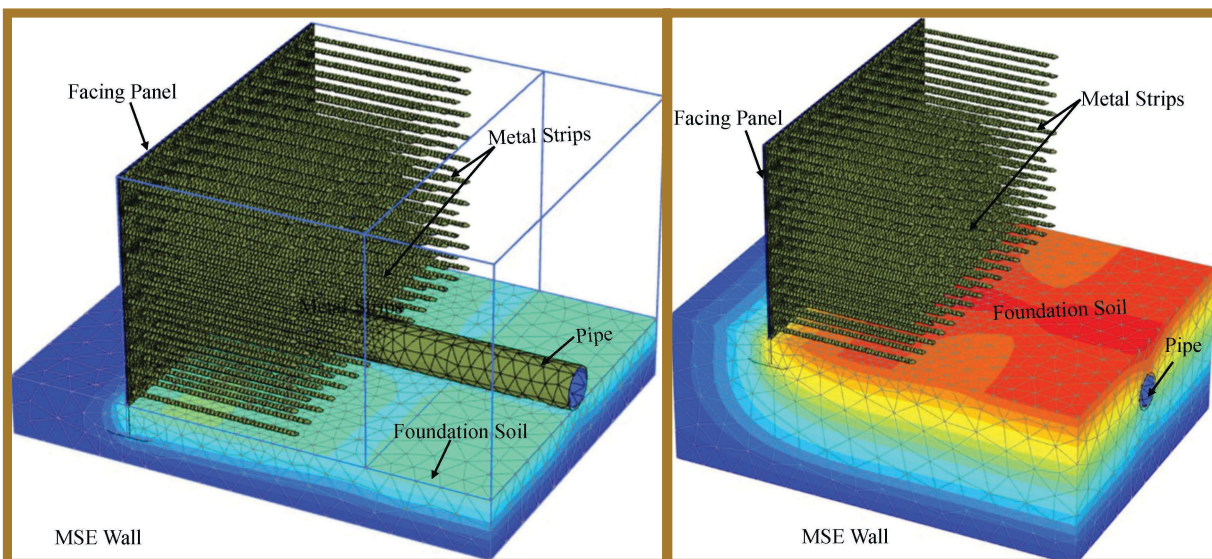


# JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION  
AND PURDUE UNIVERSITY



## Study on the Permissible Depth of Utilities Under the MSE Walls and Means and Methods of Protecting the MSE Walls When the Permissible Depth Cannot Be Provided



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## JOINT TRANSPORTATION RESEARCH PROGRAM

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<b>16. Abstract</b> Mechanically Stabilized Earth (MSE) walls may intersect utilities such as pipes and culverts, which may be located within the reinforced backfill or foundation soil. Evidence from previous failures has shown that leakage or collapse of these utilities can lead to severe deformation or loss of wall integrity. Despite the critical implications of pipe failure, there are no standardized guidelines in the U.S. regarding the placement of utilities within or beneath MSE walls, and current practices vary widely among state DOTs. This report describes the mechanical interaction between MSE walls and buried utility pipes and explores configurations where pipes are placed parallel, perpendicular, or at an angle to the wall, either in the reinforced zone or in the foundation soil. In addition, the report also includes an investigation of the minimum depth at which a pipe should be placed under the MSE wall such that failure of the pipe does not affect the MSE wall or its performance. The work consists of an extensive series of finite element analysis using PLAXIS 2D and 3D, where the wall system and pipe are explicitly considered. The results of the numerical experiments indicate that pipes significantly influence the axial force and displacement of reinforcements located immediately adjacent to the pipe. More precisely: (a) pipes placed parallel to the wall face may increase the axial force in the reinforcement by up to 60% compared to the case where there is no pipe; (b) the internal stability of the wall remains unaffected (provided reinforcement safety factors are met), but the stresses within the reinforced zone change noticeably with the pipe; (c) pipes perpendicular or skewed to the wall may reduce reinforcement demand by acting as large frictional surfaces; (d) the zone of influence of those perpendicular or skewed pipes extends over a distance of 2-2.5 times the diameter of the pipe; (e) when a pipe with diameter 36" or larger is placed at a depth of ten times the radius of the pipe underneath the wall, collapse of the pipe does have a negligible effect on the stability or performance of the wall (this finding applies to MSE walls with height up to 25 ft). The report also offers recommendations for monitoring and strengthening the pipe to detect and mitigate the consequences of damage to the pipe. The research highlights the intricate and interdependent behavior of the reinforced soil, reinforcement and pipe. While the general trends obtained from the research can be generalized, they may not be applicable to situations that fall outside the cases investigated. Case-specific analyses should be conducted to ensure that the presence of the pipe and its possible collapse do not compromise the integrity of the wall, nor its performance.			
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## EXECUTIVE SUMMARY

### Introduction

Mechanically Stabilized Earth (MSE) walls are commonly used by the Indiana Department of Transportation (INDOT) because of their cost-effectiveness, ease of construction, and minimal maintenance requirements. These structures depend on reinforced soil to achieve earth retention. While the general use of MSE walls is well understood, accommodating utilities, particularly horizontal obstructions such as storm drains, culverts, and pressurized pipelines, within or beneath the reinforced soil zone, remains a significant challenge because of the risk of potential leaks and failures. Maintenance or repair often requires dismantling portions of the wall which is a costly and complex task. Different state Departments of Transportation (DOTs) have differing recommendations for the placement of horizontal obstructions. Some, like Texas and Virginia, prohibit utilities within the reinforced zone, while others, such as Florida, Kansas, and Nebraska, permit them under specific constraints. The lack of consensus among the DOTs highlights the need for a consistent and practical design approach. INDOT (2013) discourages placing utilities within the reinforced zone but allows exceptions under certain conditions (Section 410-5.01[06]). However, there is currently no guidance about how deep such utilities should be buried under the wall to avoid compromising the wall stability in the event of utility failure. A sudden failure of a pressurized pipe located beneath an MSE wall could jeopardize its foundation, potentially leading to settlement or overall instability. While burying the pipe deeper may reduce this risk, it could also increase construction and material costs. Therefore, it is essential to determine the optimal depth for placing utilities that balances safety and cost. This research has the following major objectives: (1) establish permissible locations of utilities, including allowable depths, within the reinforced soil or underneath the MSE wall; (2) recommend design strategies for minimizing disturbances to MSE walls in the event of utility failures; and (3) recommend best practices for repairing, maintaining, and replacing utilities underneath and within MSE wall structures. This is done through an extensive literature review and a comprehensive series of numerical experiments using, as a reference, an actual MSE wall in Indiana, where a pipe is placed either inside the reinforced soil or in the foundation soil, at different locations inside the wall or under the wall, or parallel or at an angle with the facing of the wall. Different pipe sizes are investigated.

### Findings

1. The case studies reviewed show that pipes eventually leak and may cause distress in the wall. Problems associated with utility damage or failure are usually detected when the damage to the wall is extensive, in which case wall repairs are considerable,

costly, and time consuming, often requiring the dismantling and rebuilding of the wall.

2. A review of the current practice of horizontal obstructions within MSE walls, which included Federal Highway Administration, as well as the state DOTs in California, Florida, Illinois, Iowa, Kansas, Michigan, New York, Ohio, Texas, and Wisconsin, revealed that there are no consistent guidelines among the different DOTs.
3. The presence of a pipe in the soil reinforcement, parallel to the face of the wall, significantly influences the behavior of the reinforcement. Axial forces increase, especially in the reinforcement directly beneath the pipe. Such an increased demand is more pronounced when the pipe is positioned deeper inside the reinforced soil and away from the wall's face. Axial displacements of the reinforcement also increase, particularly of the reinforcement directly above the pipe, with the greatest displacement occurring when the pipe is near the bottom of the wall. Additionally, the pipe induces a substantial increase of slip between the reinforcement and the surrounding soil, particularly in the reinforcement near the pipe, due to increased mobilization of friction between soil and reinforcement. These effects are localized around the pipe and extend to a distance of about 2–2.5 times the pipe's diameter. The global stability of the MSE wall is not much affected by the presence of the pipe.
4. A pipe larger than the reinforcement spacing may increase axial forces in the reinforcement adjacent to the pipe by 60%, compared to the case with no pipe. The largest increase occurs in the reinforcement below the pipe.
5. Pipes intersecting the MSE wall perpendicular or at a small angle with the normal to the wall facing do not have a detrimental effect on the wall performance. The axial force in the reinforcement near the pipe is reduced, but such positive influence decreases with distance from the pipe. At about 2–2.5 pipe diameters, the influence of the pipe disappears. These positive effects are associated with the (large) frictional resistance that the pipe provides along its circumference, thus working as a reinforcement having a large frictional/contact area with the reinforced soil.
6. A pipe in the foundation of the MSE wall parallel to the wall may lead to higher forces in the reinforcement, most prominently in the bottom reinforcement. The global stability of the wall is not affected.
7. A pipe in the foundation soil at an angle with the normal to the wall face mostly affects the first layer of reinforcement by decreasing the axial force up to 20%. As the pipe is positioned deeper into the foundation soil, its influence further diminishes. The pipe positively impacted the overall stability of the wall by only 1 to 2%.
8. For MSE walls up to 25 ft tall, the collapse of a pipe in the foundation soil, with a diameter larger than 36 in., does not affect the performance of the wall, as long as the pipe is placed beneath the wall at a depth-to-radius ratio ( $h/r_o$ ) larger than 10, where  $h$  is the depth from the ground surface to the center of the pipe and  $r_o$  is the radius of the pipe. For walls between 25–40 ft, the ratio should be at least 11. It is important to note that these results apply to the type and geometry of the wall investigated and to the three types of soils considered in the foundation: sand, silty clay, and loam. This recommendation may not apply to pipes smaller than 36 in. in diameter. Case-specific studies will be required for these cases. Also, the recommendations are based on the mechanical failure of the pipe while the soil properties around the pipe remain unaffected; thus, associated issues, such as soil softening, have not been considered.

9. There are no proven monitoring techniques to detect leaks in buried pipes. A number of methods show promise, but they have been tested only in the laboratory. It is possible that with further developments, they may eventually be applicable to the field. Those methods include fiber optic sensors for temperature and acoustic sensing, infrared photography, time-domain reflectometry, and ground-penetrating radar. These methods can detect both water and gas leaks and even anticipate structural failures.
10. There are no proven techniques, methods or strategies to prevent or at least mitigate the failure of a pipe underneath an MSE wall. The literature is very scarce on such a problem. However, based on the information collected, there are several approaches that show potential, namely:
  - a. Double-wall containment systems where an outer pipe is placed to contain any leaks; the annular space between the two pipes may be used to install sensors to detect leaks.
  - b. Protective reinforced concrete slabs above the pipe to redistribute loads in the soil, thus shielding the MSE wall above.
  - c. Encasing the pipe in reinforced concrete to minimize degradation of the performance of the pipe because of, for example, corrosion or differential settlements.
  - d. Deep burial of the pipe to minimize the consequences of the pipe failure with the MSE.

### Implementation

Based on the work done, the following recommendations for implementation are made:

1. It is highly recommended that utilities are placed outside the reinforced zone of any MSE wall. This solution would not affect the reinforced soil, and any repairs, while still potentially disruptive, would not require dismantling the wall.
2. If utilities cannot be placed outside the reinforced zone, a case-specific design should be completed to ensure that the reinforcement has an adequate factor of safety and that the presence of the utility does not have detrimental effects on the overall performance of the wall, including its global factor of safety and tolerable deformations. If the pipe diameter is larger than the reinforcement spacing, the reinforcement must splay around the pipe with a maximum angle of  $15^\circ$ .
3. Utilities with diameters larger than 36 in., placed under MSE walls, should be located at a  $h/r_o$  ratio of at least 10 for walls up to 25 ft high, and 11 for walls up to 40 ft (where  $h$  is the distance between the natural ground surface and the center of the pipe and  $r_o$  is the radius of the pipe). The recommendation applies to the foundation soils investigated, namely sand, silty clay, and loam, and to the mechanical properties chosen for the analyses. Nevertheless, it is strongly recommended that a case-by-case design analysis is undertaken that includes all the pertinent information for each case.
4. When placing the utility at depths larger than  $h/r_o = 10-11$  is not feasible, protective systems should be considered, such as reinforced concrete slab(s) above the pipe, encasing the pipe in reinforced concrete and/or any other measures to protect the pipe and the wall.
5. There are no established or proven techniques or methods to monitor the performance of pipes buried inside or underneath MSE walls. It is recommended that further studies be conducted to develop new methods to monitor and protect the pipes. Those may require laboratory tests to develop a proof of concept and field implementation to assess the adequacy of the methods in the field.

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# 1. INTRODUCTION

## 1.1 Importance of the Research

Mechanically stabilized earth (MSE) walls are complex earthen structures that use reinforced soil to provide support. MSE wall usage has been well established at the Indiana Department of Transportation (INDOT), but accommodating underground utilities around them has been found challenging.

Obstructions within the reinforced soil mass can be classified into: (1) vertical and (2) horizontal obstructions. Vertical obstructions are structures or elements that are placed vertically through the reinforced volume of soil. Those include drilled or driven pile foundations, drainage water inlets, roadway sign structures, utilities poles, and more. Horizontal obstructions include those elements or structures that are placed horizontally through the reinforced volume of soil or under the wall and have a substantial length along the wall. Those include drainage pipes and culverts as well as utilities such as pressurized water, gas, and electricity. The focus of the report is on horizontal obstructions (the terms utility and horizontal obstruction are used interchangeably in the following).

Placing utilities through the MSE wall reinforced soil should generally be avoided because maintenance and repairs to such utilities can be extremely expensive and may require dismantling the wall. INDOT (2013) states “Utilities should not be placed through the reinforced zone. Where utility placement in the reinforced zone is unavoidable, future access must be provided to the utility without disrupting the reinforcement. The breakage or rupture of the utility must not have a detrimental effect on the stability of the MSE wall” (Section 410-5.01[06], p. 28). However, project-specific constraints on many INDOT contracts (e.g., right of way) have resulted in utility location through MSE walls. INDOT still allows for the placement of storm water sewer and culverts through MSE wall reinforced soil zones, but not pressurized pipes (e.g., water mains, natural gas lines), which may only

be placed underneath. Indeed, a burst water main, for example, passing through an MSE wall–reinforced soil zone would suddenly inundate the MSE wall causing a very probable catastrophic failure.

The issues of whether utilities should be allowed inside the reinforced volume of soil, or underneath the MSE wall and, if so, under what conditions, have not been resolved. Further, there is no consensus among the states’ Departments of Transportation (DOTs) regarding the problem of placing utilities inside or underneath MSE walls. For example, current practice at the Texas Department of Transportation (TxDOT) does not allow any horizontal obstructions within the reinforced fill, and so all utilities should be relocated away from the wall (Jayawickrama et al., 2017). This is also the case for Virginia Department of Transportation (VDOT, 2025), which states a “wall system may not be appropriate for applications: (1) where it may be necessary to gain future access to underground utilities; (2) at locations subject to scour; or (3) involving significant horizontal curvature” (p. 55).

However, other DOTs, such as Florida (FDOT; Passe, 2000) and Kansas (KDOT), allow horizontal obstructions within the reinforced soil but limit the deviation from horizontal of the reinforcement and prescribe minimum distances from the face of the wall (Figure 1.1). Other DOTs, such as Iowa DOT, have wording similar to that of INDOT. Others are more permissible, such as Nebraska DOT, which allows horizontal obstructions as long as those are accounted for in the stability of the MSE wall. The Federal Highway Administration (FHWA, 2009), states, “The current AASHTO [American Association of State Highway and Transportation Officials] LRFD [load and resistance factor design] Specifications (2007) states that MSE walls should not be used under the following conditions: When utilities other than highway drainage must be constructed within the reinforced zone where future access for repair would require the reinforcement layers to be cut” (pp. 2–38).

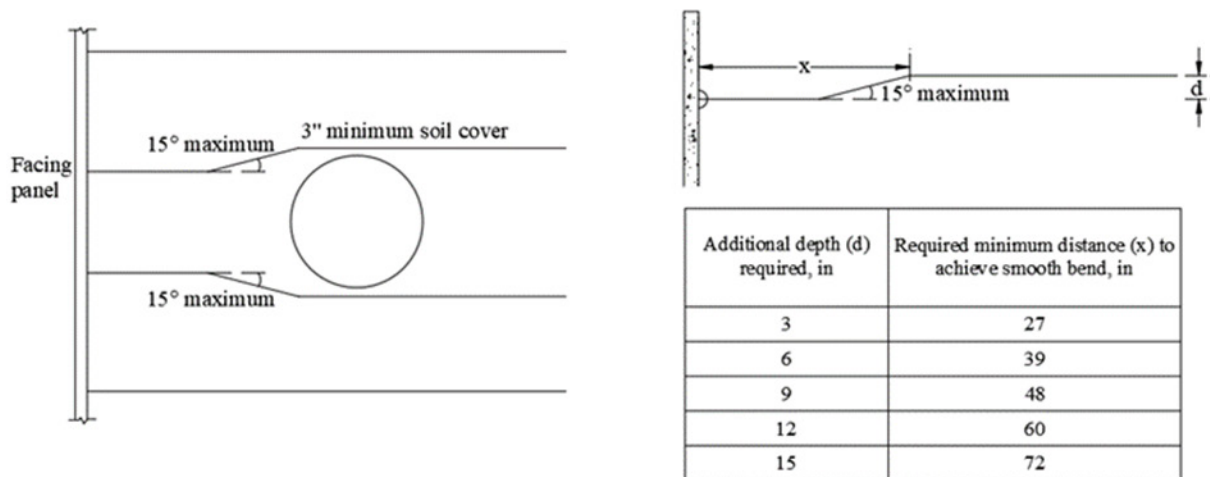


Figure 1.1 Requirements for Horizontal Obstructions Within the Reinforced Soil Mass (Redrawn From FHWA, 2009).

Strategic placement of utilities reduces the severity of catastrophic MSE wall failures, but such practice does not make MSE walls entirely immune to utility failures. If a pressurized pipe underlying an MSE wall suddenly fails, then the MSE wall foundation could become compromised leading to an external stability failure of the wall (e.g., settlement, bearing capacity, global stability, etc.). A preventative solution could be to bury the pipe deeper, but INDOT engineers have no guidance for permissible depths for pressurized pipes or other utilities/horizontal obstructions to circumvent potential disturbances to MSE walls. Moreover, the deeper the pipes are placed, the more expensive the costs of both construction (i.e., deeper trenches requiring bracing) and materials (i.e., thicker-walled pipe to resist greater in situ earth pressures).

Therefore, an optimum range of permissible depths for utilities below MSE walls needs to be determined. In addition, strategies for protecting MSE walls from utility failures need to be developed for when project constraints require that utilities be placed shallower than the determined permissible depth. The report addresses these issues and provides INDOT with criteria regarding the optimum location of utilities/horizontal obstructions within or underneath MSE walls and what strategies for protection and maintenance are best suited for each type of utility. More specifically, this report addresses the following:

1. Impact of the location of utilities within the reinforced soil or underneath the MSE wall on the stability of the MSE wall.
2. Determine the minimum depth under an MSE wall of utilities such that their failure does not compromise the stability and performance of the MSE wall.
3. Provide design strategies for minimizing disturbances to MSE walls in the event of utility failures and recommend practices for repairing, maintaining, and replacing utilities underneath and within MSE wall structures.

## 1.2 Organization of the Report

In addition to the Introduction, this report also includes seven more chapters. Chapter 2 presents a review of the common problems encountered with MSE walls. It also includes a comprehensive literature review that underscores the problems associated with utilities placed inside or below MSE walls. Finally, the chapter summarizes previously suggested consequences of placing utilities within the footprint of the MSE wall.

Chapter 3 describes current practices and recommendations by DOTs and FHWA on the placement of utilities inside the reinforced soil of the MSE wall.

Chapter 4 presents results from numerical models for a number of cases where a pipe is placed parallel to the wall. The chapter covers the material properties, mesh discretization, and provides information about the different cases investigated: pipe location inside the wall or underneath the wall, pipe size and reinforcement properties and spacing.

Chapter 5 presents the methodology and results of three-dimensional (3D) numerical models of MSE walls with a pipe running perpendicular to the wall or at an angle.

Chapter 6 discusses the minimum safe burial depth of utilities that run parallel to the wall such that in the case of pipe collapse, the impact on the safety and performance of the MSE wall is negligible.

Chapter 7 summarizes a literature review regarding the methods reported to predict leaks on buried pipes and provides suggestions to prevent or at least mitigate the impact to the MSE wall when the utility is damaged.

Chapter 8 includes a summary of the work done, conclusions, and recommendations for implementation.

## 2. LITERATURE REVIEW

MSE walls are earth structures built by strengthening the backfill using reinforcement elements. The use of MSE wall has increased dramatically in the last few decades. It is used in bridge abutments, highway embankments, airport runways, and more. An MSE wall has several components such as backfill soil, facing panels, reinforcement, and a leveling pad, as shown in Figure 2.1. In MSE walls, the backfill is stabilized by reinforcement elements, which can be either steel strips or geogrids. The front face of the wall is connected with facing panels with a coping at the top of the panel, and the base of the wall is leveled by a leveling pad. To control the drainage of the wall, utility drains may be installed near the face of the wall.

The chapter provides a review of case histories found in the technical literature where horizontal obstructions were placed inside or underneath MSE walls and describes their detrimental consequences when the utilities malfunctioned. Figure 2.1 shows a utility placed inside the reinforced backfill of the wall.

The first section of the chapter lists the most common problems with MSE walls, based on professional or surveyor results. Section 2 defines utility obstructions and describes utility issues that lead to MSE walls becoming nonoperational or to their failure. Section 3 lists the potential problems associated with failure of utilities inside the walls and includes case studies found in the literature as well as the solutions adopted to correct the problem. Finally, Section 4 includes a discussion of the issues encountered with utilities inside MSE walls.

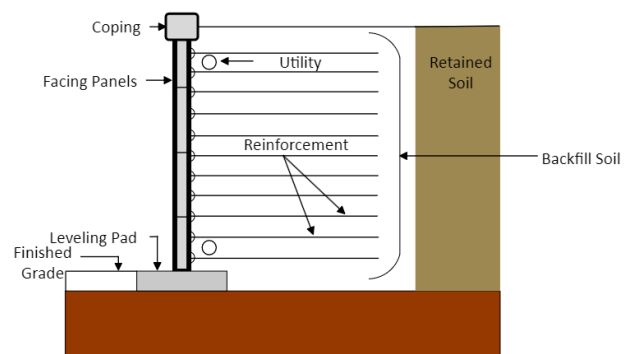


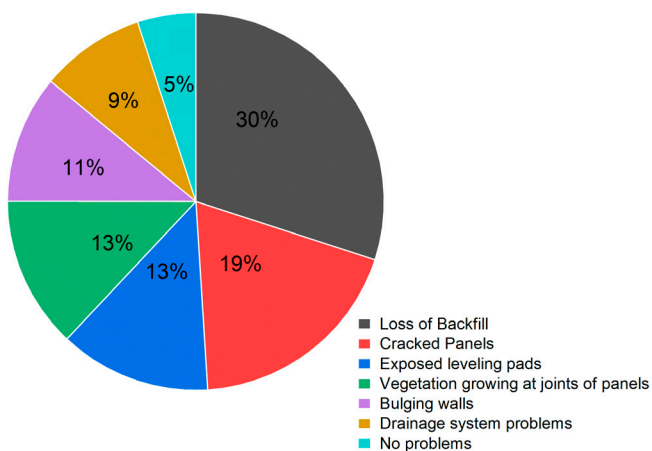
Figure 2.1 MSE Wall.

## 2.1 Common Problems Encountered With MSE Walls

This section describes inspection results of MSE walls and highlights the most common problems observed. Tarawneh et al. (2017) carried out an inspection program in which 339 MSE walls were evaluated. Figure 2.2 shows the problems encountered, together with their frequency. The most critical issue was loss of fill material from the joints of facing panels. This problem was considered as a major concern, given that excessive loss of soil can cause significant deformation of the backfill. Other problems detected included: cracked panels, vegetation at the panel joints, seepage through the panel joints, exposed leveling pads, and bowled or bulging joints.

Tarawneh et al. (2017) also described that cracked panels were reported in 19% of the walls. Cracking was often caused by bulging of the walls and differential settlement. Also, vegetation in the panel joints can cause cracking of the facing panels, and its growth is due to the continuous availability of moisture. Vegetation in the joints was reported in 13% of the walls. Infiltration or seepage water may erode the leveling pad and may ultimately cause stability problems. This problem was reported in 13% of the walls. Bowled or bulging walls are a serviceability problem and could be associated with the failure of the reinforcement connection. The problem was found in 11% of the walls. About 9% of the walls were found to have poor drainage. Only 5% of the 339 walls inspected had no problems.

Another survey (Clemente et al., 2016) was carried out by 20 professionals with experience in the design and construction of more than 10,000 MSE walls in the last 20 years. Most respondents were from the United States. The experts identified several problems, which are listed in Table 2.1. Drainage was considered the primary concern, listed by 44% of the respondents, for drainage not functioning properly. Communication and quality control and assurance were ranked as the second concern according to 33% of the respondents. The other problems listed are important but are directly or indirectly related to the primary and secondary concerns. Site characteristics and backfill, which attracts attention of only 22% of the respondents, mostly relate



**Figure 2.2** Outcomes of the Inspection Program (Adapted from Tarawneh et al., 2017).

**TABLE 2.1**  
**Problems in MSE Walls and Survey Results (Data Source: Tarawneh et al., 2017).**

Rank	Cause	Percentage of Survey Respondents
1	Drainage	44
2	Communication	33
2	CQC/CQA	33
4	Site Characteristics	22
4	Backfill	22
6	Bearing Capacity	17
6	Settlement	17
6	Poor/inexperienced designer	17
9	Internal Stability	11
9	External stability	11
9	Compaction	11
9	Seismic issues	11
13	Poor Specifications	6

to the soil properties. All other problems, namely bearing capacity, settlement, inexperienced designer, stability, and more, were addressed by less than 20% of participants; therefore, these factors/causes are less severe to the wall in comparison to the other issues.

## 2.2 Utility Obstructions

Utilities become obstructions when placed in the reinforced zone of the soil mass. The obstructions can be vertical or horizontal. Vertical utilities include pile foundations, roadway sign structures, utility poles, and more. Horizontal utilities in the MSE wall can be drainage pipes, pressurized water or gas pipes, culverts, and so on. Sometimes, utilities adjacent to the facing panel within the MSE wall can lead to wall deformation due to leakage. MSE walls may intersect a number of utilities and those may be placed over a substantial length inside of the wall. In some cases, large-diameter utilities may hinder the placement of the reinforcement and may require a special arrangement, such as bending or changing the spacing of the reinforcement around them (Hutchinson, 2022).

## 2.3 Issues With Utilities Inside MSE Walls

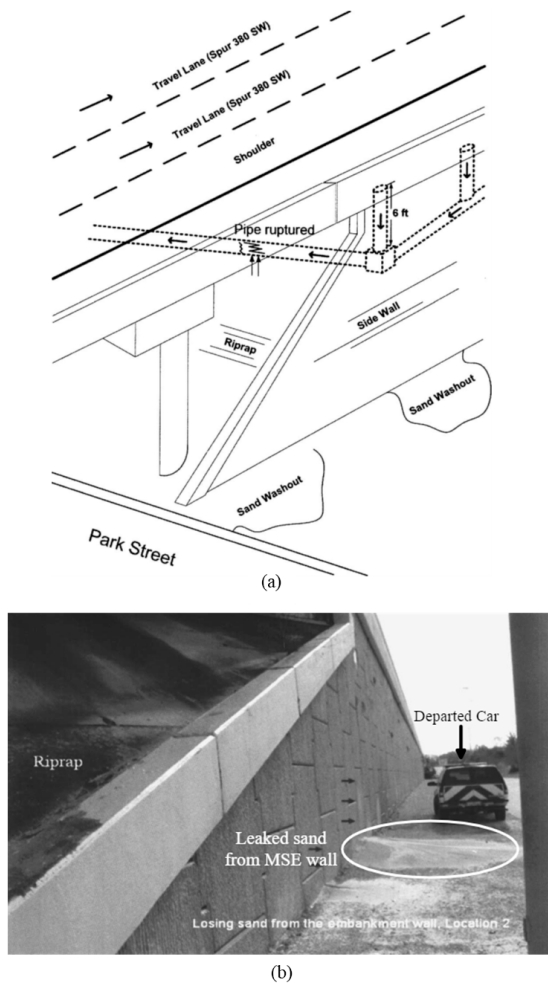
Utility failure, damaged parts, and maintenance are the major challenges in MSE walls. In many cases, utility malfunction has led to serious consequences such as failure of the wall. The following are the common reasons for utility failure:

1. Loss of backfill material
2. MSE wall differential settlement
3. Choking and clogging of utility drains
4. Corrosion of utilities
5. Deformation or cracks in the wall facing
6. Settlement of the underlain/foundation layer

### 2.3.1 Loss of Backfill Material

Loss of backfill is the result of leakage of soil inside the MSE wall due to water. When there is substantial water seepage inside the MSE wall, coarse-grained particles may be mobilized, which leads to internal erosion. A number of field cases reported in the literature illustrate the problem.

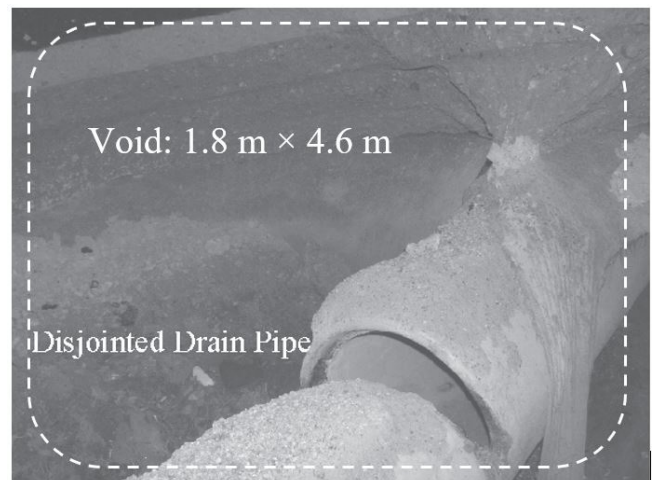
Figure 2.3a shows the drainage system in an MSE wall section at the intersection of Park Street and Spur 380 southwest-bound in Beaumont, Texas. A polyvinyl chloride (PVC) pipe was placed in the backfill that collected water from multiple inlets. It ruptured at the location shown in Figure 2.3a. A test was conducted to check the pipe for leakage. Water pumped from the inlet fell on the riprap due to ruptured pipe water and entered into the MSE wall from a gap of 50 mm between MSE wall and the side wall. The fabric filter required to prevent the leakage of fine sand ruptured. It is reported that the massive inflow of water led to a significant loss of backfill material (Figure 2.3b), causing the formation of soil mounds near the face of the wall (D.-H. Chen et al., 2007).



**Figure 2.3** MSE Wall at Park Street (a) Ruptured Pipe and (b) Leaking Sand Due to Utility Pipe Leakage (Adapted From D.-H. Chen et al., 2007).

Leaking of disjointed utility pipes can be catastrophic, if not detected. TxDOT reported a case of disjointed gravity water pipes in an MSE wall at US 290 in southwest Austin. The TxDOT personnel observed a crack on the pavement and performed an inspection using Ground Coupled Penetrating Radar (GCPR). The GCPR indicated the presence of a void underneath the pavement. Also coring detected a large (1.8 × 4.6 × 3.7 m) cavity under the pavement. Figure 2.4 shows the size of the void and the disjointed drain pipe. The joint in the pipe failed and the water leaked and washed out the backfill, resulting in a large cavity around the pipe. The formation of the void impacted the pavement, which caused the cracking observed on the surface. Fortunately, the problem was discovered before the safety of the MSE wall was compromised (D.-H. Chen et al., 2012).

TxDOT carried out another inspection of an MSE wall in the Amarillo district because several transverse cracks appeared on the pavement, and deposits of fine sand were reported adjacent to the wall, as shown in Figure 2.5. While GCPR did



**Figure 2.4** Loss of Backfill Due to Disjointed Pipe (Adapted From D.-H. Chen et al., 2012).



**Figure 2.5** Leaking Sand From MSE Wall Due to Water Seepage (Adapted From D.-H. Chen et al., 2007).



**Figure 2.6** Pavement Collapse Due to Internal Erosion of MSE Backfill (Adapted From Kara & Tahoun, 2020).

not detect any voids under the pavement, it was thought that the damage was the result of an early stage of pipe leakage (D.-H. Chen et al., 2007).

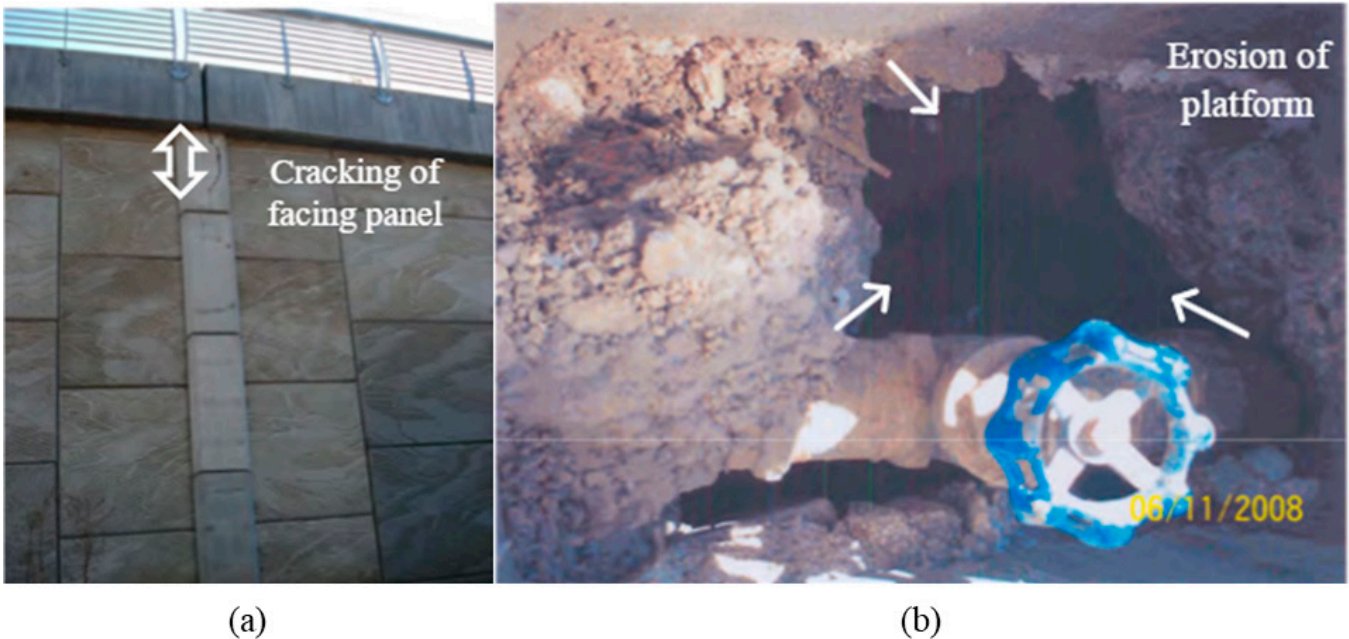
An MSE wall near a multilevel interchange located in a very congested traffic zone in Doha, Qatar, was built using loose sand. Due to the long-term continuous presence of water inside the backfill coming from drainage and storm pipes, the sand in the backfill was mobilized, internal erosion occurred, and a cavity formed within the backfill. The cavity then caused the collapse of the pavement near the wall, as shown in Figure 2.6 (Kara & Tahoun, 2020).

### 2.3.2 MSE Wall Differential Settlement

Occasionally, water leakage from utilities adjacent to an MSE wall leads to erosion of the wall base or consolidation of the foundation soil, which in turn induces differential settlements of the MSE wall leveling pad. Differential settlement is the phenomenon where nonuniform vertical displacement of multiple sections of the wall. Lee et al. (2013) conducted a study to observe the wall deformations because of leakage in an irrigation pipe. In 2004, a back-to-back MSE wall was constructed in Santa Clara, California, near Hamilton Avenue adjacent to the rail track. After construction, the wall experienced continuous settlement and lateral deformation, which required regular maintenance. The movements caused cracking of the facing panels, as shown in Figure 2.7a. In June 2008, it was found that a buried irrigation water pipeline valve was leaking which was the cause of the internal erosion, as shown in Figure 2.7b. The differential settlement between the two back-to-back walls was 48–100 mm (Lee et al., 2013).

### 2.3.3 Choking and Clogging of Utility Drains

Utility drains are designed to facilitate the flow of storm water. However, when debris is continuously deposited inside the drains, it may cause choking and clogging and, eventually, failure of the utility. Choking and clogging results in an overflow of water which may run through the face of the MSE and infiltrate into the backfill. As with previous cases discussed, the water seepage may mobilize the grains of the backfill soil or degrade its mechanical properties, which can result in failure of the wall structure.



**Figure 2.7** MSE Wall in Santa Clara, California Displaying (a) Cracking of Face Panel and (b) Internal Erosion Due to a Leaky Valve (Adapted From Lee et al., 2013).



**Figure 2.8** MSE Wall in Tucson, Arizona Displaying (a) Overflow of Water and Debris on the MSE Wall and (b) Failure Section of the MSE Wall (Adapted From Haramy et al., 2010).

Haramy et al. (2010) describe a 25-mi-long highway connected the Santa Catalina Mountain range with Mount Lemmon, in Tucson, Arizona. The highway had a 350,000 sqft MSE wall. The wall contained utility pipes and had a corrugated metal pipe culvert to discharge storm water. In June 2003, the Aspen Fire, a wild forest fire, burned the Coronado National Forest near General Hitchcock Highway. The fire was followed by heavy rainfall in 2006 (a 1000-year storm), leading to erosion of the surrounding ground and to debris flow. The combination of these two events caused the utility drains and culvert to clog. As a result, water started to overflow the road and the wall as shown in Figure 2.8a. Figure 2.8b shows the collapse of the wall as a result of the overflow due to erosion and increased water content of the fill inside the wall (Haramy et al., 2010).

### 2.3.4 Corrosion of Utilities

A corrosive embankment or corrosive stormwater can cause deterioration of metal utility pipes. Corrosion of water pipes may create leaks, which, in turn, may cause corrosion

of metallic structural elements of MSE walls. Components such as metal strips, connections, and even the pipes themselves can be subject to corrosion. Several cases of leaking utilities due to corrosion have been reported in the literature. For example, failure of the facing panels of the MSE wall on Idaho State Highway 34 occurred due to corrosion of the reinforcement approximately 45 m from the bridge abutment along the southwest approach section on July 9, 2002 (Figure 2.9). The soil used for the wall was loose- to medium-dense silty sand and was highly alkaline with a low permeability (Armour et al., 2004), which was thought to have contributed to the corrosion.

Another example of corrosion is the explosion of a natural gas conduit in Sissonville, West Virginia, on December 11, 2012 (Figure 2.10; National Transportation Safety Board [NTSB], 2014). The gas pipeline was buried in an embankment. Corrosion of the pipe caused leakage of natural gas leading to the explosion and damage of three houses and several residences nearby (NTSB, 2014).



**Figure 2.9** MSE Wall on Idaho State Highway 34. Panel Failure Due to Corrosion of Reinforcement (Adapted From Armour et al., 2004).



**Figure 2.10** Exploded Buried Pipeline Sissonville, West Virginia (Source: NTSB, 2014).

### 2.3.5 Deformation or Cracks on the Wall Face

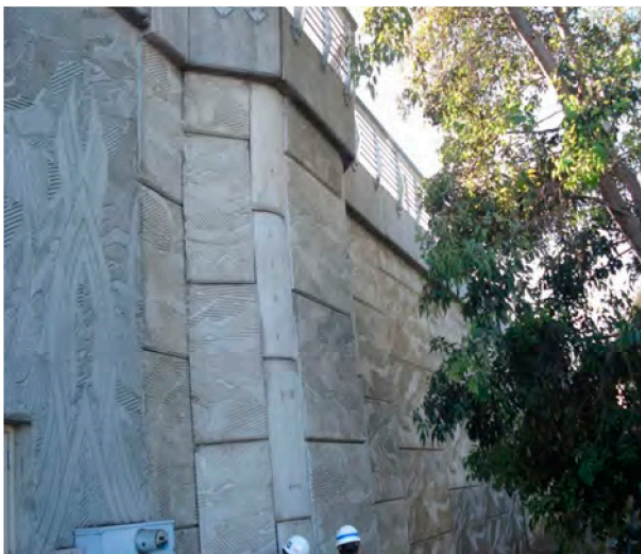
Deformation or cracks on the wall face can occur due to an increase of the force acting on the wall. Such an increase may be caused by seepage of water into the wall or because of the weight of utility pipes or conduits. An increase in pressure causes bulging of the wall, followed by cracking.

For example, the leakage of an irrigation pipe adjacent to an MSE wall in Santa Clara, California, caused the seepage of water into the MSE wall, which caused an increase of the pressure acting on the wall (Lee et al., 2013). This caused the wall to deform, as shown in (Figure 2.11).

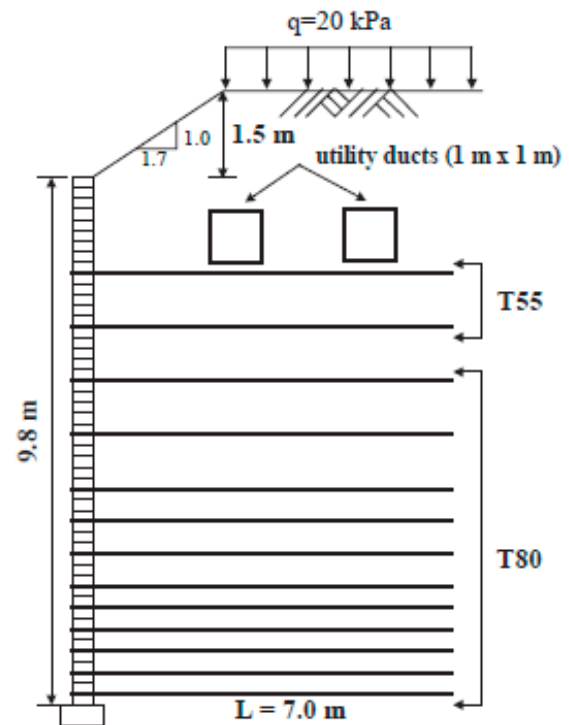
Yoo (2004) provides another example—a segmental retaining wall of approximately 300 m in length at a chemical processing plant in South Korea. The east wall was constructed with two utility ducts above the reinforced zone, with dimensions  $1 \times 1$  m. They were installed along the length of the wall (Figure 2.12). There were no measures taken in the design to protect the unreinforced zone of the wall. Six years after construction, the wall next to the ducts experienced excessive bulging. The reason for the deformations was poor construction and excess rainfall during construction of the ducts. The wall section was dismantled and reconstructed (Yoo, 2004).

### 2.3.6 Settlement of the Underlain/Foundation Layer

When the foundation of an MSE wall consolidates significantly, any intersecting utilities may experience large deformations. On Highway 87 in Santa Clara Valley, downtown San Jose, California, near the intersection of Mission Street and Guadalupe River, an MSE wall was placed on top of a thick, highly plastic and compressible clay (Hook et al., 2006). A low-pressure gravity pipe (approximately 5 psi) below the wall leaked due to excessive deformations. On 18 January 2005, during a routine inspection, it was found that the pipe was



**Figure 2.11** Deformation of the MSE Wall in Santa Clara, California. (Source: Lee et al., 2013).



**Figure 2.12** Untied Utility Ducts (Source: Yoo, 2004).

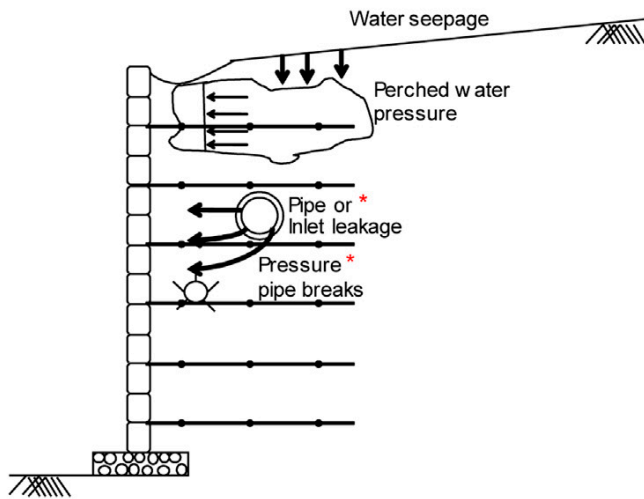


**Figure 2.13** Leakage and Joint Rotation Adjacent to the MSE Wall at Highway 87 in Santa Clara Valley (Source: Hook et al., 2006).

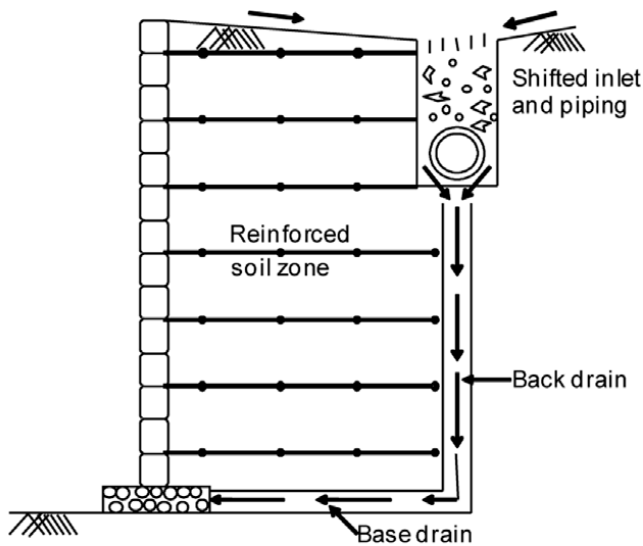
leaking. The water leak led to consolidation of the underlain layer, which caused a rotation of two concrete blocks supporting the pipe. Excavation was required to repair the pipe, and the pipe was shut down for four weeks. Figure 2.13 shows the repair of one of the deformed blocks. The total cost of the investigation and repair was about \$270,000 (Hook et al., 2006).

## 2.4 Discussion

An analysis of 320 failed MSE walls was done by Koerner and Koerner (2018). They found that 114 walls, or 37% of all the walls investigated, failed due to water problems that included pipe or inlet leakage, breakage of pressure pipes, water seepage



**Figure 2.14** Problems Due to Internal Water Leakage (Source: Koerner & Koerner, 2018).



**Figure 2.15** Placement of Water Utilities in MSE Wall, Accompanied by Back Drain (Source: Koerner & Koerner, 2013).

into the wall, and pressure from perched water due to the water trapped in clay/silty backfill. Figure 2.14 shows the different sources of water in the MSE walls that can lead to problems.

Koerner and Koerner (2013) mention that placing water inlets or pipes within the reinforced zone is poor practice. This is consistent with the case studies reviewed showing that placement of utility pipes and ducts within the reinforced zone led to excessive wall deformations (Yoo, 2004). Koerner and Koerner (2013) proposed the solution (Figure 2.15)—water utilities should be located outside the reinforced soil zone. Note that the solution includes a back drain to safely direct any leakage outside the wall.

Given the number of cases described, it seems obvious that utilities will eventually leak (e.g., corrosion, joints, cracking,

etc.). In many, if not all cases, the problem was detected when significant distress of the wall itself or of the pavement was observed. In all cases, repairs required excavation of the wall backfill or demolition of the wall. That is, the potential consequences of utility leakage are severe, and repairs are costly and require significant and lengthy disruption of service.

### 3. RECOMMENDATIONS FROM DOTs

The United States has regulations developed by FHWA and state DOTs. For the purposes of this study, in addition to FHWA guidelines, the DOTs of Texas (TxDOT), California (Caltrans), Florida (FDOT), and Michigan (MDOT) are discussed because of the size of their states and extensive investment in research. In addition, the DOTs of Illinois (IDOT), Kansas (KDOT), Ohio (ODOT), Iowa (Iowa DOT), Michigan (MDOT), and Wisconsin (WisDOT) are also included because they have weather, soil types, contractors, and more similar to those of Indiana.

#### 3.1 FHWA Guidelines

FHWA (2009) recommends avoiding the placement of any horizontal obstruction within the reinforced zone of the soil mass because repairing the utilities in this location would require an expensive dismantling of the wall. In addition, pressurized water mains are not to be placed within the reinforced zone of the MSE wall, nor should the reinforcement be tied to utility pipes.

Because MSE walls are likely to settle, utilities may leak. FHWA (2009) suggests that utilities should be placed using a double wall with inspection galleries. Flexible connections should also be used to avoid the down drag stresses on pipes and joints. FHWA (2009) also recommends:

1. For inextensible reinforcement, a minimum cover of 3 in. should be provided;
2. Reinforcement should not bend more than 15°;
3. Utility pipes should be placed at a depth,  $d$ , to achieve a smooth reinforcement bend (Figure 3.1);
4. For extensible reinforcement, a minimum cover of 3 in. should exist between geogrid and pipe, and each affected geogrid segment should be spaced equally at a distance of at least 3 in. (Figure 3.2); and
5. The minimum length to bend the reinforcement should be equal to the pipe diameter, measured from the center of the pipe to each side (Figure 3.2).

#### 3.2 DOT Guidelines

The following provides a summary of the recommendations and best practices of the following Caltrans, FDOT, IDOT, Iowa DOT, KDOT, MDOT, New York State DOT (NYSDOT), ODOT, TxDOT, and WisDOT.

- Caltrans (2021) requires reporting the effects of intersecting utilities with the MSE walls. The placement of the utilities in the reinforced zone of the wall is considered as nonstandard design.
- FDOT (Passe, 2000) allows placing the utility in the MSE wall and recommends a minimum pipe cover of 4 in. If the reinforcement

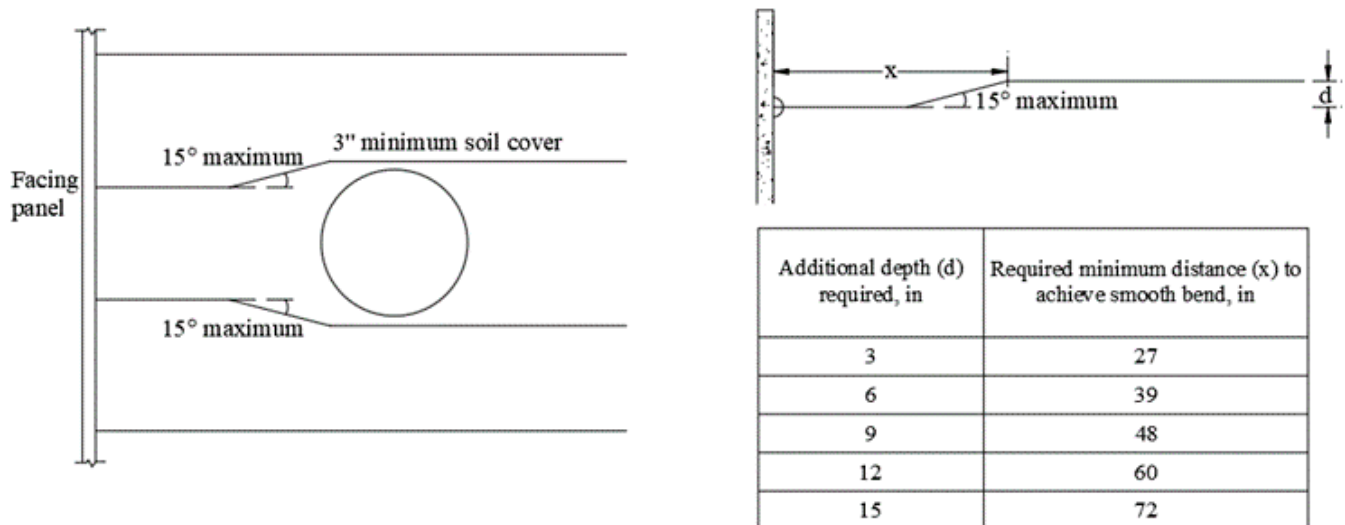


Figure 3.1 FHWA Guidelines for Inextensible Reinforcement (Redrawn From FHWA, 2009).

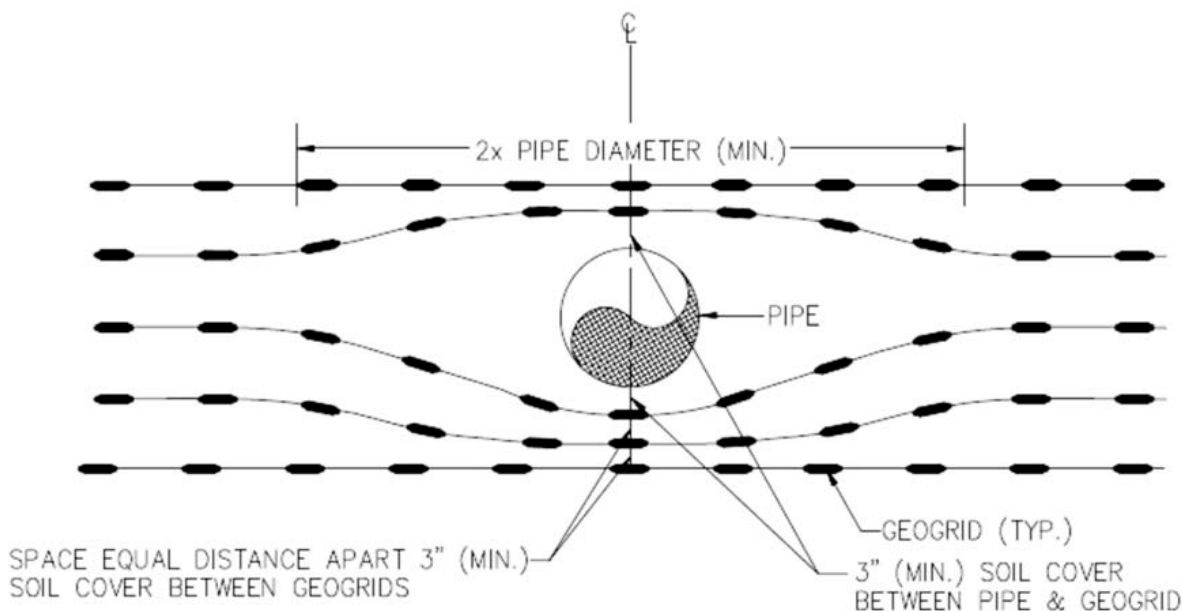


Figure 3.2 FHWA Guidelines for Extensible Reinforcement (Source: FHWA, 2009).

bend is more than 15° with the horizontal, the special design is required by the wall design engineer and supplier.

- IDOT, NYSDOT, and WisDOT do not have information about the placement of utilities in the reinforced zones of the wall.
- Iowa DOT (2014) allows the placement of utilities in the MSE wall and suggests being careful when utility lines are constructed. In addition, these utility lines must not disrupt the reinforcement of the wall.
- KDOT (n.d.) has guidelines similar to those of FDOT. The guidelines recommend not placing horizontal obstructions within the reinforced wall. In cases where placing a utility inside the wall cannot be avoided, the soil reinforcement should be smoothly cleared around obstructions. Further, when these recommendations cannot be met, then the wall supplier should be contacted.
- MDOT (2023) suggests providing an adequate spacing of the reinforcement around utilities, and reinforcement has a maximum splay angle, or the angle required to achieve a smooth transition around utility, of 15°.
- ODOT (n.d.) has similar guidelines to FDOT, in that the utility should have a minimum cover of 4 in. and a maximum splay angle of 15°.
- TxDOT (Jayawickrama et al., 2017) requires that horizontal obstructions be located outside the reinforced zone of the wall. This recommendation leads to infrequent obstructions. If the utility cannot be placed outside the reinforced soil zone, the new reinforcement layout should give the same or higher pullout capacity as the original design, that is, without the utility (Jayawickrama et al., 2017).

TABLE 3.1  
Transition Distance (FDOT, 2000; KDOT, n.d.; ODOT, n.d.).

Offset Distance (d)	Recommended Transition Distance (X)
0–3.99 in.	2'–0"
4–5.99 in.	2'–3'
6–7.99 in.	2'–7"
8–9.99 in.	3'–3"
10–11.99 in.	4'–0"
12–4.99 in.	5'–0"
15–17.00 in.	6'–0"

TABLE 3.2  
Guidelines of the DOTs.

Department of Transportation	Utilities Within Reinforced Zone	Minimum Cover to the Utility Pipes (in.)	Maximum Tilting Angle of the Reinforcement (°)
California	Nonstandard design	-	-
Florida	Allowed	4	15
Illinois	No information	-	-
Iowa	Do not disturb reinforcement	-	-
Kansas	Discouraged	4	15
Michigan	Allowed	Adequate clear spacing	15
New York	No information	-	-
Ohio	Allowed	4	15
Texas	Place utility outside reinforced zone	-	-
Wisconsin	No information	-	-

As one can see, KDOT, FDOT, and ODOT have different reinforcement transition distances than FHWA, as defined in Figure 3.1a. Table 3.1 lists the requirements from those DOTs. In all cases, the minimum cover of the utility pipes is 4 in., higher than the FHWA recommendation of 3 in.

Table 3.2 provides a summary of the standards from the different DOTs

The Federal and state guidelines have very limited information on the placement of utilities inside the reinforced soil of MSE walls. The FHWA and some DOTs provide somewhat clear specifications about reinforcement cover and transition distances between reinforcement and utility. However, this information is insufficient, and additional details such as the maximum or minimum depth allowed for the utility, the type of utility allowed, and the maximum diameter and horizontal location are lacking.

## 4. TWO-DIMENSIONAL NUMERICAL MODELING OF THE MSE WALL

### 4.1 Introduction

MSE walls are earth structures reinforced by either geosynthetics, metal strips, or others. This study explores the performance of an MSE wall with intersecting utilities. The utility

can be a gas pipe, culvert, drainage pipe, or another item. It may intersect the MSE wall at different depths, within the reinforced soil or under the wall's foundation. It can also intersect the MSE wall at different locations, either near the facing or away from the facing. Given that there are no standard guidelines about the placement of utility pipes within or under MSE walls, this study explores the interaction of a pipe with the MSE wall.

This chapter deals with a two-dimensional (2D) numerical model of the MSE wall with the utility pipe placed in the backfill and in the foundation. The first section of this chapter, Section 4.2, describes the model, material and input parameters for the numerical model and includes a pullout test of a metal strip to validate the numerical model. Section 4.3 describes the model results when a pipe is placed in the reinforced backfill. More specifically, it contains the following information regarding the effects of the pipe on the wall and its components: axial force, axial displacement, relative displacement, and yielding of the surrounding material due to the presence of the pipe. Section 4.4 contains information analogous to that in Section 4.3, but for a pipe located under the foundation of the wall. Section 4.5 describes model results of the pipe diameter is larger than the reinforcement spacing and encompasses information parallel to Section 4.3. Lastly, Section 4.6 summarizes the key findings from the numerical analyses.

### 4.2 2D Numerical Modeling

The software chosen for the simulations is PLAXIS 2D. This is a general-purpose Finite Element Method software that is used extensively in geotechnical engineering practice. One of the advantages of the code is that it has an extensive library of soil models and is capable of reproducing the stage construction process followed in practice.

The wall chosen for the simulations is based on a case study from INDOT (2019) and duplicates the geometry of a 7.62-m (25-ft) MSE wall built in Indiana that is intersected by a utility pipe. The simulations are done for the case of a circular pipe perpendicular to the cross-section of the wall. Thus, plane strain 2D simulations are performed. The pipe is located at different locations inside the wall to explore the effects of the presence of the pipe on the stability of the wall and on the reinforcement and on the reinforced fill. Figure 4.1 shows the schematic of the MSE wall with the utility pipes. The goal is to assess the impact of utility pipes intersecting the reinforced zone. Consequently, intersections can occur at various positions within the wall and with various diameters of the pipe. For the plane strain 2D simulation to comprehensively explore this, nine combinations were devised, involving placing the pipe at three distinct depths and, at each depth, at varying distances from the facing (Figure 4.1a–i). The pipe or culvert may also interact with the foundation soil, potentially intersecting the wall at different locations. Six scenarios resulting from the pipe intersecting the foundation soil were examined (Figure 4.1j–o). The pipe is positioned in front of the facing, behind the facing beneath the reinforced zone. Furthermore, all three scenarios were replicated with alterations in the pipe diameter. Figure 4.1p–s show the cases when a large

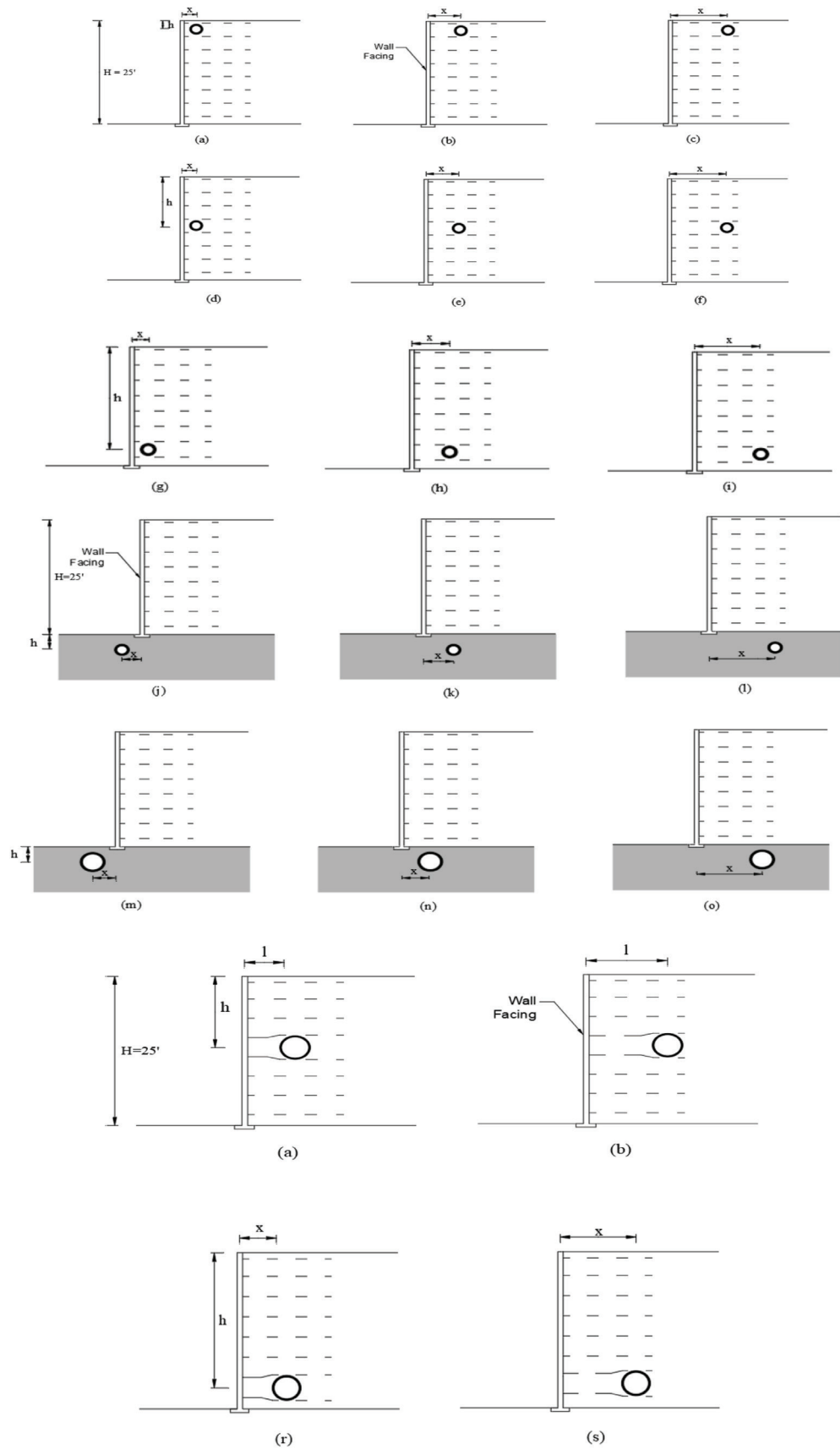


Figure 4.1 Schematic Diagrams of the MSE Wall With Utility.

pipe intersects the MSE wall in the reinforced zone. As discussed in Chapter 1, the DOTs' and FHWA's recommendations are to splay the reinforcement when the pipe diameter is larger than the reinforcement spacing. Following those recommendations, the pipe is placed at two different depths and at  $x$  distance behind the facing.

#### 4.2.1 Model Parameters

**4.2.1.1 Soil Materials.** The numerical model comprises three different soil materials: backfill, foundation, and retained soil. The soil for the backfill is a coarse-grained granular soil that it is recommended and used by INDOT (2022). All soils are modeled using the Mohr-Coulomb constitutive model with a nonassociated flow rule. The input properties of the soil are listed in Table 4.1. It is assumed, for simplicity, that the soil is uniform for the entire height of the wall. Thus, different compactions near the wall facing or around the pipe are ignored. Note that because the objective of the simulations is the investigation of a pipe in the reinforced soil, the foundation soil has given properties of a very stiff, strong soil. More realistic soil conditions for the material under the wall are explored in Section 4.4, where the effects of a pipe under the wall are explored.

**4.2.1.2 Concrete Panels and Utility Concrete Pipe.** The concrete facing panels are 1.5 m (4.92 ft) deep and 15 cm (6 in.) thick (FHWA 2009). The panels are modeled as plate elements using a linear elastic model. Their geometric properties and stiffness parameters are listed in Table 4.2. The panel is placed over the leveling pads which are 30 cm (11.8 in) wide and 15 cm (5.9 in) thick.

The utility pipe considered in the model is a concrete pipe. While other pipe materials such as metal or PVC could be used, the findings, excluding the specific internal stresses of the pipe, are representative of those obtained with other pipe types.

TABLE 4.1  
Input Soil Parameters (Following INDOT [2022] Case Study; Damians et al. [2021]).

Parameter	Value		
	Reinforced Soil	Retained Soil	Foundation Soil
Unit weight, $\gamma$	19.63 kN/m <sup>3</sup> (125 pcf)	18.85 kN/m <sup>3</sup> (120 pcf)	18.85 kN/m <sup>3</sup> (120 pcf)
Cohesion, $c$	0.10 kPa (0.01psi)	0.0 kPa (psi)	1000 kPa (145 psi)
Friction angle, $\phi$	34.0°	30.0°	0.0°
Elastic modulus, $E$	50 MPa (7252 psi)	1000 MPa (145e3 psi)	2000 MPa (290e3 psi)
Poisson's ratio, $\nu$	0.30	0.30	0.20
Dilation angle, $\psi$	4.0°	0.0°	0.0°

Note: All parameters are taken from INDOT (2022) except the stiffness of the reinforced soil, which is taken from Damians et al. (2021); the stiffness of the retained and foundation soils is assumed.

For the cases displayed in Figure 4.1a–l where the effects of the location of the pipe inside the reinforced soil or under the wall foundation are investigated, the diameter of the concrete pipe is 60.9 cm (24 in.), which corresponds to the vertical spacing of the wall reinforcement. The pipe has a thickness of 5 cm. For the cases shown in Figure 4.1m–s, to explore the effects of the pipe diameter, the pipe diameters are 91.4 cm (36 in.), and the thicknesses are 5 cm. All pipes have the properties listed in Table 4.2.

**4.2.1.3 Reinforcements.** The backfill is reinforced by ten layers of ribbed metal strips, following the INDOT (2022) case study. Each metal strip is 5 cm (1.97 in.) wide, 0.4 cm (0.16 in.) thick, and 5.6 m (18.37 ft) long. The length of the strips is calculated as 0.7H, where H is the height of the backfill, satisfying the minimum recommendations from FHWA (2009). The spacing between the reinforcements is 76.2 cm (30 in.). Although the metal strips have elastoplastic behavior, to simplify the simulations, they are modeled as linear elastic. The reinforcement is connected to the panel with pinned connection. The input properties of the metal strip are listed in Table 4.3.

**4.2.1.4 Interface Parameters.** The shear behavior of the upper and lower contact of the reinforcement with the soil is defined by a nonlinear shear failure, where the shear behavior is a function of the overburden pressure. The dilatancy angle of the interface is assumed to be equal to that of the backfill (Table 4.4). Damians et al. (2021) carried out an analysis of an MSE wall and discussed the soil facing interface, the properties of which are listed in Table 4.5. The same properties are used for the pipe-soil interface.

**4.2.1.5 Pullout Test.** Verification of the PLAXIS model, reinforcement-soil interface, and others is done by simulating a pull-out test. The test is simulated in PLAXIS 2D and follows the ASTM D6706 guidelines (ASTM International, 2021). The simulated pullout test box is 70 cm (2.3 ft) wide and

TABLE 4.2  
Properties of the Concrete Facing Panel and Pipe.

Parameter	Value
Elastic modulus, $E_{conc}$	32 GPa (4641.2 psi)
Density, $\rho$	2500 kg/m <sup>3</sup> (156 pcf)
Poisson's ratio, $\nu_{conc}$	0.15

TABLE 4.3  
Properties of the Metal Strips.

Parameter	Value
Elastic modulus, $E_{steel}$	200.0 GPa (29e3 ksi)
Number of strips per unit width, $n_{strips}$	2/m (0.61/ft)
Strip width	5 cm (2 in.)
Strip thickness	0.4 cm (0.2 in.)
Poisson's ratio, $\nu_{steel}$	0.30

0.3 m (0.98 ft) deep. The length of the reinforcement is 62.5 cm. A ribbed metal strip is placed inside the (Figure 4.2), and the properties of the reinforcement and interfaces are taken from Table 4.3 and Table 4.4, respectively. The objective of the test is to define/verify the soil reinforcement interface parameters. The behavior of the soil is modeled using the Mohr-Coulomb model, with properties of the backfill material (Table 4.1). As seen in Figure 4.2, the vertical boundaries are fixed, and a vertical normal stress of 25 kPa is applied to the pullout box (Weldu, 2015). A prescribed displacement of 1.9 cm is applied at the outside tip of the metal strip, following the experimental setup of Weldu (2015).

The pullout resistance,  $P_r$ , of the reinforcement per unit width is calculated using the equation from AASHTO (2020):

$$P_r = F^* \alpha \sigma_v C L_e$$

Where  $F^*$  is the pullout friction factor,  $\alpha = 1$  for steel reinforcement (scale correction factor),  $\sigma_v$  is the vertical stress at the

TABLE 4.4  
Soil Reinforcement Interface Properties (Damians et al., 2021).

Parameter	Value
Unit weight, $\gamma$	19.63 kN/m <sup>3</sup> (125 pcf)
Cohesion, $c$	0.10 kPa (0.01 psi)
Friction angle, $\phi$	26.6°
Elastic modulus, $E$	50 MPa (7252 psi)
Poisson's ratio, $\nu$	0.45
Dilation angle, $\psi$	4.0°

TABLE 4.5  
Soil Pipe Interface Properties.

Parameter	Value
Unit weight, $\gamma$	19.63 kN/m <sup>3</sup> (125 pcf)
Cohesion, $c$	0.08 kPa (0.01 psi)
Friction angle, $\phi$	30.1°
Elastic modulus, $E$	4.02 MPa (583 psi)
Poisson's ratio, $\nu$	0.45
Dilation angle, $\psi$	0

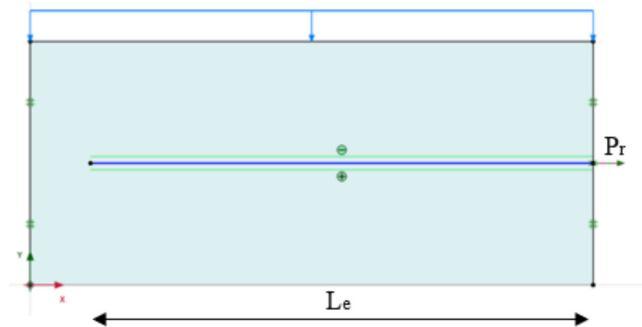


Figure 4.2 Pullout Test.

reinforcement level, and  $C$  is the overall reinforcement surface area geometry factor based on the gross perimeter of the reinforcement (2 for a strip).

The resulting pullout force for the strip is 83.6 kN/m, with a pullout friction factor  $F^*$  of 2.67. The value obtained for the friction factor from the numerical simulation is found to be consistent with the results of Weldu (2015).

### 4.3 Pipe Placed Inside the Reinforced Backfill

This study explores the placement of a circular drainage pipe at several locations in the reinforced zone to determine the effects of the presence of the pipe on the overall stability of the wall and on the wall components.

The MSE wall model was validated using field data, and the numerical simulations showed strong agreement, confirming the model's reliability. Additional details regarding validation are provided in Appendix A.

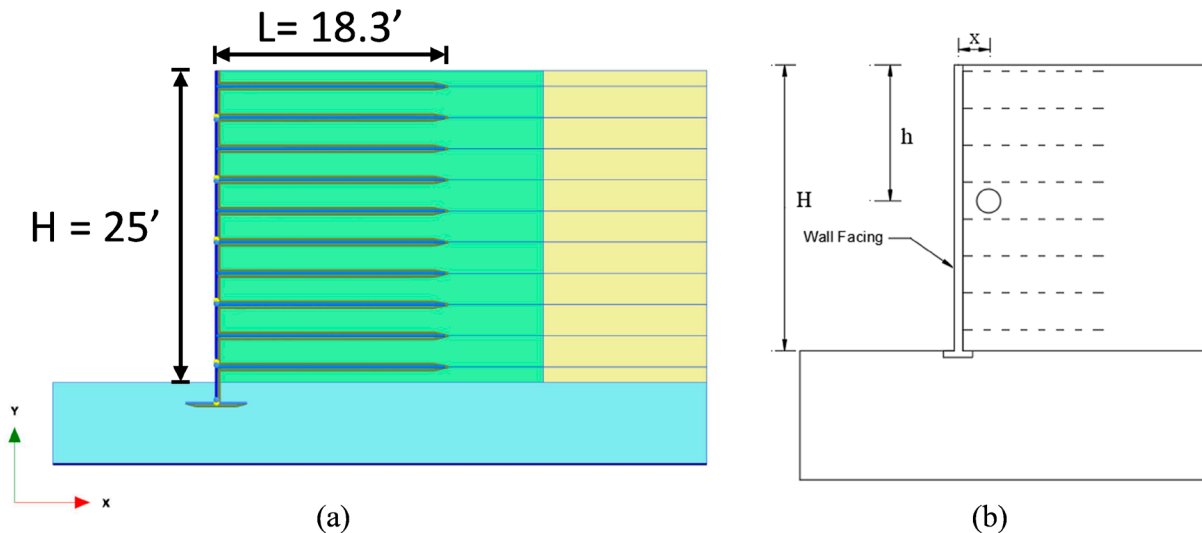
Numerical simulations are done with pipes in the reinforced zone at different depths  $h$  (where  $h$  is the depth of the centre of the pipe from the top of the wall), as follows (Figure 4.1): near the top ( $h = 76$  cm [2.5 ft]), middepth ( $h = 3.81$  m [12.5 ft]), and near the bottom ( $h = 6.85$  m [22.5 ft]). At each depth, the pipe is placed at 1 m (3.3 ft), 3 m (9.8 ft) and 5 m (16.4 ft) from the facing panel, resulting in a total of nine different simulations. A cover of 76.2 mm between the pipe and the top and bottom reinforcement is provided following FHWA (2009) guidelines. The results of each simulation are compared to those of the base case, which has no utility pipes. The construction of the wall is performed in stages as follows:

- Stage 1: The facing panel is set up with the bearing pad at the base, then the first soil layer is placed.
- Stage 2: Reinforcement strips are tied (pinned) to the wall followed by placement of the next panel. A second soil layer is placed followed by the next set of metal strips. The process is repeated until the wall height reaches the target height of 7.62 m (25 ft). A total of 11 stages are involved with the construction of the wall.

Figure 4.3a illustrates the base case, which is the MSE wall with no utility pipe. As already mentioned, the height of the wall is 7.62 m and the length of the reinforcement is 5.6 m. The backfill is reinforced with ten layers of reinforcement at a spacing of 76.2 cm. All elements in the model are 15-noded triangular elements. The mesh is composed of 9,146 nodes and 938 elements. This is the result of a sensitivity/optimization analysis where the size and number of elements in the model were changed until the results were found independent of the size and number of the elements in the mesh. The material properties are those in Table 4.1 to Table 4.4.

Figure 4.3b depicts the schematic of the MSE wall with a pipe placed in the backfill zone.  $H$  is the height of the wall,  $h$  is the depth at the centre of the pipe, measured from the top of the soil layer, and  $x$  is the distance of the center of the pipe from the facing panel.

The overall Factor of Safety (FOS) is also computed to check the stability of the wall. The values of the FOS are, for the base



**Figure 4.3** Numerical Model: (a) Base Case and (b) Schematic Diagram of MSE Wall With a Pipe.

case, 1.81, and with the pipe, 1.80, 1.80, and 1.79 when placed at 1 m (3.3 ft), 3 m (9.8 ft), and 5 m (16.4 ft) from the facing, respectively. These values show that the presence of the pipe has a negligible effect on the overall stability of the wall, although it induces a local redistribution of forces in the reinforcement and reinforced soil.

#### 4.3.1 Reference Case ( $h = 3.81$ m and $x = 3$ m)

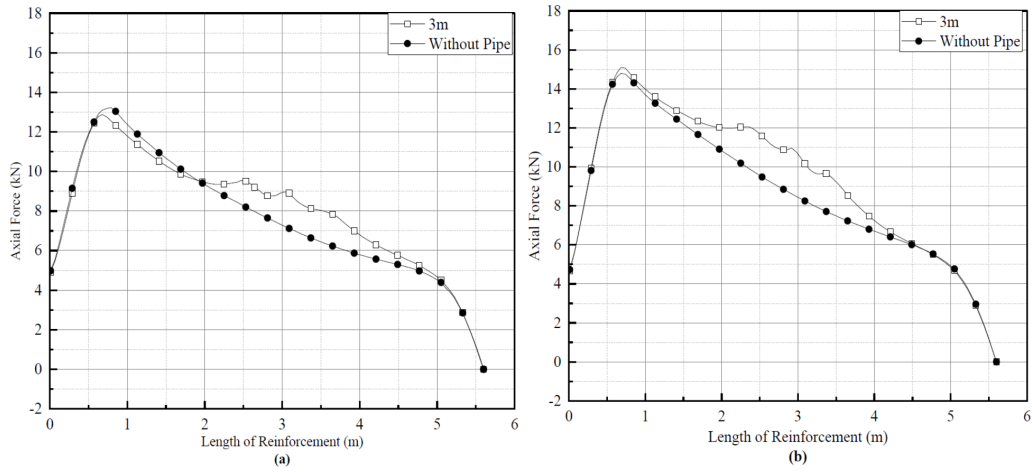
Figure 4.4 to Figure 4.8 are used to provide detailed results of a reference case, which is that of the MSE wall with the pipe placed at the middle of the wall ( $h = 3.81$  m [12.5 ft]) and 3 m from the facing panel. A discussion on the effects of location, that is, depth and distance from the facing, is provided in Section 4.4. The figures also include results for the base case. This is the same wall, same reinforcement, and so on, but without the pipe. This is done to provide comparisons between the two cases and, thus, show the effects of the placement of the pipe.

Figure 4.4 is a plot of the axial forces in the reinforcement above and below the pipe for the reference case ( $h = 3.81$  m [12.5 ft] and  $x = 3$  m [9.8 ft]) and the base case. The figure shows that the reinforcement above the pipe has an increase of 25–30% in the axial force with respect to the base case. Below the pipe, the effects are slightly smaller, with an increase in the order of 20–25%. It is interesting to note that the presence of pipe leads to a localised change in the force. That is, the effect on the reinforcement load extends about two pipe diameters beyond the center of the pipe.

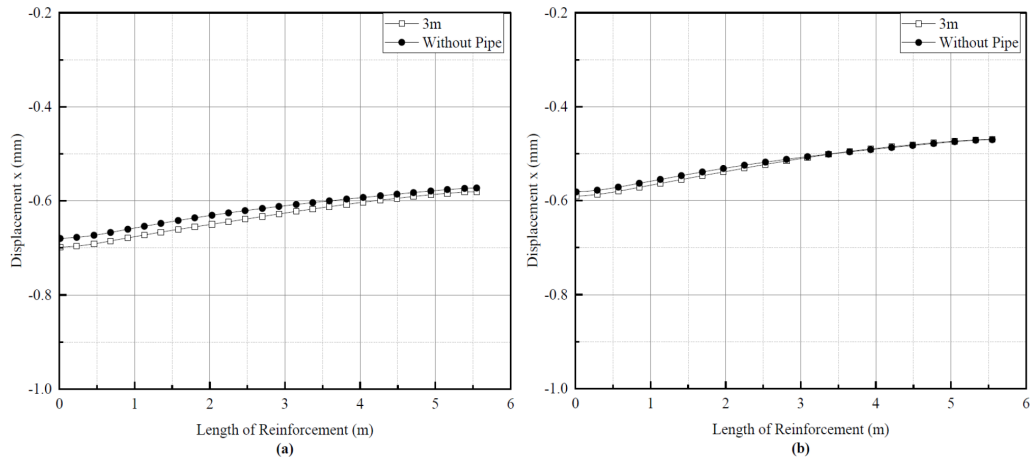
The reinforcement above the pipe has an increase in axial displacements, in contrast to the base case, as shown in Figure 4.5. The reinforcement below the pipe experiences a negligible difference in axial displacement. What is perhaps more interesting is the amount of slip between the reinforcement and the soil (the relative motion between the two at their contact surface), which is a measure of the frictional demand on the

reinforcement. Figure 4.6 and Figure 4.7 compare the relative displacement of the reinforcement above and below the pipe, respectively. The reinforcement has two contacts: the one on the top surface of the reinforcement is termed the *upper contact* and the one on the bottom surface of the reinforcement, the *lower contact*. Figure 4.6a shows that the lower contact of the reinforcement above the pipe has a higher slip than the base case. The presence of the pipe increases the magnitude of the slip between the reinforcement and the soil over a distance of about two pipe diameters from the center of the pipe, as before. It is also interesting to note that the sign of the slip is reversed on the left of the pipe, indicating that the length of the reinforcement pulling outwards increases. This is consistent with the results in Figure 4.4 and Figure 4.5 that point towards a larger demand for reinforcement due to the presence of the pipe. This suggests frictional forces mobilized between the soil and the lower reinforcement, leading to an increase in the axial load. All this is in contrast with the results in Figure 4.7b that shows a minimum effect on the slip of the lower contact of the reinforcement below the pipe. This finding is consistent with the results in Figure 4.5b, that indicate negligible effects on the axial displacement of the reinforcement below the pipe, with respect to the base case.

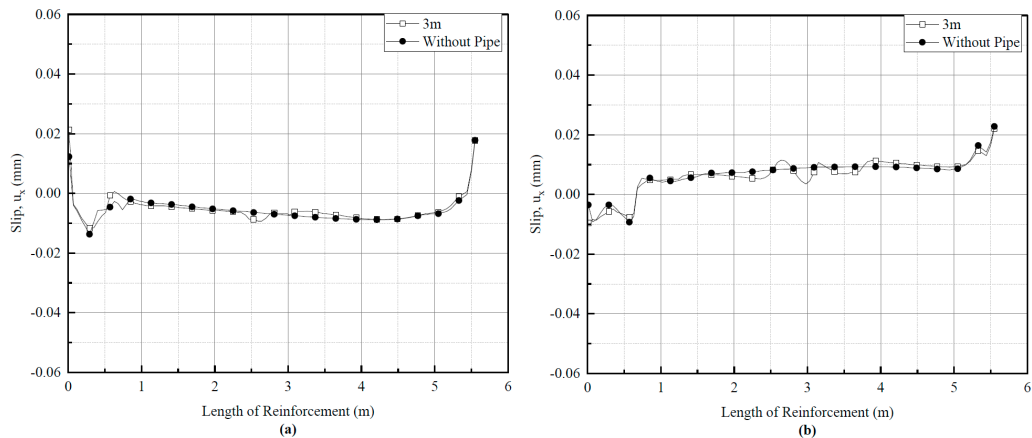
Figure 4.8 illustrates the ratio between the maximum shear stress and the mobilized shear stress in the backfill and soil of the MSE wall, without a pipe (base case, Figure 4.8a) and with the pipe (reference case, Figure 4.8b). Note that the results in the foundation soil are not meaningful because of the high strength/high stiffness given to the material; therefore, they are not included in Figure 4.8. The ratio is a measure of the demand with respect to the capacity of the soil. The contours show the capacity of the soil utilized. The presence of the pipe affects the relative shear stress, and the relative shear stress has decreased at the spring lines and increased near the crown of the pipe.



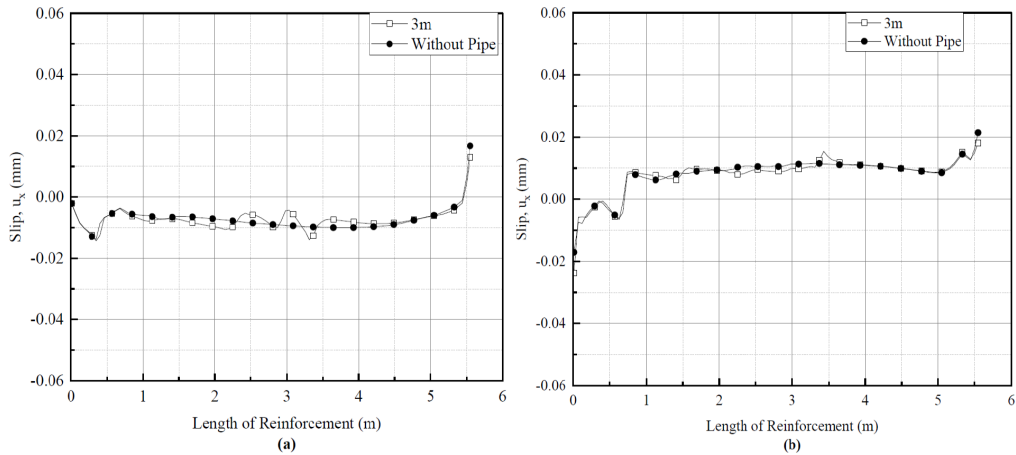
**Figure 4.4** Axial Force in the Reinforcement: (a) Above the Pipe and (b) Below the Pipe for the Base Case (No Reinforcement) and the Reference Case ( $h = 3.81$  m [12.5 ft],  $x = 3$  m [9.8 ft]).



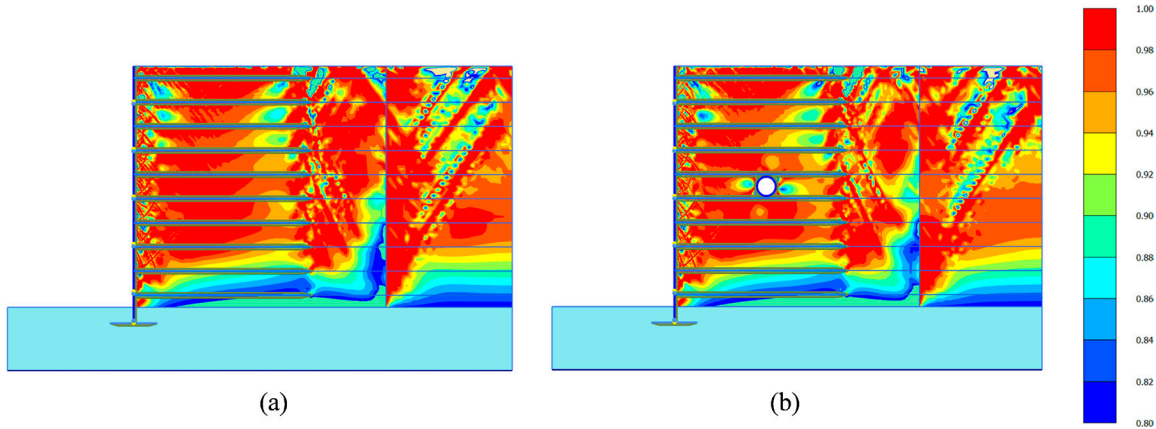
**Figure 4.5** Axial Displacement in the Reinforcement: (a) Above the Pipe and (b) Below the Pipe for the Base Case (No Reinforcement) and the Reference Case ( $h = 3.81$  m [12.5 ft],  $x = 3$  m [9.8 ft]).



**Figure 4.6** Slip in the Reinforcement Above the Pipe: (a) Upper Contact; and (b) Lower Contact for the Base Case (No Reinforcement) and the Reference Case ( $h = 3.81$  m [12.5 ft],  $x = 3$  m [9.8 ft]).



**Figure 4.7** Slip in the Reinforcement Below the Pipe: (a) Upper Contact and (b) Lower Contact for the Base Case (No Reinforcement) and the Reference Case ( $h = 3.81$  m [12.5 ft],  $x = 3$  m [9.8 ft]).



**Figure 4.8** Ratio Between the Maximum Shear Stress and the Mobilized Shear Stress in the Backfill and Soil, for (a) Base Case (No Pipe) and (b) Reference Case ( $h = 3.81$  m [12.5 ft] and  $x = 3$  m [9.8 ft]).

#### 4.3.2 Influence of the Pipe Location

Figure 4.1 shows all the cases explored regarding the location of the pipe. This Section discusses the effects of changing the location of the pipe in the reference case ( $h = 3.81$  m [12.5 ft],  $x = 3$  m [9.8 ft]), by: (1) moving the pipe horizontally, and more specifically, at distances  $x = 1$  m (3.3 ft), 3 m (9.8 ft) for the reference case, and 5 m from the facing of the wall (Figure 4.9 to Figure 4.12 ); and (2) by moving the pipe vertically, at  $h = 76$  cm (2.5 ft), 3.81 m (12.5 ft) for the reference case, and 6.85 m (22.5 ft; Figure 4.13 to Figure 4.21).

Figure 4.9 shows that for the reference case, moving the pipe close to the facing panel increases the stresses in the reinforcement below the pipe by about 15%, with changes that affect only the area of influence of the pipe, about two diameters, as already mentioned. The changes in stress in the above reinforcement are relatively smaller. Moving the pipe away from the facing, at  $x = 5$  m (16.4 ft) induces small changes in the above reinforcement and an increase of about 20–25% on the reinforcement

below the pipe, again at the location of the pipe and over a length of two pipe diameters. The changes in the magnitude of the axial force in the pipe above and below the reinforcement is due to the increase in vertical stress (not shown in the figures).

Figure 4.10 plots the changes in axial displacements of the reinforcements above (Figure 4.10a) and below (Figure 4.10b) the pipe. As one can see, and similar to the reference case, the reinforcement below the pipe experiences a negligible difference in axial displacement. Also, the axial displacements of the reinforcement below are not much affected by the location of the pipe, as seen in Figure 4.10b.

Figure 4.11 and Figure 4.12 are plots of the slip that occurs along the upper and lower reinforcement, respectively, as a function of the position of the pipe (reference case) with respect to the facing of the wall. Figure 4.11b and Figure 4.12a show that the magnitude of the slip on the inner contacts has more peaks due to shear stress around the pipe, similar to the redistribution of shear stresses around the pipe, and, at the same time, reinforcement is subjected to tension and pipe is subjected

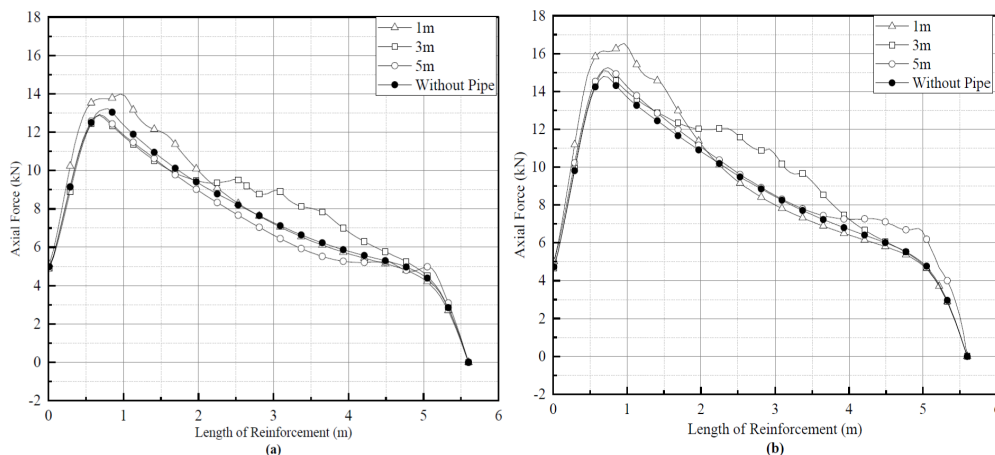
to rolling. This shows the complex interaction between soil, reinforcement, and pipe. This is consistent in all cases. However, the magnitude of slip depends on the location of the pipe, with values larger by about 30–50% at the location of the pipe than in the reference case. Figure 4.11a and Figure 4.12b also show that changes in slip are reversed at the location of the pipe on the outer surface of the reinforcement, indicating that the length of the reinforcement pulling outwards increases. This suggests that the frictional forces are mobilized between the soil and the outer contacts, leading to an increase in the axial load.

When the pipe is positioned right after the first layer of reinforcement ( $h = 76 \text{ cm}$  [2.5 ft]), or near the bottom of the backfill ( $h = 6.85 \text{ m}$  [22.5 ft]), the largest effects on the axial load on the reinforcement occur at the reinforcement below the pipe (Figure 4.13b and Figure 4.14b), with magnitudes increased by 30–50% in most cases, but can go up to 100% for the case with  $h = 6.85 \text{ m}$  (22.5 ft) and  $x = 1 \text{ m}$ , close to the facing of the wall. The change in axial load on the reinforcement above the pipe is small for the case  $h = 76 \text{ cm}$  (Figure 4.13a), or is in the form of an increase in load (Figure 4.14a) for the case with  $h = 6.85 \text{ m}$  (22.5 ft). In all cases, the effects of the pipe are confined to the reinforcements immediately above and below the pipe. Other reinforcement layers are not affected by the presence of the pipe. The only exception found is for the case of  $h = 76 \text{ cm}$  (2.5 ft), where changes in the axial force on the second reinforcement below the pipe (Figure 4.13c), where an important increase of axial load, with respect to the base case, is observed for  $x = 5$ , and a general reduction for  $x = 1 \text{ m}$  (3.3 ft) and  $3 \text{ m}$  (9.8 ft). However the changes, of the order of 15–20%, tend to be smaller than those on the reinforcement immediately below the pipe (30–50%; Figure 4.13b). By comparing the results in the two figures, it can be said that when the pipe is near the top of the wall and moving away from the facing of the wall, the axial force proportionally increases with respect to the base case. However, for a deeper pipe, the trend is the opposite: as the pipe is placed away from the facing of the wall, the axial force proportionally decreases.

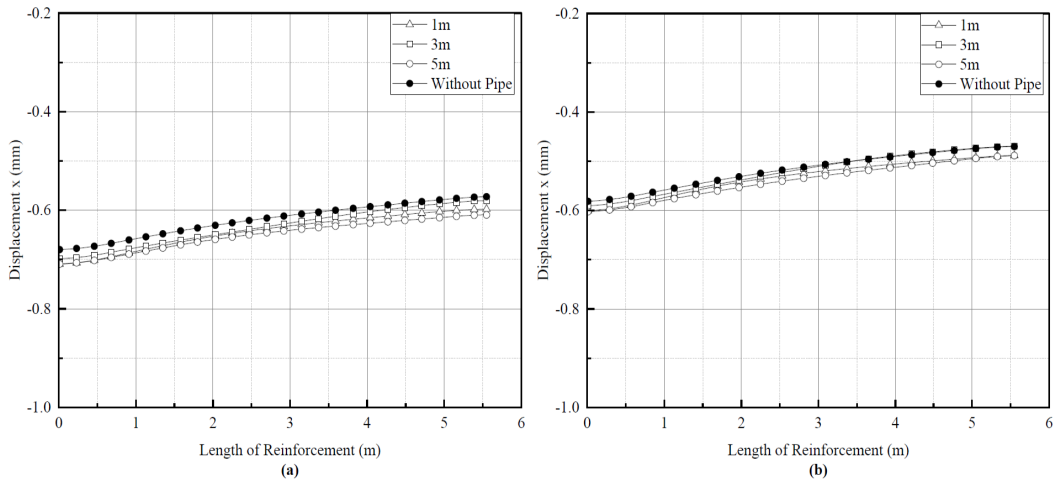
Figure 4.15 and Figure 4.16 are plots of the axial displacement for the cases  $h = 76 \text{ cm}$  (2.5 ft) and  $h = 6.85 \text{ m}$  (22.5 ft). As the pipe moves upward (Figure 4.15) the trend of axial displacements is similar to those of the base and the reference cases (Figure 4.10). The difference is in the magnitude of the displacements: the reinforcements have the largest displacements when the pipe is near the ground surface and the largest increase in displacement is induced in the reinforcement above the pipe when the pipe is placed further away from the facing of the wall. In contrast to what was found for the axial load, the second reinforcement below the pipe, for the case  $h = 76 \text{ cm}$  (2.5 ft), experiences very small changes in axial displacement. Similarly, small changes are also observed for the reinforcement below the pipe in all the cases investigated.

Figure 4.17 to Figure 4.21 are plots of the slip between the reinforcements near the pipe and the surrounding soil. The trend is similar in all cases and is also similar to what was found for the reference case. Slip is more significant on the upper contact of the two reinforcements directly above and below the pipe. It is not different than the slip that occurs in the base case for the lower contact and in reinforcements not adjacent to the pipe. Slip tends to become more negative/less positive to the left of the pipe, within the area of influence, of about 1.5–2 diameters, and less negative/more positive to the right, and also over a similar distance from the center of the pipe. The changes in the magnitude of slip, with respect to the base case, seem to increase with the depth of the pipe, but they are similar irrespective of the horizontal position of the pipe. This is attributed to the disturbance that the presence of the pipe introduces to the reinforcement-ground interaction, as it changes the stresses acting on the reinforcement.

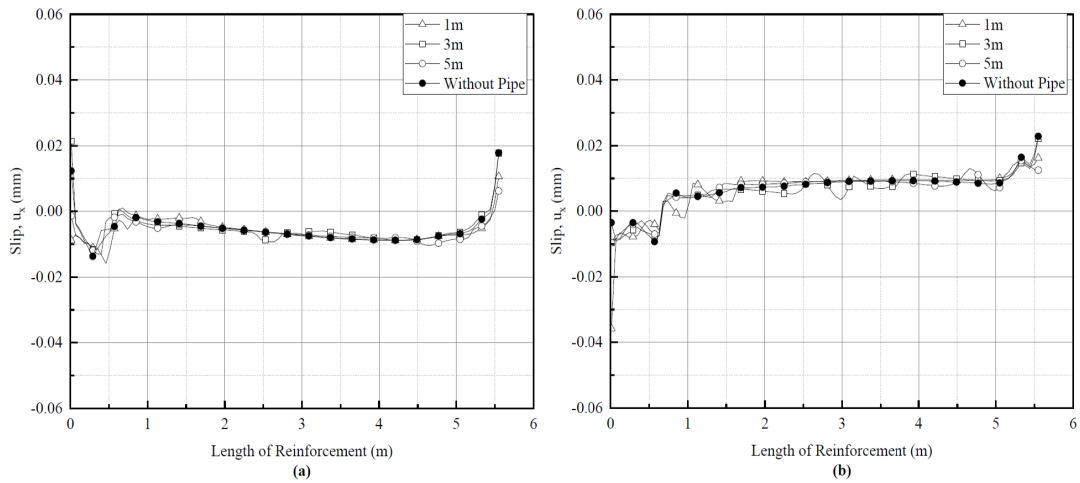
Figure 4.22 shows contours of the ratio between the shear stress capacity to the shear stress demand on the reinforced backfill and soil (as in Figure 4.8, the results in the foundation soil are not meaningful because of the high strength/high stiffness given to the material). It can be seen from the figure that the region near to the wall and the region away from the wall



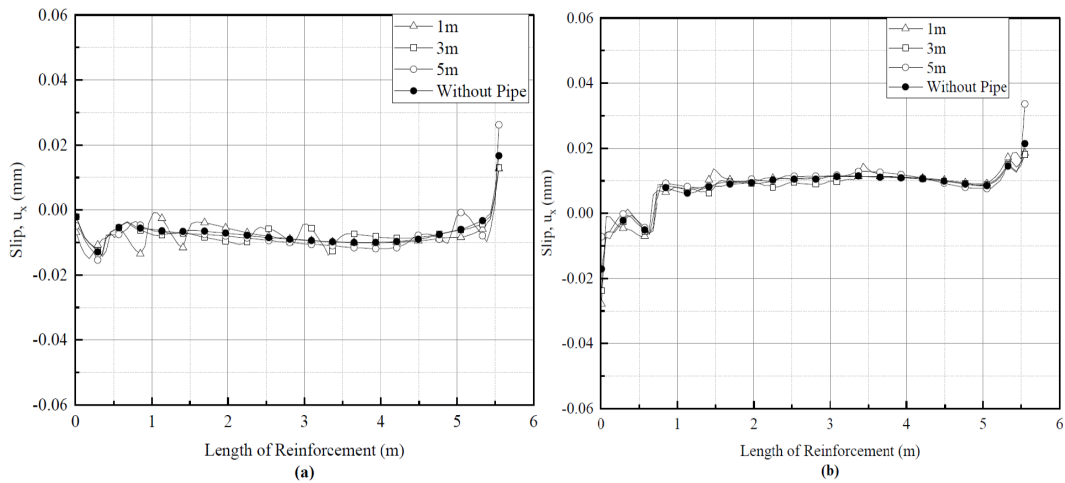
**Figure 4.9** Axial Force in the Reinforcement With Distance From the Facing Panel (a) Above the Pipe and (b) Below the Pipe. Pipe Location at  $h = 3.81 \text{ m}$  (12.5 ft).



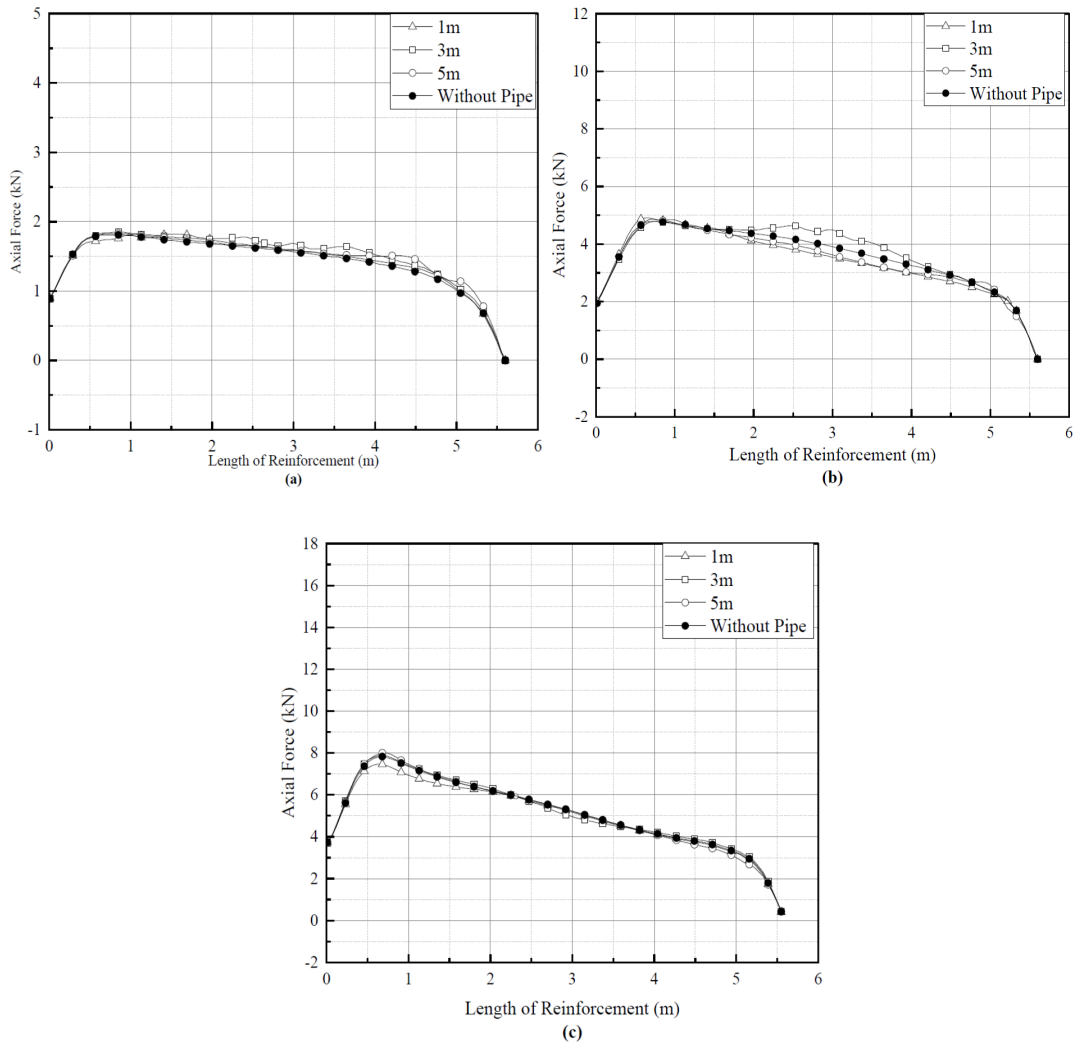
**Figure 4.10** Axial Displacement in the Reinforcement With Distance From the Facing Panel (a) Above the Pipe and (b) Below the Pipe. Pipe Location at  $h = 3.81$  m (12.5 ft).



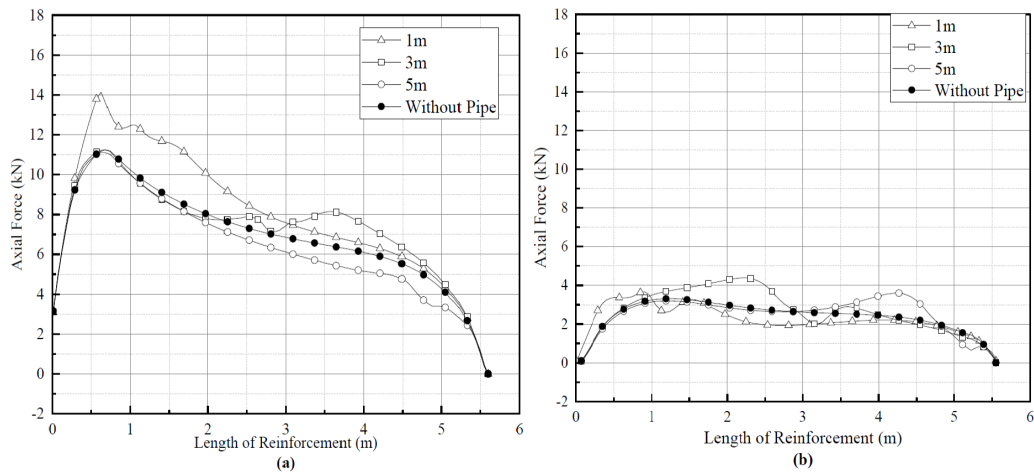
**Figure 4.11** Slip of the Reinforcement Above the Pipe (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 3.81$  m (12.5 ft).



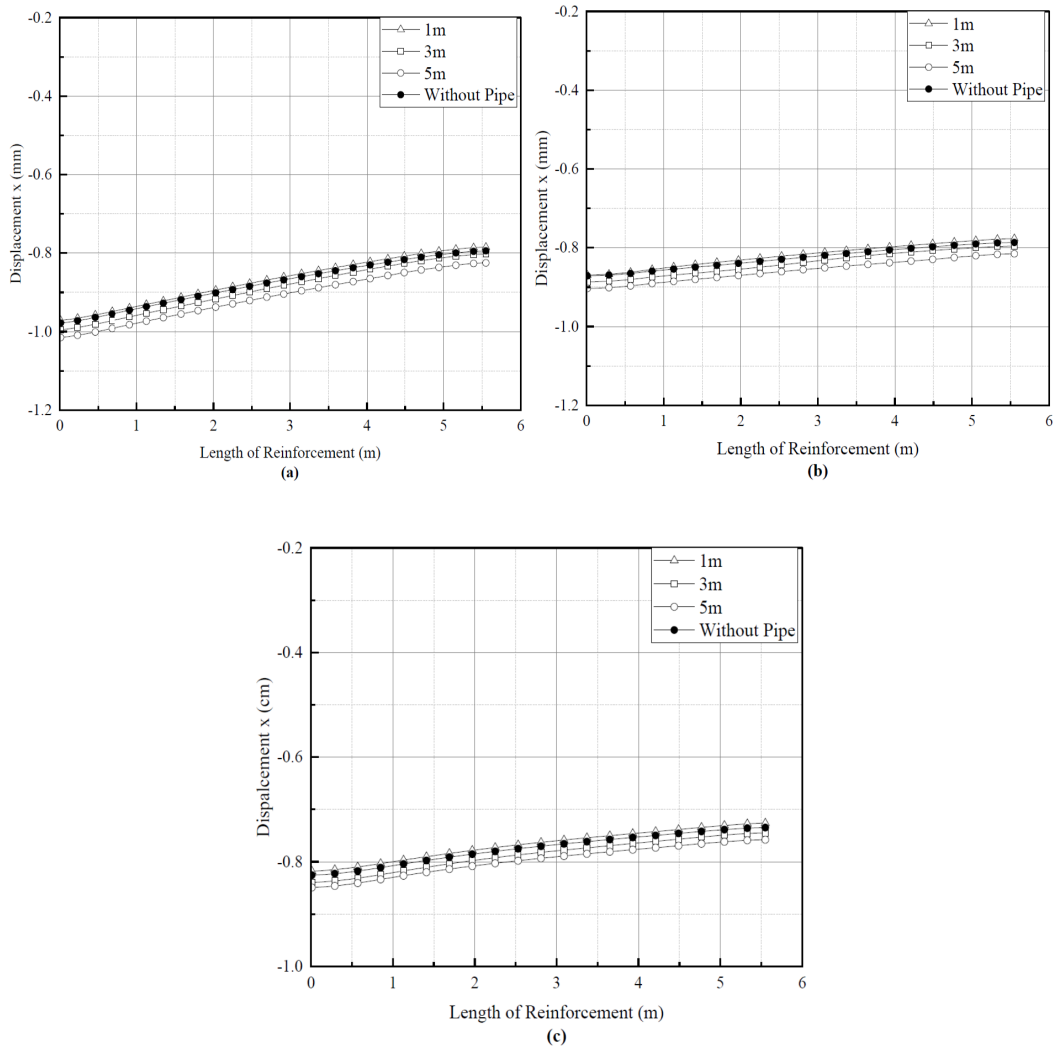
**Figure 4.12** Slip of the Reinforcement Below the Pipe (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 3.81$  m (12.5 ft).



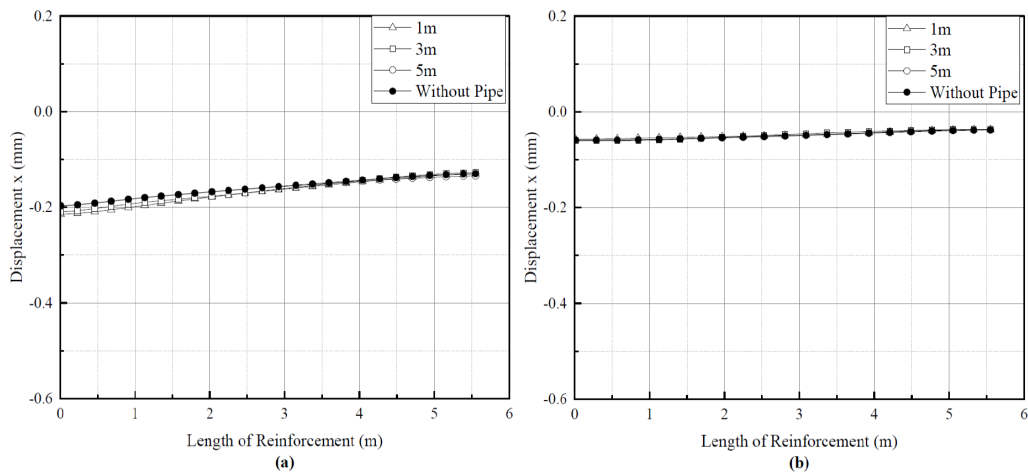
**Figure 4.13** Axial Force in the Reinforcement With Distance From the Facing Panel (a) Above the Pipe, (b) Below the Pipe, and (c) Second Reinforcement Below the Pipe. Pipe Location at  $h = 76$  cm (2.5 ft).



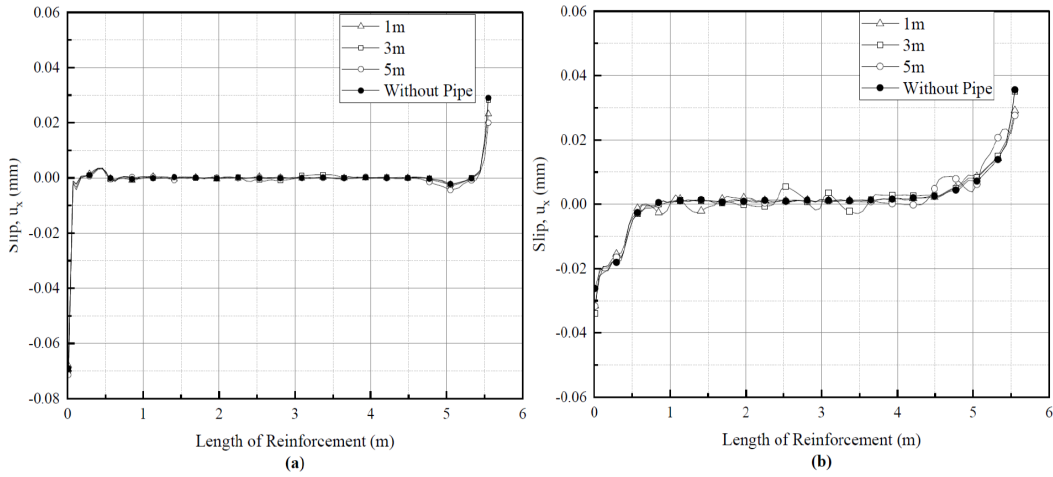
**Figure 4.14** Axial Force in the Reinforcement With Distance From Facing Panel (a) Above the Pipe and (b) Below the Pipe. Pipe Location at  $h = 6.85$  m (22.5 ft).



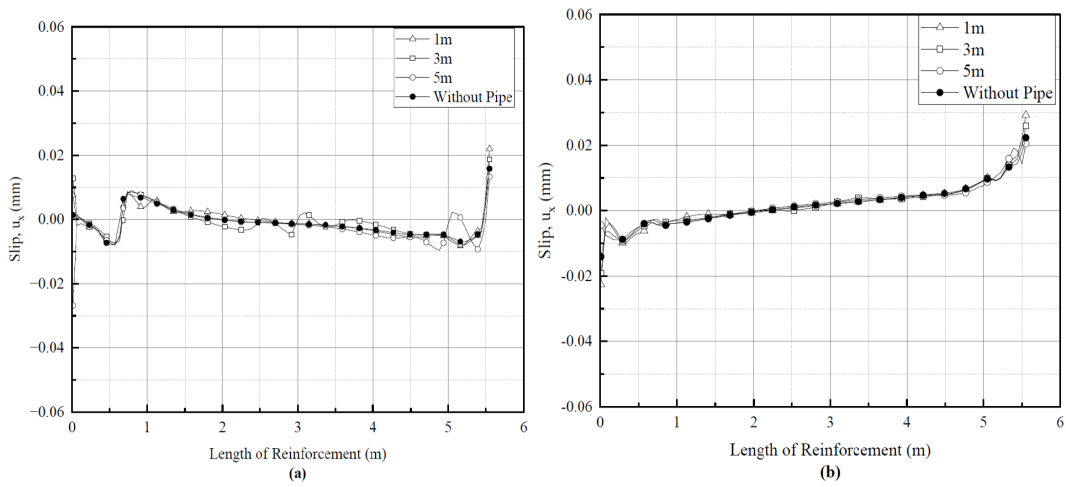
**Figure 4.15** Axial Displacement in the Reinforcement With Distance From the Facing Panel (a) Above the Pipe, (b) Below the Pipe, and (c) Second Layer Below the Pipe. Pipe Location at  $h = 76$  cm (2.5 ft).



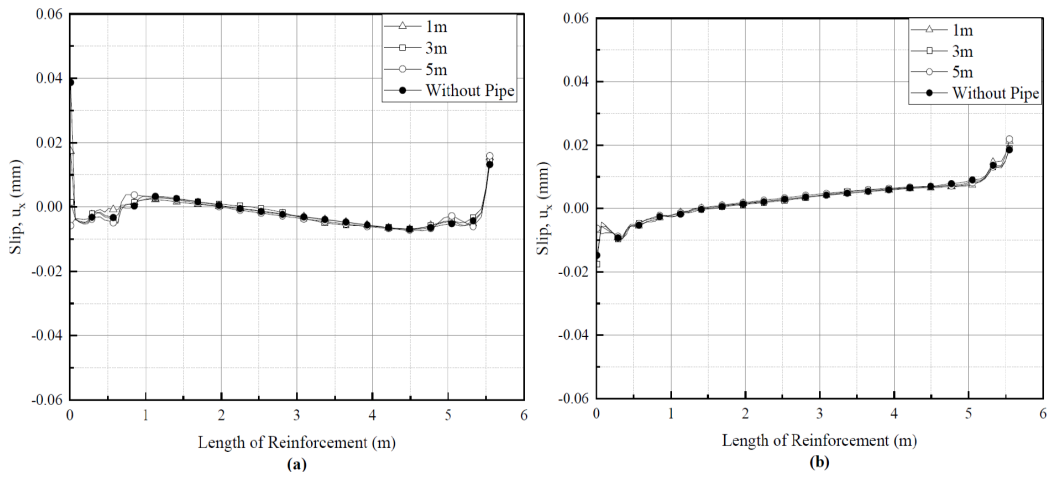
**Figure 4.16** Axial Displacement in the Reinforcement With Distance From the Facing Panel (a) Above the Pipe and (b) Below the Pipe. Pipe Location at  $h = 6.85$  m (22.5 ft).



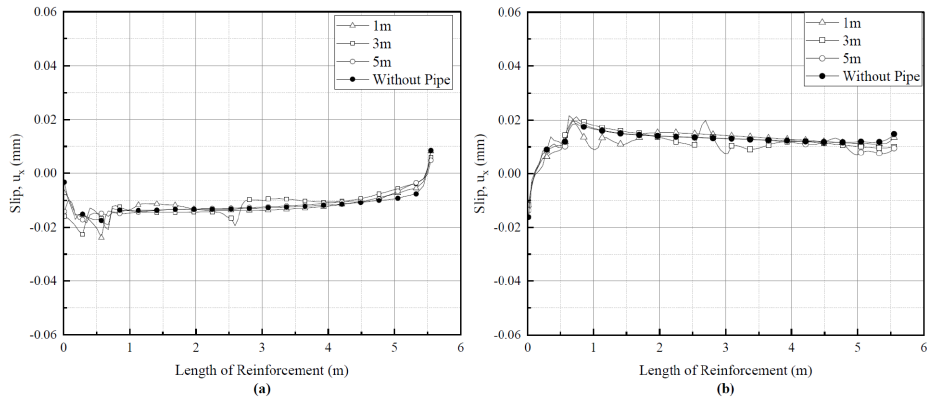
**Figure 4.17** Slip in the Reinforcement Above the Pipe for (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 76$  cm (2.5 ft).



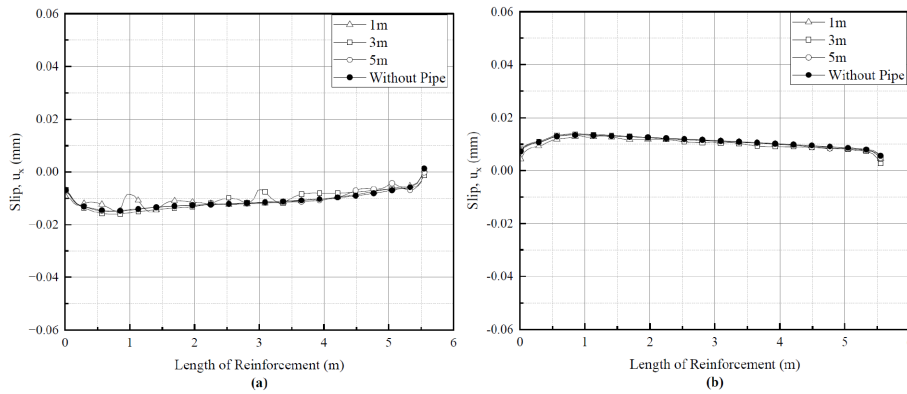
**Figure 4.18** Slip in the Reinforcement Below the Pipe for (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 76$  cm (2.5 ft).



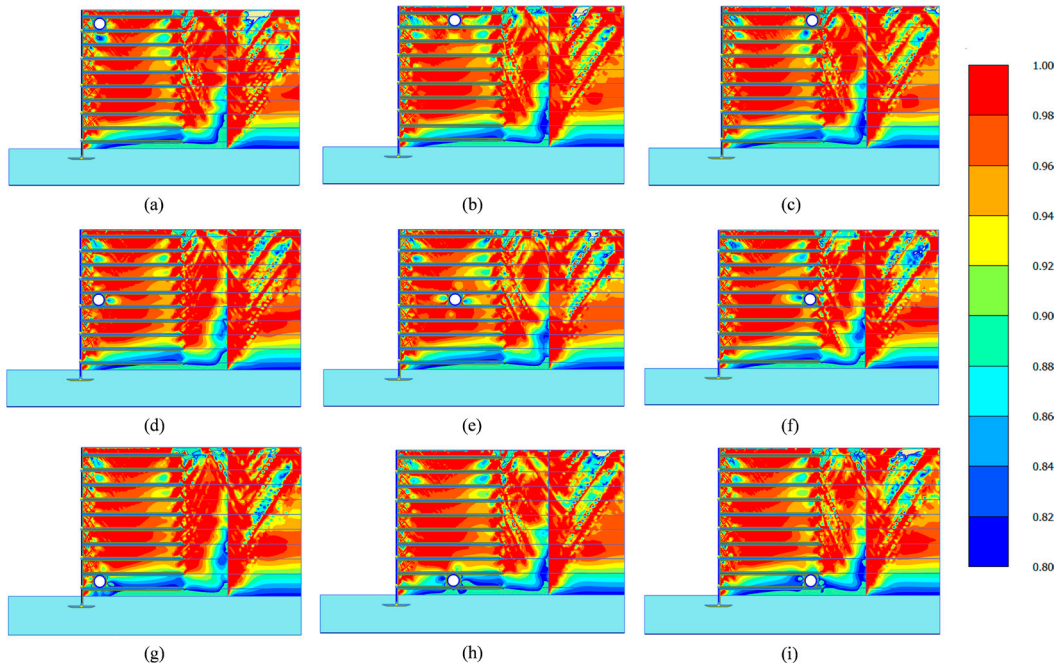
**Figure 4.19** Slip in the Second Layer Reinforcement Below the Pipe for (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 76$  cm (2.5 ft).



**Figure 4.20** Slip in the Reinforcement Above the Pipe for (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 6.85$  m (22.5 ft).



**Figure 4.21** Slip in the Reinforcement Below the Pipe for (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 6.85$  m (22.5 ft).



**Figure 4.22** Shear Stress Capacity vs. Demand for the Following Cases: (a)  $h = 76$  cm (2.5 ft),  $x = 1$  m (3.3 ft); (b)  $h = 76$  cm (2.5 ft),  $x = 3$  m (9.8 ft); (c)  $h = 76$  cm (2.5 ft),  $x = 5$  m (16.4 ft); (d)  $h = 3.81$  m (12.5 ft),  $x = 1$  m (3.3 ft); (e)  $h = 3.81$  m (12.5 ft),  $x = 3$  m (9.8 ft); (f)  $h = 3.81$  m (12.5 ft),  $x = 5$  m (16.4 ft); (g)  $h = 6.85$  m (22.5 ft),  $x = 1$  m (3.3 ft); (h)  $h = 6.85$  m (22.5 ft),  $x = 3$  m (9.8 ft); and (i)  $h = 6.85$  m (22.5 ft),  $x = 5$  m (16.4 ft).

TABLE 4.6  
Summary of the FOS From Cases a–i (Figure 4.1).

Pipe Location	x = 1 m (3.3 ft)	x = 3 m (9.8 ft)	x = 5 m (16.4 ft)
h = 76 cm (2.5 ft)	1.80	1.80	1.80
h = 3.81 m (12.5 ft)	1.80	1.80	1.79
h = 6.85 m (22.5 ft)	1.81	1.80	1.81

(end of reinforcement length) the soil is already mobilized. However, when the pipe is located 3 m (9.8 ft) from the facing at different depth, as the pipe moves downward the mobilization of the soil around the pipe is increased. It can also be noticed that the presence of a pipe changes the relative shear stress in the surroundings of the soil. In a later section, the area of influence caused by the pipe will be discussed. Table 4.6 summarizes the global FOS of the cases in Figure 4.1a–i. It shows the presence of pipe led to decrease in the FOS by 1–2%.

#### 4.4 Discussion

From the above results, it is observed that the presence of a pipe has an influence on the axial force, axial displacement, and slip of the reinforcement. The axial force increases in the reinforcement at the location of the pipe and more pronounced for the reinforcement below the pipe. It is observed that, when the pipe is near the top of the wall and moving away from the facing of the wall, the axial force proportionally increases with respect to the base case. However, for a deeper pipe, the trend is the opposite: as the pipe is placed away from the facing of the wall, the axial force proportionally decreases. The farther reinforcement is not influenced by the presence of pipe. When a pipe is placed near the top of the wall, an increase in axial force is noticed for two layers of reinforcement below the pipe, but not in all cases. The axial displacements in the reinforcement also increases and it is distinct in the reinforcement above the pipe located away from the facing. The maximum increase in the displacement occurs when the pipe is placed near the top of the wall. Moreover, it also influences the slip of the contacts. The inner contacts of the reinforcement undergo the large increase in the slip compared to the outer contacts. It is evident that the presence of the pipe causes an increase in the mobilization of frictional force between the soil and the reinforcement. The increase in slip is also confined near the location of the pipe and is consistent with the axial force. It is also observed that the influence of the pipe affects the reinforcement locally and in certain cases the global stability decreased up to 1–2%. The presence of pipe increases the shear stress mobilization of the soil around the pipe. The influence of the pipe affects the axial force, axial displacement and relative displacement 2–2.5 times the diameter of the pipe. This influence is calculated when the pipe is located 3 m (9.8 ft) from the face at different depths, because the pipe has sufficient available space on both sides of the reinforcement. These interactions highlight the complex behavior of the soil-reinforcement system in the presence of a pipe, where different layers experience varying levels of force, displacement, and slip depending on their position relative to the pipe.

#### 4.5 Pipe in the Foundation Soil

The analysis of the MSE wall will be carried out using the same MSE wall as before except the footing of the soil is replaced from very stiff and strong to soil to the realistic properties of soil. The soil properties of the foundation soil are listed in Table 4.7. The pipe is placed in the foundation soil and its invert is at a depth of 1.22 m (4 ft) and located in front of and behind the facing panel. The six cases that will be explored in this section and the schematic are shown in Figure 4.1j–o. The objective of the analysis is to explore the effects of pipe on the MSE wall and the pipe itself. This section also studies the influence of increase in pipe diameter from 60.9 cm (24 in.) to 91.4 cm (36 in.). Normalized Thrust (axial force) and moment are the ratio of thrust/moment in a pipe with MSE wall to the thrust/moment in a pipe when there is no MSE wall.

Figure 4.23 and Figure 4.24 are plots of normalized thrust and moment at the perimeter of the pipe when it is placed at the following location: 1.2 m (3.9 ft) in front of the facing, 1.8 m (5.9 ft) distance behind the facing, and 5 m (16.4 ft) behind the facing. It is observed that the pipe experiences an increase in thrust by approximately 12 times when placed in front of the wall. However, the thrust in the pipe increases by 24 times when it is placed below the MSE wall at 1.2 m from the facing. Due to the weight of the MSE wall, there is an overall increase in the normalized thrust compared to when it was in front of the wall. In addition, if it is placed behind the wall, the maximum thrust reaches up to 26 times when placed 5 m (16.4 ft) behind the facing. From Figure 4.23a, the pipe in front of the facing is found to have increase in normalized moment up to 250 times, because the loading on the pipe is nonsymmetric. When the pipe is placed below the MSE wall, the maximum normalized moment is approximately 225 times that of the pipe without the MSE wall. A similar increase in the normalized thrust is evaluated when the pipe diameter is increased from 60.9 cm (24 in.) to 91.4 cm (36 in.). With the increase in pipe diameter, the maximum normalized moment on the perimeter of the pipe in front of the wall increases up to 625 times that of the pipe without an MSE wall. Similar to the previous case, the pipe (1.8 m behind the facing) experiences a normalized moment up to 550 times when there is no MSE wall. This shows the significant increase in the forces on the pipe and even more when placed behind the

TABLE 4.7  
Input Foundation Soil Parameters (Following INDOT [2022] Case Study).

Parameter	Value
Unit weight, $\gamma$	18.85 kN/m <sup>3</sup> (120 pcf)
Cohesion, $c$	200 kPa (29 psi)
Friction angle, $\phi$	28°
Elastic modulus, $E$	1000 MPa (145e3 psi)
Poisson's ratio, $\nu$	0.20
Dilation angle, $\psi$	0.0°

Note: All parameters are taken from INDOT (2022) except the stiffness of the reinforced soil, which is taken from Damians et al. (2021); the stiffness of the retained and foundation soils is assumed.

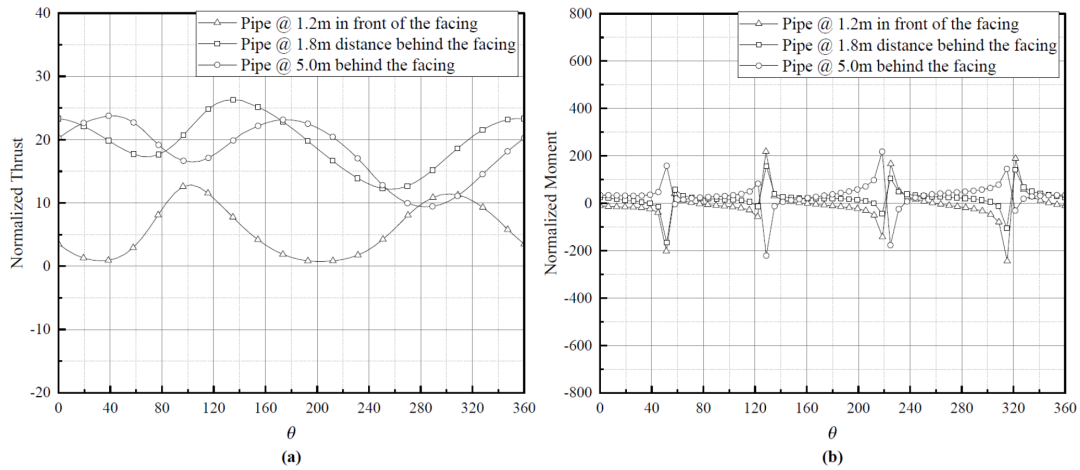


Figure 4.23 Forces on the Pipe (a) Normalized Thrust and (b) Normalized Moment.

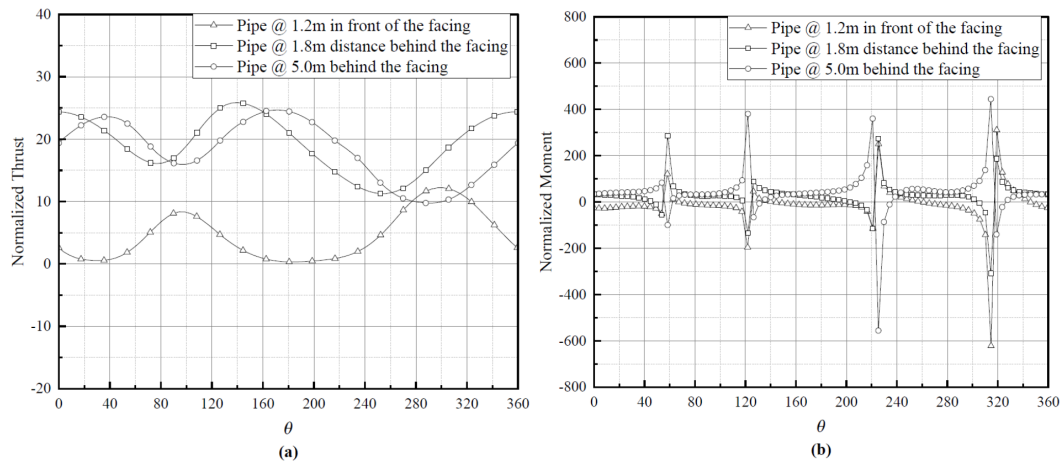


Figure 4.24 Forces on the Pipe (a) Normalized Thrust and (b) Normalized Moment.

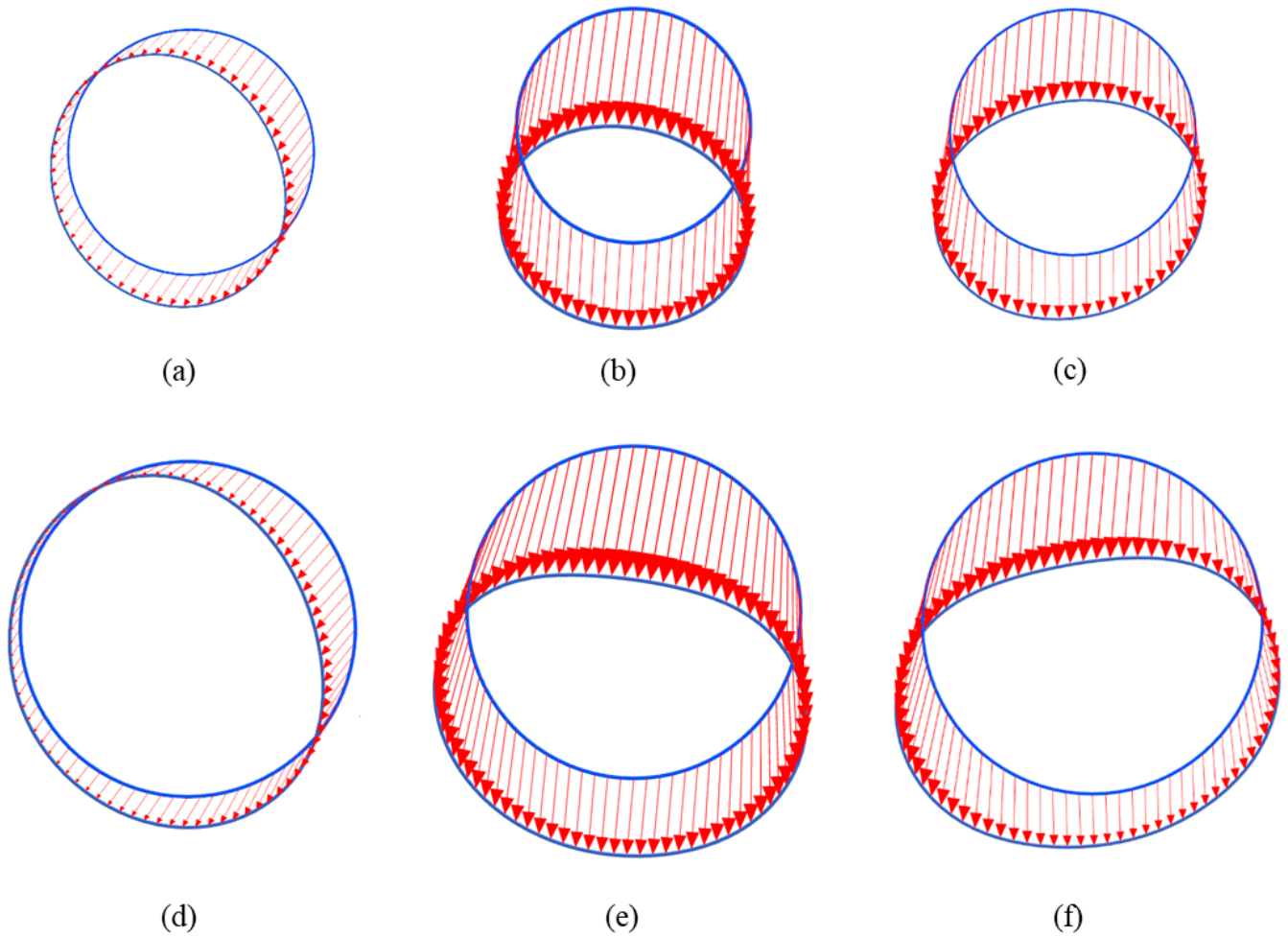
facing. The increase in pipe diameter causes substantial increase in the normalized moment.

Figure 4.25 is the deformed shape of the pipe and the deformation is scaled to 100 times, located in the foundation soil placed behind and in front of the wall. It is noted from Figure 4.25a that the pipe in front of the MSE wall undergoes horizontal and vertical deformation and the deformation is also consistent with the large diameter pipe (Figure 4.25d). The pipe placed 1.8 m behind the facing deformation mode is analogous to when placed in front of the facing, shown in Figure 4.25b. The ovaling mode of deformation is noticed when pipe is placed 5 m (16.4 ft) behind the facing. The deformation mode of the pipe is clearly visible when the pipe diameter is increased. The assessment indicates that the existence of an MSE wall would indeed impact the thrust and moment of the pipe. It is further noted that the pipe undergoes varied deformation depending on its placement. The subsequent focus is directed towards examining the presence of a pipe on the MSE wall.

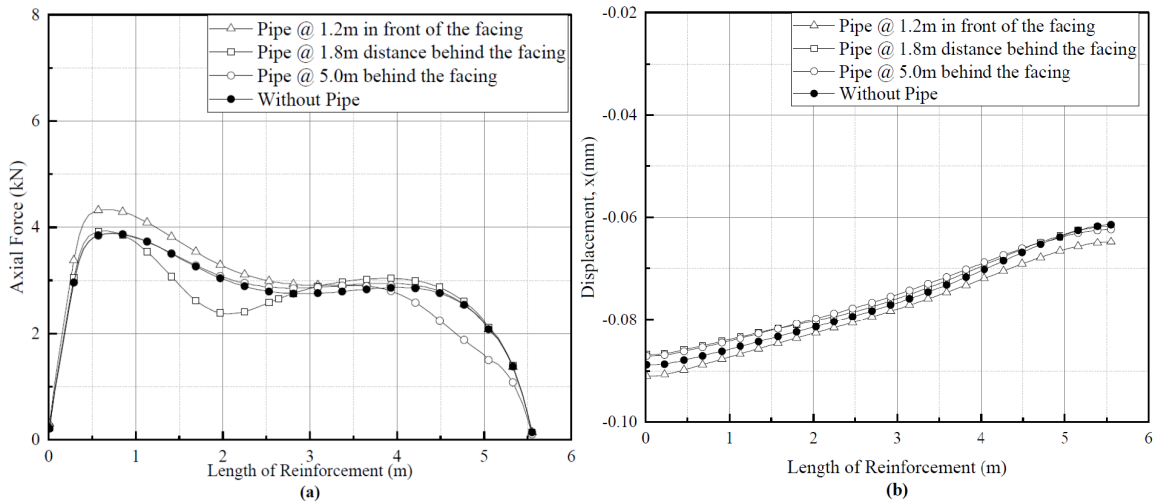
Figure 4.26a and Figure 4.26b are the axial force and displacements in the metal strips in the first layer of reinforcement.

It is found that when the pipe is placed in front of the wall the maximum increase in axial force is 8–9%. When it is placed beneath the MSE wall, the maximum increase in axial force is decreased at both locations. Figure 4.26b is a plot of axial displacements in the metal strips; it is found that the strip undergoes 7% maximum displacement when it is placed in front of the wall. The displacement of the strip is considerably reduced to 2% when it is placed behind the wall. Therefore, when the pipe is placed in front of the wall it affects the strip axial force and axial displacement. However, when a pipe is placed behind, it affects the pipe, resulting in an increase in thrust and moment.

Figure 4.28 and Figure 4.29 plot the slip in the first layer of reinforcement. As discussed before, slip is the measure of the frictional demand in the reinforcement. From Figure 4.28, it is obvious that the pipe diameter led to a very significant change in slip and aligns with the axial force. However, with the increase in pipe diameter, the slip in the first layer of reinforcement has increased and happens to be consistent with the axial force and displacement, as shown in Figure 4.27 and Figure 4.29.



**Figure 4.25** Deformed Shape of the Pipe Placed at (a) 1.2 m (3.9 ft) in Front of the Wall,  $D = 60.9$  cm (24 in.); (b) 1.8 m (5.9 ft) Behind the Wall,  $D = 60.9$  cm (24 in.); (c) 5 m (16.4 ft) Behind the Wall,  $D = 60.9$  cm (24 in.); (d) 1.2 m (3.9 ft) in Front of the Wall,  $D = 91.4$  cm (36 in.); (e) 1.8 m (5.9 ft) Behind the Wall,  $D = 91.4$  cm (36 in.); (f) 5 m (16.4 ft) Behind the Wall,  $D = 91.4$  cm (36 in.).



**Figure 4.26** First Layer of Reinforcement: (a) Axial Force and (b) Displacement. Pipe Diameter  $D = 60.9$  cm (24 in.)

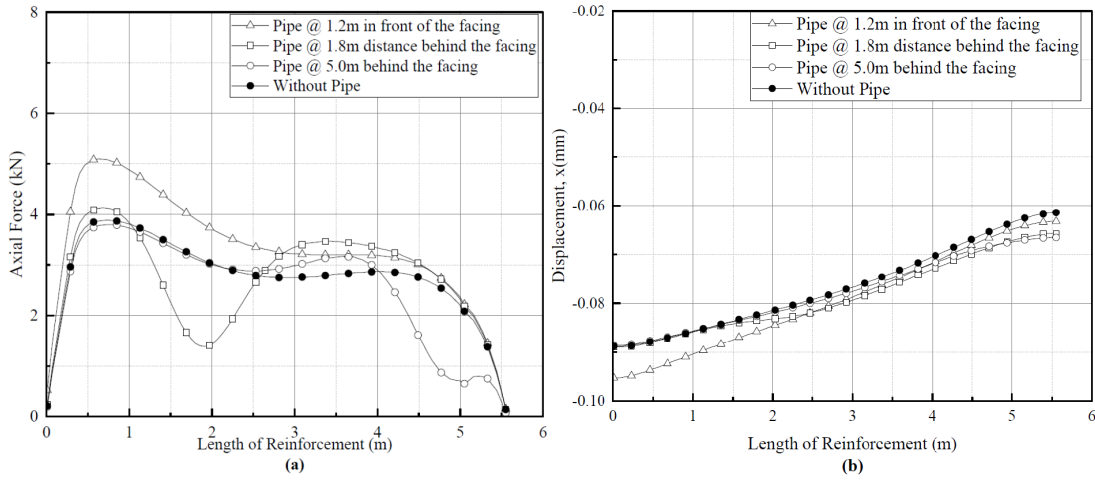


Figure 4.27 First Layer of Reinforcement: (a) Axial Force and (b) Displacement. Pipe Diameter  $D = 91.4$  cm (36 in.).

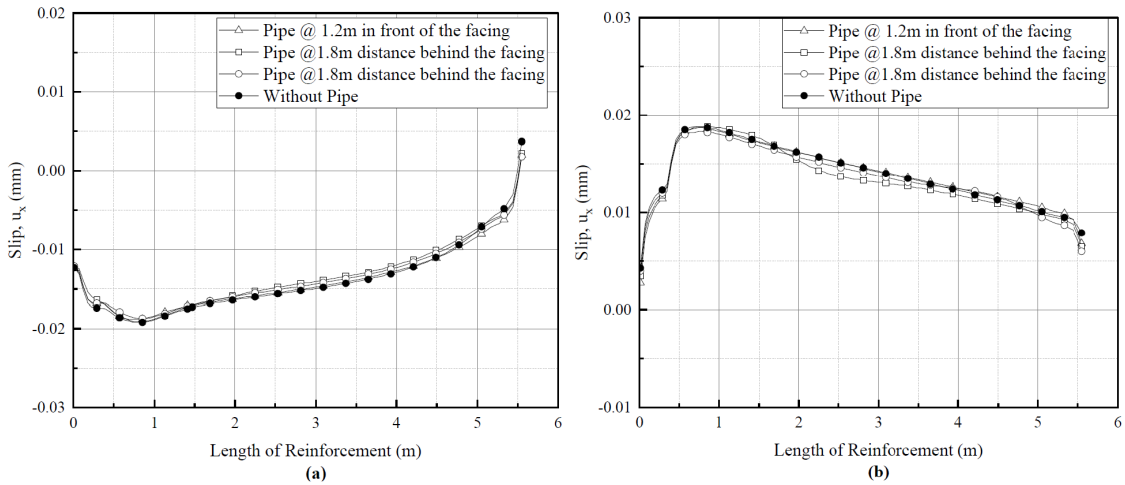


Figure 4.28 Slip in the First Layer of Reinforcement: (a) Upper Contact and (b) Lower Contact. Pipe Diameter  $D = 60.9$  cm (24 in.).

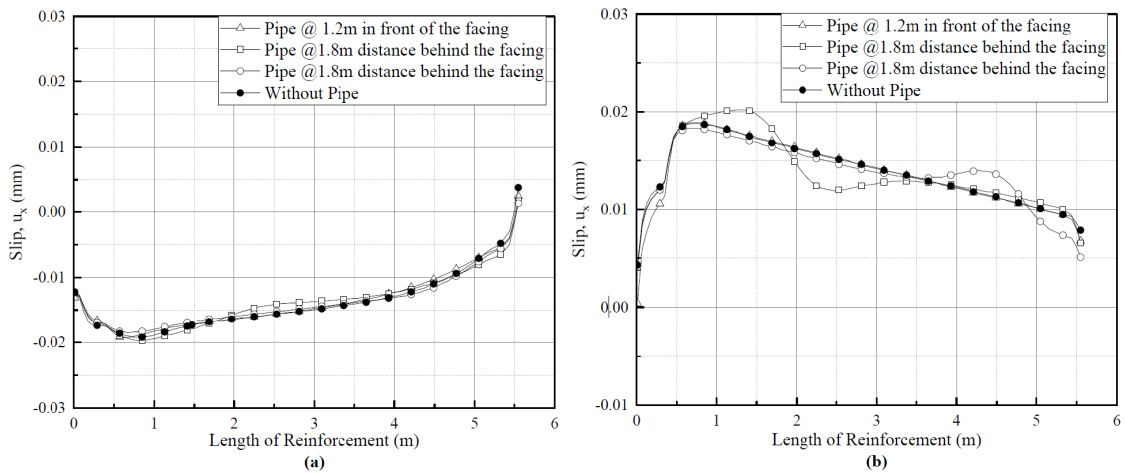
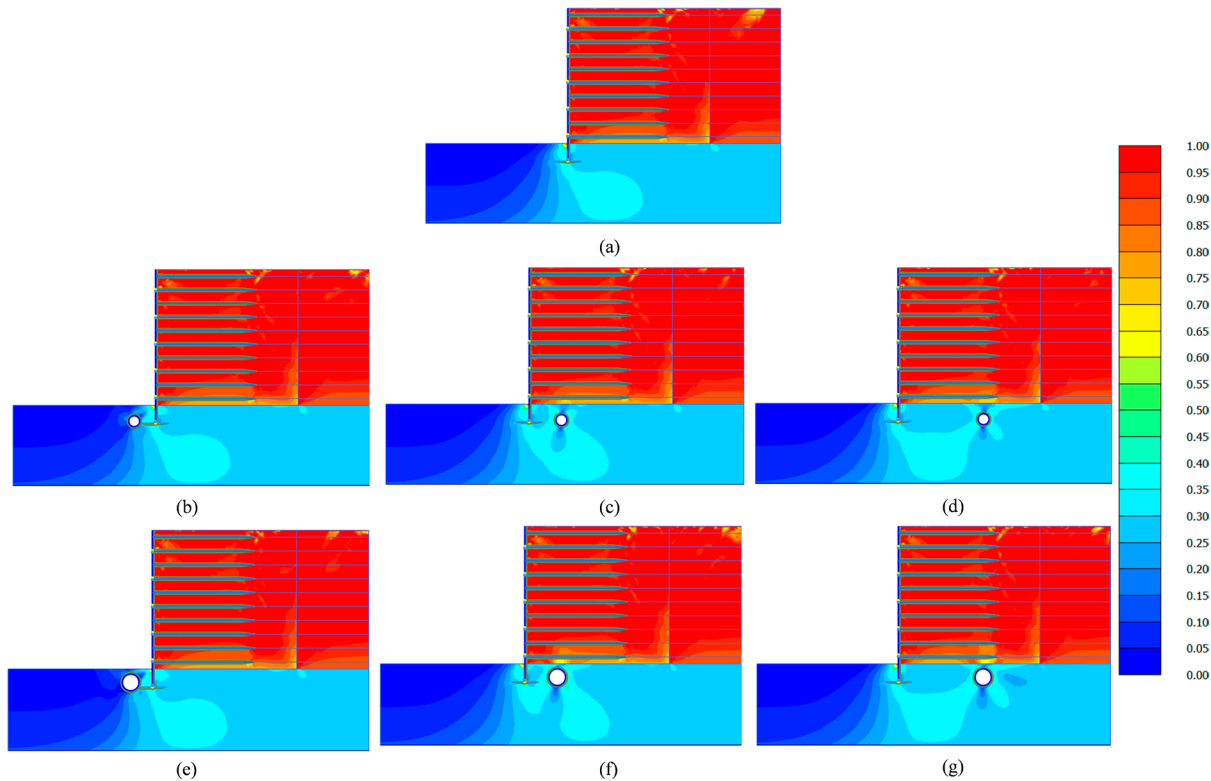


Figure 4.29 Slip in the First Layer of Reinforcement: (a) Upper Contact and (b) Lower Contact. Pipe Diameter  $D = 91.4$  cm (36 in.).



**Figure 4.30** Shear Stress Capacity vs. Demand for the Following Cases: (a) Base Case; (b) 1.2 m (3.9 ft) in Front of the Wall,  $D = 60.9$  cm (24 in.); (c) 1.8 m (5.9 ft) Behind the Wall,  $D = 60.9$  cm (24 in.); (d) 5 m (16.4 ft) Behind the Wall,  $D = 60.9$  cm (24 in.); (e) 1.2 m (3.9 ft) in Front of the Wall,  $D = 91.4$  cm (36 in.); (f) 1.8 m (5.9 ft) Behind the Wall,  $D = 91.4$  cm (36 in.); and (g) 5 m (16.4 ft) Behind the Wall,  $D = 91.4$  cm (36 in.).

This shows that the presence of a larger pipe led to an increase in the frictional demand of the reinforcement. The presence of a pipe does not change the global factor of safety, and the FOS of 1.88 remains conserved.

Figure 4.30 depicts the contours of mobilization of shear stress in the soil. The area of interest here is around the location of the pipe. It is interesting to see how the contours evolve due to the presence of the pipe near and away from the facing. A pipe close to the facing interacts with the wall; however, a pipe away from the facing does not interact, and the mobilization of shear stress is confined near the pipe. This effect is highlighted with larger pipe diameters where it can be seen that the presence of a pipe near the facing increases the shear stress mobilization in the soil and subsequently the frictional demand in the nearby reinforcement.

#### 4.6 When the Pipe Diameter is Increased

This section studies the effects of increase in pipe diameter from 60.9 cm (24 in.) to 91.4 cm (36 in.) when placed in reinforced zone. The pipe diameter is larger than the spacing of the reinforcement; therefore, the metal strip is splayed at the maximum angle of  $15^\circ$ , as suggested by INDOT (2013) and FHWA (2009) (Figure 4.31). The four cases that will be explored in this section and the schematic are shown in Figure 4.1p–s). The center of the pipe is placed at a depth of 3.81 m (12.5 ft) from the

top of the wall ( $h = 3.81$  m [12.5 ft]) and located at a distance of 3 m (9.8 ft) and 5 m (16.4 ft) from the facing. The other case in which pipe is placed at  $h = 6.85$  m (22.5 ft) and again located at 3 m (9.8 ft) and 5 m (16.4 ft) from the facing panel. Like before, all the analysis is carried out in reference to the base case which comprise of MSE wall without pipe. The further illustration of reinforcement is kept similar.

Figure 4.32 to Figure 4.40 present the results of both the MSE wall with a pipe larger than reinforcement spacing and the MSE wall without the pipe. Figure 4.32b shows that the reinforcement below the pipe has the largest increase in the axial force, by 50–60% for the case  $h = 3.81$  m (12.5 ft). For deeper depth  $h = 6.85$  m (22.5 ft), substantial increase in axial force by 100% at  $x = 3$  m (9.8 ft) can be seen in Figure 4.33b. Important changes in axial force occur at the location of the pipe. Interestingly, as the pipe moves away from the wall facing, the reinforcement experiences a similar increase in the axial force. The reinforcement above and below the pipe experiences an increase of axial load when  $h = 3.81$  m (12.5 ft), with respect to the base case, is observed for  $x = 3$  m (9.8 ft) and 5 m (16.4 ft; Figure 4.32a), however, when  $h = 6.85$  m (22.5 ft), a general reduction in axial load is observed for the reinforcement above the pipe (Figure 4.33a).

Figure 4.34 and Figure 4.35 show the reinforcement axial displacement. The effects of the pipe on the reinforcement are more pronounced on the steel strip above the pipe. As one can

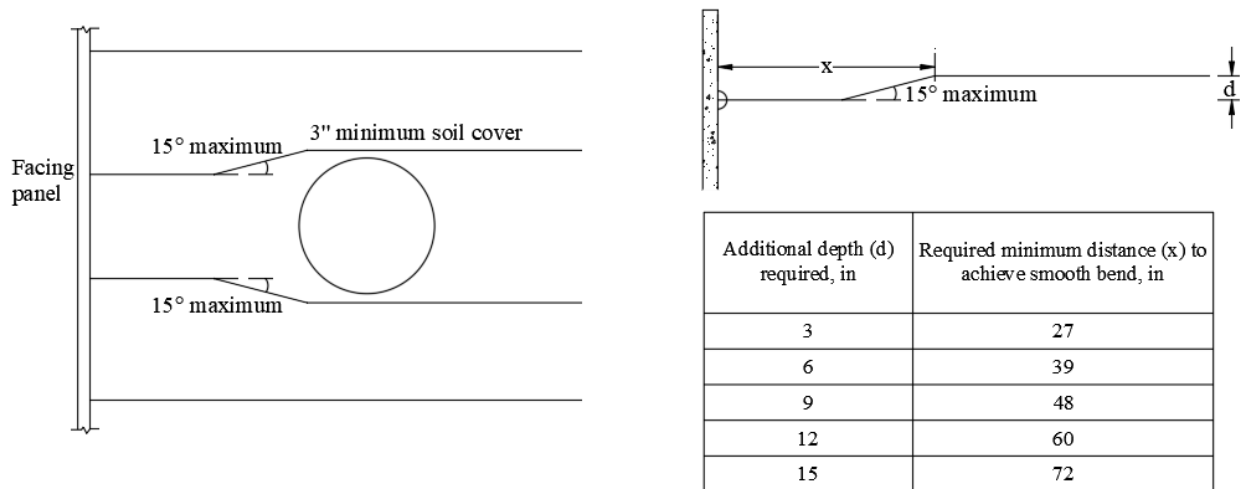


Figure 4.31 Guidelines for Inextensible Reinforcement (Redrawn From FHWA, 2009).

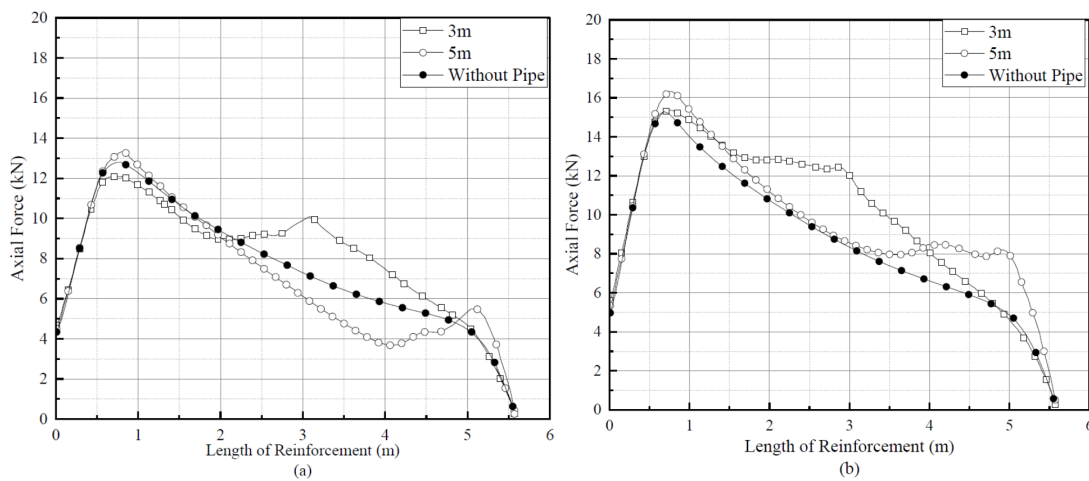


Figure 4.32 Axial Force in the Reinforcement With Distance From Facing Panel (a) Above the Pipe and (b) Below the Pipe. Pipe Location at  $h = 3.81$  m (12.5 ft).

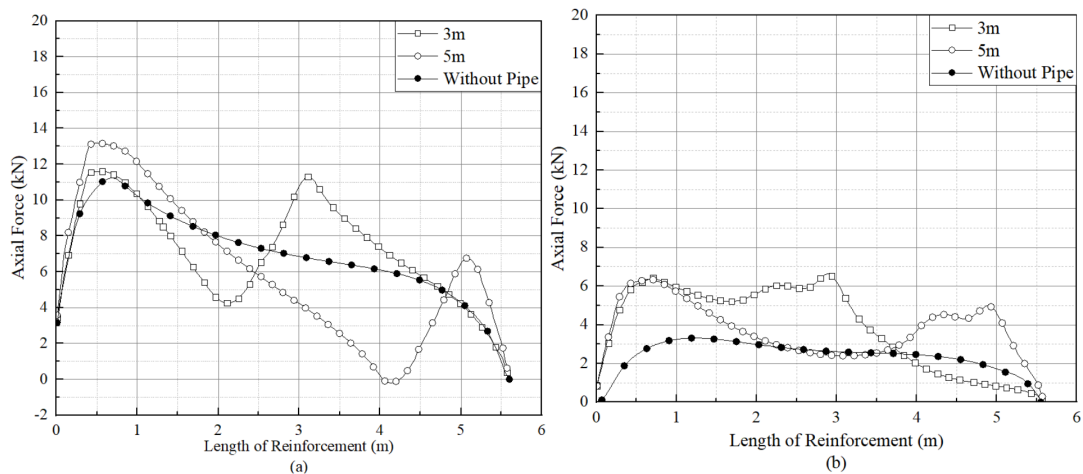
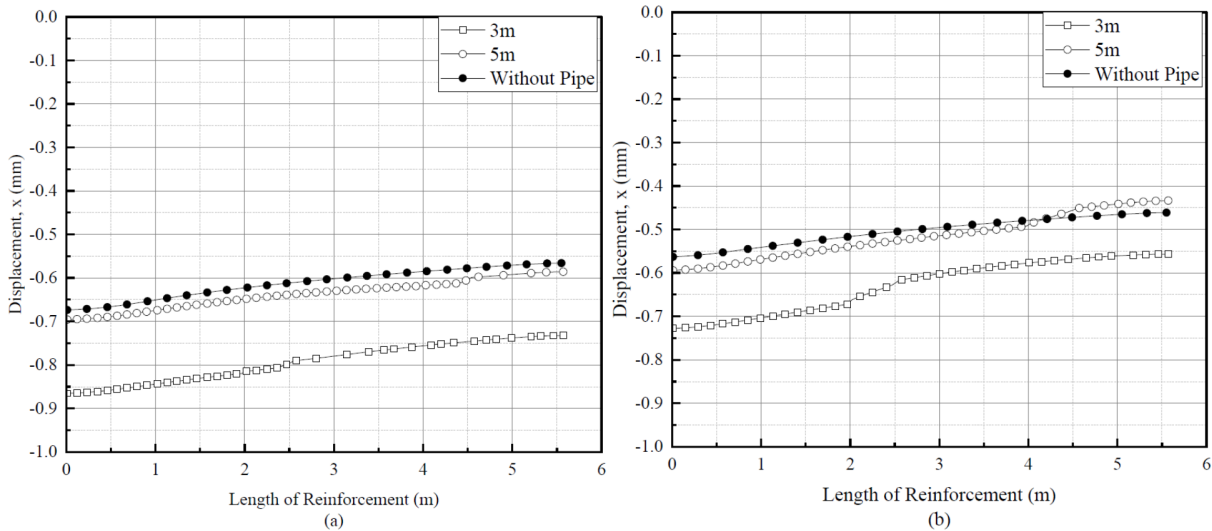
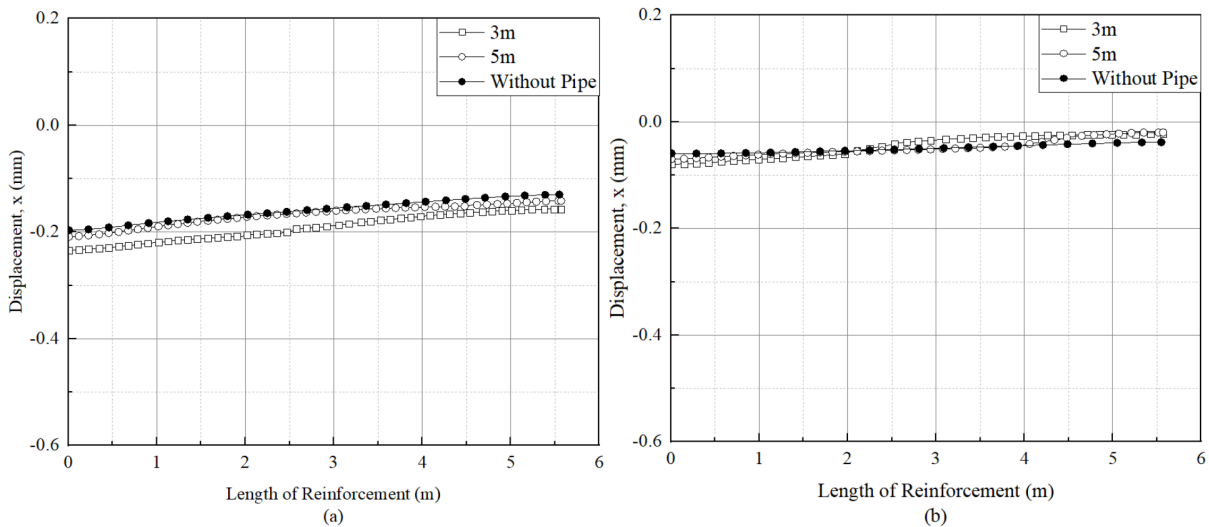


Figure 4.33 Axial Force in the Reinforcement With Distance From Facing Panel (a) Above the Pipe and (b) Below the Pipe. Pipe Location at  $h = 6.85$  m (22.5 ft).



**Figure 4.34** Displacements in the Reinforcement With Distance From Facing Panel (a) Above the Pipe and (b) Below the Pipe. Pipe Location at  $h = 3.81$  m (12.5 ft).



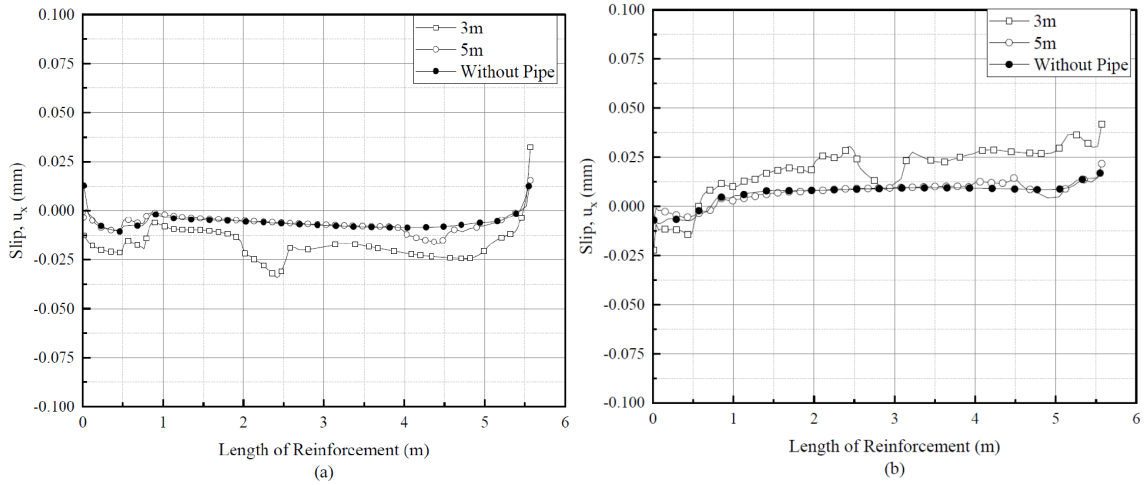
**Figure 4.35** Axial Force in the Reinforcement With Distance From Facing Panel (a) Above the Pipe and (b) Below the Pipe. Pipe Location at  $h = 6.85$  m (22.5 ft).

see in Figure 4.34a, Figure 4.35a, and Figure 4.35b, beyond the location where the pipe is placed, the displacement is rather constant. This is due to the large reduction of overburden above the reinforcement due to the bending of the steel strip.

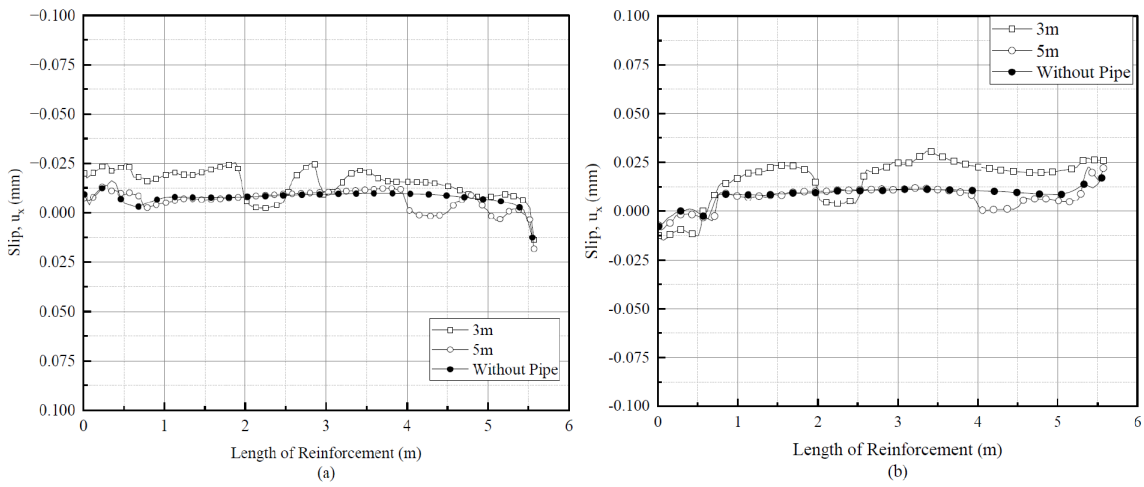
Figure 4.36 to Figure 4.39 illustrate the relative displacement/slip of the reinforcement above and below the pipe. The presence of the pipe increases the magnitude of the slip between the reinforcement and the soil throughout the reinforcement length. This effect occurs in both the reinforcements above and below the pipe (Figure 4.36 to Figure 4.39). It is noteworthy that the largest changes of slip occur at the location of the pipe. The increased slip denotes higher frictional forces mobilized between soil and reinforcement, and thus the results in Figure 4.36 to Figure 4.39

are consistent with those in Figure 4.32 and Figure 4.33. Clearly, the numerical results emphasize the complex interaction between the soil, the reinforcement, and the pipe.

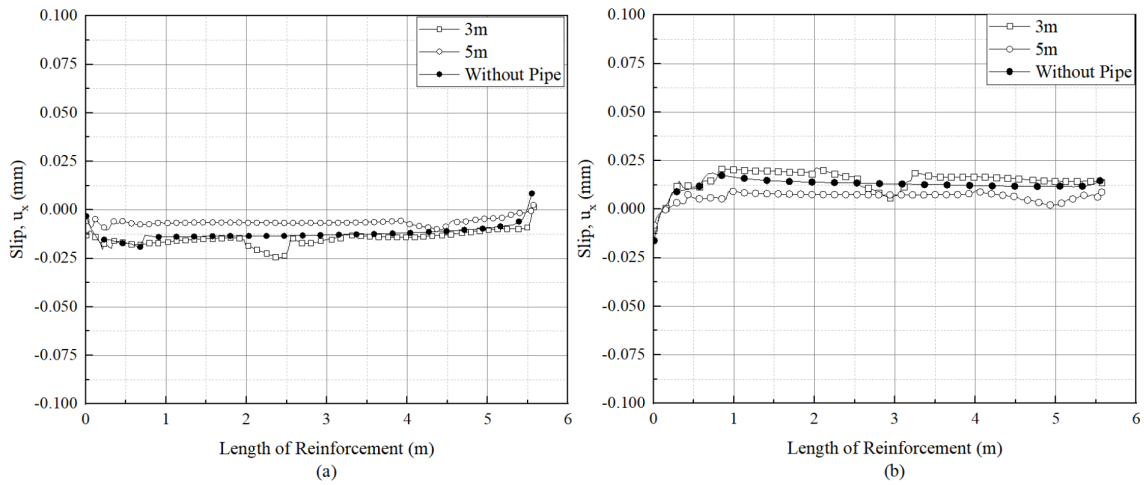
Figure 4.40 illustrates the contours of shear stress mobilization in the soil. It is evident that the presence of the pipe increases the shear stress in the surrounding soil. However, it should be noted that the foundation soil is characterized by high strength and stiffness, rendering the results less applicable. In all instances, the contours indicate an increase in shearing at the crown and invert, with a reduction at the spring lines. Additionally, the global factor of safety remains relatively constant across different depths and locations, though it has increased by 5–10% in every case (Table 4.8).



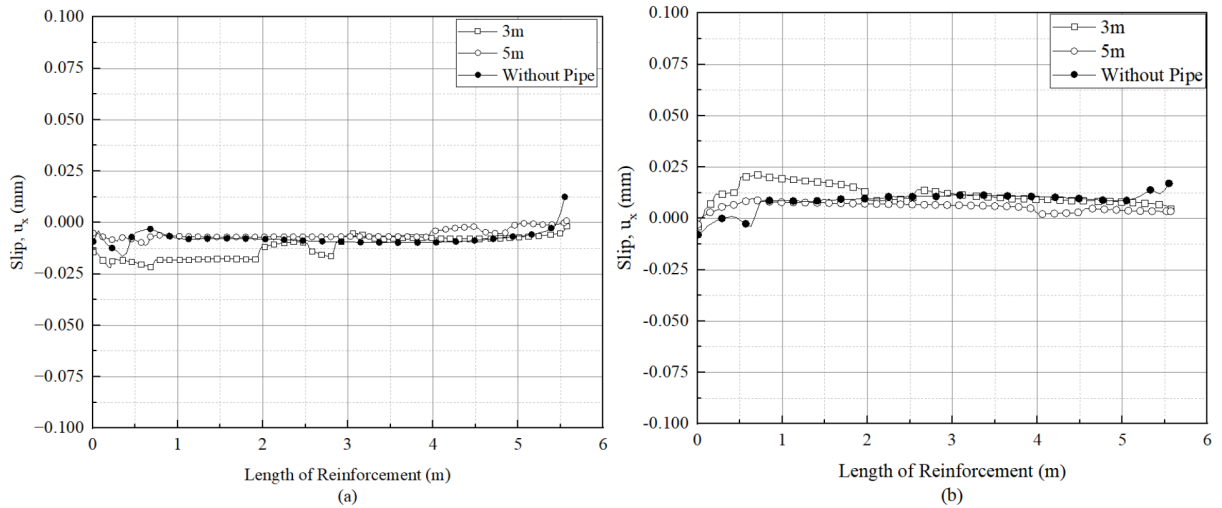
**Figure 4.36** Slip in the Reinforcement Above the Pipe for (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 3.81$  m (12.5 ft).



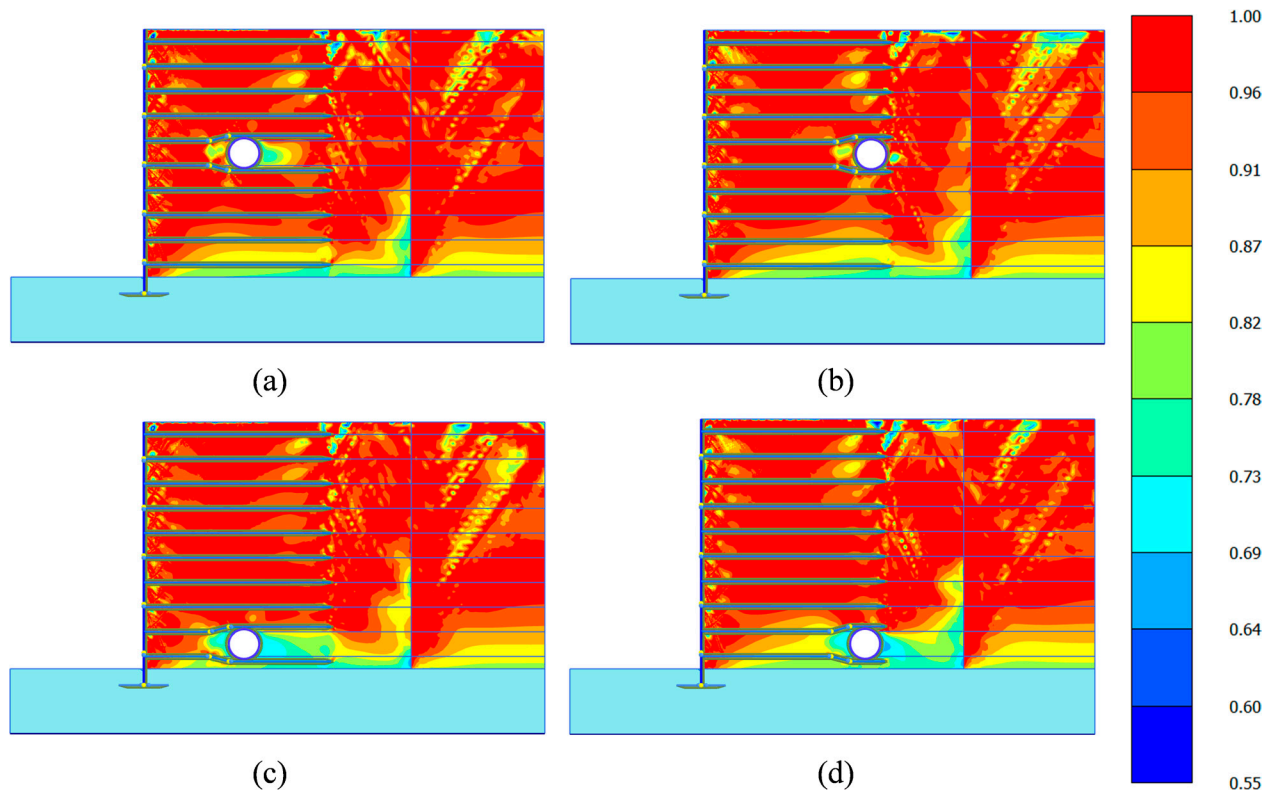
**Figure 4.37** Slip in the Reinforcement Below the Pipe for (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 3.81$  m (12.5 ft).



**Figure 4.38** Slip in the Reinforcement Above the Pipe for (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 6.85$  m (22.5 ft).



**Figure 4.39** Slip in the Reinforcement Below the Pipe for (a) Upper Contact and (b) Lower Contact. Pipe Location at  $h = 6.85$  m (22.5 ft).



**Figure 4.40** Shear Stress Capacity vs. Demand for the Following Cases: (a)  $h = 3.81$  m (12.5 ft),  $x = 3$  m (9.8 ft); (b)  $h = 3.81$  m (12.5 ft),  $x = 5$  m (16.4 ft); (c)  $h = 6.85$  m (22.5 ft),  $x = 3$  m (9.8 ft); and (d)  $h = 6.85$  m (22.5 ft),  $x = 5$  m (16.4 ft).

**TABLE 4.8**  
**Summary of the FOS from Cases p-s (Figure 4.1).**

Pipe Location	$x = 3$ m (9.8 ft)	$x = 5$ m (16.4 ft)
$h = 3.81$ m (12.5 ft)	1.93	2.00
$h = 6.85$ m (22.5 ft)	1.89	1.98

#### 4.7 Summary

This study examines the interaction between a MSE wall and a pipe oriented perpendicular to its cross-section using numerical simulations in PLAXIS 2D. It considers three distinct scenarios: (1) a pipe located within the reinforced zone, (2) a pipe situated in

the foundation soil, and (3) a pipe with a diameter exceeding the reinforcement spacing, positioned in the reinforced zone. When pipe is located in the reinforced zone, it is found that the presence of a pipe in a soil-reinforcement system significantly influences the behavior of the reinforcement, affecting axial force, displacement, and slip. Axial force increases, especially in the reinforcement directly beneath the pipe, with the effect more pronounced when the pipe is placed near the top of the wall and away from the wall's face. Conversely, when the pipe is positioned deeper, axial force decreases as it moves away from the wall's face. The axial displacement of the reinforcement also increases, particularly above the pipe, with the greatest displacement occurring when the pipe is near the top of the wall. Additionally, the pipe induces a substantial increase in slip, particularly in the upper contacts of the reinforcement near its location, due to increased mobilization of friction between the soil and reinforcement. These effects are localized near the pipe and extend to a distance of 2–2.5 times the pipe's diameter, while global stability of the system can decrease by up to 1–2%. Overall, the pipe causes complex interactions in the soil-reinforcement system, with varying impacts on different layers based on their proximity to the pipe. Larger pipe in the foundation can lead to higher frictional force mobilization in the reinforcement, causing an increase of 8–9% in the axial force. Interestingly, the global stability of the wall is remained conserved. Pipe buried behind the facing panel tend to show ovaling type of deformation. Pipe larger than the reinforcement spacing increase axial forces by up to 100% compared to the case of a wall without the pipe. The largest changes occur in the reinforcement below the pipe. Also, stresses within the reinforced soil are affected. Indeed, the shear capacity of the reinforced soil near to the wall facing and at the end of the reinforcement is completely mobilized when there is a pipe. Overall, the study emphasizes the need to specifically consider in MSE wall design the presence of a horizontal obstruction within the reinforced soil.

## 5. 3D NUMERICAL MODELING OF THE MSE WALL

### 5.1 Introduction

The chapter focuses on the 3D numerical modeling of an MSE wall intersected by a utility either within the reinforced zone or in the foundation soil. Section 5.2 outlines the various cases examined and the methodology used to accommodate the utility in the reinforced zone and the foundation soil. Section 5.3 presents the results of all the modeled cases. Finally, Section 5.4 summarizes the key findings from the study.

### 5.2 3D Numerical Modeling

This chapter presents the Finite Element analyses completed for an MSE wall incorporating a horizontal obstruction. The model replicates an actual wall constructed by INDOT on Interstate 465 (I-465; INDOT, 2022), duplicating its dimensions, characteristics, and soil properties. The software used for the 3D numerical simulation is PLAXIS 3D. The cross-section of the wall and input parameters are consistent with the 2D numerical model discussed in Chapter 4. The pipe

diameter is 1.22 m, and the 2D numerical model is extruded into the third dimension with a width of 12 m.

All soils are modeled using the Mohr-Coulomb constitutive model with a nonassociated flow rule, while the reinforcement and pipe are modeled as linear elastic materials. The pipe is positioned at various angles within the reinforced wall to examine its effect on the wall's stability. Figure 5.1a–e provides a schematic of the MSE wall with the pipe. The objective is to assess the impact of the pipe intersecting the reinforced soil. The pipe may intersect the wall either perpendicular or at an angle to the facing while crossing the reinforced zone. The foundation of the wall is assumed stiff. To accommodate the pipe at an angle, the reinforcement needs to be adjusted either by cutting or inclining it. In practice, reinforcements are typically adjusted by inclining them, and this study aims to compare the effects of these two procedures on the wall and the reinforcement.

Additionally, the pipe may interact with the foundation soil at various depths and angles; Figure 5.1f–i illustrates the scenarios with the pipe inside the foundation soil.

#### 5.2.1 Methodology

**5.2.1.1 Pipe Placed in the Reinforced Backfill.** This study explores the stability of a wall with a circular pipe placed at various angles, intersecting the wall and influencing its components. Numerical simulations are conducted with the pipe's center at a depth of 7 m (23 ft) from the top of the wall. The pipe's exterior diameter is 1.22 m (48 in.). The following configurations are explored:

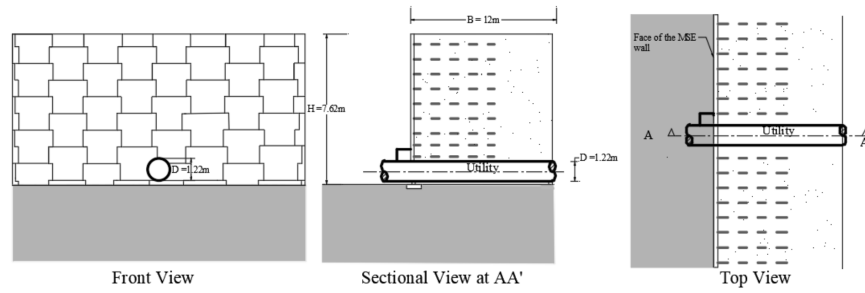
- Case 1: Pipe perpendicular to the wall (Figure 5.1a).
- Case 2: Pipe at a 15°, with reinforcements affected by the pipe cut (Figure 5.1b).
- Case 3: Pipe at a 30°, with reinforcements affected by the pipe cut (Figure 5.1c).
- Case 4: Pipe at a 15°, with reinforcements affected by the pipe inclined (Figure 5.1d).
- Case 5: Pipe at a 30°, with reinforcements affected by the pipe inclined (Figure 5.1e).

The study assesses the overall stability of the wall and its components under these conditions.

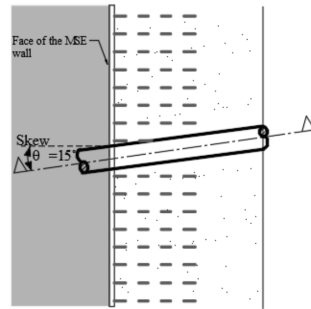
**5.2.1.1.1 Case 1: Pipe Perpendicular to the Wall.** In this case (Figure 5.1a) the model is 3D, with the MSE wall dimensions 12 m (39.4 ft) length, 12 m (39.4) width, and 7.62 m (25 ft) depth. The model boundaries have rollers in the two horizontal directions (except wall facing) and are placed far enough from the pipe such that there are no boundary effects (Figure 5.2a).

The 3D model is built in stages/layers, similar to the 2D cases. Because of the presence of the obstruction/pipe, the reinforcements occupied by the pipe are removed. For the analysis, the steel strips are numbered as 1, 2, 3, and 4 from the center of the pipe, for each layer (Figure 5.2b).

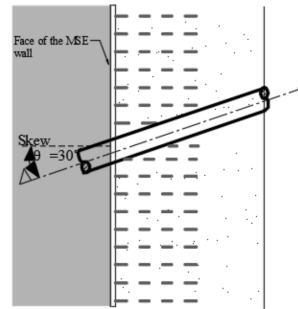
**5.2.1.1.2 Case 2: Pipe at a 15° With Reinforcements Affected by the Pipe Cut.** In this case (Figure 5.1b), the pipe is running at an angle of 15° from perpendicular to the wall facing



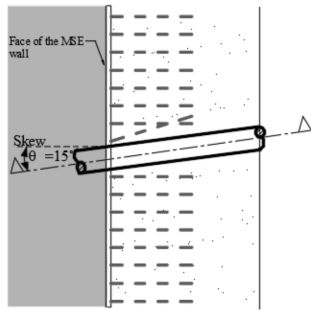
(a)



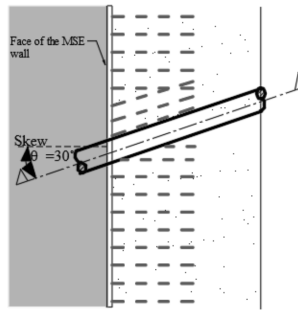
(b)



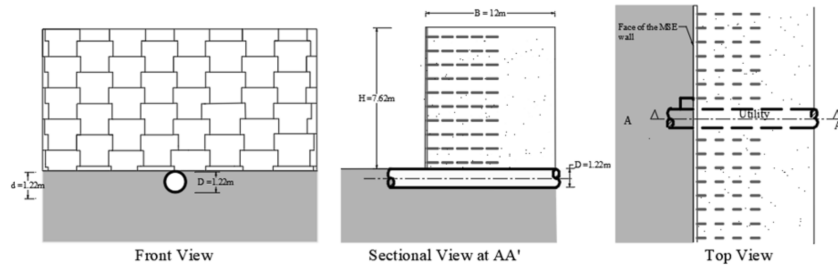
(c)



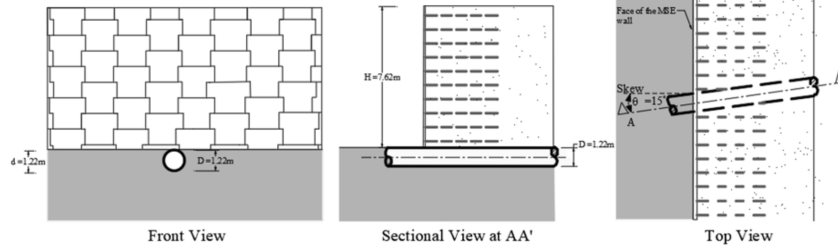
(d)



(e)

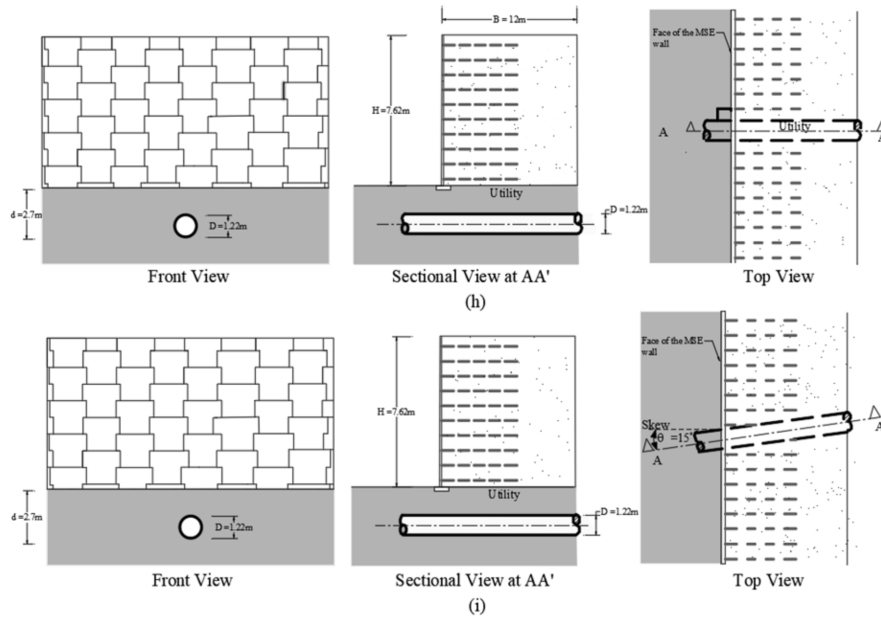


(f)

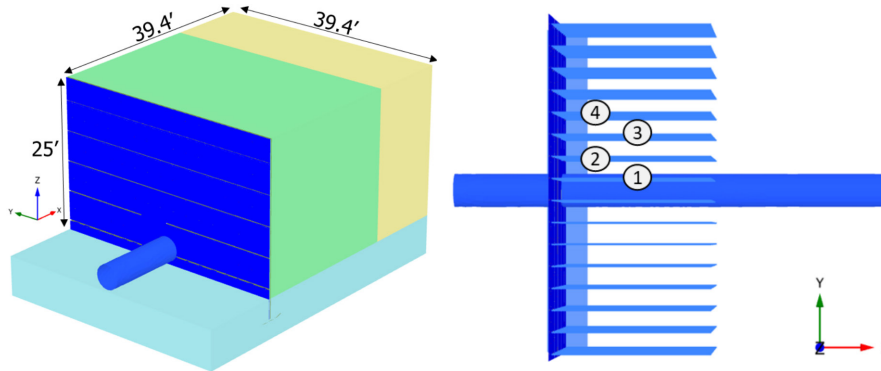


(g)

**Figure 5.1** Schematic Diagram of the MSE Wall With the Intersecting Pipe in the Reinforced Soil With: (a) Pipe Perpendicular to the Face of the Wall; (b) at  $15^\circ$  With Cut Reinforcements; (c) at  $15^\circ$  With Inclined Reinforcements; (d) at  $30^\circ$  With Cut Reinforcements; (e) at  $30^\circ$  With Inclined Reinforcements; With Pipe in the Foundation Soil With: (f) Pipe Below the Wall and Perpendicular to the Wall; (g) Pipe Below the Wall and at  $15^\circ$  With the Wall; (Continued on Next Page).



**Figure 5.1 (Continued)** Schematic Diagram of the MSE Wall With the Intersecting Pipe in the Reinforced Soil With: (h) at a Depth Under the Wall and Perpendicular to the Wall; and (i) at a Depth Under the Wall and at 15° With the Wall.



**Figure 5.2** Case 1. 3D Numerical Model (a) MSE Wall With a Pipe Running Perpendicular to the Wall and (b) Top View of Reinforcement and Pipe.

(Figure 5.3a). The pipe intersects the reinforcement at an angle of 15°, hence the need to cut/remove the steel strips affected by the pipe. The steel strips around the pipe are numbered 1, 2, 3, and 4 for each layer (Figure 5.3b).

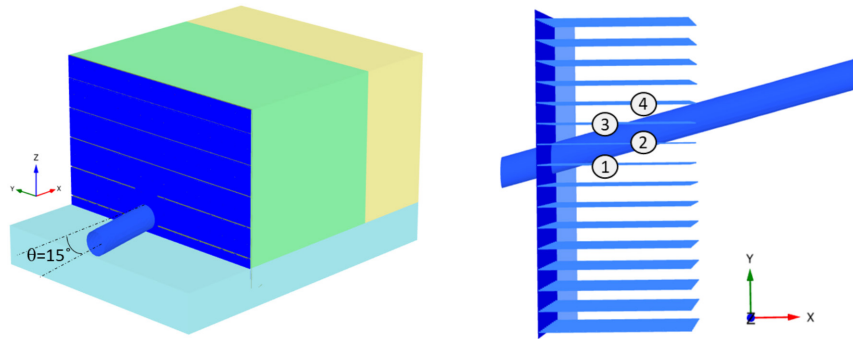
**5.2.1.1.3 Case 3: Pipe at a 30° With Reinforcements Affected by the Pipe Cut.** Case 3 (Figure 5.1c) is similar to Case 2 except that the pipe is running at an angle of 30° (Figure 5.4). In this case, the pipe is intersecting a large number of strips, which either need removed or cut. The reinforcement around the pipe is numbered from 1 to 5 for each layer (Figure 5.4).

**5.2.1.1.4 Case 4: Pipe at a 15° With Reinforcements Affected by the Pipe Inclined.** Case 4 (Figure 5.1d) depicts the same case as 2, except that the reinforcement affected by the pipe is rotated parallel to the pipe. The reinforcements are numbered from 1 to 4, the same way as before, as shown in Figure 5.5.

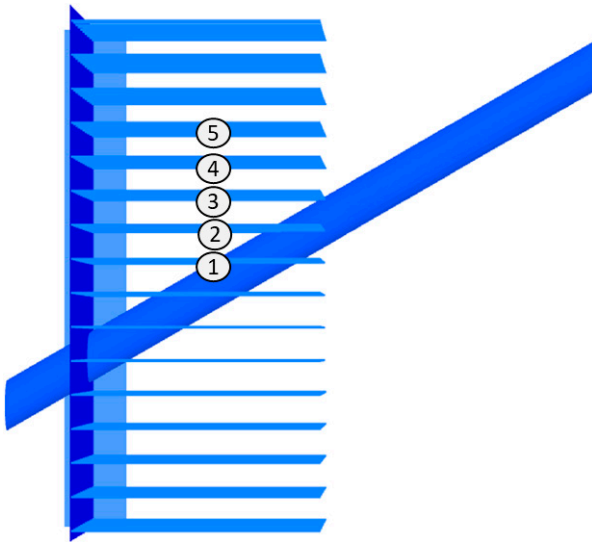
**5.2.1.1.5 Case 5: Pipe at a 30° With Reinforcements Affected by the Pipe Inclined.** In this case (Figure 5.1e), the pipe is at an angle of 30° and, again, the reinforcements affected are rotated parallel to the pipe. The strips are numbered from 1 to 5 in Layer 3 and 4. Additionally, the reinforcements 2 to 5 in Layers 1 and 2 are parallel to the pipe (Figure 5.6).

**5.2.1.2 Pipe Placed in the Foundation Soil.** The pipe may also be found in the foundation soil and may impact the overall stability of the wall and its components. The following are the cases that will be explored:

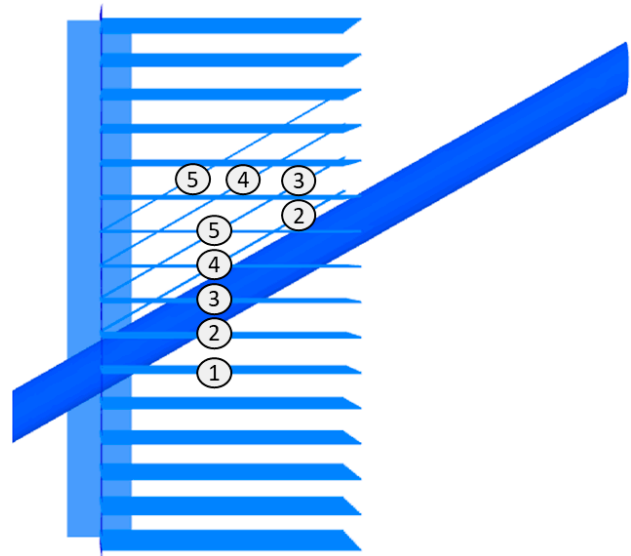
- Case 6: Pipe at a depth of invert  $d = 1.22$  m (4 ft) and perpendicular to the wall (Figure 5.1f).
- Case 7: Pipe at a depth of invert  $d = 1.22$  m (4 ft) and at an angle of 15° (Figure 5.1g).
- Case 8: Pipe at a depth of invert  $d = 2.70$  m (8.9 ft) and perpendicular to the wall (Figure 5.1h).



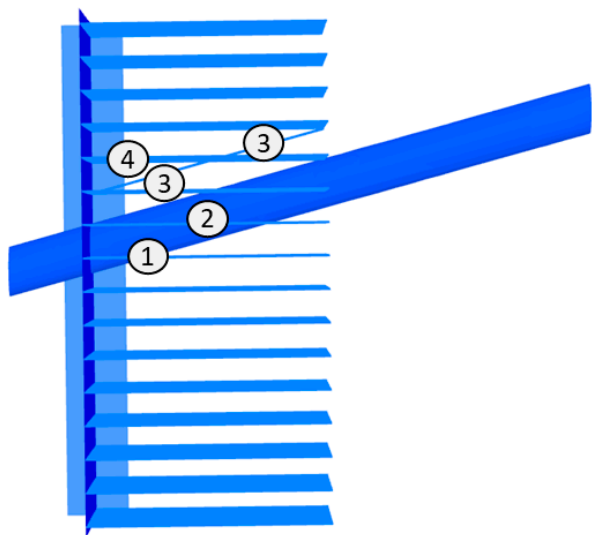
**Figure 5.3** Case 2. 3D Numerical Model (a) MSE Wall With a Pipe Running at an Angle of 15° to the Wall and (b) Top View of Reinforcement and Pipe.



**Figure 5.4** Case 3. Top View of Reinforcement and Pipe. Pipe at an Angle of 30°.



**Figure 5.6** Case 3. Top View of Reinforcement and Pipe. Pipe at an Angle of 30°.



**Figure 5.5** Case 4. Top View of Reinforcement and Pipe. Pipe at an Angle of 15°.

- Case 9: Pipe at a depth of invert  $d = 2.70$  m (8.9 ft) and at an angle of 15° (Figure 5.1i).

The study evaluates the overall stability of the wall and its components under these conditions. The depth of the foundation soil is 6 m (19.7 ft). The geometry of the numerical model is depicted in Figure 5.7.

*5.2.1.2.1 Case 6: Pipe at a Depth of Invert  $d = 1.22$  m and Perpendicular to the Wall.* In this case (Figure 5.1f), the pipe is parallel to the MSE wall and the center of the pipe is located at a depth of 60.9 cm. The reinforcement is numbered from 1 to 4, for Layers 1 and 2, as shown in Figure 5.8.

*5.2.1.2.2 Case 7: Pipe at a Depth of Invert  $d = 1.22$  m and at an Angle of 15°.* In Case 7 (Figure 5.1g), the pipe is at an angle of 15° and its center is located at a depth of 60.9 cm (24 in.). Once more, the reinforcements are numbered from 1 to 4, for each layer see Figure 5.9.

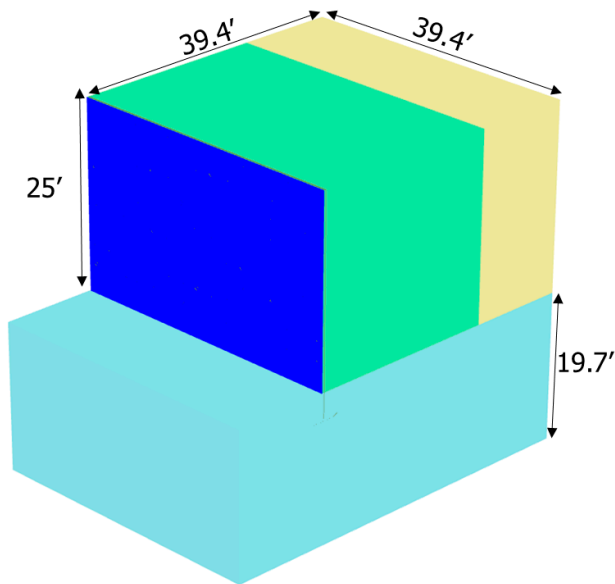


Figure 5.7 3D Numerical Model.

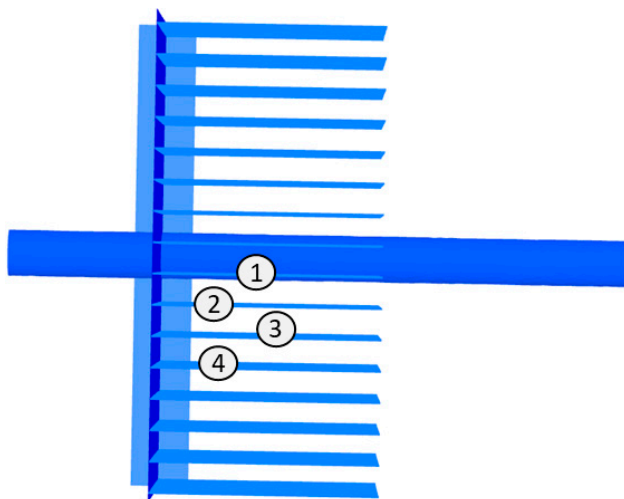


Figure 5.8 Top View of Reinforcement and Pipe. Pipe Running Perpendicular to the Wall.

5.2.1.2.3 Cases 8 and 9: Pipe at a Depth of Invert  $d = 2.70$  m and Perpendicular to the Wall and at an Angle of  $15^\circ$ . The two scenarios consider a pipe located deep enough such that its influence on the wall is negligible, that is, at an invert depth of 2.70 m (8.9 ft). In one scenario, the pipe is placed perpendicular to the wall (Figure 5.1 h), and in the other scenario, at an angle of  $15^\circ$  (Figure 5.1i). The reinforcements are numbered following the convention in Figure 5.8 for the pipe perpendicular, and in Figure 5.9 for the pipe at an angle.

### 5.3 Results

This section presents the results of the axial force, axial displacement, and slip in the reinforcement for the cases

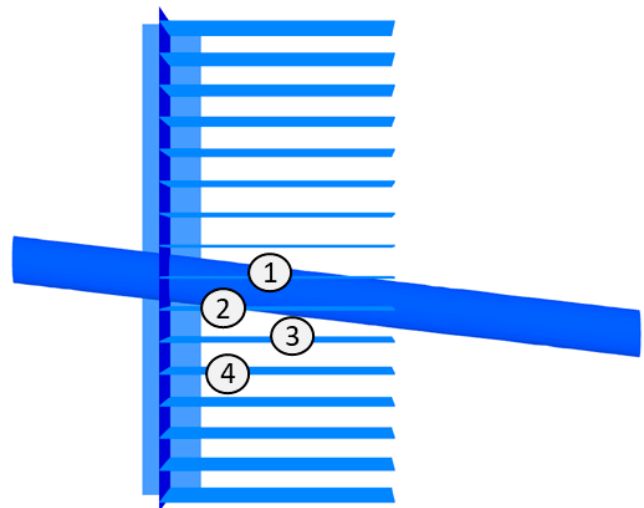


Figure 5.9 Top View of Reinforcement and Pipe. Pipe at an Angle of  $15^\circ$ .

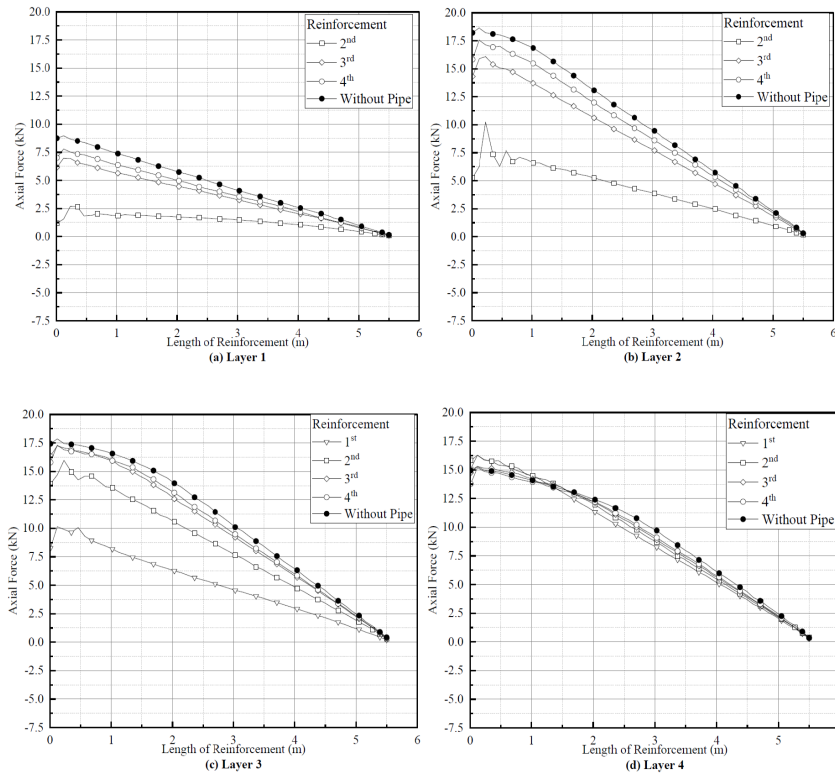
investigated. Also, the overall factor of safety is evaluated, as well as the shear stress capacity of the soil.

#### 5.3.1 Pipe Inside the Reinforced Soil

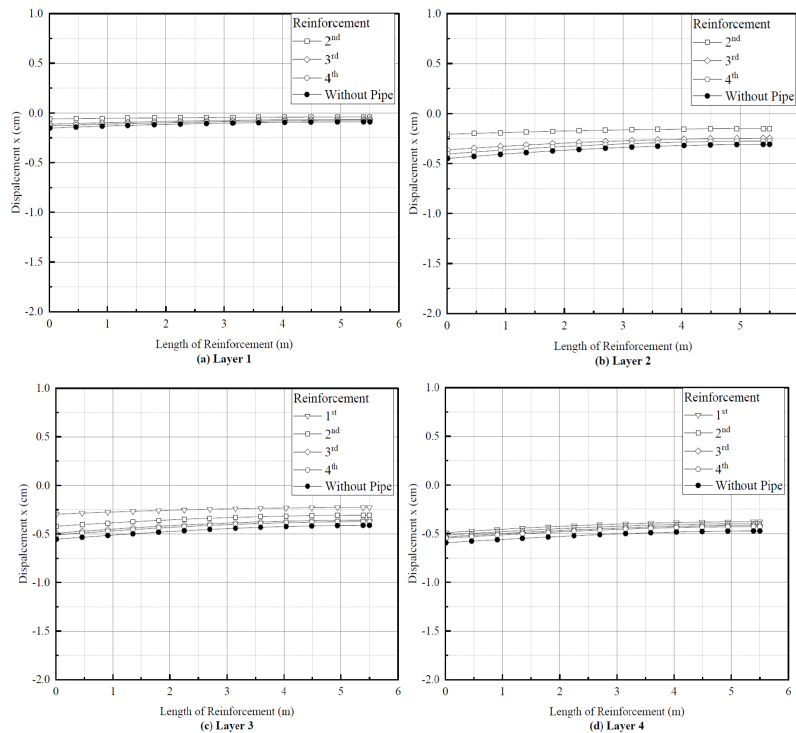
**5.3.1.1 Case 1: Pipe Perpendicular to the Wall (Figure 5.1a).** Figure 5.10 to Figure 5.12 give comparisons between the pipe running perpendicular to the wall and the base case (MSE wall with no pipe). Figure 5.10 displays the axial force in the reinforcements, from the 1<sup>st</sup> to the 4<sup>th</sup> (Figure 5.2b). As one can see, the presence of the pipe causes a decrease in axial force in strips 1, 2, and 3, with the largest decrease in the reinforcement adjacent to the pipe. The effects of the pipe on the reinforcement decrease with distance, and by the 4<sup>th</sup> strip, the changes in axial force become small. Overall, the presence of the pipe results in a notable drop in the axial force of the reinforcement next to it. This is because the pipe itself provides frictional resistance along its circumference, thus contributing to the overall stability of the wall.

Figure 5.11 is a plot of the axial displacement along the length of the reinforcement. Strips 2 and 3 show the largest reduction in displacement, approximately 40–50%. As with the axial force, the presence of the pipe causes a decrease in axial displacement of the reinforcement near the pipe, and this effect decreases as the reinforcement is farther away from the pipe. This is consistent with the axial force results, as the presence of the pipe reduces the frictional demand on the reinforcement.

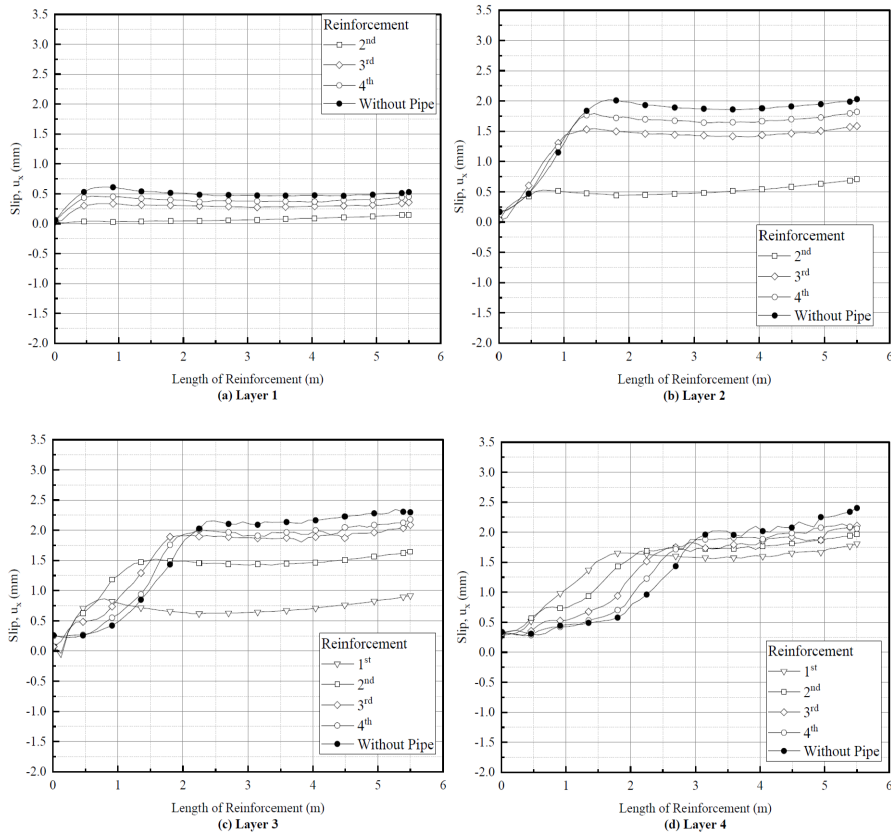
Figure 5.12 is a plot of the axial slip of reinforcements 1 to 4 in Layers 1 to 4 (Figure 5.2b). The trends shown are similar to those observed for the axial force and axial displacement. The slip in the reinforcement adjacent to the pipe is significantly reduced. An interesting observation is that the influence of the pipe is approximately 2–2.5 times its diameter. While it is expected that there will be an area around the pipe where the



**Figure 5.10** Case 1. Axial Force in the Reinforcement With Distance From the Facing Panel. Layers: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.2b for Reinforcement Numbering.



**Figure 5.11** Case 1. Axial Displacement in the Reinforcement With Distance From the Facing Panel. Layers: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.2b for Reinforcement Numbering.



**Figure 5.12** Case 1. Axial Slip in the Upper Contact of the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.2b for Reinforcement Numbering.

mechanical response is affected by the presence of the pipe, the extent of the influence applies only to the case investigated and cannot be generalized. What seems to be fundamental is that the presence of the pipe has an overall positive effect on the local stability of the wall components.

The FOS is discussed later with Case 3. As it will be seen, the presence of the pipe has beneficial effects on the overall stability of the wall.

**5.3.1.2 Case 2: Pipe at a 15° With Reinforcements Affected by the Pipe Cut (Figure 5.1b).** The presence of the pipe results in the removal of the 1<sup>st</sup> reinforcement and the cutting of the 2<sup>nd</sup> reinforcement in Layers 1 and 2 (Figure 5.3b). Figure 5.13 to Figure 5.15 present a comparison between the results of Case 2 and the base case (no pipe).

Figure 5.13 is a plot of the axial force in the reinforcements in Layers 1, 2, 3, and 4. All the steel strips experience a decrease in axial force. There is an overall decrease of the force in all the reinforcements adjacent to the pipe, with the largest decrease in the 3<sup>rd</sup> strip of Layers 1 and 2. This is somewhat similar to what happens in Case 1, with the pipe perpendicular to the wall, where the reduction in axial force was generalized. The differences between Cases 1 and 2 are due to the shorter length of some of the strips (3<sup>rd</sup> in Layers 1 and 2) and to the change of direction of the pipe. As with Case 1, the effect of the pipe

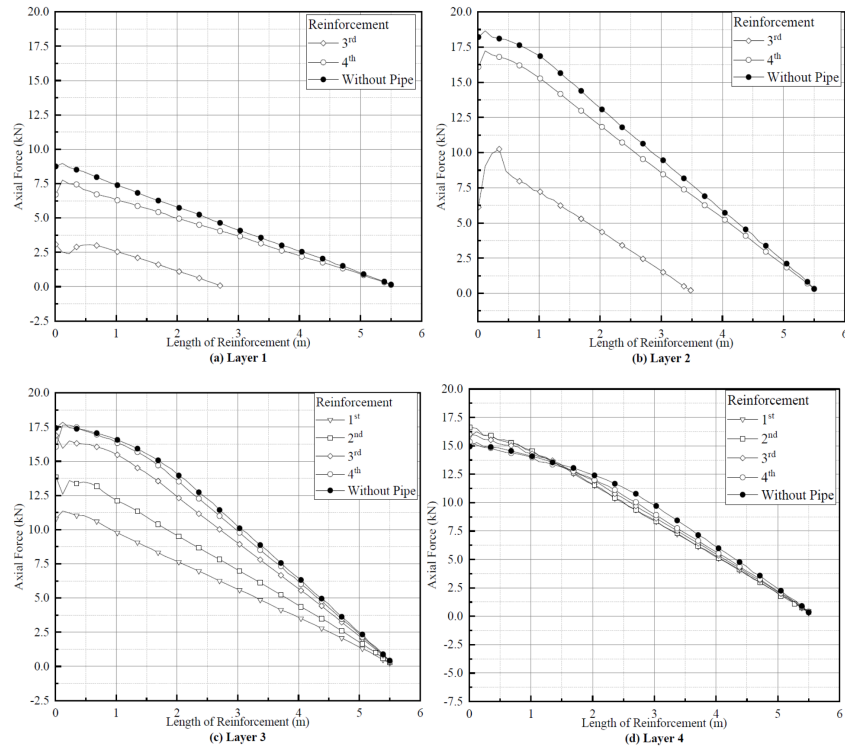
diminishes with distance (e.g., in Layer 4, the axial forces in the strips are similar to those of the base case).

Figure 5.14 displays the axial displacement in the reinforcements. Strips 1<sup>st</sup> and 2<sup>nd</sup> in Layer 3 have the largest decrease in the axial displacement, which is consistent with the results in Figure 5.13, for the axial force. As with Case 1, the presence of the pipe induces a decrease in the frictional demand on the reinforcement and thus it improves the overall wall stability.

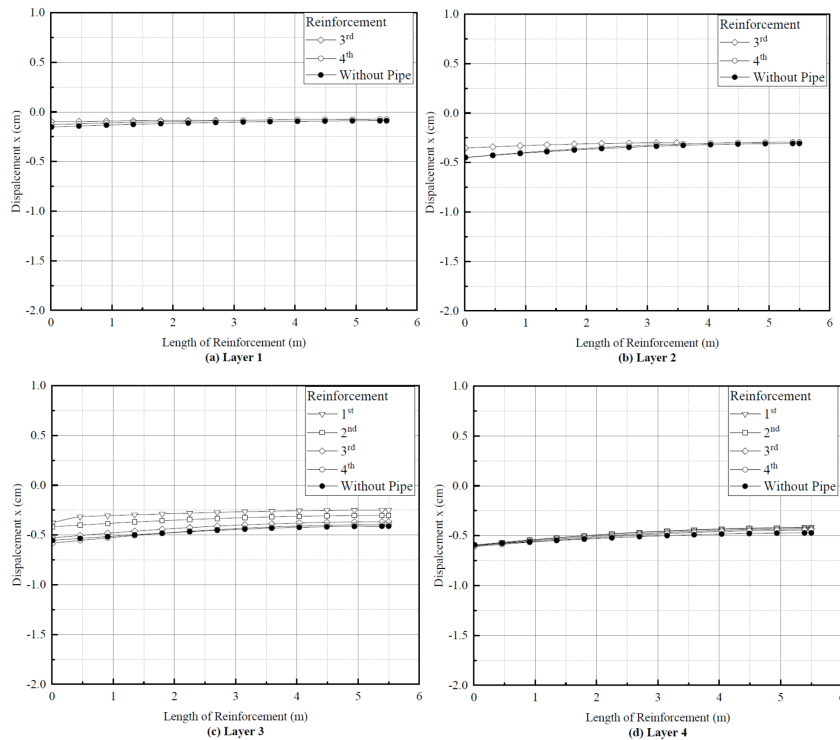
Figure 5.15 presents the slip in Layers 1 to 4. The 3<sup>rd</sup> strips in Layers 1 and 2 are cut because of the interaction with the inclined pipe, and so they show either zero or positive slip. The 1<sup>st</sup> and 2<sup>nd</sup> strips in Layer 3 show the largest decrease in slip, which is consistent with the axial force and displacement results in Figure 5.13 and Figure 5.14. As with the previous case, the area of influence of the pipe is also 2–2.5 times its diameter; as mentioned in Case 1, this is an ad-hoc result that may not be generalized.

**5.3.1.3 Case 3: Pipe at a 30° With Reinforcements Affected by the Pipe Cut (Figure 5.1c).** The pipe at an angle of 30° results in the removal of the 1<sup>st</sup> reinforcement and the cutting of the 2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup>, and 5<sup>th</sup> reinforcement in Layers 1 and 2 (Figure 5.4). Figure 5.16 to Figure 5.18 include an assessment of the results with the pipe and the base case (no pipe).

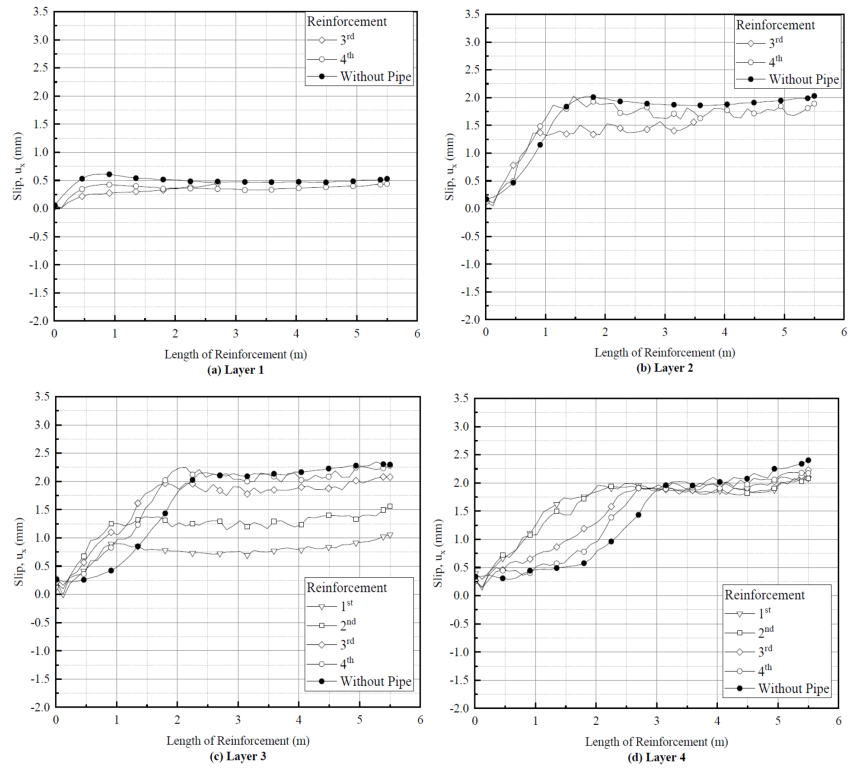
Figure 5.16 is a plot of the axial force in the reinforcements in Layers 1, 2, 3, and 4. All the steel strips experience a decrease



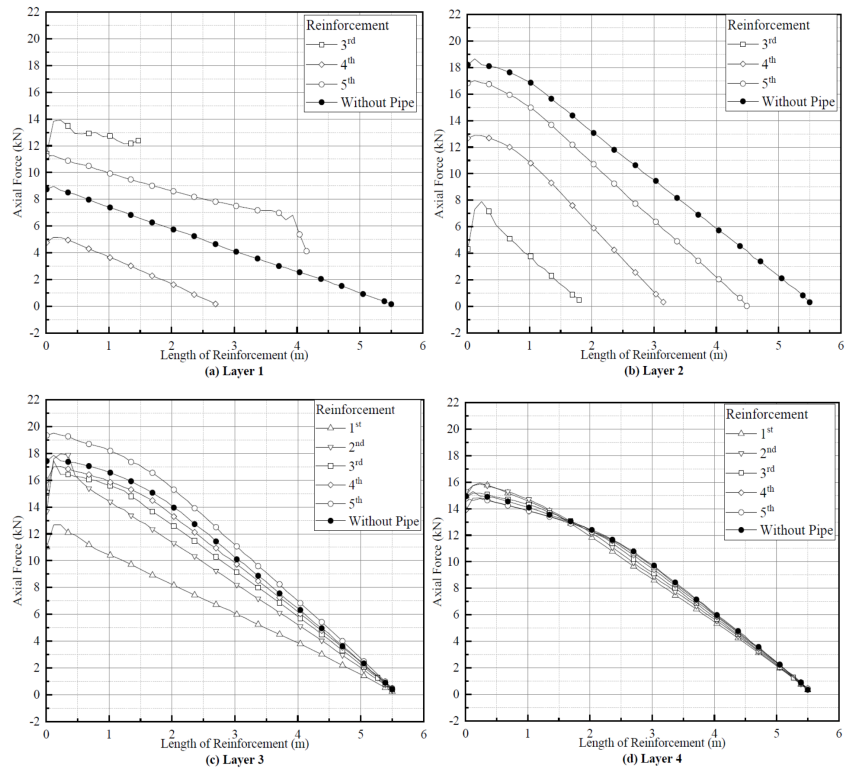
**Figure 5.13** Case 2. Axial Force in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.3b for Reinforcement Numbering.



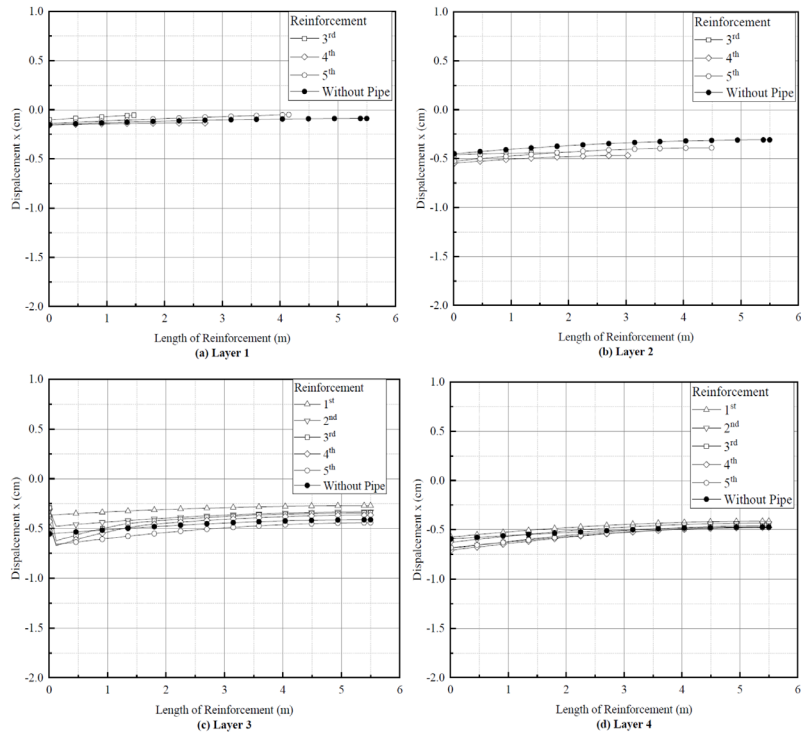
**Figure 5.14** Case 2. Axial Displacement in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.3b for Reinforcement Numbering.



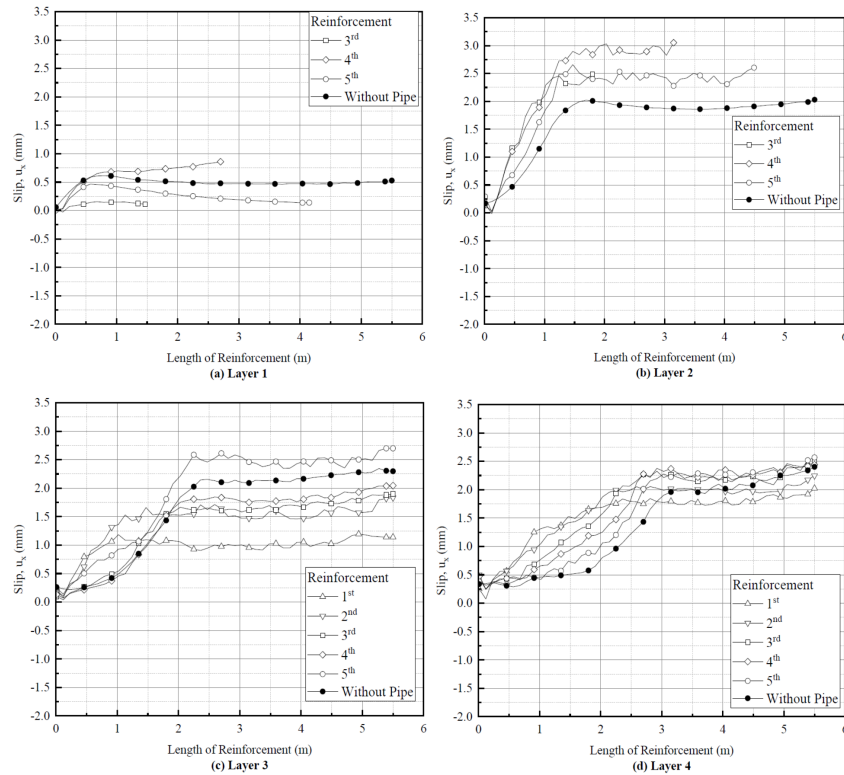
**Figure 5.15** Case 2. Axial Slip in the Upper Contact of the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.3b for Reinforcement Numbering.



**Figure 5.16** Case 3. Axial Force in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.4 for Reinforcement Numbering.



**Figure 5.17** Case 3. Axial Displacement in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.4 for Reinforcement Numbering.



**Figure 5.18** Case 3. Axial Slip in the Upper Contact of the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.4 for Reinforcement Numbering.

in axial force except the 3<sup>rd</sup> and 5<sup>th</sup> strips in Layer 1 and 5<sup>th</sup> strip in Layer 3. The 3<sup>rd</sup> and 4<sup>th</sup> strips in Layer 2 and 1<sup>st</sup> in Layer 3 experience the largest decrease. This might be due to the cutting of the strips and a decrease in frictional demand due to the presence of the pipe. From Layer 4 onwards, the effect of the pipe on the reinforcement subsides.

Figure 5.17 presents a plot of the axial displacement along the length of the reinforcement. The 3<sup>rd</sup> and 5<sup>th</sup> strips in Layer 1 (Figure 5.17a) show a decrease in displacement, whereas the 3<sup>rd</sup>, 4<sup>th</sup>, and 5<sup>th</sup> strips in Layer 2 (Figure 5.17b) exhibit an increase in displacement. The axial force follows the opposite trend for Layers 1 and 2. Starting from Layer 3, the trends for axial displacement and force become consistent with each other. The complex behavior observed in Layers 1 and 2 is likely due to the cutting of the reinforcement.

Figure 5.18 shows the axial slip for reinforcements 1 through 4, as indicated for the strips numbered 1 to 5 (Figure 5.4). The slip trends are similar to those of the axial displacement, with increased slip observed in the reinforcement adjacent to the pipe, particularly in Layer 2 and in the 5<sup>th</sup> strip in Layer 3.

**5.3.1.4 Case 4: Pipe at a 15° With Reinforcements Affected by the Pipe Inclined (Figure 5.1d).** In practice, the reinforcement impacted by obstructions is accommodated by rotating it away from the obstruction. This is what is done for Case 4.

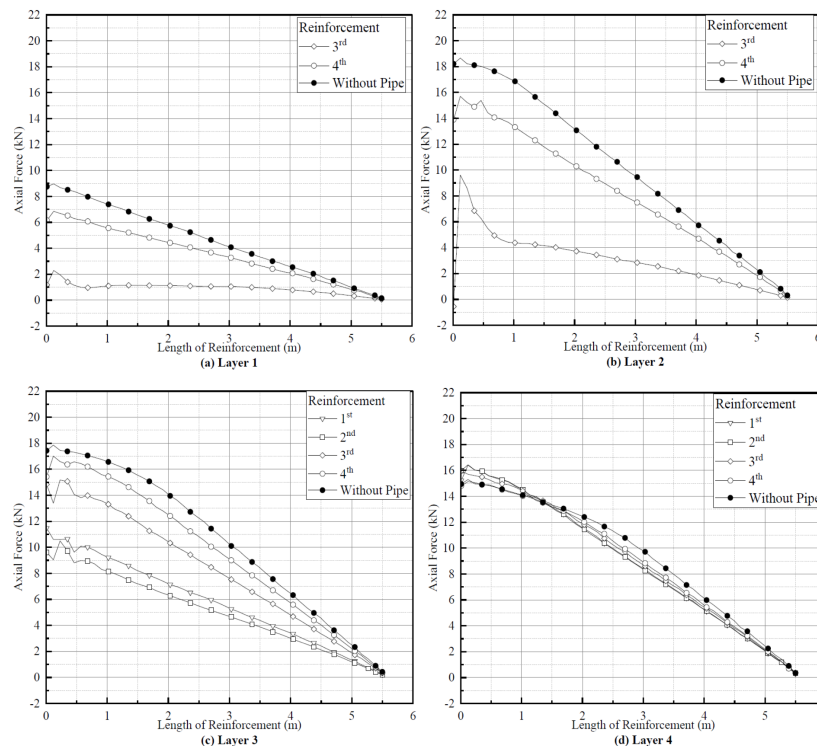
Figure 5.19 to Figure 5.21 provide a comparison between the cases of the MSE wall with a pipe at an angle of 15° (this case) and the case of the wall with no pipe (reference case). Figure 5.19

is a plot of axial force in the reinforcements 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup>, and 4<sup>th</sup> from Layers 1 to 5. All the strips undergo a decrease in their axial force. The maximum decrease is in the strips around the pipe in Layers 1, 2, and 3. Similar to the previous cases, the effect of the pipe on the reinforcement decreases with distance. Interestingly, the inclined reinforcements have lower axial force than the reinforcements that were cut (Figure 5.16). The cutting of the reinforcement led to a significant increase in axial force in the strips.

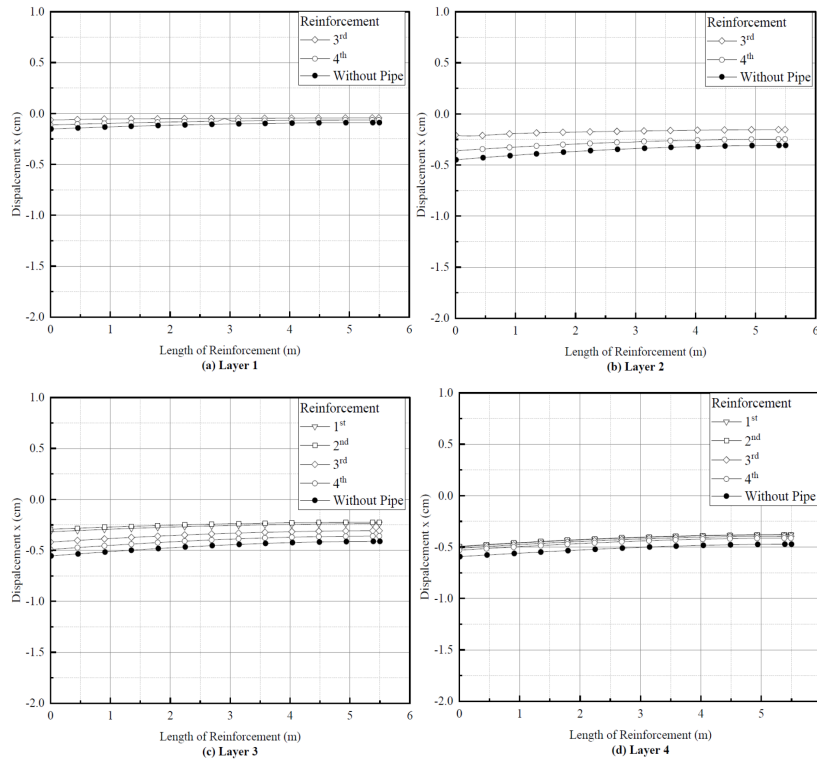
Figure 5.20 displays the axial displacement in the metal strips in Layers 1 to 4. The reinforcement around the pipe shows a decrease in the axial displacement (e.g., see 3<sup>rd</sup> strip in Layers 1 and 2 and 1<sup>st</sup> and 2<sup>nd</sup> strip in Layer 3). The decrease in displacement means a decrease in frictional demand, which is consistent with the axial force. All this is in agreement with the finding that the pipe contributes to the stability of the wall and thus decreases the load demand to the reinforcement.

Figure 5.21 shows the axial slip in the reinforcement. The 3<sup>rd</sup> strip in Layers 1 and 2 and 1<sup>st</sup> and 2<sup>nd</sup> strip in Layer 3 show a significant decrease in slip, consistent with the findings of axial force and displacements. A comparison between the results from Cases 3 and 4 suggests that cutting the reinforcement leads to an important increase in the axial force of the reinforcements. However, as it will be shown later, the overall stability of the wall is not affected.

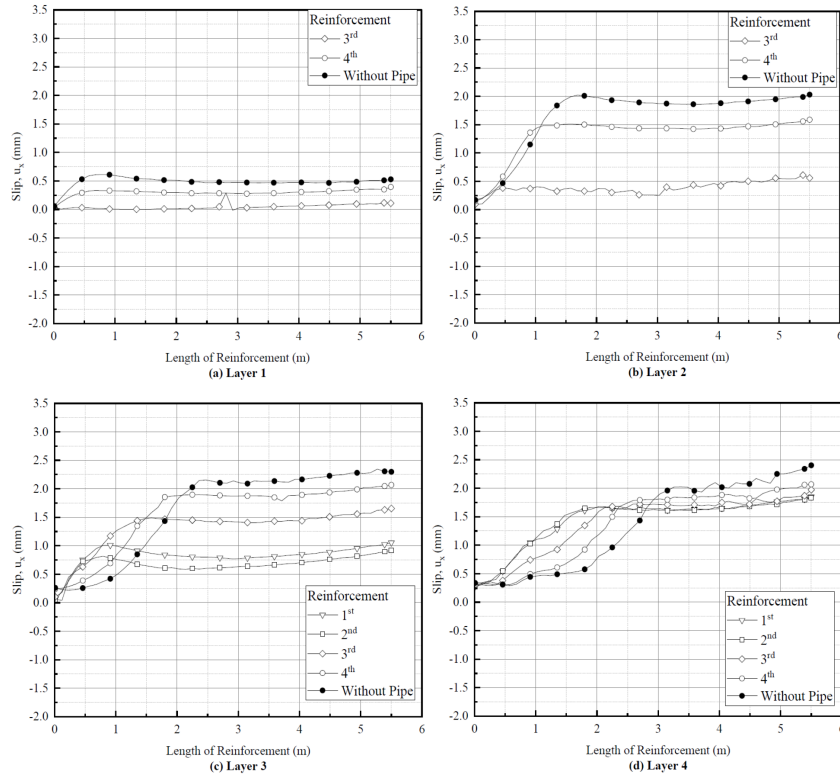
**5.3.1.5 Case 5: Pipe at a 30° With Reinforcements Affected by the Pipe Inclined (Figure 5.1c).** Case 5 is similar to Case 4, except that the pipe is inclined at an angle



**Figure 5.19** Case 4. Axial Force in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.5 for Reinforcement Numbering.



**Figure 5.20** Case 4. Axial Displacement in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.5 for Reinforcement Numbering.



**Figure 5.21** Case 4. Axial Slip in the Upper Contact of the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.5 for Reinforcement Numbering.

of 30° with the normal to the face of the wall. Figure 5.22 to Figure 5.24 contain the results of the simulations.

Figure 5.22 shows a plot of the axial force in the reinforcement. As one can see, all the strips have a decrease in the axial force, except in Layer 3 strip number 5, which shows a modest increase of 11–12%. The largest reduction in axial force occurs in Layers 1 and 2, Strip 2, and in Layer 3, Strip 1. The effect of the pipe on the farther reinforcement, as expected, is small. The observations are similar to those of Case 4.

Figure 5.23 is a plot of the axial displacements in the reinforcement. Again, the axial displacement decreases in all the reinforcements, with the exception of Strip 5 in Layer 3 that has a modest increase. The strips adjacent to the pipe experience the largest decrease, but the impact of the pipe decreases with distance, similar to what has been found in all previous cases. The results are consistent with the trends for axial force in Figure 5.22.

Figure 5.24 illustrates the slip in the reinforcement. The presence of the pipe decreases the slip in the reinforcement, with the reduction decreasing with distance. Also, the slip results are consistent with those for the axial force and displacement. It is interesting to note that cutting the reinforcement leads to a significant increase in the axial force of the reinforcement. As with all previous cases, the reinforcement around the pipe does not contribute significantly to resist the load from the soil because of the strong interaction between the (large) pipe and the soil.

**5.3.1.6 Factor of Safety and Shear Stress Capacity of the Reinforced Soil.** The overall FOS of the MSE walls, for all the cases discussed, are tabulated in Table 5.1. It is interesting to note that the presence of the pipe contributes to the overall stability of the wall, which is in agreement with noted improved effects on the reinforcement adjacent to the pipe. The positive contribution of the pipe is due to the increased contact/frictional surface between the reinforced soil and the pipe. Interestingly, as the pipe angle increases, rotation of the impacted strips provides a higher FOS compared to cutting the strips.

The shear stress capacity of the reinforced soil is investigated across a horizontal cross-section passing through the center of the pipe. Figure 5.25 displays the shear stress capacity of the reinforced horizontal cross-section, for the base case and the

TABLE 5.1  
Summary of the FOS from Cases 1 to 5 (Figure 5.1a–e).

Case No.	Pipe Angle (°)	Adjustment Method	FOS
1	0	N/A	2.06
2	15	Cutting	2.08
3	30	Cutting	2.08
4	15	Inclining	2.15
5	30	Inclining	2.13
Base Case	N/A	N/A	1.98

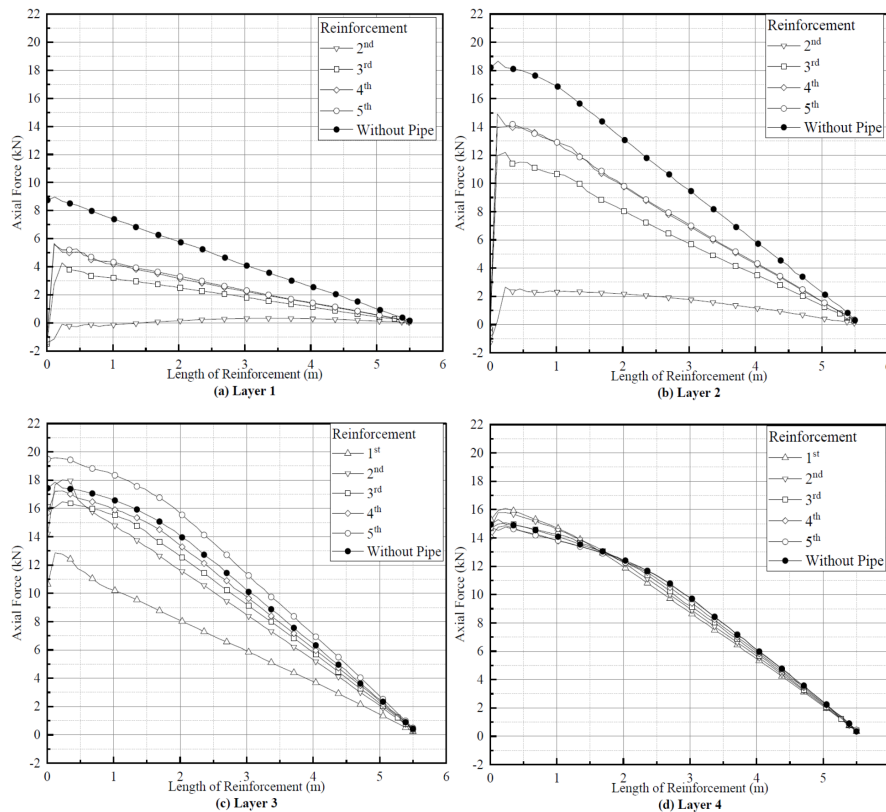
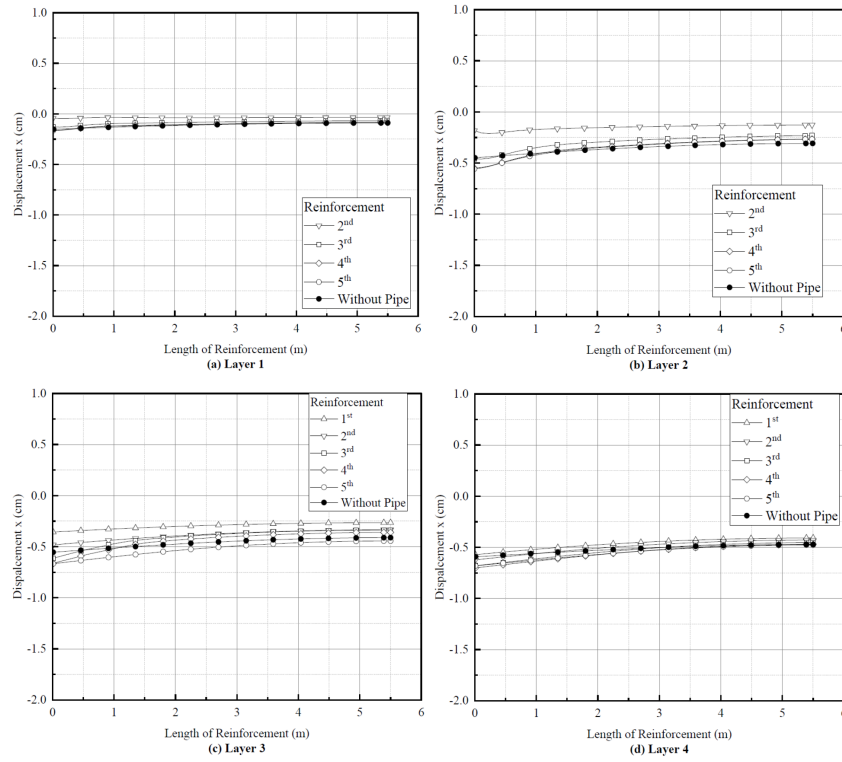
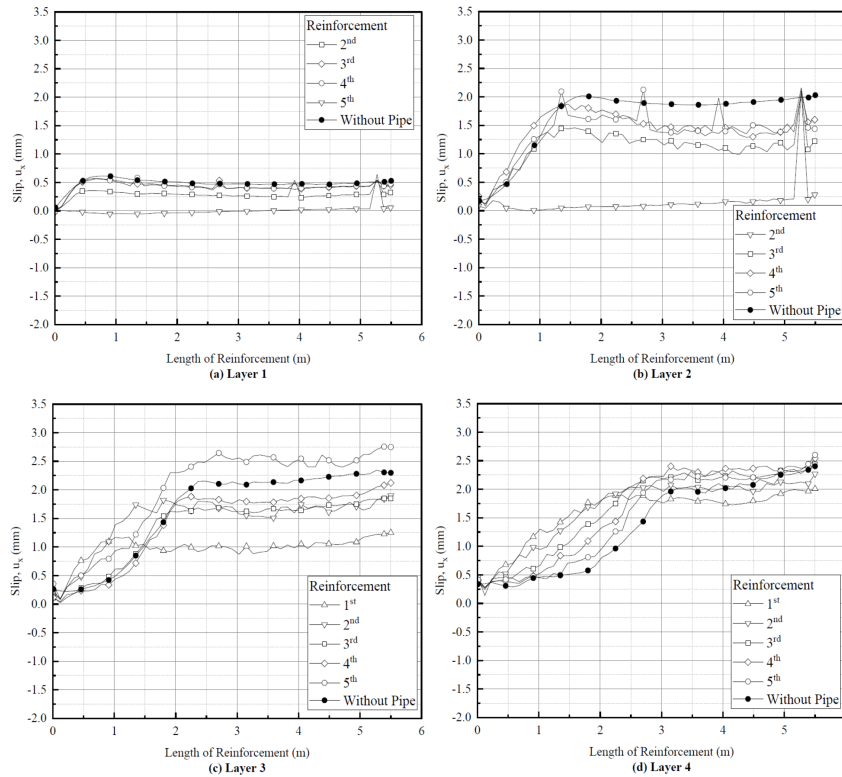


Figure 5.22 Case 5. Axial Force in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.6 for Reinforcement Numbering.



**Figure 5.23** Case 5. Axial Displacement in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.6 for Reinforcement Numbering.



**Figure 5.24** Case 5. Axial Slip in the Upper Contact of the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; (b) 2; (c) 3; and (d) 4. See Figure 5.6 for Reinforcement Numbering.

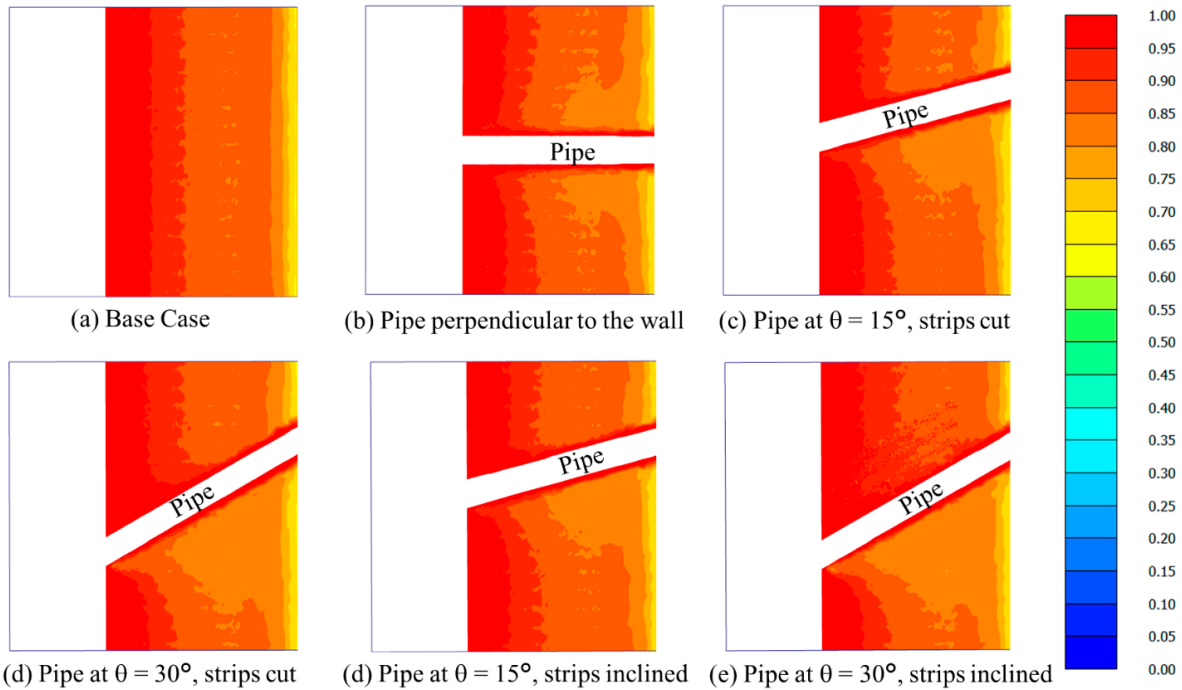


Figure 5.25 Shear Stress Capacity vs. Demand.

additional five cases investigated. The presence of the pipe changes the shear stress demand on the soil, but the changes depend on the orientation of the pipe.

For the pipe perpendicular to the wall (Figure 5.25b), there is a net decrease on the load demand on the soil surrounding the pipe. For all other cases (Figure 5.25c–e), a significant decrease of the shear demand is observed on the soil on the side of the pipe with the obtuse angle with the normal to the wall, and an increase on the side of the acute angle. There is not much difference, in terms of soil response, between the cases that have reinforcement cut or inclined

### 5.3.2 Pipe Placed in the Foundation Soil

This section studies the influence of pipe at different depths and pipe inclinations in the foundation soil. The soil foundation properties are tabulated in Table 5.2.

**5.3.2.1 Case 6: Pipe at a Depth of Invert  $d = 1.22$  m (4 ft) and Perpendicular to the Wall (Figure 5.1f).** Figure 5.26 to Figure 5.28 provide a comparison between the pipe running parallel to the wall and the base case (no pipe). Figure 5.26 displays the axial force, displacement, and slip, in the reinforcements 1<sup>st</sup> to 4<sup>th</sup> in Layers 1 and 2. The plots show that the presence of the pipe decreases the axial force only in the 1<sup>st</sup> strip of Layer 1 (Figure 5.26a), but by not much. Also, there is no difference in the axial force on the reinforcements in Layer 2.

Figure 5.27 and Figure 5.28 plot the axial displacement and slip along the length of the reinforcement. As one can see, the impact of the pipe on the reinforcement, compared with the base case, is minimal.

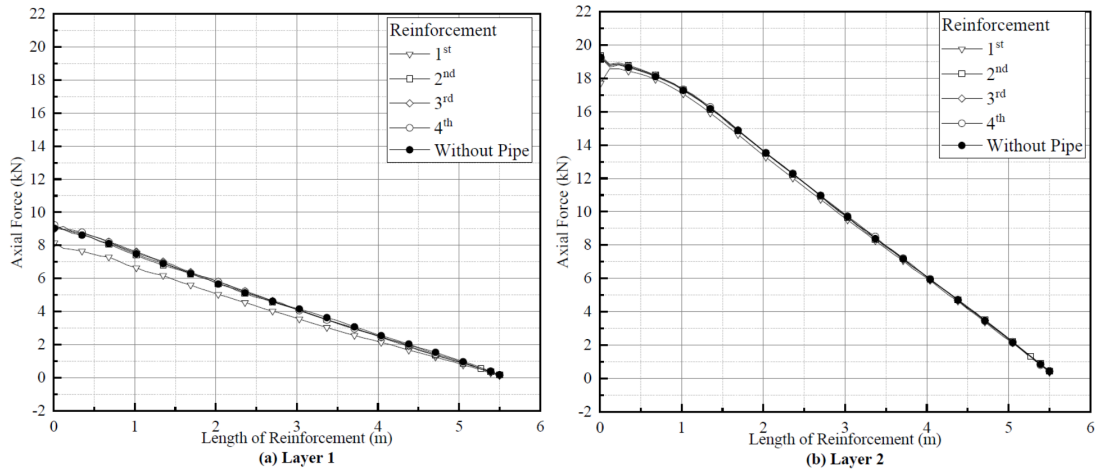
TABLE 5.2  
Input Properties of the Foundation Soil (Following INDOT [2022] Case Study).

Parameter	Value
Unit weight, $\gamma$	18.85 kN/m <sup>3</sup> (120 pcf)
Cohesion, $c$	200 kPa (29psi)
Friction angle, $\phi$	28°
Elastic modulus, $E$	500 MPa (72.52e3 psi)
Poisson's ratio, $\nu$	0.20
Dilation angle, $\psi$	0.0°

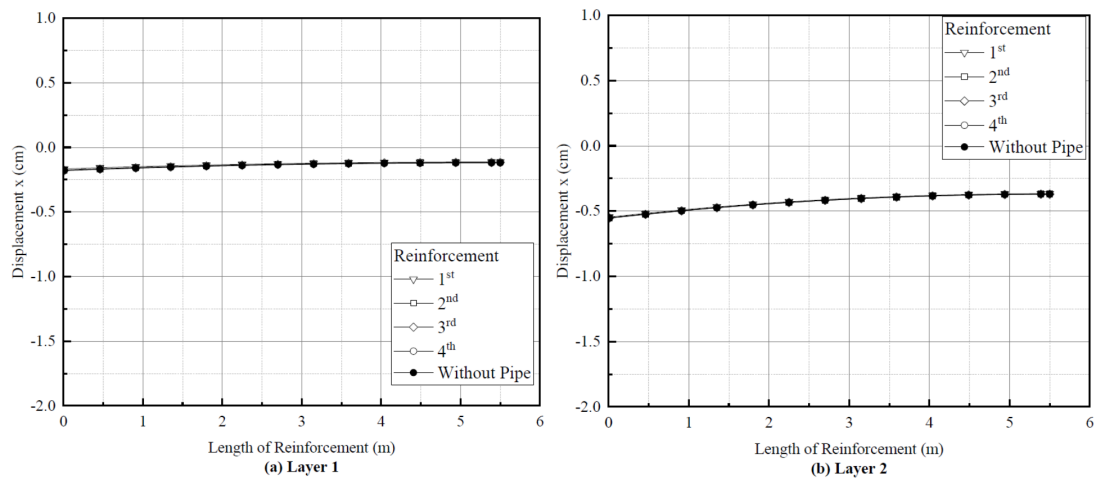
Note: All parameters are taken from INDOT (2022); the stiffness of the foundation soils is assumed.

**5.3.2.2 Case 7: Pipe at a Depth of Invert  $d = 1.22$  m (4 ft) and at an Angle of 15° (Figure 5.1g).** Figure 5.29 to Figure 5.31 present the results of the case of the wall with a buried pipe running at an angle of 15°. They also include results for the base case, that is, wall with no pipe. Figure 5.29 plots the axial force of the reinforcements 1<sup>st</sup> to 4<sup>th</sup> in Layers 1 and 2 (see Figure 5.9 for numbering of the reinforcement). The general trend is a reduction in the axial force, which is more pronounced in the 1<sup>st</sup> layer, which is the closest to the pipe. The effects on the second layer are smaller than on the first layer. A comparison with the results for Case 6, the pipe perpendicular to the wall (Figure 5.26) suggests that the effects of the inclined pipe extend over a larger area than the perpendicular pipe.

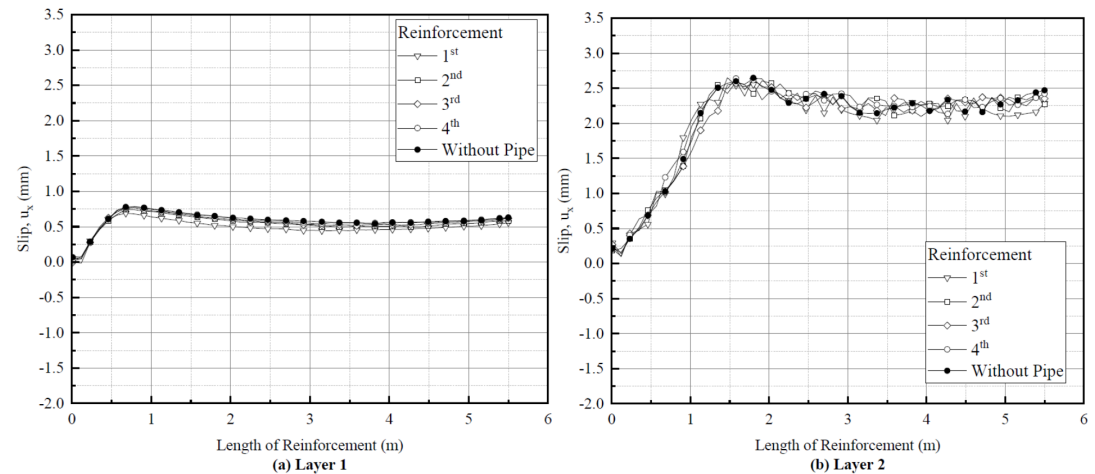
The axial displacements and slip align with the results of the axial force. That is, they decrease in the 1<sup>st</sup> and 2<sup>nd</sup> strips of Layer 1 and in the 1<sup>st</sup> strip of Layer 2. The effect on the other reinforcements is very small.



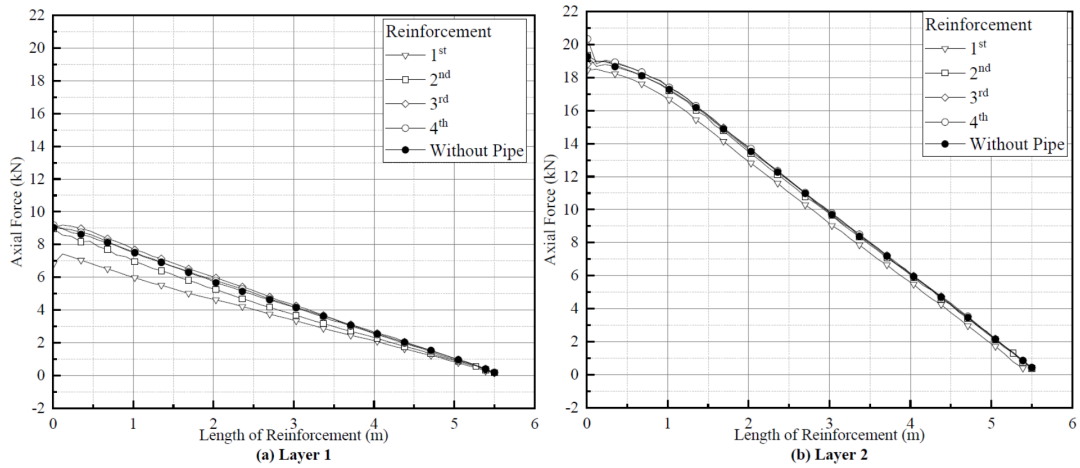
**Figure 5.26** Axial Force in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.8 for Reinforcement Numbering.



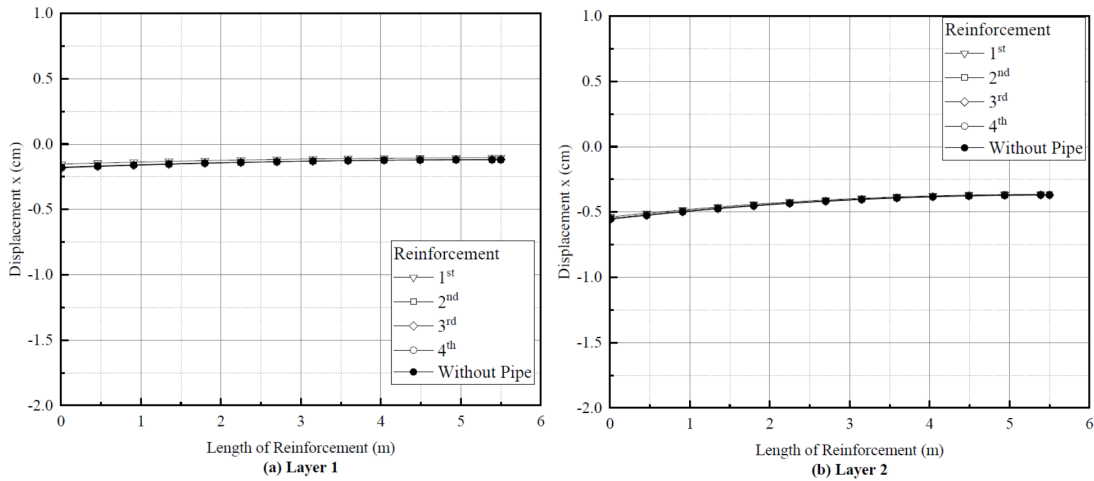
**Figure 5.27** Axial Displacement in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.8 for Reinforcement Numbering.



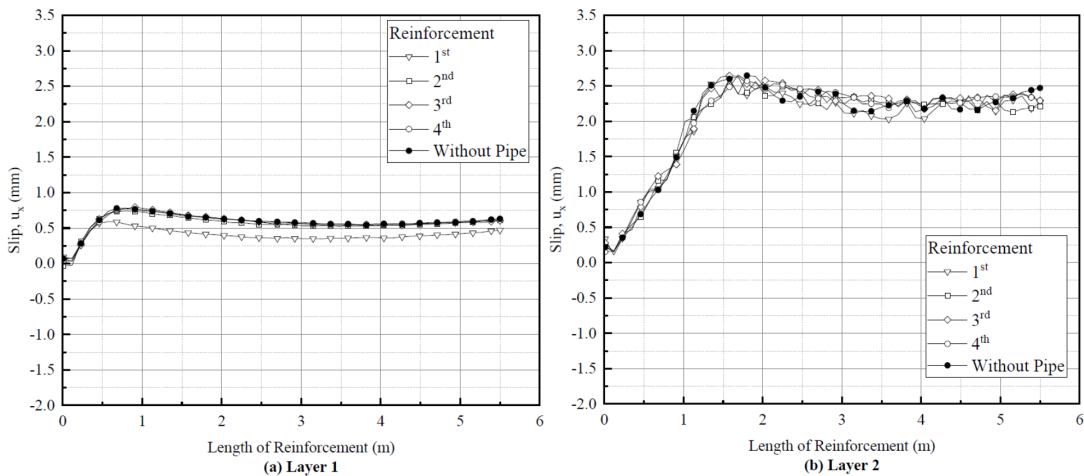
**Figure 5.28** Axial Slip in the Upper Contact of the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.8 for Reinforcement Numbering.



**Figure 5.29** Axial Force in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.9 for Reinforcement Numbering.



**Figure 5.30** Axial Displacement in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.9 for Reinforcement Numbering.



**Figure 5.31** Axial Slip in the Upper Contact of the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.9 for Reinforcement Numbering.

**5.3.2.3 Case 8: Pipe at a Depth of Invert  $d = 2.70$  m (8.9 ft) and Perpendicular to the Wall (Figure 5.1h).** Figure 5.32 to Figure 5.34 show the plots of axial force, displacement, and slip when the pipe is running perpendicular to the wall at a depth of 2.14 m, measured from the surface to the center of the pipe. As shown in the figures, the effect of the pipe on axial force, displacement, and slip in the reinforcement Layers 1 and 2 is negligible. This shows that the pipe is deep enough to not have an impact on the wall performance.

**5.3.2.4 Case 9: Pipe at a Depth of Invert  $d = 2.70$  m (8.9 ft) and at an Angle of  $15^\circ$  (Figure 5.1i).** Figure 5.35 to Figure 5.37 display the axial force, displacement, and slip when the pipe is at an angle of  $15^\circ$  with the perpendicular to the wall, and its center is located at a depth of 2.14 m. As with the previous case, Case 8, the pipe has no or minimal effect on the axial force, axial displacement or and slip in the reinforcement.

**5.3.2.5 Factor of Safety and Shear Stress Capacity of the Reinforced Soil.** The FOS of the MSE wall with a pipe within the foundation soil is provided in Table 5.3. The presence of the

pipe results in a 1–2% increase in the FOS with respect to the base case (no pipe). This is because the pipe reduces the load demand on the reinforcement, thereby contributing to a slight improvement in the overall stability.

The shear stress capacity of the reinforced soil is investigated on a horizontal cross-section located 7 m from the top of the wall, that is, at the base of the wall. Figure 5.38 displays the shear stress capacity of soil in that section. The figure shows that the pipe in the foundation of the MSE wall has little influence on the shear stress demand on the reinforced soil.

TABLE 5.3  
Summary of the FOS from Cases Shown in Figure 5.1f–i.

Case No.	Pipe Angle ( $^\circ$ )	$d$ (m)	FOS
1	0	1.22	2.17
2	15	1.22	2.17
3	0	2.70	2.14
4	15	2.70	2.13
Base Case	N/A	N/A	2.12

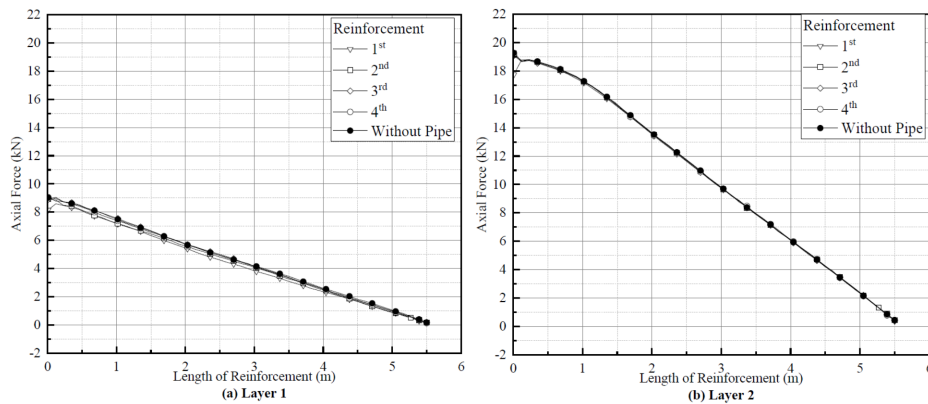


Figure 5.32 Axial Force in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.8 for Reinforcement Numbering.

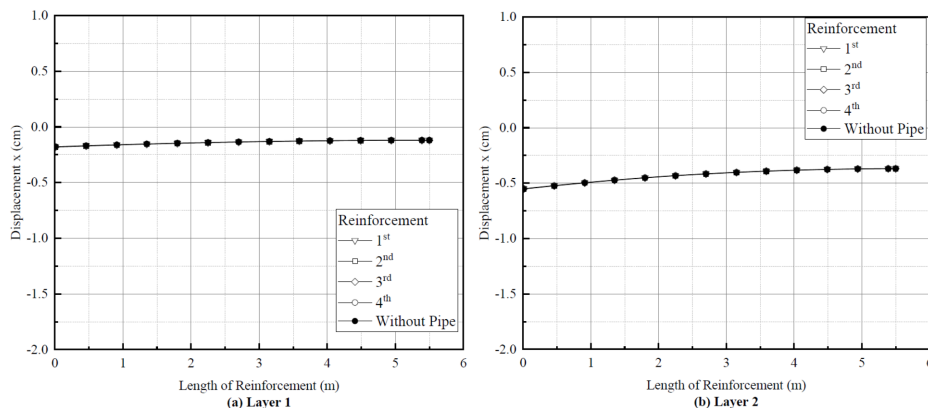
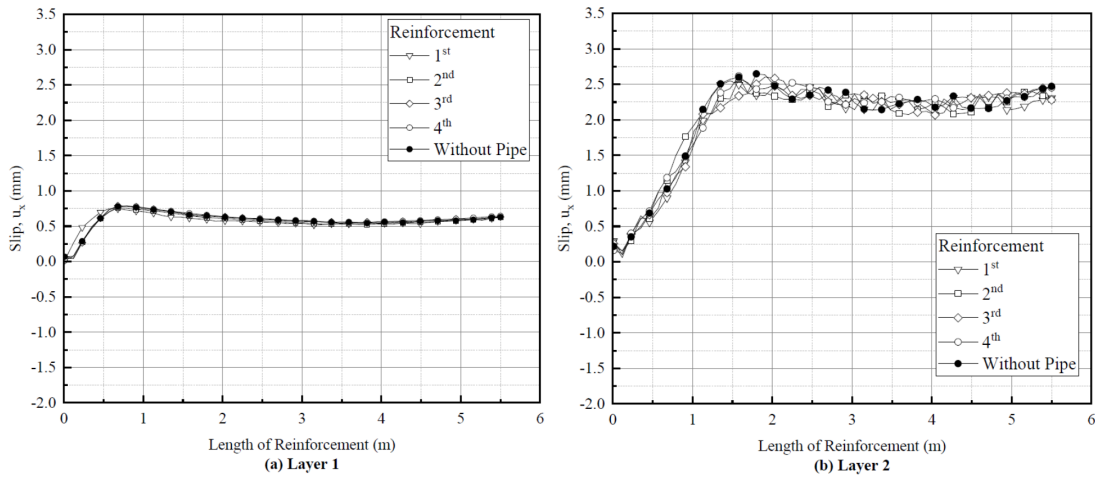
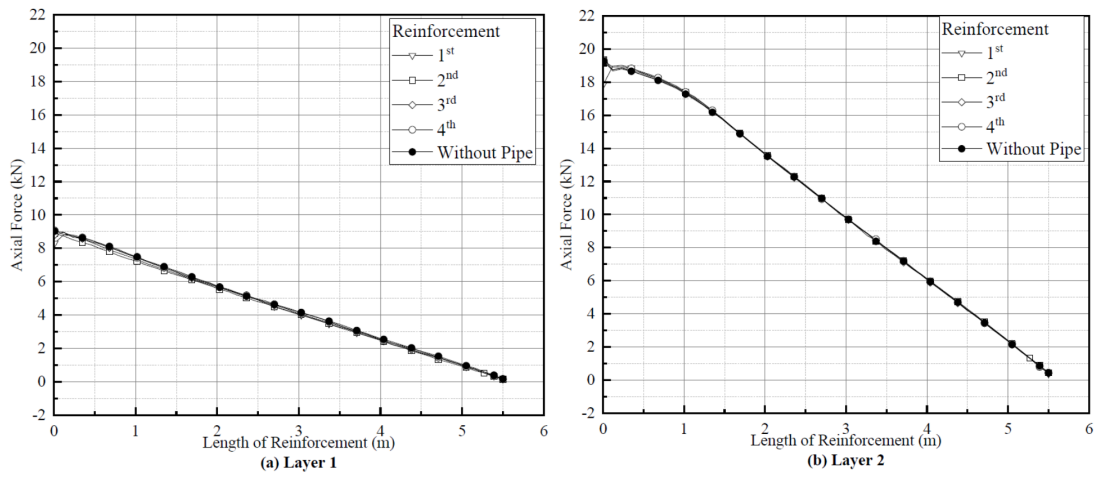


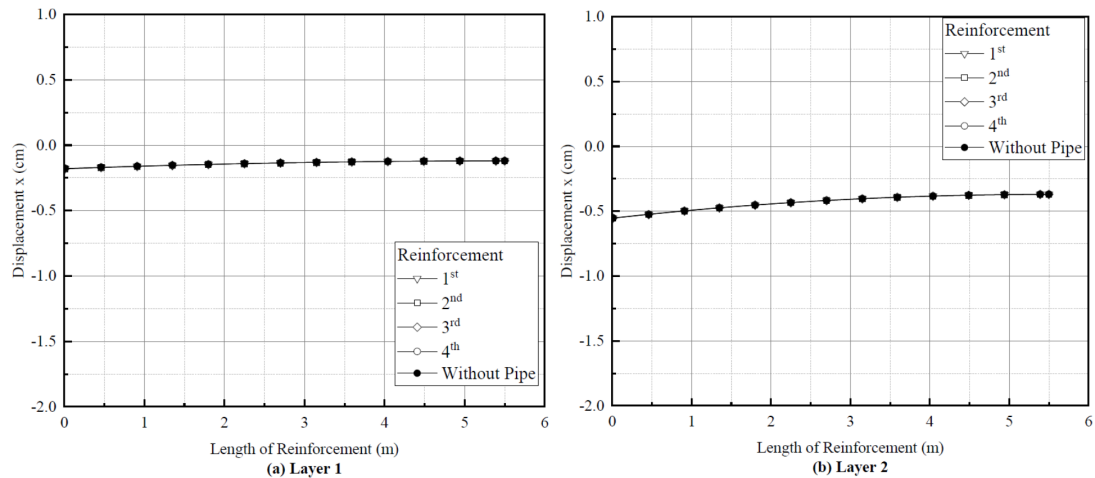
Figure 5.33 Axial Displacement in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.8 for Reinforcement Numbering.



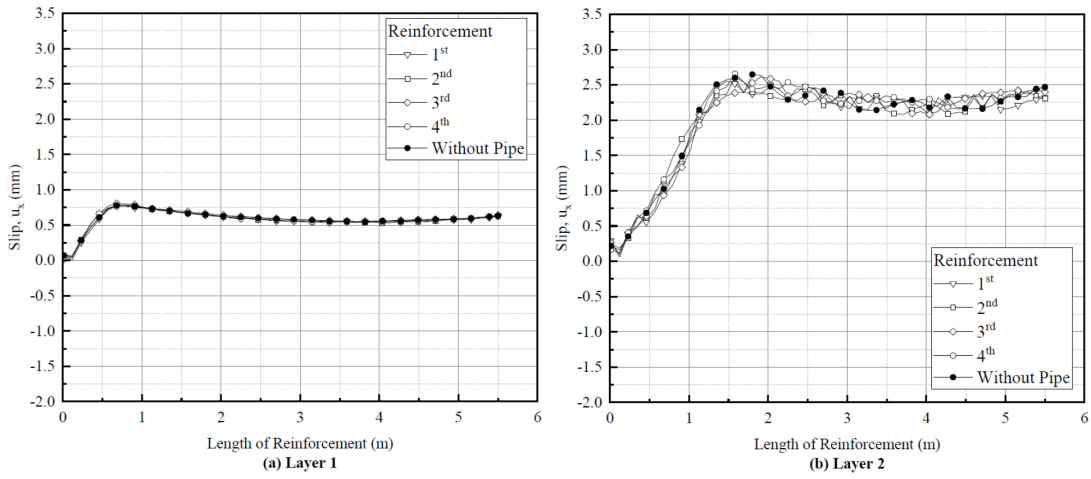
**Figure 5.34** Axial Slip in the Upper Contact of the Reinforcement With Distance from the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.8 for Reinforcement Numbering.



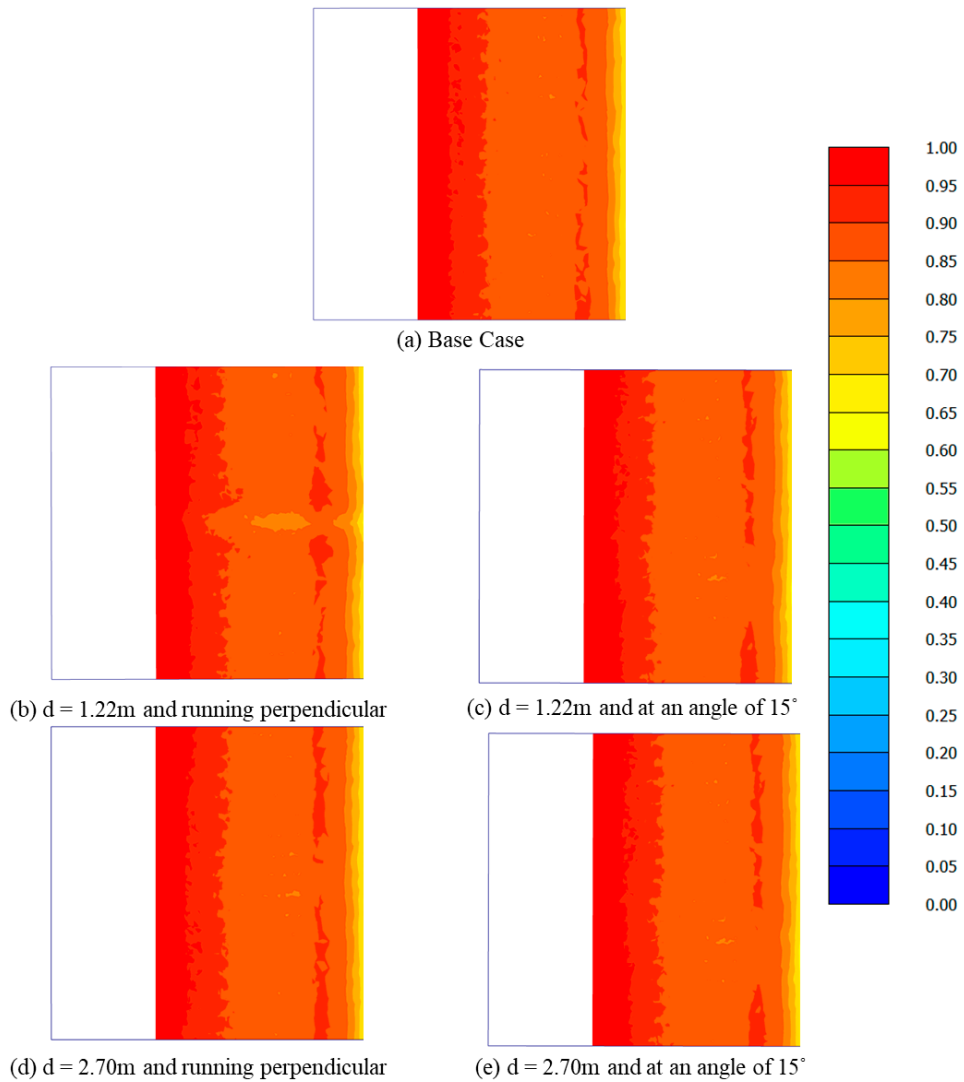
**Figure 5.35** Axial Force in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.9 for Reinforcement Numbering.



**Figure 5.36** Axial Displacement in the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.9 for Reinforcement Numbering.



**Figure 5.37** Axial Slip in the Upper Contact of the Reinforcement With Distance From the Facing Panel. Layer: (a) 1; and (b) 2. See Figure 5.9 for Reinforcement Numbering.



**Figure 5.38** Shear Stress Capacity vs. Demand.

## 5.4 Summary and Conclusions

This study explores the interaction between a MSE wall and a pipe crossing it perpendicularly and at an angle, using numerical simulations in PLAXIS 3D. Two scenarios are examined: one where the pipe is placed within the reinforced zone and another where it is located in the foundation soil. In the first scenario, the pipe's presence has a notable impact on the behavior of the reinforcement, influencing its axial force, axial displacement, and slip between the reinforcement and the soil. More specifically, the axial force is reduced, particularly in the reinforcement near the pipe. Such a decrease is prominent in the reinforcement adjacent to the pipe, but the effects decrease with distance. In all cases, the effect of the pipe on the reinforcement in Layer 4 and onwards is small or negligible. This observation is consistent with the findings for the axial displacement and slip in the reinforcement. The noted benefits of the pipe in the response of the reinforcement are due to the frictional resistance that the pipe provides along its circumference, thus contributing to the overall stability of the wall. Interestingly, inclining/rotating the reinforcement impacted by the pipe results in a higher FOS than cutting it. The presence of the pipe slightly increases the shear demand of the soil on the side of the pipe that makes an acute angle with the normal to the face of the wall and reduces it on the opposite side.

A pipe in the foundation soil, beneath the MSE wall, impacts the axial force in the first layer of reinforcement. Such influence significantly decreases from the second layer onward. This pattern is also observed when the pipe is inclined with respect to the perpendicular to the wall facing. As the pipe is positioned deeper into the foundation soil, its influence further diminishes. The overall stability of the wall is impacted by only 1–2%.

This study qualitatively and quantitatively evaluates the effects of the presence of a horizontal obstruction/pipe on an MSE wall and its components. Most importantly, the research emphasizes the need to specifically consider in MSE wall design the presence of a horizontal obstruction within the reinforced soil or underneath the wall.

## 6. NUMERICAL ANALYSIS OF HORIZONTAL OBSTRUCTION FAILURES UNDER MSE WALLS

### 6.1 Introduction

Buried utilities such as gas and pressure pipes often deteriorate over time due to weathering or corrosion, which may eventually lead to collapse. The analysis provided in this chapter expands upon the work presented in Ahmad and Bobet (2026). A detailed summary of several reported cases of pipe leakage and failure can be found in Ahmad and Bobet (2025a; 2025b). This problem becomes significantly more complex when these utilities lie beneath overlying infrastructure, such as MSE walls or embankments. Repair or maintenance of such utilities is particularly challenging in these cases, often requiring partial or full dismantling of the wall to access the buried pipes. In the event of a utility collapse, the resulting ground disturbance can compromise the stability of the overlying structure, potentially causing traffic disruptions and safety hazards. Therefore, it is

essential to ensure the long-term protection and serviceability of both the buried utilities and the structures built above them.

This chapter presents a numerical analysis of an MSE wall constructed over a buried pipe that is assumed to be failing. The primary objective of this study is to determine the minimum burial depth required for a utility pipe beneath an MSE wall such that its failure does not adversely affect the wall performance. All analyzed cases consider a circular pipe oriented parallel to the wall face. Section 6.2, describes the model, material, and input parameters for the numerical model. Section 6.3 describes the model results when a failing pipe is placed in granular soil. More specifically, it contains information regarding the effects of the pipe on the reinforcement and deformations of the cross section of the wall. Sections 6.4 and 6.5 contain information analogous to that in Section 6.3, but for silty clay and loam in the foundation. Lastly, Section 6.6 summarizes the key findings from the numerical analyses.

### 6.2 Numerical Modeling

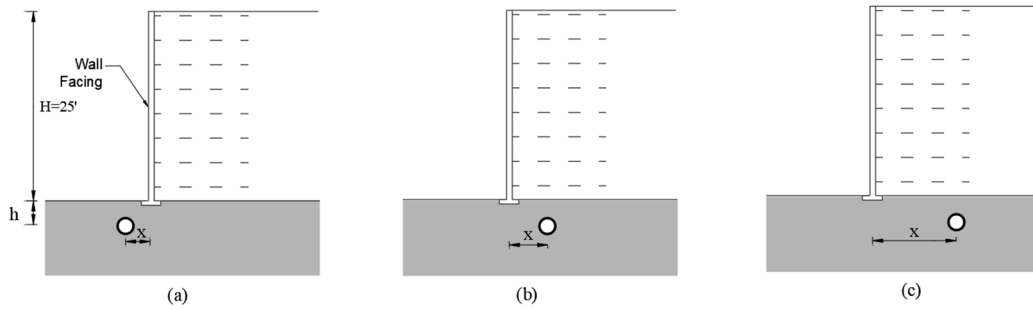
The analyses are performed using PLAXIS 2D, where the utility pipe is modeled at varying depths, different distances from the wall face, and with different diameters. The construction stages of the MSE wall and the associated input parameters follow the procedures outlined in Sections 4.2 and 4.3 of Chapter 4. All soils are modeled using the Mohr-Coulomb constitutive model with a nonassociated flow rule, while the reinforcement and pipe are modeled as linear elastic materials. The pipe is positioned perpendicular to the cross section of the wall. Pipe failure is simulated by gradually reducing its stiffness to a fraction of its original value. A failure condition is considered to occur when either the safety factor of the system (wall and pipe) drops below 1.0 or the pipe loses its ability to carry load.

At the end of the simulation, if a failure of the pipe is produced, results are collected on changes in axial load, axial deformations of the critical strip (the strip at the bottom of the wall), and overall factors of wall safety. To determine a safe pipe burial depth, the following criteria must be met: (1) the axial force in any reinforcement does not increase by more than 20% with respect to that when the pipe was intact; (2) the wall facing does not experience more than 2 in. of additional deformation due to the pipe collapse.

Figure 6.1 presents a schematic of the MSE wall and the intersecting utility pipe. Three pipe locations were analyzed, as shown in Figure 6.1a–c. The locations included one where the pipe was located in front of the wall and two, behind the wall.

The analysis considers three different foundation soil types: sand, loam, and silty clay, as outlined in Table 6.1. These soil profiles were provided by INDOT. They were collected from two sites in Indiana: one located 0.08 miles North of E. Hill Street in the City of Wabash, and the other along US 6 over I-80/94 in Lake County. It is assumed that the failure of the wall does not affect the mechanical properties of the wall. Figure 6.2 shows the location of those two sites.

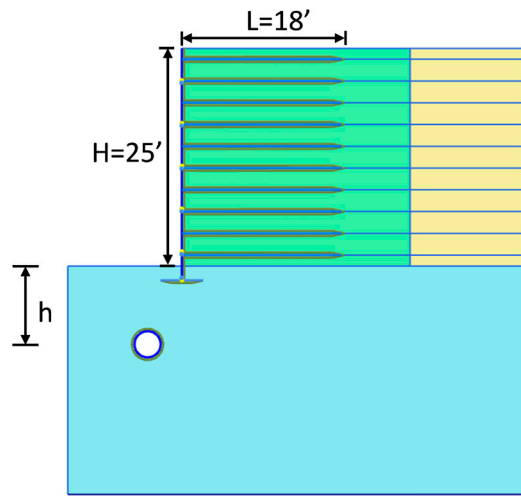
In addition to soil type, the study investigates the effects of burial depth, pipe diameter, soil cohesion, and wall height on the stability and performance of the MSE wall.



**Figure 6.1** Schematic of MSE Wall With a Utility Pipe in the Foundation Soil.

**TABLE 6.1**  
**Input Parameters for the Soil Underneath the MSE Wall.**

Parameter	Value		
	Sand	Loam	Silty Clay
Station	51+00	14+67	48+90
Unit weight, $\gamma$ (pcf)	125	120	120
Cohesion, $c$ (psi)	0	14.5	7.25
Friction angle, $\phi$ (degrees)	36	28	28
Elastic modulus, $E$ (ksi)	21.8	13.1	8.7
Poisson's ratio, $\nu$	0.20	0.20	0.20
Dilation angle, $\psi$ (degrees)	15.0	0.0	0.0



**Figure 6.3** Cross Section of a 25 ft MSE Wall With a Pipe Placed at a Depth of  $h$ .



**Figure 6.2** Map Showing the Location of the Soils Used for the Analyses.

Figure 6.3 illustrates a 25-ft-tall MSE wall with a pipe placed in the foundation soil. The pipe has a radius  $r_o$  of 18 in. This is the same wall and geometry used in all previous cases (see Chapters 4 and 5). The pipe is initially placed at  $h/r_o = 4$ , and the depth is progressively increased to determine the minimum safe depth. As mentioned, it is considered that failure of the pipe does not impact the performance of the MSE wall when: (1) the axial force in any reinforcement layer does not increase by more than 20%; and (2) the wall facing does not experience more than 2 in. of additional deformation.

### 6.3 Foundation Soil: Sand

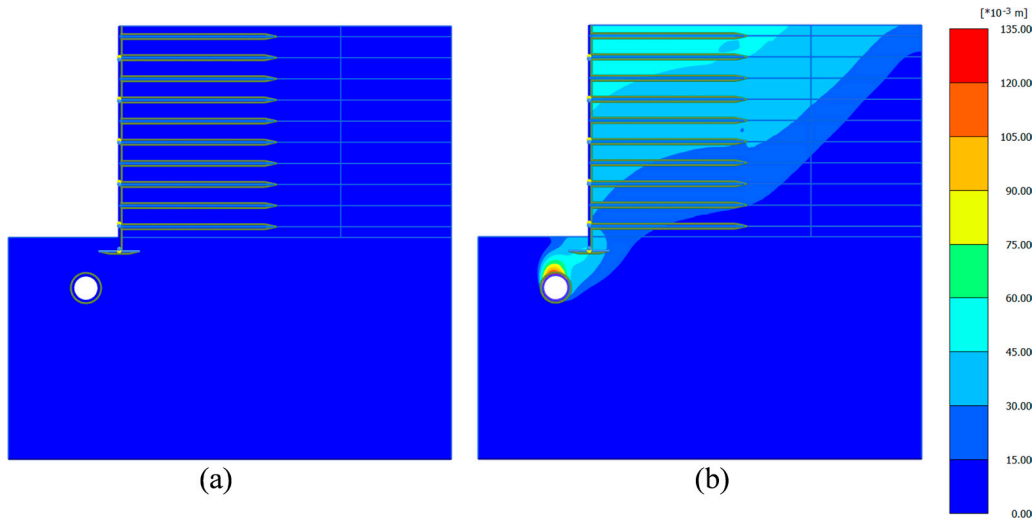
This section presents the analysis of the failure of the pipe underneath the wall, when the foundation soil is sand (see Table 6.1 for the sand properties used in the simulations). The pipe is modeled as a linear elastic material placed at various depths and distances from the facing panel of the wall. Pipe failure is simulated by reducing its stiffness, with the analysis terminating when the FOS is less than 1 or the pipe fails. The sand has no cohesion, which makes reaching numerical convergence challenging.

The parametric analysis, conducted at different depths of the pipe, try to establish whether the nondimensional parameter, depth to radius ratio ( $h/r_o$ ), can be used to determine the minimum burial depth of the pipe such that the collapse of the pipe would not compromise the performance of the wall. Additional cases were run for a 40-ft-tall wall, to examine whether wall height affects the minimum safe burial depth of the pipe. In all cases, particular attention was given to the first layer of reinforcement (i.e., the reinforcement placed at the bottom of the wall and, thus, the closest to the pipe), given that it was found to have the largest changes in axial force. Subsequent reinforcement layers are generally less affected by the pipe collapse because they are located further from the zone of influence of the pipe failure.

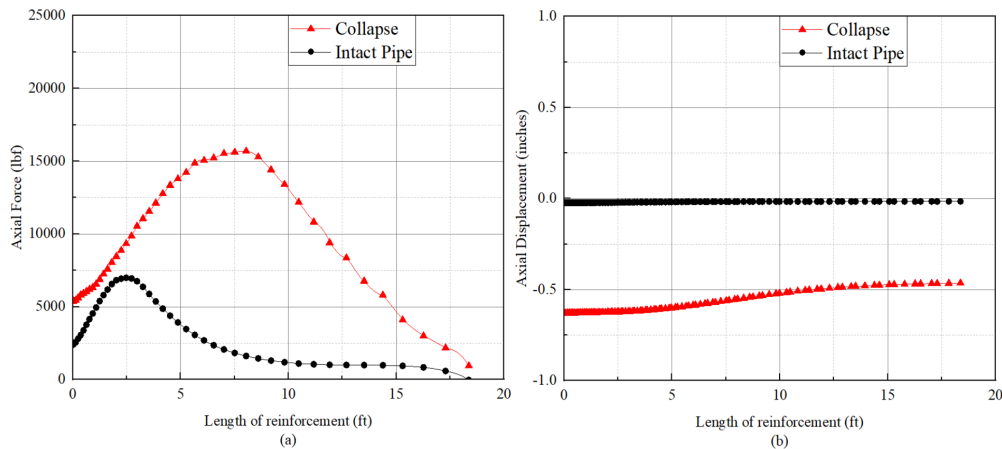
Figure 6.4 and Figure 6.5 examine the impact of a shallow buried pipe ( $h/r_o = 4$ ), 36 in. in diameter, placed in front of the MSE wall, and provide a comparison between the intact and collapsed pipe scenarios.

Figure 6.4a shows the wall with the intact pipe. It has an FOS of 1.4 and, as one can see, the pipe induces no noticeable deformation in the surrounding soil. In contrast, the collapsed pipe in Figure 6.4b reduces the FOS to 0.9, triggers a localized loss of confinement around it, and induces significant soil deformations, which propagates upwards towards the wall. Figure 6.5 further highlights the consequences of the collapse. A substantial increase in the axial force of the bottom reinforcement, by 125%, is observed (Figure 6.5a), as well as large axial deformations in the reinforcement (Figure 6.5b). The results suggest that the collapse of the pipe generates sufficiently large deformations in the sand such that they reach the reinforcement, thus increasing its frictional demand, resulting in axial forces and displacements that exceed the acceptable limits established. Therefore, this depth is found unsafe for pipe placement.

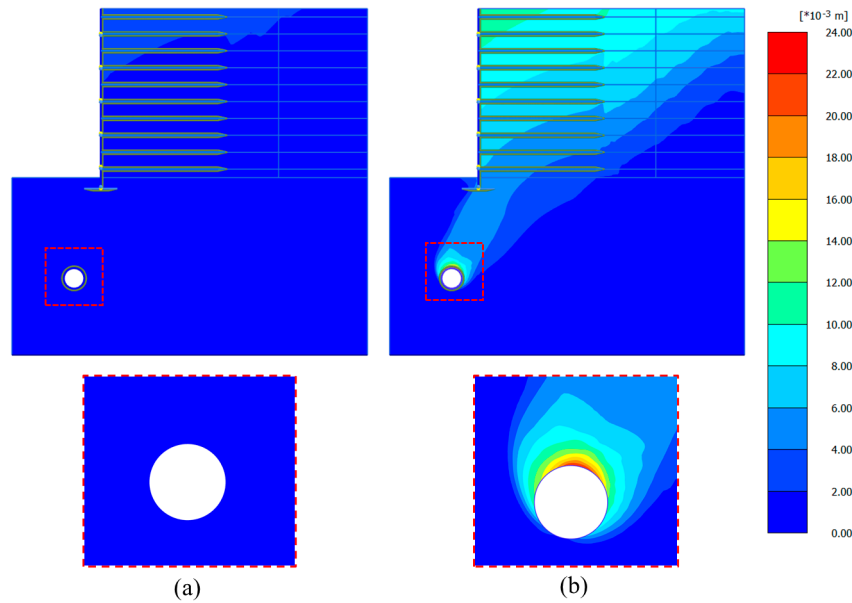
Figure 6.6 and Figure 6.7 examine the behavior of the MSE wall when the pipe is placed at a greater depth, at  $h/r_o = 10$  ( $r_o = 18$  in.). Figure 6.6 compares the wall deformations for the



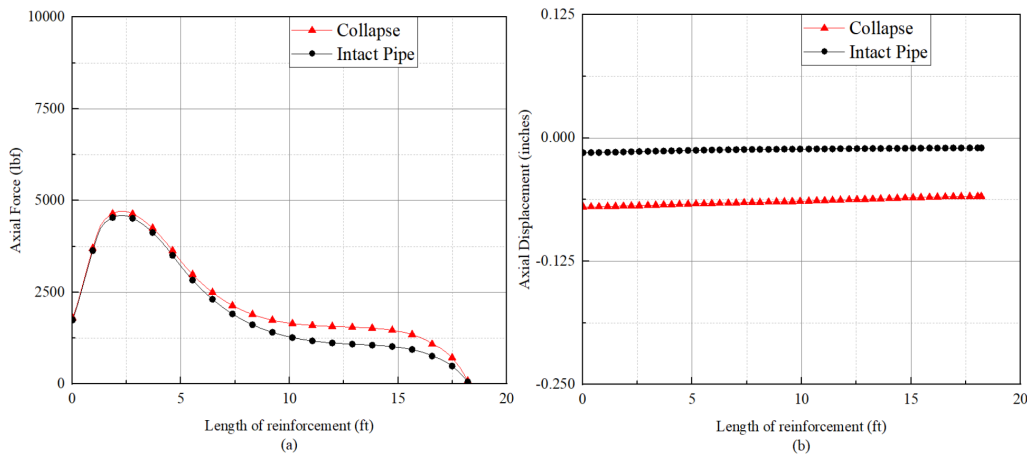
**Figure 6.4** Deformation Contours of the 25 ft Wall With Pipe Located at  $h/r_o = 4$  (Where  $r_o = 18$  in.) in Front of the Wall; (a) Intact Pipe, and (b) Collapsed Pipe.



**Figure 6.5** (a) Axial Force, and (b) Axial Displacement in the First Layer of Reinforcement for the Pipe Located at  $h/r_o = 4$  (Where  $r_o = 18$  in.).



**Figure 6.6** Deformation Contours of the 25 ft Wall With Pipe Located at  $h/r_o = 10$  (Where  $r_o = 18$  in.) in Front of the Wall (a) Intact Pipe, and (b) Collapsed Pipe.



**Figure 6.7** (a) Axial Force, and (b) Axial Displacement in the First Layer of Reinforcement for the Pipe Located at  $h/r_o = 10$  (Where  $r_o = 18$  in.).

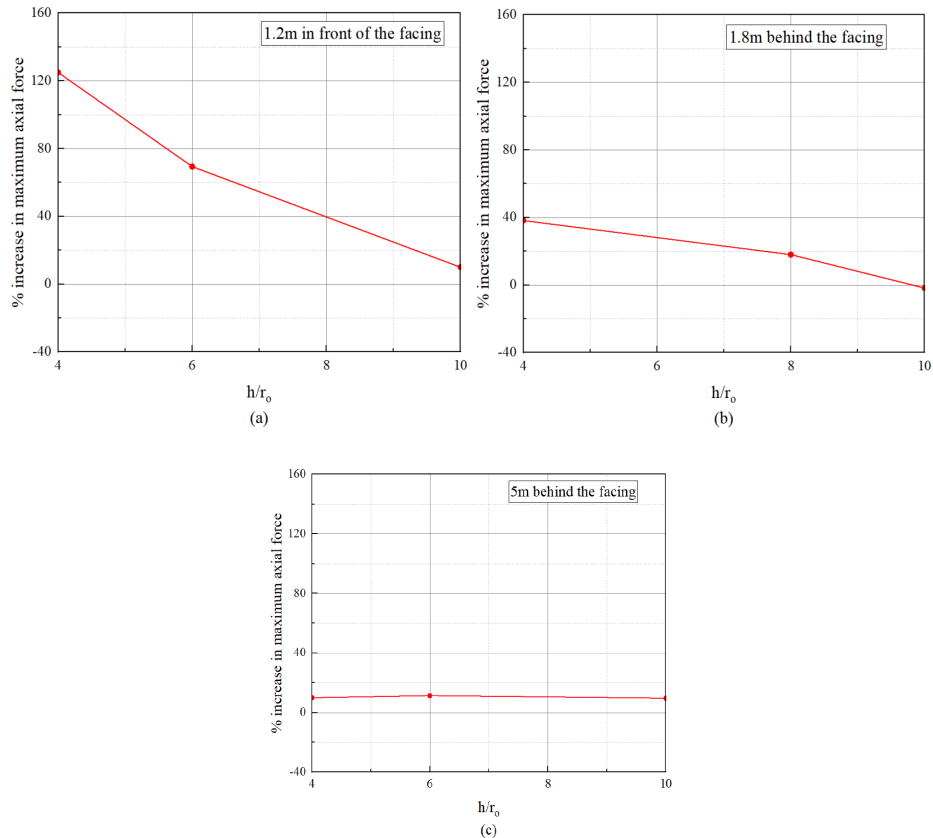
intact (Figure 6.6a) and collapsed pipe conditions (Figure 6.6b). The wall with the intact pipe exhibits an FOS of 1.48, and the presence of the pipe does not cause any noticeable deformation in the soil. In contrast, with the collapsed pipe there are significant deformations around the pipe's perimeter. However, due to the large embedment depth of the pipe, the deformations induced in the soil remain confined to the location of the pipe and do not propagate upwards and do not impact the wall facing or its reinforcement layers.

Figure 6.7 presents the axial deformations in the first layer of reinforcement for the intact and collapsed pipe conditions. At the burial depth investigated,  $h/r_o = 10$ , the increase in axial force remains within the acceptable criteria (Figure 6.7a). The axial deformations of the reinforcement increase, but they are

small, as shown in Figure 6.7b. These results suggest that placing the pipe at a depth  $h/r_o = 10$  may be considered a safe depth for the pipe beneath MSE walls.

### 6.3.1 Effect of Depth

Figure 6.8 is a plot of the increase in maximum axial force with the depth to radius ( $h/r_o$ ) ratio, for a pipe with 36 in. diameter. The figure shows the results at three different locations of the pipe: 3.9 ft (1.2 m) in front of the wall (Figure 6.8a); at 5.9 ft (1.8 m) behind the front of the wall (Figure 6.8b); and at 16.4 ft (5 m) behind the front (Figure 6.8c). The figures show that, as expected, the deeper the pipe, the smaller the impact on the axial force of the critical reinforcement. Also, as the pipe moves



**Figure 6.8** Increase in Maximum Axial Force in the First Layer of Reinforcement Due to a Pipe Placed in Granular Soil at Different  $h/r_o$  Ratios, for  $r_o = 18$  in. Results are Shown for Three Pipe Locations Relative to the Wall Facing: (a) 3.9 ft in Front of the Facing; (b) 5.9 ft Behind the Facing; and (c) 16.4 ft Behind the Facing.

away from the front of the wall, its effect on the reinforcement decreases. The most critical location is when the pipe is located in front of the wall (Figure 6.8a). Nevertheless, for a depth to size ratio  $h/r_o = 10$ , the increase in maximum axial force in the critical reinforcement is always smaller than that established by the criterion chosen. Thus, this burial depth of  $h/r_o = 10$  can be considered as the minimum allowed for the safety of the wall, and for a pipe with diameter of 36 in.

### 6.3.2 Effect of Pipe Diameter

To evaluate the effect of pipe size, additional simulations were conducted with the pipe diameter reduced by half, that is,  $r_o = 9$  in. Figure 6.9 plots the axial force in the reinforcement for two cases:  $h/r_o = 10$  (Figure 6.9a) and  $h/r_o = 12$  (Figure 6.9b). When the pipe is placed at  $h/r_o = 10$ , the collapse of the pipe increases the axial force more than 40% with the respect of the intact pipe case, thus indicating that this case does not meet the safety criterion. However, when the pipe is placed deeper, at  $h/r_o = 12$ , the axial force remains within acceptable limits, satisfying the criterion.

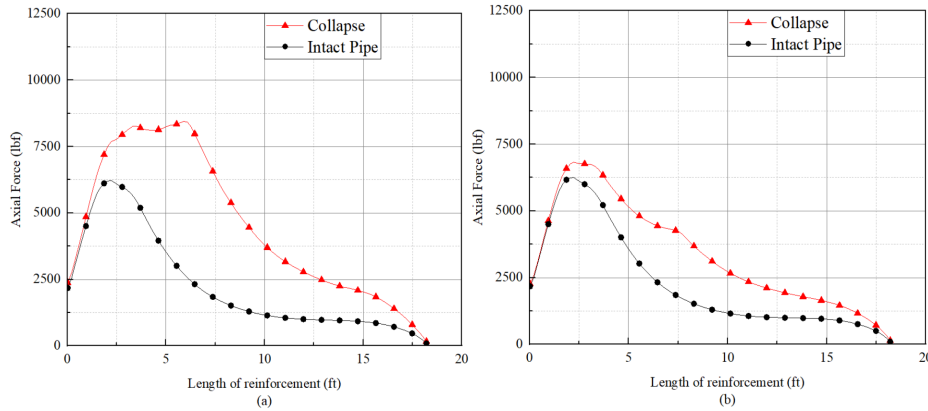
Although the relative depth is the same as that of the larger pipe (discussed earlier), the actual burial depth is shallower. As a result, the deformation in the soil caused by the collapsed pipe

reaches the reinforcement layer, leading to higher axial forces. By increasing the depth to  $h/r_o = 12$  the deformations induced in the soil by the collapse are confined to an area around the pipe and the effects on the critical reinforcement are mitigated.

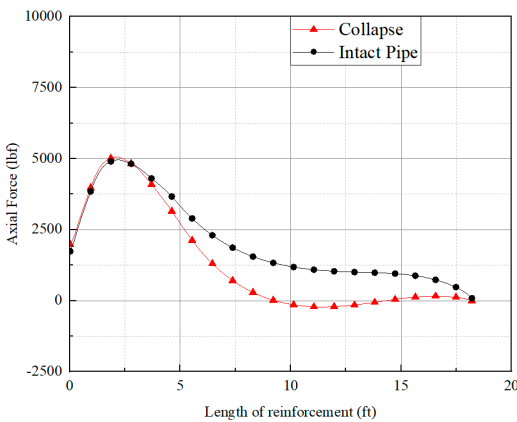
Additional simulations were performed with the pipe diameter doubled, that is, to  $r_o = 36$  in., to evaluate whether the criterion of  $h/r_o = 10$  remained valid. Figure 6.10 presents the axial force in the first layer of reinforcement for this pipe size and for the case of intact pipe and for the collapsed pipe. The results indicate that the increase in axial force remains within acceptable limits, and the associated deformation is also small (not shown). Therefore,  $h/r_o = 10$  can be considered a safe depth for the larger-diameter pipe. This conclusion also holds for the other two locations of the pipe, that is, at 5.9 ft and 16.4 ft behind the face of the wall.

### 6.3.3 Effect of Wall Height

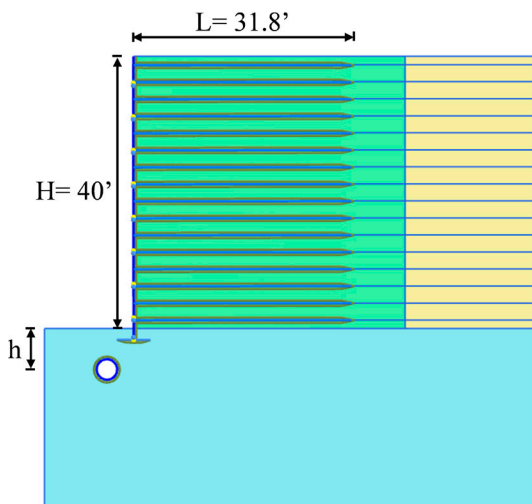
Figure 6.11 shows a 40-ft-tall MSE wall with a pipe placed in its foundation. The length of the strips is calculated as  $0.7H$ , where  $H$  is the height of the wall, satisfying the minimum recommendations from FHWA (2009). The overall FOS calculated using the strength reduction method is 1.48. The properties of the backfill, retained soil, and foundation soils are the same as used for 25-ft-tall wall. The construction of the wall is performed in



**Figure 6.9** Axial Forces on the First Layer of Reinforcement When the Pipe is Placed in Front of the Wall Facing and Radius is Halved ( $r_o = 9$  in.) (a)  $h/r_o = 10$ , and (b)  $h/r_o = 12$ .



**Figure 6.10** Axial Force on the First Layer of Reinforcement When the Pipe is Placed in Front of the Wall Facing with a Radius  $r_o = 36$  in., and  $h/r_o = 10$ .



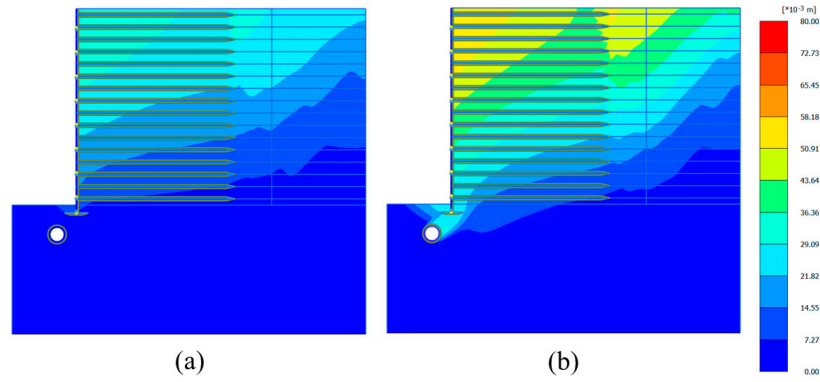
**Figure 6.11** Cross Section of a 40 ft MSE Wall With a Pipe Placed at a Depth  $h$ .

stages as discussed in Chapter 4, from Table 4.1 through Table 4.5. The pipe has a radius  $r_o$  of 18 in. Analyses were carried out for the pipe placed at two different depths, corresponding to  $h/r_o$  of 4 and 11, both cases with the pipe placed in front of the wall, which is the most critical location.

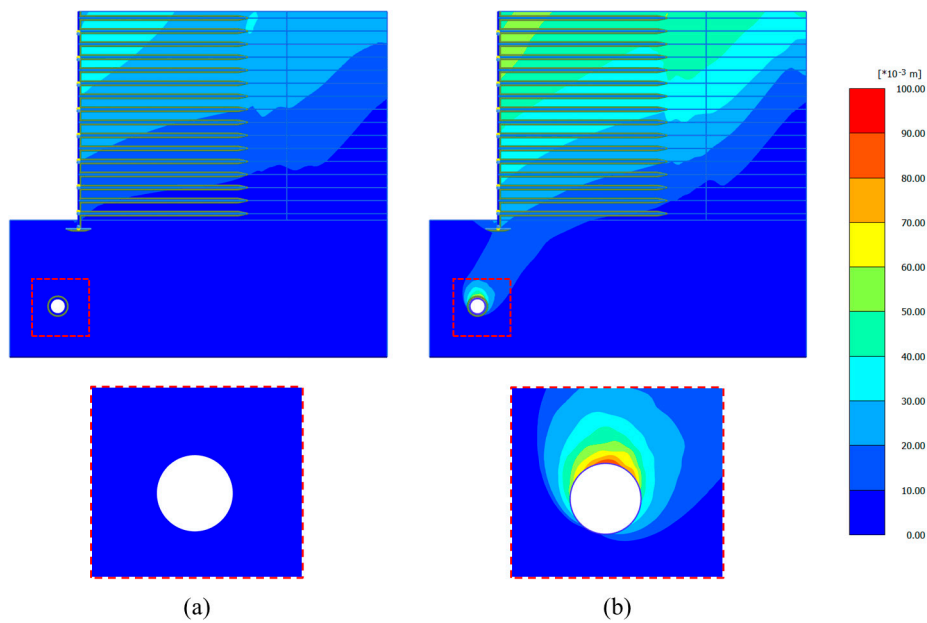
Figure 6.12 and Figure 6.13 provide contours of wall deformation for the intact and collapsed pipe cases, with the pipe placed at a depth of  $h/r_o = 4$  and  $h/r_o = 11$ , respectively. As mentioned, in all cases, the pipe is located in front of the wall. As shown in Figure 6.12a, the intact pipe causes no noticeable deformation in the surrounding soil. In contrast, the collapsed pipe (Figure 6.12b), induces significant localized deformation around its perimeter and reaches the wall and the facing panel. When the pipe is placed at a depth of  $h/r_o = 11$  (Figure 6.13b), the deformation is local to the pipe and does not affect the wall.

Figure 6.14 is a plot of the axial force in the first layer of reinforcement, for a pipe placed in front of the wall at  $h/r_o = 4$  (Figure 6.14a) and at  $h/r_o = 11$  (Figure 6.14b). The plots also include, for comparison, the axial force in the reinforcement when the pipe is intact. As one can see in Figure 6.14a, when the pipe is placed at a depth  $h/r_o = 4$ , the axial force increases by 74% with respect to the intact pipe case, thus exceeding the acceptable limit. In contrast, when the pipe is located at a depth  $h/r_o = 11$  (Figure 6.14b), the increase remains below the permissible limits. This suggests that, for a taller wall, deeper placement of the pipe is necessary to mitigate the impact of pipe collapse. Therefore, for tall walls, a depth of  $h/r_o$  greater than 11 should be considered.

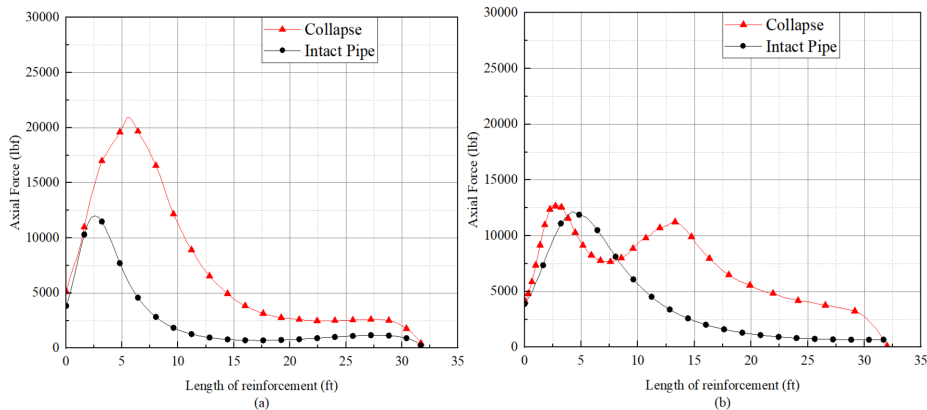
Figure 6.15 presents the axial force in the first layer of reinforcement for a pipe placed 5.9 ft behind the wall at depths  $h/r_o = 4$  (Figure 6.15a) and at  $h/r_o = 11$  (Figure 6.15b). The plots include results from the intact and collapsed pipe scenarios. When the pipe is placed at a depth  $h/r_o = 4$ , the axial force increases by 40%, exceeding the acceptable limit. In contrast, when the pipe is located at a depth  $h/r_o = 11$ , the increase remains within permissible limits. These observations are consistent with the case already discussed (Figure 6.14) and confirm the finding that for tall walls a depth of  $h/r_o = 11$  or greater is necessary to guarantee the stability of the wall, irrespective of the location of the pipe.



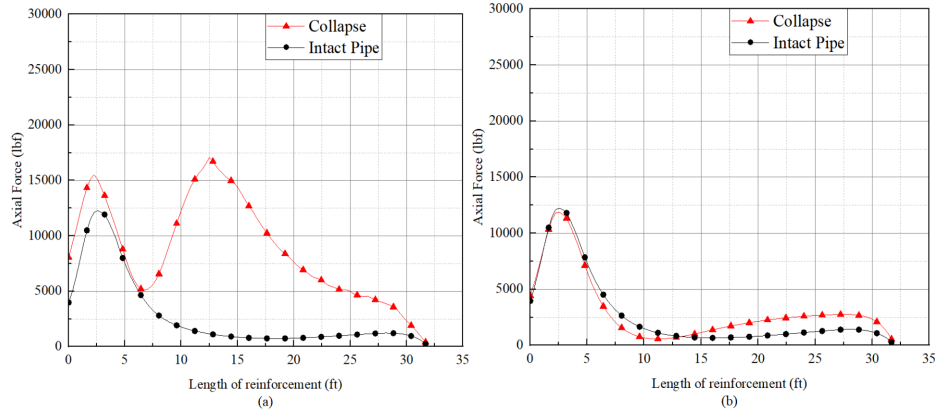
**Figure 6.12** Deformation Contours of the 40 ft Wall With Pipe Located at  $h/r_0 = 4$  (Where  $r_0 = 18$  in.) in Front of the Wall. (a) Intact Pipe, and (b) Collapsed Pipe.



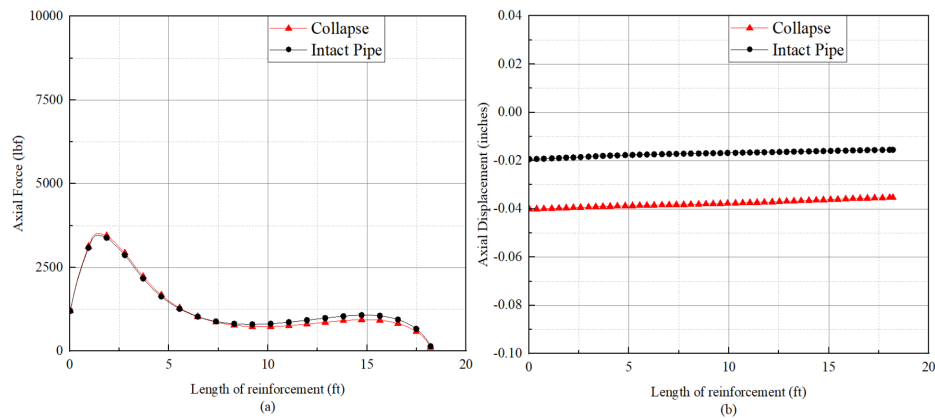
**Figure 6.13** Deformation Contours of the 40 ft Wall With Pipe Located at  $h/r_0 = 11$  (Where  $r_0 = 18$  in.) in Front of the Wall. (a) Intact Pipe, and (b) Collapsed Pipe.



**Figure 6.14** Axial Forces on the First Layer of Reinforcement When the Pipe is Placed in Front of the Wall Facing ( $r_0 = 18$  in.). (a)  $h/r_0 = 4$ , (b)  $h/r_0 = 11$ .



**Figure 6.15** Axial Forces on the First Layer of Reinforcement When the Pipe is Placed Behind the Wall Facing ( $r_o = 18$  in.). (a)  $h/r_o = 11$ , (b)  $h/r_o = 4$ .



**Figure 6.16** Axial Forces and Displacements on the First Layer of Reinforcement When the Pipe is Placed in Front of the Wall Facing, at  $h/r_o = 10$ , with  $r_o = 18$  in. (a) Axial Force; and (b) Axial Displacement.

#### 6.4 Foundation Soil: Silty Clay

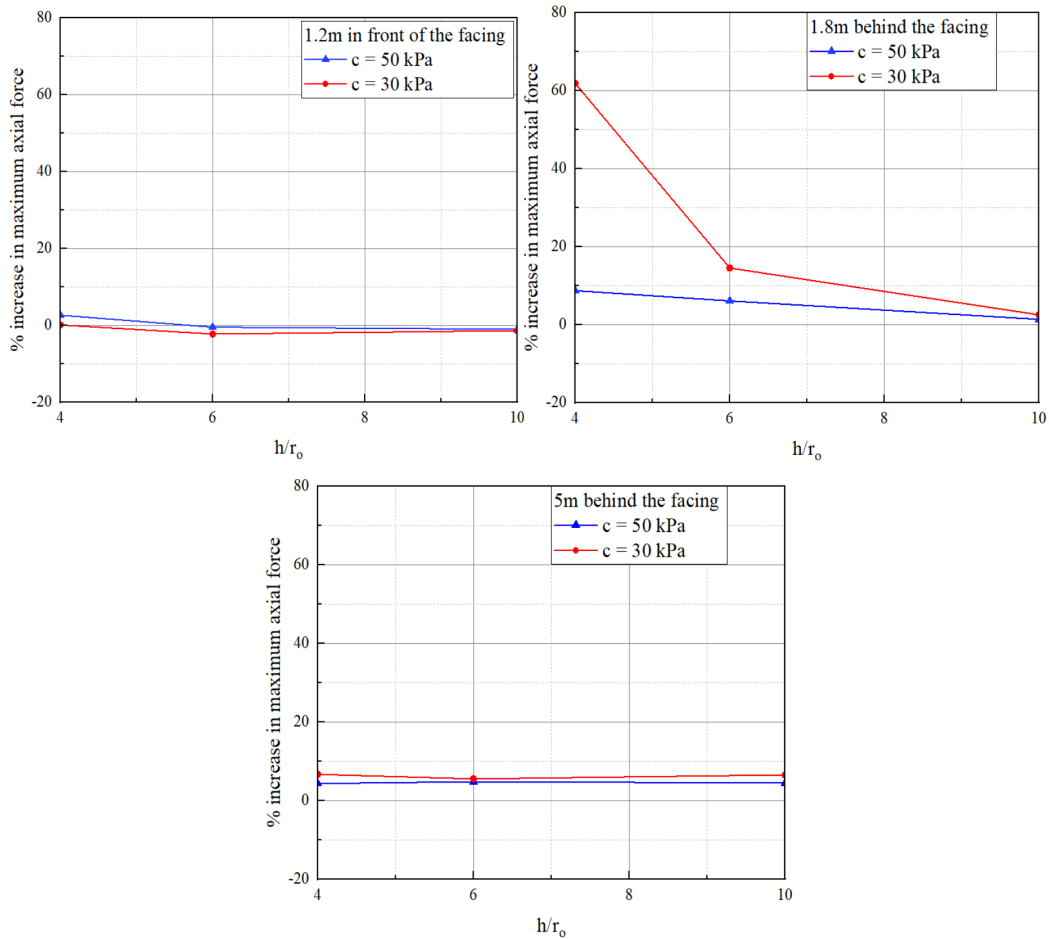
This section investigates the effect of silty clay in the foundation soil when the pipe collapses. The minimum safe burial depth of the pipe is discussed first, followed by a sensitivity analysis of the impact of the magnitude of cohesion. The geometry of the wall (25 ft tall; Figure 6.3), backfill and fill properties, modeling approach, size of the pipe, method of pipe collapse, etc. are all the same as those discussed for the pipe in sand. The only difference is the properties of the foundation soil. Those are listed in Table 6.1.

Figure 6.16 shows the axial force and displacement of the bottom/critical reinforcement for a pipe placed in front of the wall, at a depth of  $h/r_o = 10$  ( $r_o = 18$  in.). The plot also includes the results when the pipe is intact. While the collapsed induces a larger displacement in the reinforcement (Figure 6.16b), the change is small (on the order fraction of inches) and does not significantly affect the axial force in the reinforcement (Figure 6.16a).

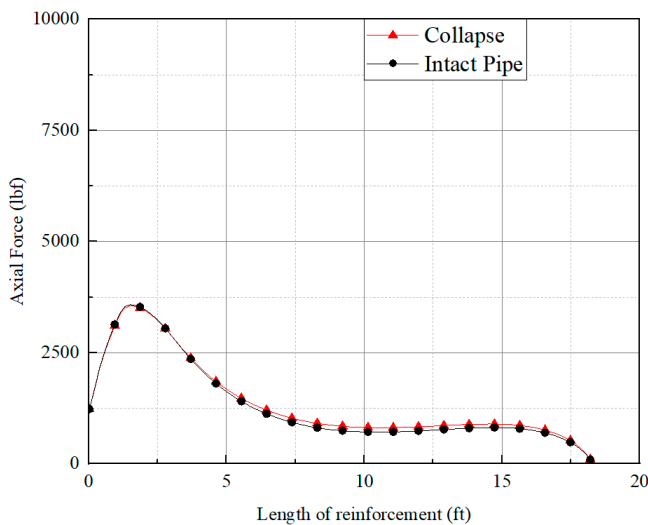
It is important to note that the analysis assumes drained conditions. The presence of water in the clay foundation would reduce the effective stress in the soil. A sudden collapse of the

pipe could induce excess pore pressures, which in turn would further change the effective stresses in the soil. This scenario has not been considered, as it is outside the scope of the work, where failure of the pipe is assumed as progressive.

Figure 6.17 summarizes the percentage increase in maximum axial force of the critical reinforcement as a function of the  $h/r_o$  depth ratio. All results apply to a 36 in. diameter pipe, that is, with  $r_o = 18$  in. Figure 6.17a shows results for a pipe placed 3.9 ft (1.2 m) in front of the wall, and Figure 6.17b–c, for pipes located, respectively, at 5.9 ft (1.8 m) and 16.4 ft (5 m), behind the face of the wall. The figures display results for cohesion values of 7.25 psi (50 kPa, Table 6.1) and for a reduced value of 4.35 psi (30 kPa). The two values are intended to represent the soil in its natural condition, and the soil with an increased water content that may be produced by the pipe leaking. The results show that when the pipe is located 5.9 ft (1.8 m) behind the facing panel (Figure 6.17b), there is an increase in axial force at shallow depths. However, the increase quickly reduces as the pipe is embedded deeper. The failure of pipes placed at other locations induce small changes in axial force across all depths. As expected, failure of the pipe in the lower cohesion soil results in larger axial forces in the critical reinforcement. Nevertheless,



**Figure 6.17** Increase in Maximum Axial Force in the First Layer of Reinforcement Due to a Pipe Placed in Silty Clay at Different  $h/r_0$  Depth Ratios, for a Pipe With  $r_0 = 18$  in. Results are Shown for Three Pipe Locations Relative to the Wall Facing: (a) 3.9 ft in Front of the Facing; (b) 5.9 ft Behind the Facing; and (c) 16.4 ft Behind the Facing.



**Figure 6.18** Axial Forces on the First Layer of Reinforcement When the Pipe is Placed in Front of the Wall Facing. Pipe Radius  $r_0 = 9$  in., and  $h/r_0 = 10$ .

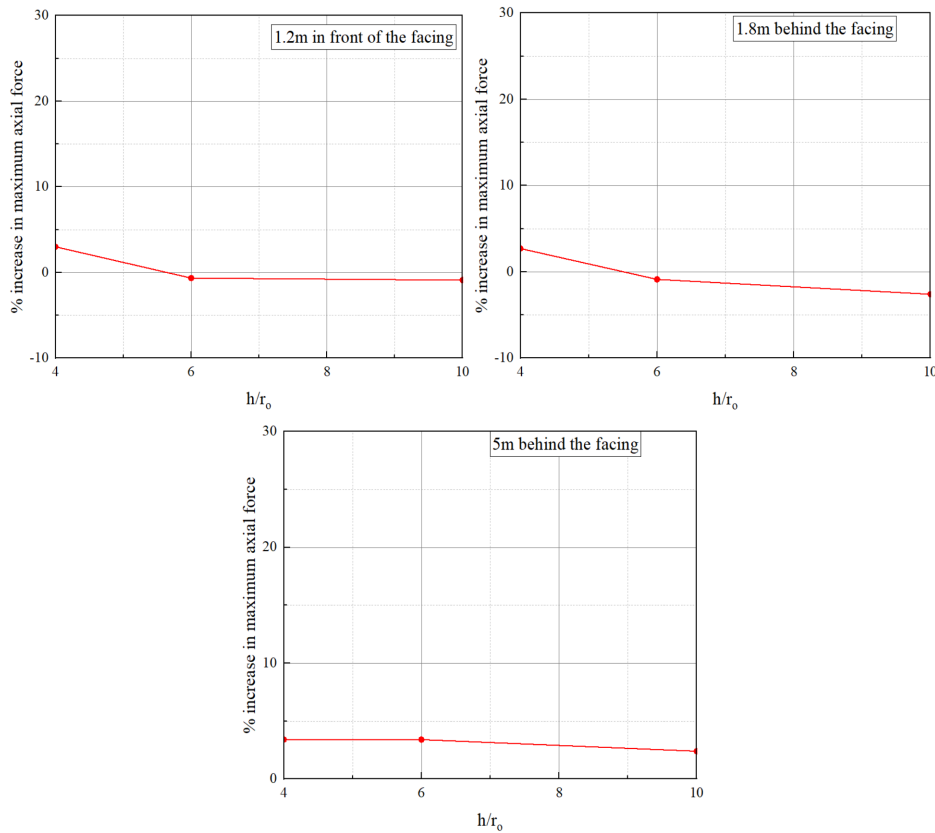
the results suggest that a depth of  $h/r_0 = 6$  or greater may be sufficient to prevent detrimental effects on the wall due to the collapse of the pipe.

To assess the influence of pipe size, additional simulations were performed with the pipe diameter reduced by half, while keeping the ratio  $h/r_0 = 10$ . Figure 6.18 shows the axial force in the critical reinforcement when the pipe is intact and when it collapsed. The results show that at this depth, the failure of a pipe with 18 in. diameter does not affect the performance of the wall.

### 6.5 Foundation Soil: Loam

This section investigates the collapse of a pipe in loam, a soil stiffer and stronger than silty clay (Table 6.1). As with the previous cases, the only differences in the models are the properties of the foundation soil.

Figure 6.19 plots the percentage increase in maximum axial force of the critical reinforcement as a function of the  $h/r_0$  depth ratio for a 36 in. diameter pipe. The figure shows results for



**Figure 6.19** Increase in Maximum Axial Force in the First Layer of Reinforcement Due to a Pipe Placed in Loam at Different  $h/r_0$  Depth Ratios. Pipe Size,  $r_0 = 18$  in. Results are Shown for Three Pipe Locations Relative to the Wall Facing: (a) 3.9 ft in Front of the Facing; (b) 5.9 ft Behind the Facing; and (c) 16.4 ft Behind the Facing.

different locations and depths of the pipe. The results indicate the expected trend of smaller effects of the failure of the pipe on the wall than those for the silty clay foundation. This is because of the higher stiffness and strength of the loam compared with those of the silty clay. As with previous cases, the larger effect of the pipe failure is found when the pipe is located closer to the wall. Also, as the pipe is buried deeper into the ground, its collapse has smaller effects on the wall.

### 6.6 Summary and Conclusions

This study investigates the interaction between an MSE wall and a collapsed pipe placed perpendicular to the cross section of the wall using numerical simulations in PLAXIS 2D. The criteria used to consider when the collapse of the pipe would be acceptable, in terms of maintaining the wall performance were: (1) the axial force in any reinforcement would not increase by more than 20% with respect to when the pipe was intact; (2) the wall facing would not experience more than 2 in. of additional deformation due to the pipe collapse. Three foundation soil types were considered: (1) sand, (2) silty clay, and (3) loam. The pipe was analyzed at three locations relative to the facing: 3.9 ft in front of the wall facing, 5.9 ft behind, and 16.4 ft behind the wall facing.

In granular soil, the collapse of an 18 in. radius shallow pipe can significantly influence the MSE wall reinforcement performance. It was found that the worst location of the pipe was when placed in front of the facing of the wall. At shallow depths,  $h/r_0 = 4$ , the axial force in the first layer of reinforcement increased by up to 125% due to the pipe failure. The influence of the pipe failure on the wall performance diminishes when the pipe is placed deeper. At a depth of  $h/r_0 = 10$  or larger, the axial force remains within acceptable limits, suggesting that this depth may serve as a safe threshold. Additional simulations with doubled (radius of 36 in.) and halved (radius of 9 in.) pipe diameters, while maintaining the same  $h/r_0$ , were conducted. The results showed that the large pipes, at burial depths equal or larger than  $h/r_0 = 10$  would not affect the performance of the wall. Smaller pipes, however, would need larger embedment under the wall than that given by the  $h/r_0 = 10$  ratio. The influence of wall height was also examined, and the findings suggested that the  $h/r_0 \geq 11$  depth criterion for a 25–40-ft-tall wall.

In silty clay, the collapse of the pipe had a relatively minor effect on the critical reinforcement even at depth ratios of  $h/r_0 = 4$ . A sensitivity analysis was conducted by reducing the cohesion to simulate soft clay conditions. As expected, with a reduced cohesion, the critical the reinforcement experienced larger axial forces and displacements than for the case with

larger cohesion. Similar to the case with a granular soil foundation, the results supported the notion that the worse location for the pipe, if it fails, is close to the facing of the wall. Also similar was the finding that the impact of the pipe collapse on the performance of the wall quickly diminished with increasing the burial depth of the pipe. For depth larger than the height to radius ratio of ten, that is, for  $h/r_o \geq 10$ , the failure of the pipe was found to have negligible effects on the MSE wall. However, the analysis did not include the potential softening of the clay in the foundation due to the pipe leaking or the long-term effects of the pipe collapse.

Lastly, loam, representing a stiffer, stronger soil than silty clay, as the MSE soil foundation was investigated. As expected, due to its higher strength and stiffness, a pipe collapse in loam showed a smaller effect on the wall than the pipe in the silty clay. The results confirmed that  $h/r_o = 10$  can be considered a safe depth as well.

This study highlights the importance of considering buried utilities, particularly ageing pipes, during the design of MSE walls. The response of the wall and reinforcement to a pipe collapse is highly dependent on the foundation soil type, pipe location, and burial depth. The findings from this investigation suggest that  $h/r_o = 10$  may serve as a guideline for safe pipe placement over a wide range of soils, provided that the diameter of the pipe is larger than 36 in. For smaller pipes, larger burial depths may be required. The findings are strongly dependent on the assumptions, sizes, and properties used for the numerical tests and should be used as general guidelines. It is strongly recommended that a detailed analysis be conducted for any specific case to determine any impact that a buried utility underneath a MSE wall may have, both under (intact) working conditions and under the possibility of pipe failure. Such analyses are particularly important when the pipe is located near the facing of the wall, the location that has been found as the most critical.

## 7. MONITORING, MITIGATION AND REMEDIATION

### 7.1 Introduction

This chapter presents the techniques for monitoring, mitigating, and remediating issues related to underground utilities. Leaks in ageing utilities are inevitable and can occur due to factors such as loose connections or cracks in the pipes.

This chapter is organized in three more sections, in addition to this Introduction. Section 7.2 outlines the laboratory-developed monitoring techniques designed to detect leaks in utilities that carry fluids. Section 7.3 describes the mitigation and remediation strategies specifically for utilities located beneath MSE walls. Finally, Section 7.4 provides a summary of the monitoring, mitigation, and remediation strategies discussed in the chapter.

### 7.2 Monitoring Techniques

Leakage in pipes during their service life is likely; therefore, routine monitoring of pipes and their joints is essential to prevent catastrophic failures or excessive deformation of the

ground around them. Regular monitoring and maintenance can extend the lifespan of pipelines and reduce associated risks. Monitoring techniques offer innovative solutions for early leak detection, enabling proactive interventions.

This study emphasizes the importance of integrating monitoring technologies into routine inspection protocols to improve pipeline reliability and safety.

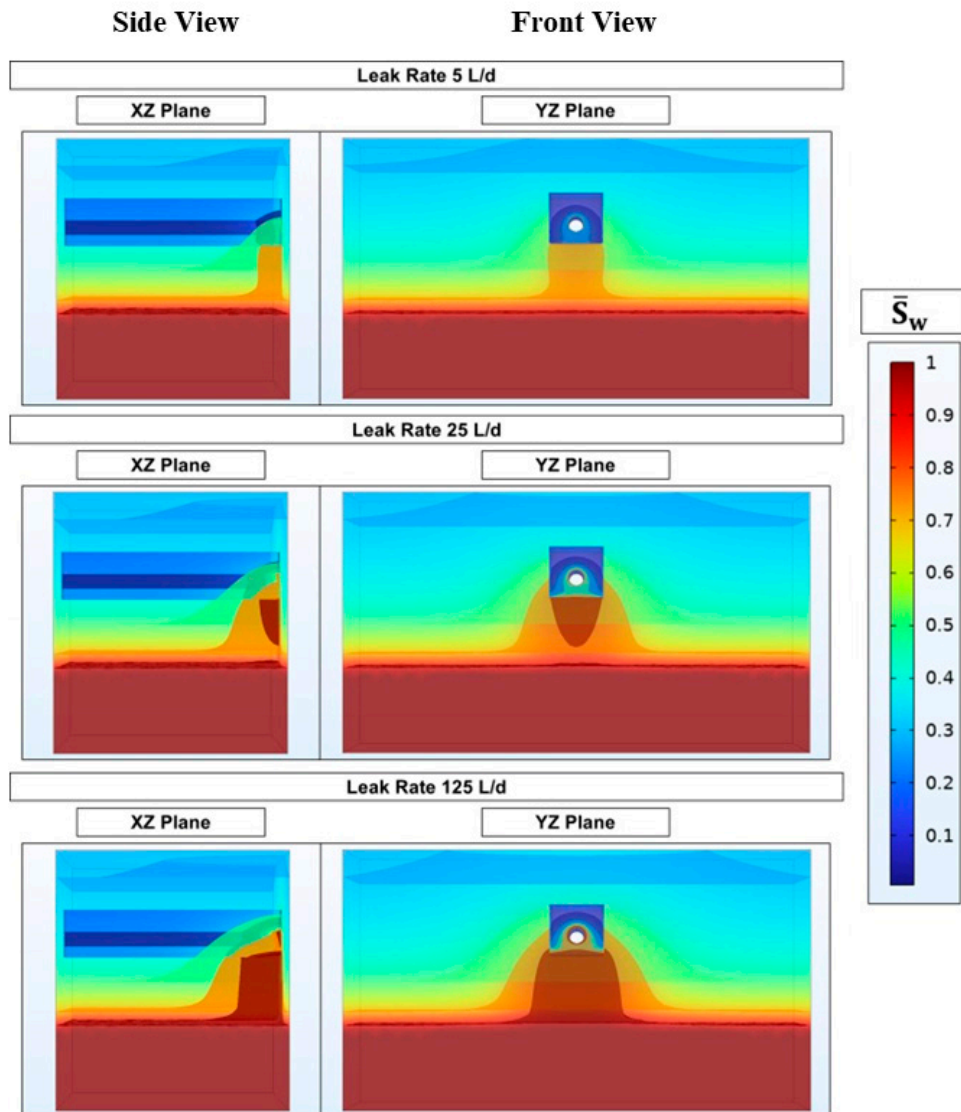
#### 7.2.1 Leak Detection Using Optical Fiber (D'Aniello et al., 2024)

In this laboratory experiment, fiber optic sensors were placed 1–2 cm from a 20 cm diameter pipe to detect leaks. The pipe was tested at leak rates of 5, 25, and 125 liters per day (L/d). An active distributed temperature sensing (DTS) method was employed, in which the fiber optic cable was periodically heated to capture temperature changes. Unlike passive DTS, which depends on ambient temperature variations, active DTS introduces a controlled heat pulse, enabling the measurement of how quickly and how much the surrounding material absorbs and dissipates heat. When a leak occurs, water infiltrates the surrounding soil and increases local water saturation. This increased saturation enhances thermal conductivity and specific heat capacity in the soil water and stores heat more effectively than air-filled pores. As a result, the leaked area exhibits a different thermal response that depends on the rate at which the cable cools or fails to heat up as expected. The presence of water near the sensor draws heat away more quickly, leading to a measurable temperature drop or a reduced temperature rise compared to dry soil. In the experiment, even small leaks caused measurable temperature anomalies typically on the order of 0.1–3 °C depending on the heating power, time, and leak rate. Figure 7.1 shows the effective water saturation ( $S_w$ ) distribution and the thermal response zone increased with leak rate.

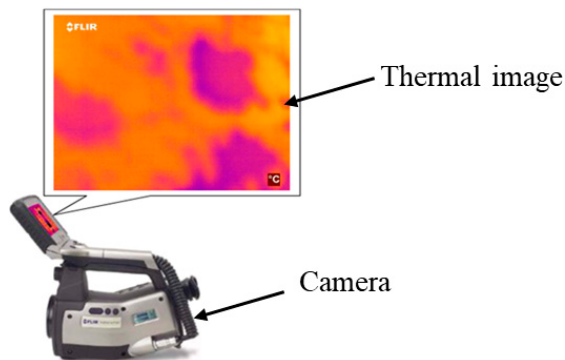
#### 7.2.2 Detection Using Infrared Photography (Fahmy et al., 2010)

The objective of this experiment was to detect and locate underground leaks in pressurized water mains using infrared (IR) thermography, supported by acoustic sensing for validation. The setup consisted of water pipes buried approximately 1.8 m below a paved road surface. Above the road, an infrared camera system was mounted on a moving vehicle at heights ranging from 1.2–12 m above the pavement. Figure 7.2 shows the IR camera captured thermal images of the pavement surface where leaks caused subtle heat and moisture variations. The dark areas show no leak, which is normal pavement, while the bright area denotes leaking because the heat is transferred upward due to moisture.

To validate findings, acoustic sensors, specifically hydrophones and accelerometers, were attached at two points along the pipe system, typically at fire hydrants on each end of a pipe segment (48–300 m in length, 150–200 mm diameter). These sensors captured vibrations or sounds generated by escaping water. A processing unit calculated the time difference between signals, triangulating the leakage location. Thus, sensors were on the pipe (via hydrants), and the camera observed from above, not in direct contact with the pipe.



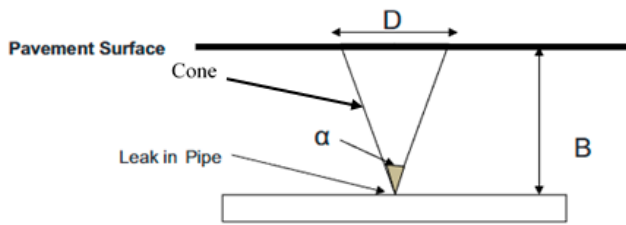
**Figure 7.1** Distribution of Effective Water Saturation ( $S_w$ ) From a Leaking Pipe Into the Surrounding Area (Adapted From D’Aniello et al., 2024).



**Figure 7.2** The Infrared Camera Displays Thermal Contrast on the Pavement Surface Caused by a Water Leak (Adapted From Fahmy et al., 2010).

The experiment found a strong correlation, not necessarily one-to-one but functionally predictive, between pipe temperature (underground), ambient air temperature (above the pavement), and pavement surface temperature. This correlation allowed researchers to assess when thermal contrast from a leak would be most detectable. Detection worked best in early morning hours (11:00 p.m.–6:00 a.m.) during overcast conditions in fall and spring. Warmer pipe temperatures increased heat flow upward through moist soil, creating detectable surface contrasts.

The thermal signature formed a near-circular area on the pavement, modeled as the base of a cone with an angle between  $80.4^\circ$  and  $123.4^\circ$ , pointing down toward the actual leak in the pipe (Figure 7.3). The size of this thermal spot, in combination with the pipe depth, allowed estimation of the precise location of the leakage.



**Figure 7.3** Determination of Leak Location (Adapted From Fahmy et al., 2010).

### 7.2.3 Gas Leak Detection Using Optical Fiber (Z. Chen et al., 2023)

Pinhole leaks can be detected in gas pipelines with the use of fiber optic cables that use acoustic sensing. In this laboratory experiment, steel pipes measuring 150 cm in length and 12 mm in diameter were embedded in a tank filled with silica sand. When a leak occurred, a gas-filled cavity formed around the pipe. The size of the cavity increased with the size of the hole in the pipe. As a result, the soil displaced around the pipe at the location of the leak. This resulted in vibrations that were then detected by the optical fiber. It was found that noise from the gas leak was less noticeable than the vibrations caused by the movement in the soil. Further research still needs to be done to compare how external noises affect sensing using the fiber optic cable.

### 7.2.4 Water Leak Detection Using Optical Fiber (Scarpetta et al., 2023)

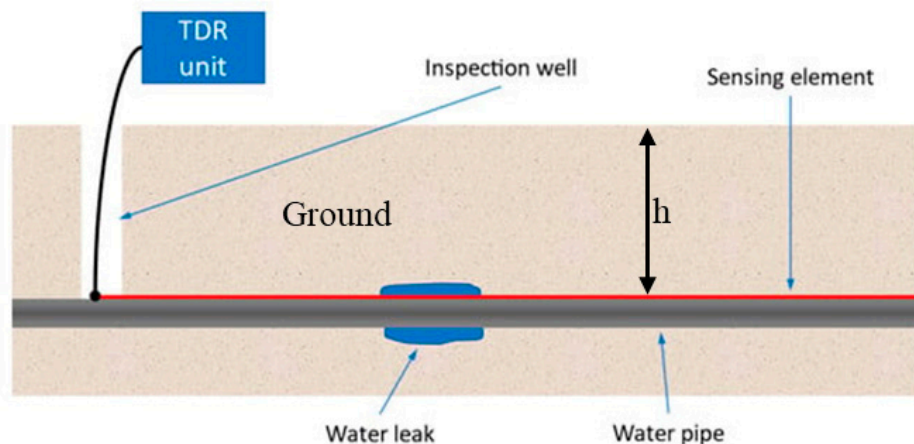
Time domain reflectometry (TDR) is a sensing technique that can be used to detect water leaks in underground pipes. Figure 7.4 shows an optical fiber placed along the pipe and connected to a TDR unit. The sensing element (SE) used in the experiments was a 15-m-long biwire cable laid out on the floor to simulate its placement near a buried pipe. The SE was connected to a TDR unit composed of an arbitrary waveform generator and an oscilloscope, via a coaxial cable and T-junction. One advantage of this setup is that leaks can be identified along

the length of the pipe using a single measurement, thus reducing inspection time.

Water leaks were simulated in two ways: (1) by submerging a section of the SE directly in water, and (2) by placing a container of water on top of the SE, with the container bottom acting as a dielectric barrier. These tests captured large and small leaks, respectively, with signal responses recorded in each case. The TDR system transmitted a voltage pulse and measured the reflectogram, which changes when water alters the dielectric constant of the surrounding medium. In direct contact, strong reflections made it easy to find leak locations. However, for an indirect contact, a baseline dry reflectogram was used for comparison, allowing the isolation and localization of weak signals linked to smaller leaks. The experiment confirmed that the proposed TDR inversion technique could reliably identify the location and size of water leaks, with typical localization errors under 13 cm for small leaks and under 33 cm for larger, 2-m-long leaks.

### 7.2.5 Detection of Underground Pipes Using Ground-Penetrating Radar (Mizutani et al., 2024)

The authors used ground-penetrating radar (GPR) to inspect underground pipes and detect their location. The method is helpful when the location of the pipes is unknown because the pipes can be located within a distance of 12 cm. A vehicle-mounted GPR runs over the ground, and 3D point clouds are formed based on linearity, density, and echo patterns. The point cloud is used to identify cracks, deformations, and changes in the materials of the pipe. 2D GPR scans in their experiments revealed that buried pipes were identified using the depth and dielectric constant of the surrounding soil. In the experiments, four pipes were buried 1 m below the ground surface, and four pipes, 50 cm. Results from the GPR were successfully used to accurately identify the location and orientation of all eight pipes. Due to low resolution in the transverse direction, the detection of pipes placed parallel to the direction of motion of the GPR was not accurate. Despite this limitation, time-series radar imaging can predict pipe breakage detection by comparing changes in the pipe radar images over time.



**Figure 7.4** Schematic of the Leaking Pipe With a TDR Unit (Adapted From Scarpetta et al., 2023).

### 7.3 Mitigation and Remediation

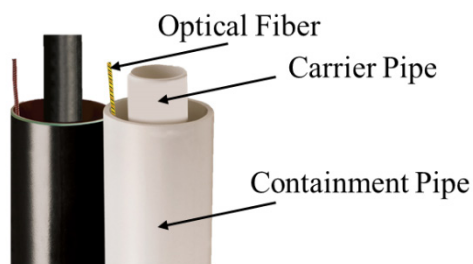
Utility pipes have been buried underground for decades and, over time, they may fail due to ageing, material degradation, and/or loss of structural integrity. While the occurrence of such failures cannot be entirely prevented, their consequences can be effectively contained and localized to mitigate adverse impacts on overlying MSE walls.

To ensure the structural safety of MSE walls, the following protective measures and procedures are either currently in practice or can be adopted in future designs.

#### 7.3.1 Double Wall Containment

One of the common practices by the oil and gas industry to mitigate the risk of pipeline leaks is the use of double wall containment systems. Figure 7.5 shows the double wall containment system. The fundamental structure of a double containment system involves placing a smaller diameter pipe inside a larger diameter pipe. The inner pipe is called the carrier pipe, which transports the hazardous or sensitive fluids such as oil, gas, and acids. It is made up of carbon steel, stainless steel, fiber-reinforce plastic (FRP), or PVC, and a wide variety of materials is available. Some systems could have multiple carrier pipes. The outer pipe is known as the containment pipe, which encases the carrier pipe to contain any potential leaks. There are several options such as fiberglass, PVC, and steel. Between the carrier and containment pipes is the annular space, or annulus. This space serves several functions. It can be used for monitoring through the installation of leak detection systems such as optical fibers that sense the presence of fluids. It may also be filled with inert gases (e.g., nitrogen) or evacuated to create a vacuum, both of which reduce corrosion risk and improve thermal insulation. In some cases, this space can be part of the secondary containment system, temporarily holding leaked fluid. To maintain pipe alignment and allow for thermal expansion/contraction, centering supports are installed approximately every 10 ft along the carrier pipe. These supports prevent mechanical stress and ensure system longevity.

Inspection of the carrier pipe can be done through the annulus. For example, inspection of welds in the carrier pipe can be done through radiographic monitoring. Pressure monitoring in the annulus is an easy method to check the containment.



**Figure 7.5** Double Wall Containment Piping System (Adapted From Rovanco Piping Systems [n.d.]

Additionally, strain-sensitive optical fibers placed along the containment pipe can detect deformations or stress concentrations, potentially indicating pipe degradation. To facilitate inspection and maintenance, access outlets may be installed on the outer pipe near structural features (e.g., MSE walls). These outlets allow for pressure readings, strain monitoring, and even fluid sampling, if needed.

This system offers several significant advantages. The probability of failure of the carrier and containment pipe simultaneously is very low, thus providing improved safety to an MSE wall above the pipe. It also provides enhanced environmental protection because the outer pipe prevents leaks from reaching the surrounding ground. In addition, routine pressure monitoring would help with early detection of the leak. If there is vacuum or inert gas in the annular space, the corrosion risk of the inner pipe is significantly reduced. Maintenance of the inner pipe is facilitated; if a section of the carrier pipe fails, it can be isolated by removing only the affected portion of the pipe.

The potential disadvantages of this method are a greater initial investment due to increased material usage and labor requirements. The method may require a higher complexity during construction because it requires precise alignment of the two pipes, additional materials, and specialized monitoring systems.

#### 7.3.2 Slab Protection

Pipes installed beneath MSE walls are often subjected to significant stresses from overburden pressures, potential settlements or lateral movements induced by the wall. These stresses can cause pipe deformation or failure, which may compromise the stability of the MSE wall.

Pipes installed beneath MSE walls are often subjected to significant stresses from overburden pressures, potential settlements or lateral movements induced by the wall. These stresses can cause pipe deformation or failure, which may compromise the stability of the MSE wall.

To prevent structural failure of the pipe, one effective approach would be the use of a protective slab system installed above the pipe. This slab would then work as a barrier that redistributes the load away from the pipe. In the event of pipe failure, whether due to corrosion, collapse, or leaking, the slab would bridge the loss of bearing capacity of the lost pipe and prevent the upward propagation of failure. The slab is typically constructed with reinforced concrete and should be designed to span over the pipe with sufficient length, as a function of the pipe size, depth, and surrounding ground. Depending on the risk level and pipe diameter, the slab may be required to accommodate pipe movement and thermal expansion. Access to the pipe for inspection or maintenance may be facilitated by maintenance ports, allowing for limited intervention without major excavation.

This method provides several advantages. It isolates the pipe collapse from the MSE wall, thus reducing the risk of global instability. It limits the upward progress of the failure and allows targeted repairs without disturbing the wall system.

The solution also introduces challenges. The installation of a structural slab increases construction complexity and cost, particularly in retrofits or constrained spaces. It also requires careful coordination between structural and utility design teams to ensure that loading paths, clearances, and service requirements are all satisfied.

### 7.3.3 Deeper Pipe

An alternative approach to protect the MSE wall involves placing the pipe at a sufficient depth, particularly at a depth-to-radius ratio greater than 10 for pipes with diameters exceeding 36 in. At this embedment, even in the event of pipe failure, the effects are unlikely to propagate upward to the reinforced zone of the MSE wall, thereby preserving the structural integrity of the wall. This observation is supported by the analysis presented in Chapter 6, which demonstrates that deep placement effectively isolates wall stability from pipe related failures.

However, this method introduces notable challenges related to access, inspection, and maintenance. While indirect monitoring can be facilitated through optical fibers or embedded sensors, direct inspection and repair are significantly more difficult at greater depths. Although access points such as manholes or inspection chambers can be installed, these additions increase construction complexity and cost. Furthermore, the feasibility of this approach depends on the type of material being transported, which may impose additional constraints on monitoring and safety requirements.

## 7.4 Summary

This chapter addresses the monitoring, mitigation, and remediation strategies for buried utilities, aimed at protecting MSE walls from potential utility failures. Monitoring techniques are important for early leak detection to prevent catastrophic damage. Various laboratory-tested methods, including fiber optic sensors for temperature and acoustic sensing, infrared photography, TDR, and GPR, have shown high potential in controlled environments. These technologies can detect both water and gas leaks and even anticipate structural failures. However, using these methods in field applications has challenges such as in situ conditions, material heterogeneities, and external noise. Future studies could focus on validating these methods on a larger scale and enhancing their reliability for practical applications. In addition to monitoring, effective mitigation and remediation strategies are crucial for limiting the consequences of leaks or structural failures. This chapter discusses three approaches: (1) double wall containment systems, which provide redundancy and enable early detection through integrated sensors in the annular space; (2) protective concrete slabs, which help redistribute loads and localize the impact of potential failures, thereby shielding the overlying MSE wall; and (3) deep burial of utility pipes, which minimizes the interaction between failed utilities and the reinforced zones of MSE walls, preserving structural stability.

Each mitigation method does introduce cost and construction complexities; however, their integration with advanced monitoring systems offers a more resilient and cost-effective long-term

solution. An approach that combines early detection with strategic design enhancements can significantly reduce maintenance efforts, improve infrastructure safety, and extend the service life of both utilities and associated geotechnical structures.

## 8. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR IMPLEMENTATION

### 8.1 Summary of the Work Done

The objective of this study is to understand the interaction between an intersecting utility and an MSE wall and provide recommendations for the safe placement of the utility inside or beneath the MSE wall, such that the stability of the wall is not compromised. The objectives have been achieved through the following tasks:

1. A literature review was conducted to collect information on the impact of existing utilities inside and underneath MSE walls. It was found that there are a number of reasons that contribute to the failure of the utility, such as loss of backfill, MSE wall differential settlements, choking and clogging of utilities, corrosion, deformation and/or cracks in the wall facing, and settlement of the foundation soil. The review suggests that utilities will eventually leak, and repairs will be needed, which most often require excavation of the wall backfill and/or demolition of the wall. A review of federal and state guidelines was conducted to understand existing recommendations for utility placement within MSE walls. FHWA, Caltrans, FDOT, IDOT, Iowa DOT, KDOT, MDOT, NYSDOT, ODOT, TxDOT, and WisDOT provide some specifications related to reinforcement cover and transition distances between utilities and reinforcement. However, guidance on this issue remains limited and even contradictory, particularly for utilities located within the reinforced soil zone.
2. The interaction between utility pipes and MSE walls was investigated using the finite-element method software PLAXIS to simulate an actual 25-ft MSE wall from INDOT. The wall was located at I-465 and was constructed with granular soil in the reinforced zone. A circular concrete pipe with a diameter of 24 in. or 36 in. was considered in the analyses. The scenarios investigated included: (1) circular pipe within the reinforced zone, parallel to the wall, with diameter smaller and larger than the reinforcement spacing; (2) pipe located underneath the MSE wall at different distances and depths from the facing panel; and (3) circular pipe intersecting the MSE wall at an angle, either perpendicular or skewed to the wall, either within the reinforced zone or in the foundation soil. The influence of the pipe location on the safety factor of the MSE wall, axial force, displacement and soil-reinforcement slip on the critical reinforcement, and performance of the reinforced soil or soil foundation were examined.
3. Numerical analyses were completed to determine the minimum safe burial depth of pipes within the foundation soil of the MSE wall, with the objective of determining the minimum depth at which failure of the pipe would not compromise the performance of the wall. The analyses were performed for three different soil types, per recommendations of the Study Advisory Committee (SAC): sand, silty clay, and loam. The pipes were positioned both in front and behind the facing panel of the wall.
4. An extensive literature review was conducted to identify existing or promising technologies to prevent or at least minimize the impact of utility failure inside or underneath an MSE wall, as well as instrumentation to detect damage to the utility or water leaks.

## 8.2 Conclusions

The main conclusions drawn from this study are as follows:

1. The case studies reviewed on MSE walls with intersecting horizontal obstructions show that pipes eventually leak and may cause distress in the wall. Problems associated with utility damage or failure are usually detected when the damage to the wall is extensive, in which case wall repairs are considerable, costly and time consuming, often requiring the dismantling and rebuilding of the wall.
2. A review of the current practice of horizontal obstructions within MSE walls, which included FHWA, Caltrans, FDOT, IDOT, Iowa DOT, KDOT, MDOT, NYSDOT, ODOT, TxDOT, and WisDOT, revealed that there are no consistent guidelines among the different DOTs.
3. The presence of a pipe in the soil reinforcement, parallel to the face of the wall, significantly influences the behavior of the reinforcement. Axial forces increase, especially in the reinforcement directly beneath the pipe. Such an increased demand is more pronounced when the pipe is positioned deeper inside the reinforced soil and away from the wall's face. Axial displacements of the reinforcement also increase, particularly of the reinforcement directly above the pipe, with the greatest displacement occurring when the pipe is near the bottom of the wall. Additionally, the pipe induces a substantial increase in slip between the reinforcement and the surrounding soil, particularly in the reinforcement near the pipe, due to increased mobilization of friction between the soil and reinforcement. These effects are localized around the pipe and extend to a distance of about 2–2.5 times the pipe's diameter. The global stability of the MSE wall is not much affected by the presence of the pipe.
4. A pipe larger than the reinforcement spacing may increase axial forces in the reinforcement adjacent to the pipe by 60%, compared to the case with no pipe. The largest increase occurs in the reinforcement below the pipe.
5. Pipes intersecting the MSE wall perpendicular or at a small angle with the normal to the wall facing do not have a detrimental effect on the wall performance. The axial force in the reinforcement near the pipe is reduced, but such positive influence decreases with distance from the pipe. At about 2–2.5 pipe diameters, the influence of the pipe disappears. These positive effects are associated with the (large) frictional resistance that the pipe provides along its circumference, thus working as a reinforcement having a large frictional/contact area with the reinforced soil.
6. A pipe in the foundation of the MSE wall, parallel to the wall, may lead to higher forces in the reinforcement, most prominently to the bottom reinforcement. Similar to the case of the pipe inside the reinforced soil, the global stability of the wall is not affected.
7. A pipe in the foundation soil, at an angle with the normal to the wall face, mostly affects the first layer of reinforcement, by decreasing the axial force up to 20%. As the pipe is positioned deeper into the foundation soil, its influence further diminishes. The pipe positively impacted the overall stability of the wall by only 1–2%.
8. For MSE walls up to 25 ft tall, the collapse of a pipe with diameter larger than 36 in. does not affect the performance of the wall, as long as the pipe is placed beneath the wall at depth of  $h/r_o$  larger than 10, where  $h$  is the depth from the ground surface to the center of the pipe and  $r_o$  is the radius of the pipe. For walls between 25–40 ft, the ratio should be at least 11. It is important to note that these results apply to the type and geometry of the wall investigated and to the three types of soils considered in the foundation:

sand, silty clay and loam. This recommendation may not apply to pipes smaller than 36 in. in diameter. Case-specific studies will be required for these cases. Also, the recommendations are based on the mechanical failure of the pipe, while the soil properties around the pipe remain unaffected; thus, associated issues such as soil softening have not been considered.

9. There are no proven monitoring techniques to detect leaks in the pipes. A number of methods show promise, but they have been tested only in the laboratory. It is possible that with further developments, they may eventually be applicable to the field. Those methods include fiber optic sensors for temperature and acoustic sensing, IR photography, TDR, and GPR. These methods can detect both water and gas leaks and even anticipate structural failures.
10. There are no proven techniques, methods or strategies to prevent or at least mitigate the failure of a pipe underneath an MSE wall. The literature is very scarce on such a problem. However, based on the information collected, there are a number of approaches that show potential, namely:
  - a. Double-wall containment systems, where an outer pipe is placed to contain any leaks; the annular space between the two pipes may be used to install sensors to detect leaks.
  - b. Protective reinforced concrete slabs above the pipe, to redistribute loads in the soil, thus shielding the MSE wall above.
  - c. Encasing the pipe in reinforced concrete to minimize degradation of the performance of the pipe because of corrosion or differential settlements, for example.
  - d. Deep burial of the pipe to minimize the consequences of the pipe failure with the MSE.

## 8.3 Recommendations for Implementation

Based on the work done, the following recommendations for implementation are made:

1. It is highly recommended that utilities are placed outside the reinforced zone of any MSE wall. This solution would not affect the reinforced soil and any issues or repairs, while still potentially disruptive, would not require dismantling the wall.
2. If utilities cannot be placed outside the reinforced zone, a case-specific design should be completed to ensure that the reinforcement has an adequate factor of safety and that the presence of the utility does not have detrimental effects on the overall performance of the wall, including its global factor of safety and tolerable deformations. If the pipe diameter is larger than the reinforcement spacing, the reinforcement must splay around the pipe with a maximum angle of 15°.
3. Utilities with diameters larger than 36 in. placed under MSE walls should be located at a depth-to-radius ( $h/r_o$ ) ratio of at least 10 for walls up to 25 ft high, and 11 for walls up to 40 ft ( $h$  is the distance between the natural ground surface and the center of the pipe and  $r_o$  is the radius of the pipe). The recommendation applies to the foundation soils investigated, namely sand, silty clay, and loam, and to the mechanical properties chosen for the analyses. Nevertheless, it is strongly recommended that a case-by-case design analysis is undertaken that includes all the pertinent information for each case.
4. When placing the utility at depths larger than  $h/r_o = 10$ –11 is not feasible, protective systems should be considered such as reinforced concrete slab(s) above the pipe, encasing the pipe in reinforced concrete and/or any other measures to protect the pipe and the wall.

- There are no established or proven techniques or methods to monitor the performance of pipes buried inside or underneath MSE walls. It is recommended that further studies be conducted to develop new methods to monitor and protect the pipes. Those may require laboratory tests to develop a proof of concept and field implementation to assess the adequacy of the methods in the field.

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## APPENDICES

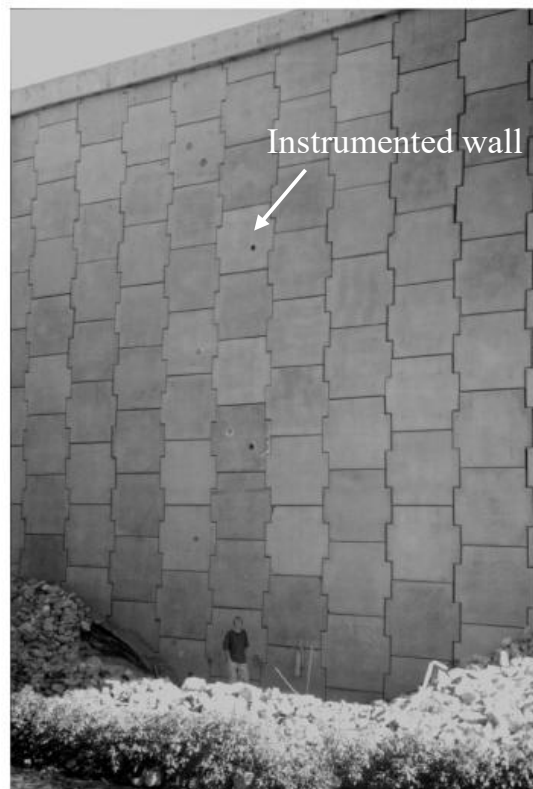
Appendix A. Numerical Validation of an MSE Wall from Field Data

# Appendix A. Numerical Validation of an MSE Wall from Field Data

## A.1 Introduction

The appendix presents the validation of a mechanically stabilized earth (MSE) wall instrumented at the south abutment of the US 24 bypass near Logansport, Indiana. This wall was monitored by Runser et al. (2001), who recorded reinforcement strip forces, which are used for comparison in this study. Numerical simulations were conducted using PLAXIS 2D, a widely adopted finite element method (FEM) software in geotechnical engineering; the rationale for selecting this software is discussed in Chapter 3.

The case study involves a 55.4-ft-tall (16.9 m) MSE wall (Runser et al., 2001), as illustrated in **Figure A.1**. The numerical model replicates the wall's cross-section under plane strain conditions, aiming to validate the modeling approach used in the report by comparing simulated results with field-measured data.



**Figure A.1** Instrumented Section of the MSE Wall (Adapted From Runser et al., 2001).

## A.2 Input Parameters

### A.2.1 Soil Materials

The numerical model comprises three different soil materials: reinforced, retained and foundation soils. The reinforced and retained soils are coarse-grained granular soils, as discussed in Runser et al. (2001). All soils are modeled using the Mohr-Coulomb constitutive model with a nonassociated flow rule. The input properties of the soils are listed in **Table A.1**. Note that, because the objective of the simulations is the validation of the modeling procedure, the foundation soil has been given properties of a very stiff, very strong soil.

*Table A.1 Input Soil Properties.*

Parameter	Value		
	Reinforced Soil	Retained Soil	Foundation soil
Unit weight, $\gamma$ (kN/m <sup>3</sup> )	20.8	19.7	17.0
Cohesion, $c$ (kPa)	0.10	0.1	1000
Friction angle, $\phi$ (degrees)	38.0	35.3	28
Elastic modulus, $E$ (MPa)	>1m face 40.0, <1m face 10.0	50.0	2000
Poisson's ratio, $n$	0.30	0.30	0.30
Dilation angle, $\psi$ (degrees)	8.0	5.3	0.0

Note: All parameters are taken from Runser et al. (2001), except those in italic that are assumed.

### A.2.2 Reinforced Soil

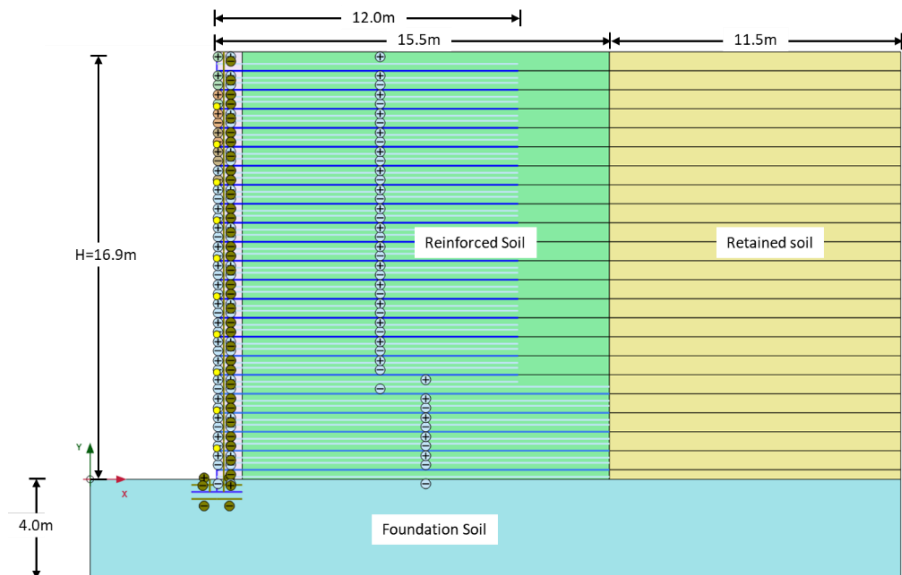
The soil is reinforced with 22 layers of ribbed metal strips (Runser et al., 2001). Each metal strip is 5 cm wide, 4 mm thick, and 12 m long except the bottom five reinforcement layers that are 15.5 m long. The spacing between the reinforcements is 0.75 m (2.5 ft). To simplify the simulations, they are modeled as linear elastic. The reinforcement is connected to the panel with a soft spring that allows vertical and rotational movements with respect to the panel. The input properties of the metal strips are listed in **Table A.2**. The friction of the interface is the tangent of the soil friction angle.

**Table A.2** Input Properties of the Metal Strips.

Parameter	Value
<b>Metal Strips</b>	
Elastic modulus, $E_{\text{steel}}$ (GPa)	200.0
Number of strips per unit width (1 m), $n_{\text{strips}}$	-
Strip width (m)	0.05
Strip thickness (m)	0.004
Poisson's ratio, $n_{\text{steel}}$	0.30

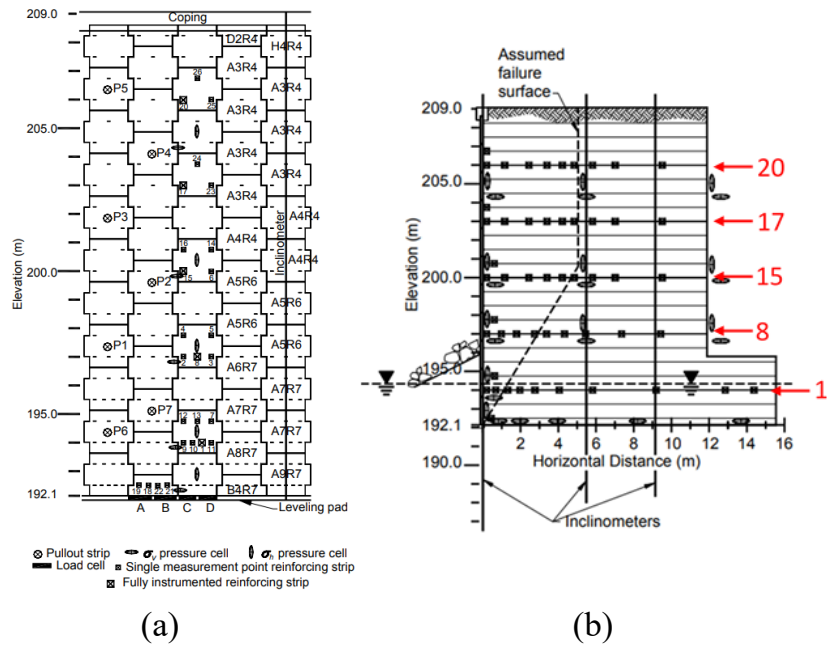
**Figure A.2** presents a cross-section of the MSE wall. To simulate construction, the soil within 1 m of the facing panel is modeled with reduced stiffness of 10 MPa. Given the assumption of a stiff foundation soil, its depth is limited to 4 m in the model. The construction of the wall is carried out in stages:

- Stage 1: The first facing panel is installed with the bearing pad at the base, and the first soil layer is placed.
- For the following stages: Reinforcement strips are positioned and connected to the wall, followed by the installation of the next panel. The next soil layer is then added, followed by another set of metal strips. This process is repeated until the wall reaches its target height of 7.62 m.



**Figure A.2** Cross-Section of the MSE Wall.

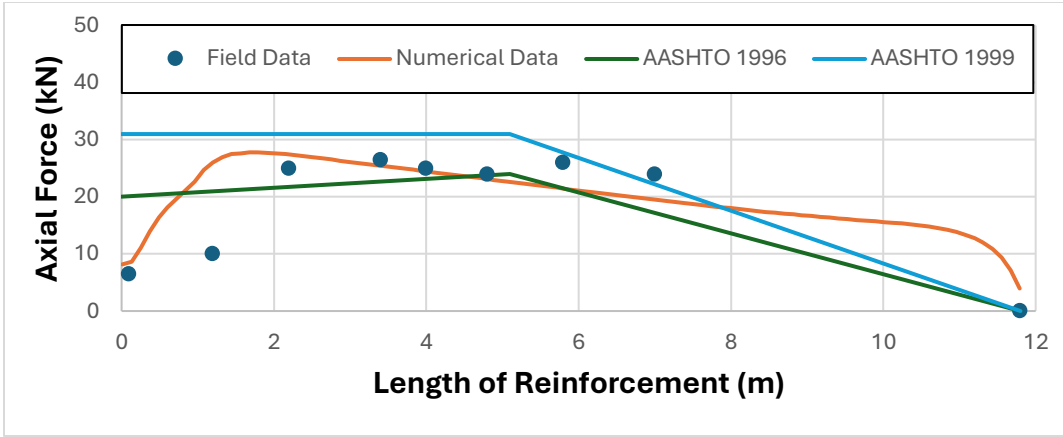
As shown in **Figure A.3**, the wall is instrumented with pressure cells and load cells installed on the facing panels and reinforcement strips. Some reinforcement strips are instrumented at a single location, while others are fully instrumented along their length. A fully instrumented strip is installed every fourth layer from the top, resulting in a total of five fully instrumented strips (**Figure A.3**).



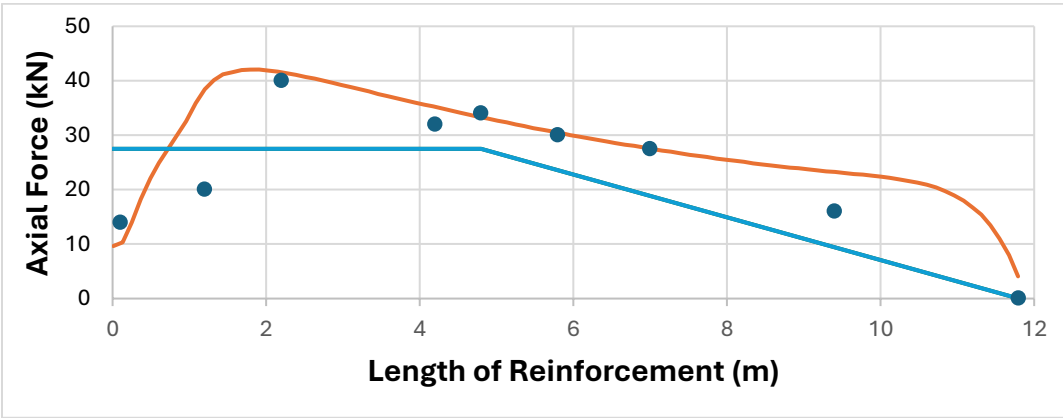
**Figure A.3** (a) Front View of the MSE Wall; and (b) Instrumentation of the Strips (Numbers in Red Represent Instrumented Strip Number; Adapted From Runser et al., 2001).

### A.3 Results

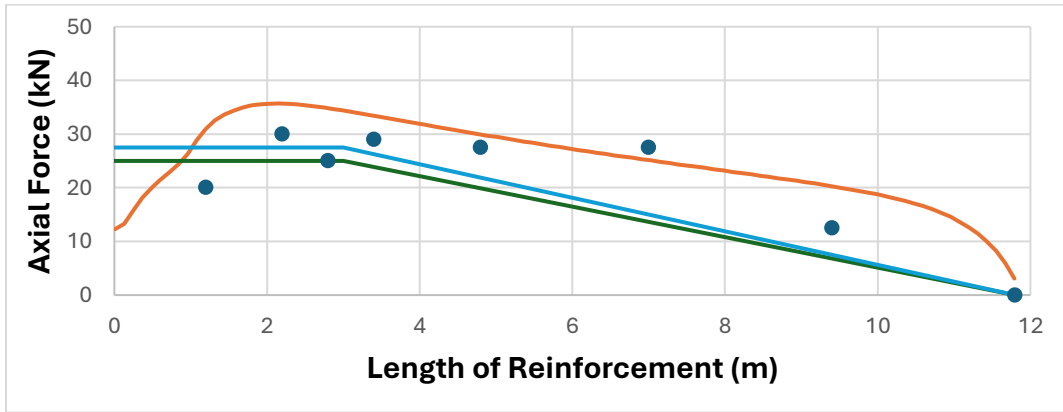
**Figure A.4** presents the distribution of axial tension along the length of the reinforcement strips, where field measurements, numerical simulation results, and design predictions based on AASHTO 1996 and AASHTO 1999 guidelines, are compared. The numerical results show good agreement with both the measured data and the AASHTO design curves, successfully capturing the overall trend. However, near the strip ends, the numerical model exhibits a sharp change in the slope of the axial force, which deviates from the observed and expected behavior. This discrepancy is likely the result of limitations inherent to the 2D plane strain modeling.



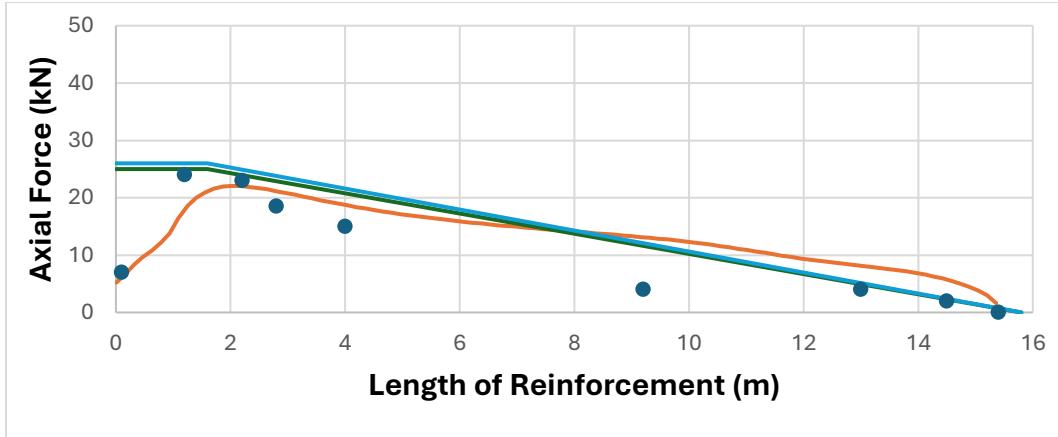
(a)



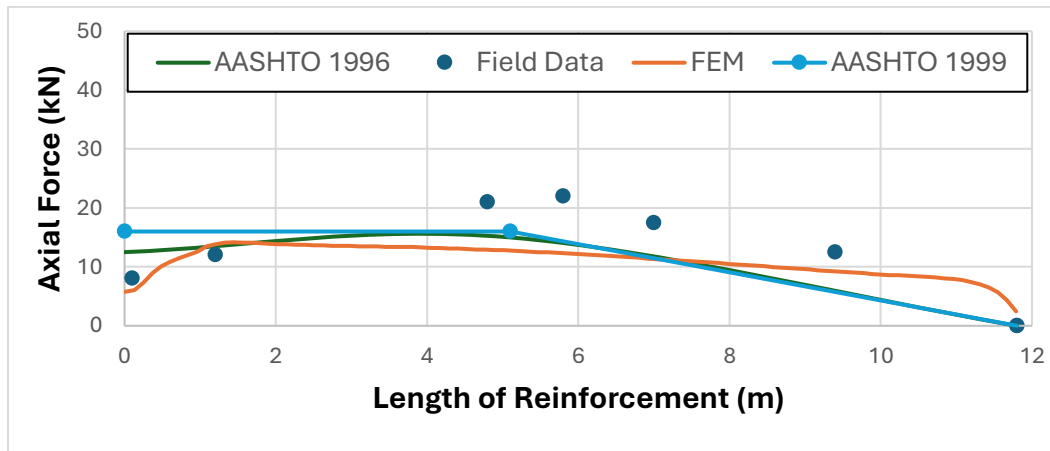
(b)



(c)



(d)



(e)

**Figure A.4** Axial Force Along the Length of the Reinforcement for: (a) Layer 1; (b) Layer 4; (c) Layer 12; (d) Layer 16; and (e) Layer 20 (see **Figure A.3** for the Location of the Layers).

**Figure A.5** illustrates the variation of maximum axial tension and connection tension with strip elevation. The figure compares field measurements, numerical predictions, and design values based on AASHTO (1996 and 1999) guidelines. The numerical results show good agreement with both the maximum and connection tensions and experimental data, thus accurately capturing the overall load distribution in the reinforcement.

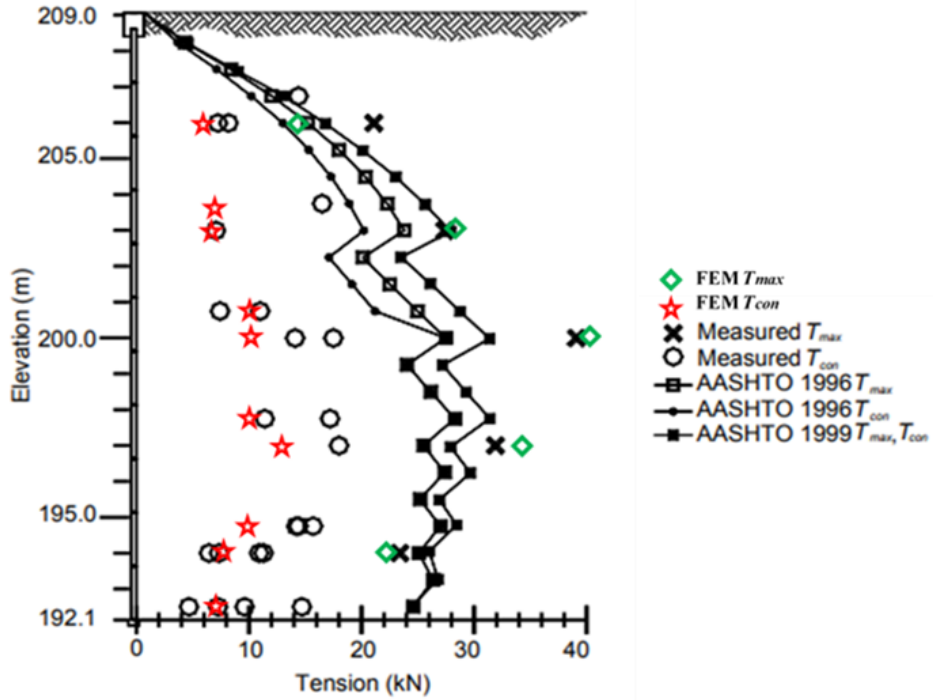


Figure A.5 Axial Force at the Connection and Maximum Axial Force in the Strip at Different Elevations (Adapted from Runser et al., 2001).

## Appendices References

Runser, D. J., Fox, P. J., & Bourdeau, P. L. (2001). Field performance of a 17 m-high reinforced soil retaining wall. *Geosynthetics International*, 8(5), 367–391. <https://doi.org/10.1680/gein.8.0200>

## About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1 — evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at [docs.lib.purdue.edu/jtrp/](https://docs.lib.purdue.edu/jtrp/).

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