portion of the mix. The topsoil will be added to sand in a ratio that might not be uniform throughout each bag, even though it should be in the 25 to 30% range. At this point, nothing is known about the quality of the sand and its potential nutrient content, but it is assumed that the nutrient supply from sand will be low. It is also important to recognize that the nutrient requirements of the plants used are for the most part unknown and in all probability quite variable. Therefore, it is recommended that standard nutrient additions be made as used for other roadside vegetation. In this case, a starter fertilizer application is recommended, especially for seedings done in the spring.

These nutrient additions should be made to the soil/sand mix during preparation of the medium and filling of the Deltalok bags. For spring seedings, an additional 20 lbs each of nitrogen, P_2O_5 and K_2O should be applied, either in the hydroseeding mix or through the irrigation line or from a tank truck. One option for supplying nitrogen would be a slow-release N product. However, most controlled-release N sources cost several times more per pound of N than the soluble sources, and their use in this sector is not considered economically feasible. However, controlled release fertilizers have higher efficiency of nutrient utilization and reduce the impact on the environment and the possible contamination of the subsurface water with N. Probably the best option would be to add the fertilizer as indicated above for preparation of the soil medium and then add annual additions in irrigation water. Plant material can be monitored periodically to determine foliar levels of nutrients for detection of deficiencies and remediation through the irrigation lines.

Fertilizer recommendations are made on an acre basis, which is assumed to be 2 million lbs of dry soil, the approximate weight of one acre of soil down to the plow depth. That is equivalent to 2,000,000 lbs per 24,400 cubic feet of soil (assuming a plow depth of about 6.7 inches). The effective depth for the noise wall is about twice this, so additions should be made for this greater depth. Another assumption is the amount of nutrient removal expected. This varies by species so we will make recommendations that meet the needs of most plants. A good working number for our purposes is that plants will remove about 100 lb/A of P and 300 lb/A of K. These numbers are simply an estimate based on recommendations for forage production. The amounts for P and K are equivalent to 0.41 lb P and 1.2 lb K per 100 cu ft of dry soil. This could be supplied at bag filling using 0-11-46 fertilizer at a rate of 2.7 lb per 100 cu ft of soil. For nitrogen, it is assumed that plants will remove the equivalent of about 100 lb of N per acre. It would be best to apply half of the N in the bags and half over the top in springtime. The N could be applied as urea (46-0-0) at a rate of about 0.5 lb per 100 cu ft of dry soil. This same amount of urea could be applied in springtime through the irrigation system. For maintenance, these same levels of nutrient additions should be made annually and adjusted as necessary according to annual leaf nutrient tests.

<u>Summary of fertilizer recommendation:</u>

2.7 lbs of 0-11-46 per 100 cu-ft of top soil

0.5 lbs of 46-0-0 per 100 cu-ft of top soil

8.8 Water Needs and Supply

To ensure success of vegetation of any type on the green noise wall, an irrigation system is essential. Every consultant we spoke with when discussing plant materials emphasized this point. This is essential because of the steep slope of the wall and limited potential for penetration of water from the outer surface into the depths of the bags and further into the inner core. The system must provide adequate moisture to all locations on the wall, be as automatic as possible, and be constructed of high quality materials that do not require time consuming maintenance. In order to design a system that will meet these requirements, we consulted with Mr. Dan Kamburoff (Columbus Irrigation Co.) and Mr. Bill Wolfram (TORO Micro-Irrigation, supplier to Columbus Irrigation Co.).

Several factors are important to consider in the design. An irrigation system designed for a growing mix with a high proportion of sand must include features to maintain moderate moisture, rather than replenish moisture when the medium is completely dry. Attempting to rewet a completely dry sandy medium would be difficult, due to failure of capillary action in large soil pores, and resulting in poor or uneven rewetting and unfavorable growth conditions. Therefore, replenishing moisture at infrequent intervals with a sprayer, overhead irrigation, or hose applications from a water truck would not be a good option. The only viable alternative would be a totally different noise wall design, such as a standard wall with trees and other vegetation growing next to it and relying on rainfall only.

The steep slope of the green noise wall will likely make water infiltration from upper levels to lower levels difficult. For this reason, the irrigation plan should include drip lines, not standard trickle irrigation lines, that supply water over a wide compensating range of pressures, i.e. such that at low pressures (10-15 psi) the emitter provides turbulent-flow and at higher pressures (15-60 psi) the emitter is fully pressure compensating. Standard trickle systems do not withstand winter conditions and would require annual removal and drainage. Modern drip lines are made of materials that can withstand freezing and thawing and could be laid in the wall during construction. The drip lines would be installed at different height intervals from upper to lower levels of the wall to compensate for differing volumes of soil and potential water movement from top to bottom by gravity (Figure 8.7). Drip lines spaced at narrower intervals closer to the top of the wall, and wider intervals at the bottom would provide the necessary higher volumes of water at the top. Providing higher volumes of water at the top and slightly lower volumes at lower levels would allow good infiltration but prevent over saturation of lower levels.

For a standard trickle system, water is delivered under pressure and flow is determined by the operator of the system based on expected water usage. Unless the system is monitored daily, this system inevitably wastes water on rainy or overcast days and might result in water stress on days of high evaporative demand. The proposed system is constructed of DripIn pressure-compensating (from 15–60 psi) driplines with built-in emitters that deliver precise water application directly to the root zone (Figure 8.6). The system will keep the Deltalok bags hydrated throughout the growing season at a level equivalent to the soil water holding capacity. Within a reasonable pressure range, as the soil dries with plant water uptake the gradient will withdraw water from the supply lines as needed. The pressure-compensating design makes it ideal for slopes, high wind areas, and areas with limited water supply or low pressure. Emitters are designed to be clog resistant and contain a trifluralin pellet that prevents root penetration of the irrigation line.

To supply water for such a system, it is expected that a "homeowner size" well with a 5 inch casing and 4 inch pump that delivers 25 gallons per minute would be more than adequate to hydrate the wall. Given the efficiency of water withdrawal from the lines, a delivery of 10 to 15 gallons would likely be adequate. The water source should have low concentrations of dissolved solids to avoid clogging drip lines and emitters. A drinking quality water source should be adequate for this purpose, without needing any additional water treatments. Columbus Irrigation can test water sample from proposed sources to determine if water quality is suitable.

Water from the well source will be supplied through a 6 inch PVC riser or access pipe, and will enter a 6 inch round valve box situated below the frost line. This will allow drainage and shut off of the irrigation system before winter to avoid freezing damage. Water will be routed into a 12" x 20" valve box housing an air release, manual shut off, back flow preventer, solenoid main valve, filter and pressure regulator. Water will then move through another 12" x 20" valve box where lines will be split to supply the north and south face of the green noise wall using zone valves and distribution lines. Distribution lines will be fed through four 2" PVC 90 degree elbows to protect the bends in the distribution lines from kinking, twisting or breakage. At the opposite end of the wall, the 20 lines exiting the wall will be routed through four 2"PVC 90-

degree elbows to protect the bend in the lines. Lines will then be fed through another 12” x 20” valve box fitted with figure-8 closures.

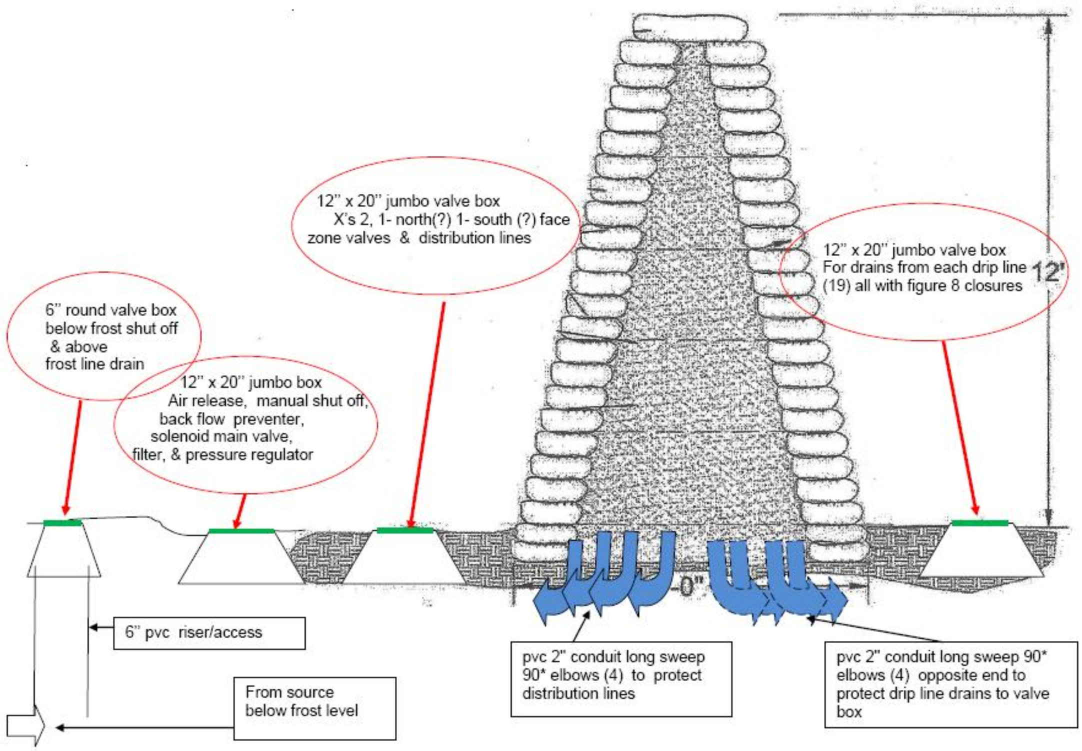


Figure 8.6: Proposed Drip Irrigation System

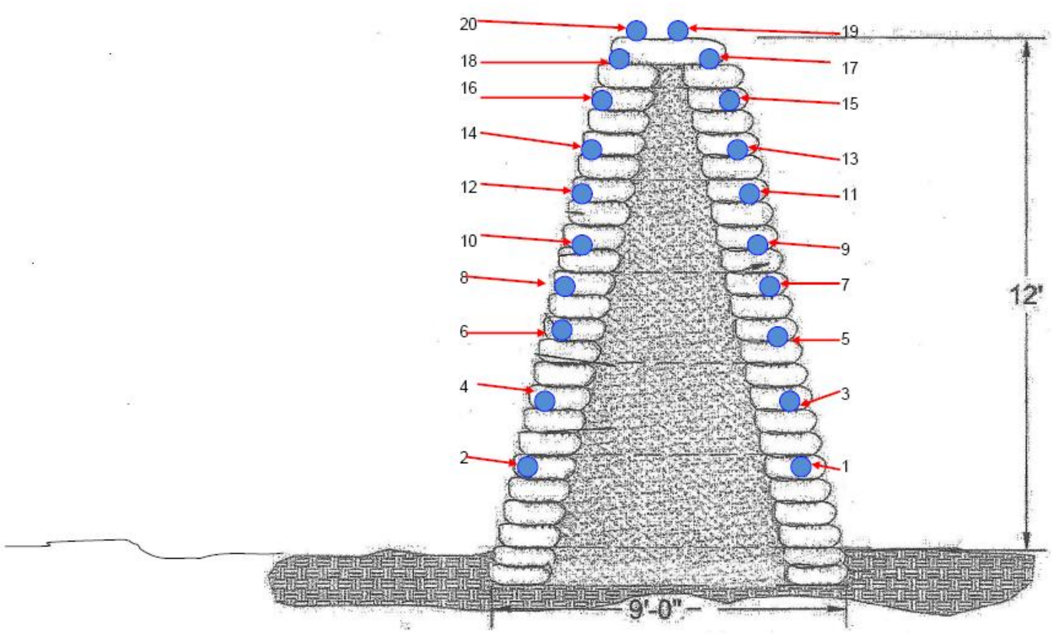


Figure 8.7: Drip Lines Distribution

Drip lines will be constructed of Toro Drip-in PC Dripline with Rootguard, 20 mm in diameter, with a flow rate of .53GPH (Figure 8.8). This product is designed for difficult topographical conditions, low and varying water pressures, and installations requiring long lateral runs. It features high strength and durability, discharge uniformity, and high resistance to plugging. In-line emitters are completely enclosed and extruded as an integrated part of the tubing in the manufacturing process. In the field, these emitters have a typical life of 20 years or more. The inclusion of trifluralin herbicide in the Rootguard emitters inhibits the growth of roots into the emitters to prevent plugging. The Rootguard technology releases the herbicide into the soil surrounding the emitter at a uniform rate over a long period of time. This protection is guaranteed to prevent longitudinal root growth into the emitters for 10 years.

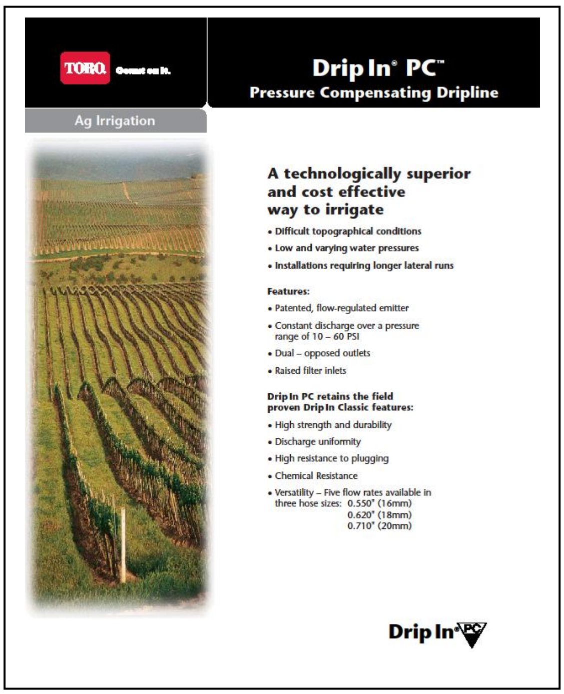


Figure 8.8: TORO Drip Lines

The design calls for drip lines to be installed every 2 or 3 layers of Deltalok bags, with 2 layers of bags between lines nearer the top of the wall, and 3 layers of bags between lines nearer the bottom of the wall. All drip lines will be installed in front of Deltalok plates (toward the outside of the wall), and will be installed on layers without geogrid reinforcement. The irrigation design is calculated to provide adequate moisture to the entire wall surface of approximately 0.25

Acre. The drip system will be controlled by a Toro 12 Station Total Control timer with 120 vac input, 24 vac output and 1.67 amps. Features of this timer include flexible programming, heavy-duty surge protection from lightning and power surges, and battery backup.

To compensate for the lack of a nearby water source, a water well could be drilled at the proposed barrier site. This well will include a steel casing, submersible pump and pressure tank. Standard maintenance will be required, but in this situation the tank must be drained at the end of each season and the pump primed each spring. Maintenance will also be required to monitor and program the Total Control system at the beginning of each growing season. For safety and security, the pressure tank should probably be enclosed in a small structure at the site.

Chapter 9
Traffic Noise Analysis

9.1 Introduction

The previous chapters examined the structural stability of the Deltalok system and investigated its ability to retain moisture to sustain vegetation. In Phase II of this research project, a full scale Deltalok system barrier will be constructed and evaluated. The full scale barrier will measure 400 ft long, 9 ft wide and 12 ft high. This chapter presents the results of an investigation of the anticipated acoustical performance of that full scale Deltalok barrier installed at a specific location along an interstate highway which is similar to those encountered in numerous highway improvement projects.

The full scale Deltalok barrier will be constructed in Licking County, Ohio, roughly twenty miles east of Columbus. It will be located along the westbound direction of I-70 (going to Columbus), just south of Carpenter Road and west of the Tollgate Road overpass. Figure 9.1 shows an aerial photo of the test site. Figure 9.2 shows a photographic picture of the site showing I-70 and the Tollgate Road overpass.

Figure 9.1: Phase II Barrier Location

Figure 9.2: Picture at Phase II Barrier Site
Showing Interstate 70 and the Tollgate Road Overpass

In order to evaluate the effectiveness of the full scale Deltalok system in reducing traffic noise at the I-70 site, the anticipated noise reduction was evaluated using the Federal Highway Administration's (FHWA) Traffic Noise Model Version 2.5 (TNM 2.5). To verify the TNM model worked accurately at the I-70 site, traffic noise predictions were compared to actual field measurements. With the model verified, the effectiveness of the Deltalok barrier was evaluated by examining the predicted insertion calculated by TNM 2.5.

9.2 TNM Modeling

The FHWA TNM is a valuable tool for the design of highway noise barriers (*17*, *18*). This program allows for the assessment of current noise levels and predicts the anticipated future noise levels. TNM 2.5 includes a database of speed-related noise emission levels for a variety of vehicle types (automobiles, medium trucks, and heavy trucks). In addition, it contains a database of emission levels that accounts for the effects of accelerating vehicles, such as those affected by traffic control devices (stop signs, signals, tollbooths, or on-ramps), as well as the effects of roadway gradients. Sound propagation is computed by accounting for the effects of ground and atmospheric absorption, divergence (i.e., geometric spreading of sound energy over distance), topography, man-made barriers, vegetation, and rows of buildings. To ensure a high level of accuracy, all TNM databases and calculations are based on 1/3-octave band analysis, and the results are recombined to give noise levels in the A-weighted broadband. The A-weighted system is commonly used in traffic analysis because it is highly correlated to human response to noise.

In order to successfully model the site location, a Geographic Information System (GIS) was used to overlay original (1960s) construction plan drawings of I-70 on recent (2006) aerial photos of the test site. Linework representing the highway centerlines, lane group centerlines, and a barrier baseline was developed in the GIS and exported for use in a computer aided drafting (CAD) program. CAD was used to reestablish the centerline stations consistent with the original construction plans and develop 50 ft roadway and barrier segments for TNM. CAD was also used to locate the TNM receiver points. The base elevation of the roadway and barrier was developed from cross-sections included with the original roadway plans and the elevations of the receiver points were obtained from Licking County GIS data.

Figure 9.3: Original Plans Overlaid Recent Aerial Photo with
Highway Centerlines and Barrier Baseline

9.3 Verification Model

With the site geometry loaded into TNM, a verification model was needed to confirm the accuracy of TNM 2.5 at this location. Verification involved comparing TNM model predictions to actual noise measurements obtained at the proposed green noise barrier site. The traffic noise monitoring was conducted by ODOT Office of Environmental Services (OES) on March 19, 2010. The average noise level was found to be 72.4 dBA at a distance of 90 ft from the edge of the pavement. The noise monitoring location is shown on Figure 9.4. Consistent with FHWA and ODOT guidance, the traffic noise monitoring lasted for 15 minutes, during which the observed traffic was 3,200 vehicles per hour (vph), with 60% of the traffic traveling eastbound.

Figure 9.4: Noise Measurement Site at Phase II Barrier Location

The receiver location, along with the traffic information, was entered into the TNM model and the program predicted the noise level for the monitoring period conditions. The result of the modeling was a noise level of 73.5 dBA, 1.1 dBA above the actual monitored noise level. The TNM model is considered to be accurate if the model predicts the traffic noise within plus or minus three decibels (+/-3dBA) of the actual monitored noise level. Since the model was within the three (3) decibel range that is required for a model to be accurate, TNM 2.5 can be used to accurately predict the performance of the proposed green noise barrier at the I-70 location.

9.4 Barrier Evaluation Model

With the model being verified as accurate, the TNM was used to estimate the traffic noise levels with and without the proposed green noise barrier. Since the program does not contain a Deltalok shaped noise barrier, both a concrete barrier wall and an earth berm were used in the analysis. Because of their thickness and shape, earth berms are generally believed to produce slightly higher noise reductions than concrete barrier walls. The proposed Deltalok noise barrier is expected to have noise reduction properties as good as or better than a traditional concrete barrier.

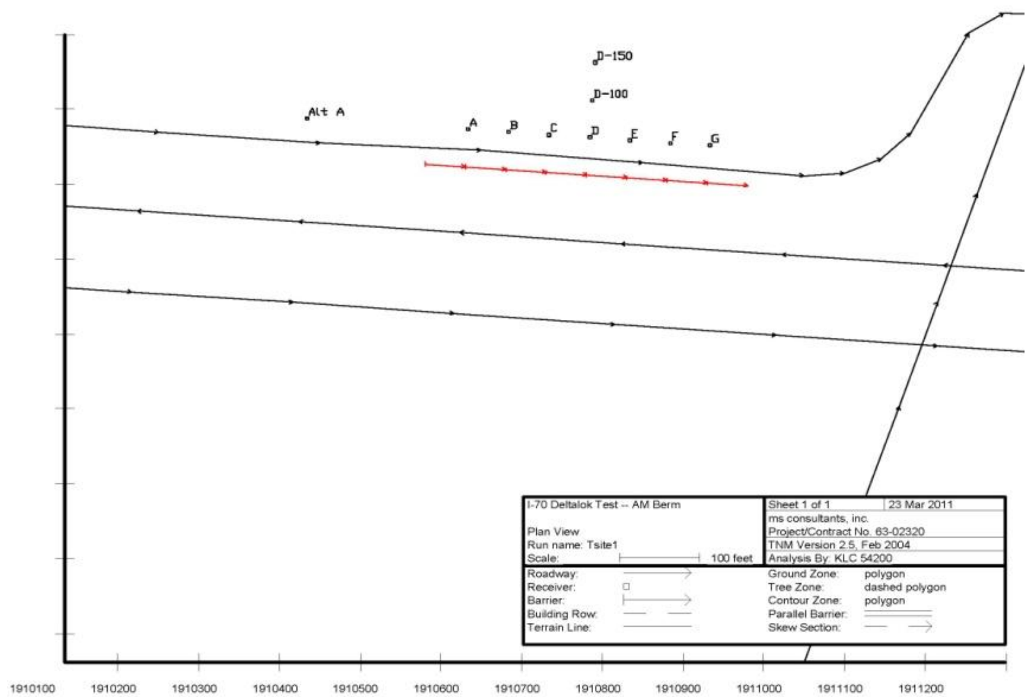


Figure 9.5: TNM Version 2.5 Model – Plan View

As shown in Figure 9.5, a series of seven evaluation points, labeled A thru G, were located 50 ft behind and parallel to the proposed barrier. Two additional evaluation points, labeled D-100 and D-150, were included in the analysis. These points are located at the center of the barrier at a distance of 100 ft and 150 ft, respectively, behind the barrier.

The model was run using traffic data from Tuesday, May 19, 2009, which is believed to be representative of the Average Daily Traffic for the entire year. For that day, the peak hourly volume in the westbound direction was found to be from 7:00 am to 8:00 am, with a traffic flow of 1,281 vehicles in the eastbound direction and 3,075 vehicles in the westbound direction. This hour was used instead of the afternoon peak hour because more traffic would be traveling toward Columbus, in the lanes nearest the barrier. It should be noted that the evaluation model did not account for the traffic on the Tailgate Road overpass. Even though the effect of this traffic is expected to be negligible, it will need to be determined when the barrier is constructed to ensure the accuracy of the analysis.

The TNM 2.5 results for the points at the center of the proposed 400 ft long and 12 ft high green noise barrier are presented in Table 9.1. For the complete set of TNM results, please see Appendix C. As can be seen from this table, the earth berm resulted in slightly higher noise reduction than the concrete barrier. This is important because the research team expects the noise reduction of the Deltalok system to be as good as or better than a traditional earth berm.

The TNM model also predicted that the noise reduction at a location 100 ft away from the barrier, a location considered to be the outdoor activity area associated with the site's inhabitants, would be a minimum of 6.5 dBA. FHWA and ODOT require a noise barrier to provide at least a minimum of 5 dBA to be considered feasible (a reduction of less than 5 dBA might not be perceptible to the inhabitants). The Traffic Noise Model predicted that the proposed Deltalok green noise barrier will exceed this requirement and should provide noticeable noise reduction to the site's inhabitants. Furthermore, ODOT's Standard Policy on noise mitigation has a design goal of 8 dBA for the front row receptors. TNM predicted a noise reduction minimum of 8.9 dBA at 50 ft from the center of the 400 ft long, 12 ft high barrier. This would be 0.9 dBA above the design goal, for the front row receptors in many typical highway noise barrier locations.

Table 9.1: Predicted Noise Reduction (at the Center of the Barrier) using TNM 2.5

	Concrete Barrier	Earth Berm
50 feet	8.9 dBA	9.0 dBA
100 feet	6.5 dBA	6.7 dBA
150 feet	4.5 dBA	4.6 dBA

9.5 Conclusions

The previous data shows that the proposed green noise barrier will likely meet FHWA and ODOT's noise reduction requirements. Therefore, the Deltalok green noise barrier should be a feasible noise mitigation option. Once the Deltalok barrier is constructed along I-70 and vegetation is established, the research team intends to measure the actual noise reduction levels behind the green noise barrier, and compare them to those obtained using TNM 2.5.

Chapter 10
Preliminary Cost Analysis

10.1 Introduction

Cost is a key factor that will determine the feasibility of the Deltalok green noise barrier and potential use as an alternative to traditional concrete barriers. This chapter presents an estimate of the total costs associated with the construction of the proposed green noise barrier. In addition, it provides a comparison between the estimated cost of this barrier and that of a traditional concrete barrier.

10.2 Estimated Cost of Proposed Greer Noise Barrier

The total estimated costs associated with the construction of the proposed full scale green noise barrier along interstate I-70 in Licking County using the Deltalok system are presented in Table 10.1. Two quotes were obtained from two different contractors. The numbers presented in this table are based on the lower quote. As can be seen from this table, the total estimated cost of the proposed green noise barrier is $321,000. This figure includes the cost of the Deltalok bags delivered to the job site filled and stacked on pallets, mobilization and site preparation, barrier materials and construction, a drip irrigation system, a water well, initial vegetation, and vegetation maintenance (including plant replacement as needed) for two growing seasons. The contractor will also be responsible for obtaining all required permits for construction. The cost of the Deltalok bags filled and delivered to the job site is $145,200, the cost of the actual construction is $133,100, the cost of the water well and irrigation system is $21,000, and the cost of vegetation (materials, planting, and maintenance) is $21,700. Therefore, the total cost of the barrier is primarily determined by the cost of the Deltalok components, bag filling and delivery, and initial construction.

Table 10.1: Estimated Costs Associated with the Proposed Green Noise Barrier

Item	Cost
Deltalok components 12,700 Deltalok bags, standard unit connections, and zip ties.	$83,200
Bag filling and shipping All bags filled with 30% amended topsoil and 70% sand, closed with zip ties, and delivered to job site.	$62,000
Site preparation Grubbing, fence removal, silt fence, signage, and temporary power.	$9,100
Wall construction Core fill material blended at 80% ODOT Item 304 or recycled concrete aggregate and 20% topsoil, in place and compacted. Deltalok system erected, with geogrid as specified.	$124,000
Working well and irrigation system As per details in Chapter 8.	$21,000
Initial vegetation and vegetation maintenance Planted with contractor's choices from within recommendations by researchers, maintained for two growing seasons from date of initial planting, and plant replacement as needed.	$21,700
Total Cost	**$321,000**

10.3 Cost Comparison with a Traditional Concrete Barrier

Table 10.2 presents a comparison between the proposed green noise barrier and a traditional concrete barrier in terms of total cost and cost/ft^2. The total cost of the traditional concrete barrier was estimated from the Summary of Contracts Awarded by ODOT in 2010 (issued by ODOT Office of Contracts) for Item 606 (Special – Noise Barrier (Absorptive), Over 10 ft to 14 ft Height). As can be observed from this table, the total estimated cost of the full scale green noise barrier ($321,000) is more than twice the cost of a traditional concrete barrier ($148,560). This is not unexpected given the relatively short length of the proposed barrier and the fact that the Deltalok system has never been used as a green noise barrier in Ohio. If successful, the cost of the Deltalok system is expected to decrease in the future as contractors become more familiar with this product. It is also noted that this cost estimate includes a water well to compensate for the lack of a nearby water source at the barrier site. If the Deltalok system is constructed at a location where water is readily available, the barrier cost could be reduced.

Table 10.2: Cost of Proposed Green Noise Barrier versus a Traditional Concrete Barrier

Barrier Type	Total Cost	Cost/ft^2
Green Noise Barrier	$321,000[a]	$66.87[c]
Traditional Concrete Barrier	$148,560[c]	$30.95[b]

[a]From Table 10.1.

[b]Based on ODOT's Summary of Contracts Awarded in 2010 for Item 606 (Special – Noise Barrier (Absorptive), Over 10 ft to 14 ft Height).

[c]Assuming a barrier length of 400 ft and a barrier height of 12 ft.

10.4 Conclusions

The total estimated cost of the proposed green noise barrier is higher than a traditional concrete barrier. This is not unexpected given the relatively short length of the proposed barrier and the fact that the Deltalok system has never been used as a green noise barrier in Ohio. If successful, the cost of the Deltalok system is expected to decrease in the future as contractors become more familiar with this product. Nevertheless, it is expected to be higher than a traditional concrete barrier due to the added costs from vegetation. Therefore, while this product may not be suitable for all locations, it might be a good option for locations that are considered unique or have a special interest by the community. Examples of such locations include historic properties, schools, local and state parks, and other natural settings. The benefits associated with a green noise barrier for these communities cannot be quantified for inclusion in any cost comparison. Funding for such projects could be covered in-part by the affected residents or communities that have a strong desire for a green alternative to traditional concrete barriers.

Chapter 11
Conclusions and Recommendations

11.1 Introduction

This chapter provides a summary of the work performed in Phase I and the conclusions related to the feasibility of constructing a full scale green noise barrier along interstate I-70 in Licking County. The recommendations for implementation are presented at the end of this chapter.

11.2 Summary

This study included a thorough review of available green noise barrier products based on information obtained from the producers and their websites. In addition, it included a questionnaire that was sent out to more than three hundred national and international experts in traffic noise analysis and abatement to document their experience with this type of barriers. Tables 11.1 and 11.2 summarize the outcome of the literature review. Table 11.1 presents a summary of the various green noise barrier designs identified in the literature. Table 11.2 provides a comparison between traditional and green noise barriers in terms of construction materials, construction process, noise reduction, maintenance, cost, service life, aesthetics and potential risks.

By examining the advantages and disadvantages of each of the available green barriers, the Deltalok product was determined to be the most likely product to succeed in Ohio. As discussed in Table 11.1, the Deltalok product is a reinforced earth structure that utilizes geogrid as reinforcement and ecology bags that can sustain vegetation as facing units. Standard unit connectors are placed between the bag layers to hold the bags in proper position. The space between the bags in each layer is filled with granular material and compacted to form the core of the structure.

A prototype Deltalok wall, measuring 15 ft in length, 9 ft in width and 12 ft in height, was constructed in Covington, Ohio (north of Dayton) to evaluate its structural stability and ability to retain moisture. The prototype wall was equipped with various sensors and devices to monitor its earth pressure and deformation characteristics and examine the moisture and temperature distributions within the barrier. The prototype wall was monitored for a period of two months. The data collected from these sensors and the visual inspections allowed for making several recommendations regarding the construction of the Deltalok system and its use as a green noise barrier.

A laboratory plant study was designed and executed to determine the factors that affect plant survivability on green noise barriers and make recommendations on the vegetation selection. Four different plant mixes were selected for planting in different sections along the full scale wall to evaluate their adaptability. Mix 1 is a grass mix that ODOT would normally apply through hydroseeding to serve as a control treatment. Mix 2 includes grasses and native prairie forb species. Mixes 3 and 4 are a combination of herbaceous species plus some selected woody species. The woody species are the same for Mix 3 and Mix 4. The difference is that Mix 3 is underlaid with hydroseeded grasses from Mix 1 (seeded at 2/3 the normal seeding rate), while Mix 4 is underlaid with hydroseeded grasses and forbs from Mix 2 (seeded at 2/3 the normal seeding rate). The plant study also addressed the effect of hydroseeding compounds on grass germination and establishment, soil modification, and water needs and supply for the proposed green noise barrier. It was not possible in this phase to evaluate plant establishment and long-term survival in a natural highway environment since this requires constructing a full scale barrier and actually planting it, as planned in the second phase.

A traffic noise analysis study was conducted to investigate the anticipated noise reduction from the proposed full scale green noise barrier. The Federal Highway Administration (FHWA) Traffic Noise Model (TNM) Version 2.5 was used for this purpose. To verify that the TNM model worked accurately at the I-70 site, traffic noise predictions were compared to actual field measurements. With the model verified, the effectiveness of the Deltalok barrier was evaluated by examining the predicted insertion loss calculated by TNM 2.5. Since this program does not contain a Deltalok shaped noise barrier, both a concrete barrier and an earth berm were used in the analysis.

Finally, the cost of the proposed green noise barrier was compared to a traditional concrete barrier with the same length and height. The total cost of the proposed green noise barrier was estimated from the lower of two quotes provided by two local contractors. Meanwhile, the total cost of the traditional concrete barrier was estimated using ODOT's Summary of Contracts Awarded in 2010 (issued by ODOT Office of Contracts) for Item 606 (Special – Noise Barrier (Absorptive), Over 10 ft to 14 ft Height).

Table 11.1 Available Green Noise Barriers

Noise Barrier Design	Construction Method	Advantages	Disadvantages
Living Willow Wall	The living willow wall design uses two wooden frames placed several feet apart to retain and support the willow trees and a soil core. The soil core provides the noise reduction and moisture retention for the willow trees while the geotextile retains the soil and prevents erosion. The willow trees act as a façade to increase the aesthetics of the barrier. A drip irrigation system is installed during construction to provide moisture to the willow trees.	The advantage of this design is that it utilizes wood and willow trees which are natural, sustainable resources. Additionally, the construction does not require large machinery which reduces the congestion of job sites and the amount of greenhouse gasses emitted. The combination of soil and vegetation is expected to provide noise reduction that is comparative to traditional noise barriers.	Willow trees are a type of vegetation that requires large amounts of moisture to survive; hence, an irrigation system is needed for this barrier. This design cannot accommodate heights greater than 12 feet which limits its use. The construction of this barrier is also labor intensive and requires skilled labor.
PileByg	There are two pilebyg designs, living and dead. Both designs use two wooden frames to retain a core composed of two layers of 120 mm rock wool. The wooden frame also allows for living or dried willow rods to be woven through the frame. The core of the barrier provides the noise reduction while the willow branches provide the aesthetics.	The PileByg has the advantage of increased aesthetics in comparison to traditional noise barriers. The living willow rods blend with the natural environment while the dried rods age with time and provide a natural look. Additionally, vine like vegetation can be planted to improve aesthetics.	These barriers require a concrete foundation along the length of the barrier to insert and stabilize the dry willow rods, which increases the costs of construction. The main disadvantage is that the barrier may not be capable of providing the required noise reduction desired by DOT's to be considered a reasonable noise mitigating technique.

Criblock	The Criblock uses concrete members that are stacked in an interlocking design. This design creates a void space in the center of the structure that is backfilled with soil. The soil allows vegetation to be planted on the face of the structure and allows the structure to reduce traffic noise.	The Criblock design is a structurally stable design and can be used at various heights and locations. The precast concrete members are set in place which reduces the construction time and the relatively small size eliminated the need for large machinery. The concrete and soil provide excellent noise reduction because concrete reflects sound while the soil absorbs it.	There is uncertainty over whether this design could be used as a freestanding structure since previous applications have been primarily retaining walls and embankments. The open spaces that allow vegetation to grow may be susceptible to erosion from wind and rain when used as a free standing structure. Finally, the structure uses concrete and steel which makes these walls less green than other green noise barriers.
Timbergrid	The Timbergrid uses a series of wooden panels that are stacked in an interlocking design. This design creates a void space in the center of the structure that is backfilled with course aggregate. These spaces allow planting bags that are filled with soil to be places within the structure and vegetation to be planted on the structure.	The Timbergrid design uses wooden members which make these barriers more sustainable than traditional noise barriers that use concrete and steel. The course aggregate creates void spaces that trap noise while the wooden members absorb noise. The wooden members provide increased aesthetics and the addition of vegetation can help these barriers blend in with their surroundings. The Timbergrid company claims the barrier has a 60 year service life.	The service life of these structures can only be achieved with regular staining to protect the wood from inclement weather and solar damage. Additionally, the granular material inside the structure allows water to drain away from the structure which means that the vegetated bags would need irrigation to survive. The combination of staining and irrigation increases the maintenance and labor costs which discourages the use of these structures.

Evergreen	The Evergreen design uses precast concrete trays that are stacked on top of each other. These concrete trays have a flower box design that allows soil to be retained within the barrier. Additionally, the trays can be stacked to meet the required height to provide the desired noise reduction.	The Evergreen design has been proven to be a structurally stable noise barrier. Additionally these barriers provide good noise reduction, which can be attributed to the size of the barrier and the thickness of the concrete and soil.	The open spaces between the concrete trays leave the structure susceptible to erosion from wind and rain. Also, the near vertical design of the structure restricts moisture from reaching the various levels of the barrier. With a lack of vegetation and soil the aesthetics and noise reduction of the barrier may be significantly reduced.
Recywall	The Recywall uses a combination of vertical supports and horizontal members to retain the soil. These supports and members are composed of recycled plastic that are lightweight. The members create a soil core that allows vegetation to be placed along the face of the barrier.	The members are made of recycled plastic which increases the sustainability when compared to traditional concrete noise barriers. The combination of plastic and soil both reflects and absorbs sound that provides better noise reduction that traditional concrete noise barriers while the vegetated surface increases the aesthetics.	The plastic members are subject to deformation under high and low temperatures and may deteriorate when exposed to direct sunlight. This may weaken or reduce the structural strength of the structure. This design may be susceptible to erosion from wind and rain due to the open spaces formed by the plastic members. Finally, the vertical faces reduce the amount of moisture that can be retained within the structure. This means that the barrier would need irrigation in order to sustain the vegetation.

Supported Earth Embankment	Supported earth embankments have a variety of forms and designs. In general, they use either concrete supports or a steel mesh to retain the soil. These structures are similar to earth berms but with a smaller footprint and allow vegetation to be planted along the entire face of the structure.	These barriers use less concrete and steel than traditional barriers which increases the sustainability. Furthermore, if the vegetation is successful, these structures provide greater aesthetics than other noise barrier designs because the steel mesh allows vegetation to be planted over the entire face of the structure.	This design uses concrete and steel which is less sustainable than other green noise barriers designs that use natural or recycled materials. When concrete is used, the units are heavy and require large machines to lift them into place. Finally, the barriers may be susceptible to erosion from wind and rain especially when the steel mesh is used.
Plant Boxes	Plant boxes are a structure that can be added to existing traditional noise barriers. These units are concrete boxes that are placed in front of the noise barrier and allow soil to be retained and vegetation to be planted.	These structures improve the aesthetics of traditional noise barriers by allowing vegetation to be planted in front of them. The boxes can sustain vegetation of a variety of sizes which brings a natural appearance to the barriers.	These structures do not solve the problems faced by traditional barriers but improve their aesthetics. This means that there are added costs to traditional noise barriers.
Deltalok	The Deltalok design uses specially designed bags to retain soil. The Deltalok bags are stacked in an overlapping pattern and adjacent bags are connected by standard units that are plastic plates with spikes protruding from each face. These stacked bags create a space in the center of the barrier that	The deltalok bags and standard units are made of recycled material providing increased sustainability. The design is versatile and allows the incorporation of a variety of plants including small trees, bushes and grass. Finally, the barrier is	The small footprint and steep sloping faces may not allow the barrier to capture and retain enough moisture. Insufficient moisture may require an irrigation system to sustain the vegetation increasing the maintenance costs of the structure. Furthermore, the

	is backfilled with soil to form a soil core. The soil core is composed of a granular material that provides the noise reduction for the structure.	expected to have noise reduction between that of a traditional noise barrier and an earth berm thanks to the soil cores ability to absorb sound.	barrier may be susceptible to settlement in the bags and core of the structure. This loss of height may reduce the noise reduction properties of the barrier.

Table 11.2 Comparison Between Traditional and Green Noise Barriers

	Traditional	Green
Construction Materials	The most common traditional noise barriers use a combination of prefabricated concrete panels and steel reinforcement with concrete vertical supports.	Green noise barriers have a variety of designs. In general they use a number of materials including concrete, steel, wood, recycled plastic and earth retaining materials such as geogrids and geotextiles.
Construction Process	The construction process is relatively quick due to the prefabricated concrete panels. The units are delivered to a job site and set in place. The drawback is that large machines are required to hoist the heavy units into place.	The construction process is dependent on the design used. For structures like the living willow wall, Pilebyg and Deltalok it can be labor intensive due to the precision required to ensure that the structure will provide the desired noise reduction and aesthetic properties.
Noise Reduction	Traditional noise barriers are designed to reduce noise by reflecting noise away from communities adjacent to highways. This can be achieved by increasing the height as required to meet the design goal of 8 dBA.	Green noise barriers are expected to have a noise reduction between that of a traditional noise barrier and an earth berm of the same height. The noise reduction is achieved from the soil within the structure that absorbs rather than reflecting traffic noise.

Maintenance	The maintenance requirements for traditional noise barriers are minimal. They require some debris removal and repainting if necessary.	Green noise barriers demand considerable maintenance. Along with debris removal, the barriers require irrigation to maintain the vegetation. They also may require reseeding when the vegetation dies, trimming and weed control. Occasional soil replenishment may be necessary on some green noise barrier designs due to erosion from wind and rain.
Cost	\$25.00 to \$35.00 per ft^2	\$50.00-\$70.00 per ft^2
Service Life	30 to 40 years	The service life of green noise barriers varies by the design and materials used. There is additional uncertainty because many of the designs have not been used in large scale or numerous applications. It should be noted that many of the green noise barriers that were constructed in the early to mid 1990's are still structurally viable.
Aesthetics	Traditional noise barriers have an obtrusive appearance and are often the source of complaints from residents and commuters.	If successful, green noise barriers have increased aesthetics thanks to their ability to incorporate various types of vegetation. This makes them visually pleasing to both residents and commuters.
Potential Risks	There are few risks associated with traditional noise barriers. These structures have been used for decades, providing a variety of examples to learn from.	Green noise barriers have the potential of vegetation failure due to inclement weather conditions, drought or lack of moisture, disease, competition from undesirable plants such as weeds, etc. An irrigation

		system is needed in most of the green noise barrier designs presented in Table 11.1 to sustain vegetation. Improper winterization of the irrigation system prior to winter may lead to freezing and complete damage to the waterlines. As a result, the vegetation may not survive. Finally, the noise reduction properties of some of the green noise barrier designs such as the living willow wall and the Deltalok system may change over time due to barrier settlement and changes in vegetation. Such reduction in height can be accounted for during the design stage of the barrier.

11.3 Key Findings and Conclusions

The following is a summary of the key findings and conclusions based on the research performed under Phase I:

- Structural stability:
  - The instrumentation plan of the prototype Deltalok wall included an earth pressure cell placed at the center of the prototype wall to measure vertical pressure, four vibrating wire displacement transducers (or crackmeters) mounted on the geogrid at various heights within the wall to measure geogrid deformation, and a number of survey points located on the exterior of the wall to monitor wall deformation.
  - The total vertical pressure measured using the earth pressure cell immediately after construction was equal to 5.9 psi, which is less than the estimated at-rest vertical pressure, $\sigma_v = \gamma h$, of 10 psi (assuming a soil unit weight of 120 lb/ft^3 and a barrier height of 12 ft). This implied that the vertical load was not uniformly distributed at the base of the wall and the outer portion of the base was carrying a greater portion of the load than the middle. This was attributed to the effect of soil arching, which is not uncommon in soil embankments, and the transfer of the vertical load to the sides of the wall through the

geogrid reinforcement. In order to better understand this phenomenon, it is recommended that more pressure cells be used in the second phase of this study.

- The data from the vibrating wire displacement transducers was used to calculate the strain and load in the geogrid. The maximum geogrid strain occurred 33 inches (2.75 ft) above ground and was equal to 3.4%. This strain corresponded to 621.5 lb/ft load in the geogrid. This load was found to be significantly lower than the long-term and ultimate tensile strengths of the geogrid, which implied that the prototype wall was internally stable in the transverse direction. There is more concern about the internal stability of the prototype wall in the longitudinal direction due to the relatively low strength for the geogrid in that direction and the short length of the wall. A full scale barrier would have a plane strain response reducing the effects of the longitudinal forces in the geogrid near the middle of the wall. Therefore, additional reinforcement might be needed towards the end of the structure to increase its resistance to longitudinal deformation.
- The total vertical settlement in the prototype wall was found to be 4.98 inches (or about one layer of Deltalok bags) after two months. The prototype wall is expected to continue to settle. Therefore, it is recommended to construct the barrier using a minimum of two additional layers of Deltalok bags to compensate for the effect of settlement on the reduction in acoustic performance of the Deltalok wall. To accommodate the increase in barrier height, a layer of geogrid should be used every three rows of Deltalok bags rather than four to better resist the tensile forces within the structure.
- The previous results suggested that the proposed green noise barrier will be structurally stable in the short term. However, additional evaluations are needed to determine its long-term stability.

- Temperature and moisture distributions:
  - The prototype Deltalok wall was instrumented with eight temperature and eight moisture sensors to monitor the temperature and moisture distributions within the barrier.
  - Higher temperatures were noticed on the south side than on the north side. This was expected because the south side received direct sunlight, which raised the temperature of the soil within the Deltalok bags during the day. Additionally, the south side saw more fluctuation in temperature than the north side. The increases in temperature were lost quickly at night, causing the noticeable fluctuations.

- By comparing the temperature readings on the same side, it was noticed that the temperature at the top of the barrier was greater than the temperature on the lower parts of the barrier. This was true for sensors on both the north and south sides. This variation was caused by the bottom of the barrier being in contact with the ground, which reduced its temperature. Meanwhile, the top of the barrier was exposed to direct sunlight, which increased its temperature. Since this data was collected in the months of April and May, wind did not significantly impact the temperature distribution within the barrier. However, it is expected that the top of the barrier will have a lower temperature in the winter months because it is exposed to wind and does not have a large mass to retain heat. In contrast, the top of the barrier is expected to be warmer in the summer months because of the exposure to sun.
- Higher moisture contents were noticed on the south side of the barrier than on the north side. This variation was probably caused by the direction of rain storms in Ohio.
- It was also noticed that the soil moisture content at the top of the barrier was lower than the bottom of the barrier. This was expected because the top of the barrier had less soil to retain moisture and was more prone to evaporation due to exposure to wind and sun.
- The prototype wall was watered using a soaker hose until reaching the water holding capacity. The soaker hose was then turned off and the moisture content was monitored. A 30 to 40% reduction in moisture content was observed within one week after the removal of the soaker hose.
- The previous results indicated that the proposed full scale green noise barrier will be susceptible to wide variations in temperature and moisture on its north and south sides and along its height. These variations should be taken into consideration in choosing the plant mixes for the Deltalok noise barrier.
- The previous results also indicated that the proposed green noise barrier may not be able to retain enough moisture to sustain vegetation. This loss in moisture was observed for all locations within the barrier.

- Vegetation:
  - The vegetation survivability on the proposed green noise barrier will be affected by several factors including moisture availability, exposure to sunlight, soil composition (pH and nutrients), salt sensitivity, and time of planting.

- Water availability will be critical for the success of vegetation. This will be particularly the case during the initial growing season. The Deltalok structure has a relatively small footprint that may not allow enough rain water to infiltrate into the barrier. Furthermore, it has steep faces that may not allow moisture to be retained within the structure. Therefore, it will not be possible to achieve proper establishment without irrigation and irrigation will be needed if dry periods occur or persist after establishment. The irrigation system must provide adequate moisture to all locations on the wall, be as automatic as possible, and be constructed of high quality materials that do not require time consuming maintenance.
- The research team consulted with Columbus Irrigation Company and TORO Micro-Irrigation, supplier to the Columbus Irrigation Company, regarding the irrigation of the Deltalok green noise barrier. It was determined that a drip irrigation system would be the most adequate in providing sufficient moisture to the barrier. The proposed irrigation system consists of 20 drip lines that will be installed at different heights within the barrier during construction to account for differing volumes of soil and potential water movement from top to bottom by gravity. It was also determined that a water well is needed at the proposed barrier site to compensate for the lack of a nearby water source. This well will include a steel casing, submersible pump and pressure tank. Standard maintenance will be required, but in this situation the tank must be drained at the end of each season and the pump primed each spring. Maintenance will also be required to monitor and program the drip irrigation control system at the beginning of each growing season. For safety and security, the pressure tank should probably be enclosed in a small structure at the site.
- The soil pile that was identified near the green noise wall test site for use in the Deltalok bags was evaluated to ensure that it contained the necessary soil nutrients. Soil samples were taken from the soil pile and tested for pH, Lime Test Index, available phosphorus (P), exchangeable potassium (K), calcium (Ca), magnesium (Mg), and cation exchange capacity (CEC). The chemical test results revealed a soil pH well within the range of tolerance and reasonable amounts of nutrients for the selected plant mixes. However, to account for plant uptake and maintain a desirable reservoir of nutrients, it is recommended to modify the soil/sand mix in the Deltalok bags.

- Planting, whether accomplished by hydroseeding or live planting, must be scheduled at a time when optimum growth conditions for establishment prevail. The best time will be determined by time of wall construction, favorable environmental conditions (likely mid spring or early fall), and availability of plant propagules at the scheduled planting time.
- A laboratory study was conducted to evaluate the effect of hydroseeding slurry components on seed germination and establishment of native grass and forb species that might be used on the green noise wall. This study revealed that standard slurry compounds are safe to use with the native prairie species. Therefore, no changes are needed to the hydroseeding procedure currently used by ODOT.
- Another experiment was conducted in the greenhouse to determine early establishment success of seeds inside the Deltalok bags. Mini bags were filled with a typical sand/soil mix and saturated with water. A mix containing water, colloidal tackifier and seeds was applied. Seeds of several species, representing a range of size, shape, and morphology, were used. Bags with soil and seed attached were watered by an automated irrigation system in the greenhouse. Germination success was evaluated on regular basis based on seed germination and root penetration of the bag. This experiment revealed that while grass seeds were able to penetrate the Deltalok bags, none of the forbs emerged through the bag due to blockage by the fabric. Therefore, it was concluded that the forb mixes should be hydroseeded on the outside of the bag to ensure successful emergence.

- Traffic noise reduction:
  - Using the TNM model, the predicted noise reduction at a location 50 ft away from the center of the proposed full scale barrier was 8.9 dBA assuming a concrete barrier and 9.0 dBA assuming an earth berm. Both values are higher than ODOT’s noise barrier design requirement of 8.0 dBA for front row receptors. The proposed Deltalok noise barrier is expected to have noise reduction properties as good as or better than a traditional concrete barrier. Therefore, the Deltalok green noise barrier should provide sufficient noise reduction at the proposed barrier site.
- Cost:
  - The total estimated cost of constructing the proposed green noise barrier was $321,000. This figure included the cost of the Deltalok bags delivered to the job site filled and stacked on pallets, mobilization and site preparation, barrier materials and construction, a

drip irrigation system, a water well, initial vegetation, and vegetation maintenance (including plant replacement as needed) for two growing seasons.

- The estimated cost of the proposed green noise barrier ($321,000) was higher than a traditional concrete barrier ($148,560). This was not unexpected given the relatively short length of the proposed barrier and the fact that the Deltalok system has never been used as a green noise barrier in Ohio. If successful, the cost of Deltalok system is expected to decrease in the future as contractors become more familiar with this product. Nevertheless, it is expected to be higher than a traditional concrete barrier due to the added costs from vegetation.

10.4 Recommendations for Implementation

This study revealed that although important questions have been answered regarding the use of the Deltalok system in Ohio, additional research is needed to clearly identify the advantages and limitations of this product as a noise mitigation option. Based on the research conducted under Phase I, it is believed that the Deltalok system will be structurally stable and capable of producing the desired noise reduction. However, it was not possible in this phase to evaluate plant establishment and long-term survival in a natural highway environment since this requires constructing a full scale barrier and actually planting it, as planned in Phase II. Proceeding with Phase II will also enable the research team to evaluate the long-term performance of the Deltalok system and accurately assess the maintenance needs of this type of noise barriers in Ohio.

Based on the results of Phase I, the following recommendations are made to ensure the success of vegetation on the full scale barrier:

- Plant the proposed green noise barrier in the mid spring or early fall because of the favorable environmental conditions during these periods.
- Install a drip irrigation system covering the whole height of the barrier to compensate for the varying water infiltration levels and potential water movement from top to bottom by gravity.
- Add 2.7 lbs of 0-11-46 and 0.5 lbs of 46-0-0 fertilizers per 100 ft^3 of top soil used in the Deltalok bags to account for plant uptake of phosphorus, potassium and nitrogen, and maintain a desirable reservoir of these nutrients.

- Apply forb seed mixes by hydroseeding on the outside of the Deltalok bags. The grass seed mixes could be mixed with the soil inside the Deltalok bags or applied on the outside of the Deltalok bags through hydroseeding.

It is also recommended to construct the full scale green noise barrier using a minimum of two additional layers of Deltalok bags to compensate for the effect of settlement on the reduction in acoustic performance of the barrier. The settlement of the Deltalok structure could also be minimized through the use of additional layers of geogrid and by ensuring proper compaction of backfill materials during the construction of the structure. It is recommended to use a layer of geogrid every three rows of Deltalok bags instead of four.

If successful, the Deltalok green noise barrier will provide an environmentally friendly green alternative to traditional concrete barriers that are currently being used in Ohio. While this product may not be suitable for all locations due to its high initial and maintenance costs, it might be a good option for locations that are considered unique or have a special interest by the community. Examples of such locations include historic properties, schools, local and state parks, and other natural settings. The benefits associated with a green noise wall for these communities cannot be quantified for inclusion in any cost comparison. Funding for such projects could be covered in-part by the affected residents or communities that have a strong desire for a green alternative to traditional concrete barriers.

REFERENCES

1. Federal Highway Administration (2010). Highway Traffic Noise: Analysis and Abatement Guidance. Revised January 2011.
2. Federal Highway Administration (1980). Noise Fundamentals Training Document: Highway Noise Fundamentals.
3. Truax, B. (1999). Handbook for Acoustic Ecology. 2nd Edition. Accessed May 2011: http://www.sfu.ca/sonic-studio/handbook/Sine_Wave.html.
4. Giancolli, D. (2008). Physics for Scientists and Engineers. Pearson Prentice Hall, 4th Edition.
5. Illinois Department of Transportation (2011). Highway Traffic Noise – Fundamentals website. Accessed May 2011: http://www.dot.state.il.us/desenv/noise/part1.html.
6. McCormick Taylor (2006). Statewide Investigation of Noise Abatement Alternatives. Final Report. Ohio Department of Transportation (ODOT).
7. ODOT (2010). Standard Procedure for Analysis and Abatement of Highway Traffic Noise. ODOT Standard Procedures No. 417-001(SP), Effective: February 8, 2010. Ohio Department of Transportation (ODOT), Columbus, Ohio.
8. Labrecque, M. and T. I. Teodorescu (2005). "Preliminary Evaluation of a Living Willow (Salix Spp.) Sound Barrier along a Highway in Québec, Canada." Journal of Arboriculture, 31(2), pp. 95-98.
9. The Living Wall (http://www.thelivingwall.net/).
10. PileByg (http://www.pilebyg.dk/).
11. Retaining Walls Northwest, Inc. (http://www.retainingwallsnw.com).
12. Timbergrid (http://www.timbergrid.com).
13. Evergreen (http://www.evergreenwall.com).
14. Schmidt, R. (1998). Living Noise Barrier. Report No. WI/FEP-01-98, Wisconsin Department of Transportation (WisDOT), Madison, Wisconsin.
15. Danish Road Institute (2009). Noise Barrier Design, Danish and some European Examples. Report 174. 53 pages.
16. Deltalok, Inc. (http://www.deltalok.com/).

17. Menge, C. W., Rossano, C. F., Anderson, G. S., and C. J. Bajdek (1998). FHWA Traffic Noise Model, Version 1.0 Technical Manual. Report No. FHWA-PD-96-010, Federal Highway Administration (FHWA), Washington, D.C.

18. Lau, M. C., Lee, C. S.Y., Rochat, J. L., Boeker, E. R., and G. G. Fleming (2004). FHWA Traffic Noise Model User's Guide (Version 2.5 Addendum). Federal Highway Administration (FHWA), Washington, D.C.