A Case History of MSE Wall Failure: Finite Element Modeling and Evaluation

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ABSTRACT

This paper presents a case history of a mechanically stabilized earth (MSE) wall failure along with the results of finite element modeling and evaluation of the failure mechanism. The 11.5-meter high wall is comprised of steel reinforcing strips embedded in compacted backfill and connected to reinforced concrete facing panels. Some of the facing panels were installed atop abandoned drilled caissons that were originally constructed for an adjacent building. At ten of the caisson locations, the reinforcing strips sheared at the connection with the wall panels, and the panels fell off the wall. Results of the finite element analyses indicate that failure occurred due to excessive tensile stresses in the reinforcing strips as a result of differential settlement between the panels and the strips. Parametric analyses were performed for the present and final loading conditions to help devise corrective measures to prevent any future failure of the MSE wall.

INTRODUCTION

Mechanically Stabilized Earth (MSE) walls are used extensively as earth retaining structures because of their cost-effectiveness and ability to withstand much larger differential settlements than conventional reinforced concrete retaining walls. Various types of MSE wall facings and reinforcements are used depending on the specific application, soil conditions and wall height. The MSE wall studied in this paper is comprised of steel reinforcing strips connected to reinforced concrete facing panels. This type of wall can withstand significant differential settlement along the length of the wall as long as the wall panels and the reinforcing strips behind the panels can settle together. Excessive differential settlement between the wall panels and reinforcing strips can cause a significant increase in tensile stresses in the strips and may result in failure of the wall. This paper presents a case history of an MSE wall that failed due to excessive differential settlement between the wall panels and the reinforcing strips.

DESCRIPTION OF CASE HISTORY

This case history involves an international airport terminal that is currently under construction. The facility includes an MSE wall that runs approximately parallel and adjacent to the outer perimeter of the terminal building and retains the fill
for the apron areas that surrounds three sides of the building (Figure 1). The MSE wall was constructed with steel reinforcing strips embedded in compacted backfill and connected to reinforced concrete facing panels. The wall is to be constructed in two phases, and its present height (first phase) is 11.5 meters. Drilled caisson foundations for the terminal building were installed prior to MSE wall construction, and subsequently the building design/footprint and MSE wall alignment were revised. As a result, portions of the current MSE wall alignment run along the previous outer perimeter of the building where caissons have already been installed. The MSE wall was installed along this revised alignment, and some of the wall panels rest on concrete caps constructed on top of the caissons (Figures 1 and 2a).

![MSE Wall Alignment and Repair Locations, Thickness of Compressible Soils, and Recorded Wall Settlement.](image)

**Figure 1.** MSE Wall Alignment and Repair Locations, Thickness of Compressible Soils, and Recorded Wall Settlement.

The caissons are bearing on rock, and therefore, the MSE wall panels resting on caisson caps did not undergo any settlement. However, behind the wall, the reinforced soil backfill and the reinforcing strips settled due to consolidation of the underlying compressible soils and compression of the wall backfill under its own weight. This resulted in significant differential settlement between the reinforcing strips and the wall panels at the caisson locations. The MSE wall was designed with reinforcing strips sloped up (away from wall) by 0.15 meter over a length of 1.2 meters (Figure 3) to accommodate the differential settlement described above. However, the actual maximum differential settlement was significantly greater than what could be accommodated in the above design. As a result, at ten of the caisson locations (Figure 1), the reinforcing strips failed at the connection with the wall panels, and the panels fell off the wall. The backfill material from behind the panels
poured out through these ‘openings’ between panels and fell in front the wall. The MSE wall was subsequently repaired (see Figure 4) at the failure locations (Bhowmik, 2009).

Figure 2. MSE Wall on Caisson Configuration (Schematic): (a) Present; (b) Final.

Figure 3. MSE Wall on Caisson Configuration and Sloped Reinforcing Strip Detail (Schematic).
OBJECTIVES OF PRESENT STUDY

As part of the final phase of construction, the MSE wall will be extended vertically, a cantilever retaining wall will be constructed behind the extended wall, and the apron pavement will be constructed atop the cantilever retaining wall (Figure 2b). The elevation difference between the top of the existing MSE wall and the top of the future apron pavement is 3 meters. The apron pavement will also be subjected to traffic loading when the terminal is in operation. All of these additional loads will result in additional tensile stresses in the reinforcing strips. Since failure has already occurred at a number of locations and the reinforcing strips will be subjected to additional stresses, there are concerns regarding the future performance of the MSE wall, specifically at the caisson locations where failure has not occurred yet, but the stress conditions could be at incipient failure.

The primary objectives of the present study were to evaluate the performance of the MSE wall (specifically, stresses in the reinforcing strips at the caisson locations), investigate the causes of failure, and to help devise corrective measures required to ensure its stability under the present and final loading conditions.

GEOTECHNICAL INFORMATION

Subsurface Soil Conditions

The project site is located within the Piedmont physiographic province of Georgia, and the subsurface soil profile is generally comprised of a layer of fill underlain by a natural soil profile consisting of residual soils underlain by partially weathered rock (PWR) and parent bedrock. PWR is locally defined as a weathered rock material with Standard Penetration Test (SPT) resistance in excess of 50 blows
for 0.15 meter of penetration. The fill and residual soils consist mostly of loose to medium dense micaceous silty/clayey fine sand and/or firm micaceous sandy silt/silty clay. Standard Penetration Test (SPT) blow counts for the fill and residual soils ranged mostly from 4 to 25 blows per 0.3 meter. The total thickness of compressible soils (i.e., the combined thickness of fill and residual soils with an SPT blow count of 30 or less) ranged from about 1 to 12.5 meters (Figure 1). Such abrupt variations in soil conditions within a short distance are quite common in the Piedmont geologic setting.

Predicted and Measured Settlements

Based on consolidation characteristics of the soils at the site, settlement along the MSE wall alignment was predicted to range from 150 to 610 mm. Settlement monitoring for the site consisted of settlement plates installed in the apron area behind the wall prior to fill placement and settlement monitoring points installed on the outer faces of the wall panels during construction of the MSE wall. Recorded settlement of the apron fill in areas adjacent to the MSE wall ranged from 135 to 520 mm, and the settlement of the wall panels ranged from 15 to 665 mm (Figure 1). A comparison of the wall failure locations and the recorded wall panel settlement data indicates that, in general, failure occurred in areas with the greatest amount of settlement. In the areas adjacent to the failure locations, the recorded settlement of the wall panels (with no caisson under them) ranged from about 150 to 665 mm.

MSE WALL DESIGN AND AS-BUILT INFORMATION

Reinforcing Strip Connection and Allowable Stresses

The reinforcing strips are connected to the facing panels using tie strips that are embedded in the panels, and a bolted connection is used between the reinforcing strips and the tie strips. Under short-term loading conditions, the allowable tensile force in the reinforcing strips is controlled by tensile stresses at the bolt-hole locations (due to reduced cross sectional area at the bolt holes). For long-term loading conditions, the wall design accounts for the anticipated loss of thickness of the reinforcing strips due to corrosion, and the allowable tensile force in the reinforcing strips is controlled by tensile stresses in the reduced thickness of the reinforcing strips (i.e., reduced due to thickness loss by corrosion).

The reinforcing strips have an ultimate tensile strength of 550 MPa and a yield stress of 450 MPa. The allowable tensile stresses in the reinforcing strips are 280 MPa and 250 MPa for short- and long-term loading conditions, respectively.

MSE Wall and Caisson As-built Information

The geometric configuration of the MSE wall panels resting on caisson caps is depicted in Figure 3. The distance by which the caisson cap extends behind the back face of the MSE wall (distance ‘d’) is of particular importance since the stresses in the reinforcing strips are significantly influenced by distance ‘d’. Available as-built data indicates that distance ‘d’ varies along the length of the wall, and it ranges from about 0.03 to 0.4 meter. However, the as-built values of ‘d’ for some locations have not been confirmed by field measurement.
ANALYSES AND EVALUATION

Method of Analyses

The MSE wall was modeled using the finite element method to evaluate the cause of failure and to assess the performance of the wall under the present and final loading conditions. The finite element model was developed using the computer program PLAXIS, Version 9, and the soil behavior was simulated using the Mohr-Coulomb model. The ‘Staged Construction’ feature in PLAXIS enables a realistic simulation of construction and excavation processes by activating and deactivating clusters of elements, application of loads, changing water tables, etc. (PLAXIS BV, 2006). This feature was used in the analyses for a realistic assessment of stresses and displacements at various stages of construction of the MSE wall, including the future vertical extension of the wall, and addition of the cantilever retaining wall, apron pavement and traffic loading.

Average Soil Profile

An average soil profile along the existing MSE wall was developed for use in our analyses and evaluation based on the available geotechnical information. The average soil profile consists of a 10.7-meter thick layer of compressible soils above a 2.1-meter thick layer of PWR underlain by parent bedrock. The average existing ground surface and groundwater elevations are 289.5 and 283.5 meters, respectively. The soil properties used in the analyses are shown on Figure 5. The thickness of compressible soils was varied in the analyses to evaluate its effect on the performance of the MSE wall. The soil properties were also varied to encompass the different types of soils encountered along the length of the MSE wall.

![Figure 5. Soil Profile and Wall Geometry.](image-url)
MSE Wall and Caisson Geometry

The geometric configuration of the MSE wall used in the finite element model is depicted in Figures 2a, 2b and 5. The concrete facing panel dimensions and spacing of reinforcing strips vary along the length and height of the wall. An average set of dimensions and spacing were used in the finite element model. The bottom elevation of the MSE wall is 288 meters, i.e., the bottom of the wall is 1.5 meters below the existing ground surface elevation (Figure 5). The existing wall is 11.5 meters high with a current top elevation of 299.5 meters. At the caisson locations (Figures 2a and 2b), the bottom elevation of the wall (which is the same as the top elevation of the caisson cap) is 289 meters. The existing top elevation of the apron fill behind the MSE wall is about 302.5 meters which is also the future top elevation of the apron pavement. Above the top elevation of the existing MSE wall, the apron fill is offset 3.7 meters behind the wall, and it has a slope of about 2H:1V (Figures 2a and 5).

In the final phase of construction, the MSE wall will be extended vertically by 1.2 meters, a cantilever retaining wall will be constructed behind the extended wall, and the apron pavement will be constructed on top of the cantilever retaining wall, as shown in Figure 2b. The elevation difference between the top of the existing MSE wall and the top of the future apron pavement is 3 meters. The apron pavement will also be subjected to traffic loading when the terminal is in operation.

For the MSE wall panels resting on caissons, since the as-built values of ‘d’ (Figure 3) for some locations have not been confirmed by field measurement, ‘d’ was varied from 0.1 to 1.2 meters (i.e., up to the maximum possible value, which is equal to the width of the caisson cap) to study its effects on the performance of the wall.

RESULTS AND DISCUSSIONS

The finite element modeling and analyses consisted of numerous cases with various combinations of MSE wall and caisson configurations and material properties. Only the cases with the most critical variables are presented in this paper. For each case, the tensile stresses in the reinforcing strips are compared with the corresponding allowable stress, yield stress and ultimate strength to assess the performance of the MSE wall.

Present MSE Wall Configuration

The results of the finite element analyses for the present MSE wall configuration are presented in Figures 6a through 6c. As shown in Figure 6a, the tensile stresses in the reinforcing strips are well below the allowable stress when there is no caisson under the wall panels. The effects of the presence of a caisson under the wall panels are depicted in Figure 6b. As shown, the stresses increase significantly when the wall panels rest on a caisson, and the stresses increase as ‘d’ increases. As indicated earlier, the reinforcing strips were sloped up by 0.15 meter over a length of 1.2 meters to accommodate the differential settlement between the wall panels and the reinforcing strips. However, as ‘d’ increases, a wider portion of the reinforced soil behind the MSE wall is restrained from any vertical displacement, and this negates a greater part of the beneficial effects of the sloped reinforcement. For a d-value of 1.2 meters, the beneficial effects of the sloped reinforcement are completely negated. The tensile stresses in the reinforcing strips exceed the allowable stress at locations near
the lower part of the wall for values of ‘d’ greater than about 0.4 meter. For a d-value
of 1.2 meters, the stresses at some points near the lower part of the wall approach the
yield stress.

Figure 6c shows the effects of the thickness of compressible soils on the
stresses in the reinforcing strips for a d-value of 1.2 meters. As shown in this figure
and as expected, the stresses increase as the thickness of compressible soils increases.
This is because the differential settlement between the wall panel and the reinforcing
strips increases as the thickness of compressible soils increases. For a compressible
soil thickness of 3 meters, the tensile stresses in the reinforcing strips approach the
allowable stress at some points near the lower part of the wall. For a compressible soil
thickness of 6 meters, the stresses in the reinforcing strips significantly exceed the
allowable stress, and for a compressible soil thickness of 10.7 meters, the stresses
approach the yield stress at some points near the lower part of the wall.

The thickness of compressible soils ranges from about 6 to 12.5 meters in the
areas where the wall failures occurred. At these locations, the tensile stresses in the
reinforcing strips must have reached the ultimate strength. However, the results of the
analyses discussed above indicate that stresses only approach the yield stress. In this
regard, it should be noted that the actual tensile stresses in the reinforcing strips could
be greater than the computed stresses due to variability in soil conditions and possible
differences between actual wall geometry/material properties and the corresponding
model assumptions. Also, once the tensile stresses in the reinforcing strips reach the
yield stress, the resulting excessive deformation may cause a reduction in the cross
sectional area of the strips, and the tensile stresses may increase further and
eventually reach the ultimate strength. At the failure locations, the reinforcing strips
broke at the lowermost panel above the ground surface which is consistent with the
computed maximum stresses in the reinforcing strips (Figures 6b and 6c).

Figure 6. Maximum Tensile Stresses in Reinforcing Strips for Present Configuration:
(a) No Caisson under Wall; (b) With Caisson under Wall - Effects of Distance ‘d’; (c)
With Caisson under Wall - Effects of Compressible Soil Thickness, t.
Final MSE Wall Configuration

The results of the analyses for the final MSE wall configuration are presented in Figures 7a through 7c. As shown in Figure 7a, the tensile stresses in the reinforcing strips are well below the allowable stress when there is no caisson under the MSE wall. The stresses increase significantly when the wall panels rest on a caisson, and the stresses increase as ‘d’ increases (Figure 7b). The tensile stresses exceed the allowable stress at locations near the lower part of the wall for values of ‘d’ greater than about 0.1 meter. For a d-value of about 0.45 meter, the stresses at some points near the lower part of the wall approach the yield stress, and the stresses reach the ultimate strength for d-values greater than about 0.55 meter.

The effects of the thickness of compressible soils on the stresses in the reinforcing strips are shown in Figures 7c for a d-value of 1.2 meters. For a compressible soil thickness as low as 1.5 meters, the tensile stresses in the reinforcing strips exceed the allowable stress. For a compressible soil thickness of 3 meters, the stresses exceed the yield stress, and for a compressible soil thickness of about 4.5 meters, the stresses reach the ultimate strength.

It is noted that high stresses will be developed in the reinforcing strips at the top of the MSE wall due to loading from the cantilever retaining wall that will be constructed behind the MSE wall. The MSE wall designer has been advised to design reinforcing strips accordingly.

Figure 7. Maximum Tensile Stresses in Reinforcing Strips for Final Configuration: (a) No Caisson under Wall; (b) With Caisson under Wall - Effects of Distance ‘d’; (c) With Caisson under Wall - Effects of Compressible Soil Thickness, t.

SUMMARY AND CONCLUSIONS

The results of the finite element modeling and evaluation of the MSE wall and a set of conclusions and recommendations based on this study are summarized in the following:
(i) At a number of locations along the existing MSE wall at a new international terminal, the wall panels were installed atop abandoned drilled caissons. At ten of these locations, the reinforcing strips sheared at the connection with the wall panels, the panels fell off the wall, and the soil backfill fell in front of the wall.

(ii) The results of the finite element analyses indicate that due to excessive differential settlement between the wall panels resting on caissons and the reinforcing strips behind the panels, the maximum tensile stresses in the reinforcing strips increased by over six times and reached their ultimate strength. As a result, the reinforcing strips broke-off at their bolted connections with the tie strips that are embedded in the wall panels.

(iii) The two major parameters that vary along the length of the MSE wall and significantly influence the tensile stresses in the reinforcing strips are: (a) the distance ‘d’ by which the caisson cap extends behind the back face of the wall panels and (b) the thickness of compressible soils. The tensile stresses in the reinforcing strips increase as ‘d’ increases and as the thickness of compressible soils increases. In the analyses, the d-value was varied from 0.1 to 1.2 meters and the thickness of compressible soils was varied from 1.5 to 10.7 meters.

(iv) The reinforcing strips were sloped up by 0.15 meters over a length of 1.2 meters to accommodate the anticipated differential settlement between the wall panels and the reinforcing strips. However, as ‘d’ increases, a wider portion of the reinforced soil behind the wall panel is restrained from any vertical displacement, and this negates a greater part of the beneficial effects of the sloped reinforcement. For a d-value of 1.2 meters, the beneficial effects of the sloped reinforcement are completely negated.

(v) Under the final loading conditions, the tensile stresses in the reinforcing strips may reach the ultimate strength in areas with compressible soil thickness greater than about 4.5 meters. For compressible soil thicknesses of 4.5 and 10.7 meters, the minimum d-values at which the maximum tensile stress will likely reach the ultimate strength are estimated to be 1.2 and 0.5 meter, respectively.

(vi) Based on the results of these analyses and evaluation, fourteen panel locations were selected for visual inspection of the conditions of the reinforcing strips. The inspection consisted of saw-cutting the panels to expose the bolted connections between the reinforcing and tie strips and observing the extent of yielding and/or failure at the bolt holes. The downward slopes (away from the wall) of the reinforcing strips were also measured to estimate the differential settlement between the wall panels and the backfill. Slopes in excess of 15 degrees were observed at five of the fourteen locations, and at one of these five locations, the reinforcing strip was found broken at the bolt hole. At these locations, the entire panel columns will be lowered to relieve stresses in the reinforcing strips.

(vii) MSE walls are flexible structures, and they can withstand significant differential settlement along the length of the wall as long as the wall panels and the reinforcing strips behind the panels can settle together. Excessive differential settlement between the wall panels and reinforcing strips can cause a significant increase in tensile stresses in the strips and may result in failure of the wall.
(viii) Where significant differential settlement is anticipated between wall panels and reinforcing strips, a detailed evaluation of deformation modes and stresses in various components of the wall should be performed during design in addition to the conventional calculations for internal and global stability of the MSE wall.

REFERENCES
