RESEARCH

Utah Department of Transportation - Research Division
4501 South 2700 West, Box 148410 - Salt Lake City, Utah 84114-8410

UDOT CONNECTING COMMUNITIES

Report No. UT-10.03

MODELING AND ANALYSIS TO QUANTIFY MSE WALL BEHAVIOR AND PERFORMANCE

Prepared For:

Utah Department of Transportation Research Division

Submitted By:

Brigham Young University
Department of Civil & Environmental Engineering

Authored By:

Travis M. Gerber
Colin R. Cummins

Date:

August 2009

Report No. UT-10.03

MODELING AND ANALYSIS TO QUANTIFY MSE WALL BEHAVIOR AND PERFORMANCE

Prepared For:

Utah Department of Transportation
Research Division

Submitted By:

Brigham Young University
Dept. of Civil & Environmental Engineering

Authored By:

Travis M. Gerber and Colin R. Cummins

August 2009

THIS PAGE LEFT INTENTIONALLY BLANK

DISCLAIMER

THIS PAGE LEFT INTENTIONALLY BLANK

Technical Report Documentation Page

1. Report No. UT- 10.03	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MODELING AND ANALYSIS TO QUANTIFY MSE WALL BEHAVIOR AND PERFORMANCE		5. Report Date August 2009 6. Performing Organization Code
7. Author Travis M. Gerber and Colin R. Cummins		8. Performing Organization Report No. BYU Report No. CEG 2009-01
9. Performing Organization Name and Address Department of Civil & Environmental Engineering Brigham Young University 368 CB Provo, UT 84602		10. Work Unit No. 5H06049H 11. Contract or Grant No. 07-9230
12. Sponsoring Agency Name and Address Utah Department of Transportation 4501 South 2700 West Salt Lake City, Utah 84114-8410		13. Type of Report & Period Covered FINAL April 2007 to July 2009 14. Sponsoring Agency Code PIC No. UT06.705

15. Supplementary Notes

Prepared in cooperation with the Utah Department of Transportation, Utah State University, and the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

To better understand potential sources of adverse performance of mechanically stabilized earth (MSE) walls, a suite of analytical models was studied using the computer program FLAC, a numerical modeling computer program widely used in geotechnical engineering. The suite of models represents different MSE wall configurations, focusing on differences in overall height, underlying ground slope, wall setback, and wall embedment. From these models, the distributions of relative deformation along both the vertical face and horizontal top surface of MSE walls were quantified, as were factors of safety with respect to shear strength. Limit equilibrium slope stability analyses and bearing capacity analyses were also performed to complement the FLAC results. By doing this work, the relative impacts that wall characteristics such as sloping foundation soils, wall setback and embedment, and differential compaction of the MSE wall fill have on wall behavior and performance is now better understood and quantified.

17. Key Words	18. Distribution Statement	23. Registrant's Seal
Mechanically stabilized earth walls, MSE walls, modeling, FLAC, finite difference, limit equilibrium, slope stability, bearing capacity	Not restricted. Available through: UDOT Research Division 4501 South 2700 West Box 148410 Salt Lake City, Utah 84114-8410 www.udot.utah.gov	

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	45	

THIS PAGE LEFT INTENTIONALLY BLANK

ACKNOWLEDGEMENTS

This report was prepared as part of a larger collaborative research effort entitled "Performance Assessment and Failure Modes Analysis of UDOT's MSE Wall Inventory" with the participation of Brigham Young University, Utah State University, and the Utah Department of Transportation (UDOT). The larger part of the work and overall scope of the project are presented in a separate report, "An Inspection, Assessment, and Database of UDOT MSE Walls" authored by James A. Bay, Loren R. Anderson, Travis M. Gerber, and Ryan B. Maw (2009).

THIS PAGE LEFT INTENTIONALLY BLANK

TABLE OF CONTENTS

THIS PAGE LEFT INTENTIONALLY BLANK

LIST OF TABLES

THIS PAGE LEFT INTENTIONALLY BLANK

LIST OF FIGURES

EXECUTIVE SUMMARY

To better understand potential sources of adverse performance of mechanically stabilized earth (MSE) walls, a suite of analytical models was studied using the computer program FLAC, a numerical modeling computer program widely used in geotechnical engineering. The suite of models represents different MSE wall configurations, focusing on differences in overall height, underlying ground slope, wall setback, and wall embedment. From these models, the distributions of relative deformation along both the vertical face and horizontal top surface of MSE walls were quantified, as were factors of safety with respect to shear strength. Limit equilibrium slope stability analyses and bearing capacity analyses were also performed to complement the FLAC results. By doing this work, the relative impacts that wall characteristics such as sloping foundation soils, wall setback and embedment, and differential compaction of the MSE wall fill have on wall behavior and performance is now better understood and quantified.

Specifically, it was concluded that both bench (i.e., slope setback) width and wall embedment play important roles in MSE wall behavior; deformations in walls founded on relatively steep slopes increase markedly when bench width and/or embedment depth is reduced; factors of safety similarly decrease. In general, combinations of bench width and embedment depth which result in the same horizontal distance between the base of the wall and the face of the slope produce similar factors of safety with respect to shear strength and bearing capacity. The failure mode of an MSE wall founded on a slope may be a combination of slope stability, bearing capacity, and overturning mechanisms. The factor of safety determined in a full constitutive model may be lower than those calculated with simple procedures like equilibrium slope stability which address only one failure mode. Relative to an MSE wall founded on a 2H:1V slope with a 4-ft wide bench and 2-ft embedment, if the bench width is decreased to 1-ft, an embedment increase of 1.3 to 1.5 ft (with an accompanying increase in strap length due to the increase in effective wall height) will produce a comparable degree of performance. Greater embedment would be required for 1.5H:1V slopes. A notable zone of differential vertical displacement coinciding with the presence of less compact MSE wall backfill soil can exist immediately behind the face of MSE walls; the design of overlying slabs and structures should not rely on support from this typically 3-ft wide zone of MSE wall backfill.

THIS PAGE LEFT INTENTIONALLY BLANK

1.0 INTRODUCTION

To better understand potential sources of adverse performance of mechanically stabilized earth (MSE) walls, a suite of analytical models was studied using the computer program FLAC, a numerical modeling computer program widely used in geotechnical engineering. The suite of models represents different MSE wall configurations, focusing on differences in overall height, underlying ground slope, wall setback, and wall embedment. From these models, the distributions of relative deformation along both the vertical face and horizontal top surface of MSE walls were quantified, as were factors of safety with respect to shear strength. Limit equilibrium slope stability analyses and bearing capacity analyses were also performed to complement the FLAC results. By doing this work, the relative impacts that wall characteristics such as sloping foundation soils, wall setback and embedment, and differential compaction of the MSE wall fill have on wall behavior and performance is now better understood and quantified.

THIS PAGE LEFT INTENTIONALLY BLANK

2.0 METHODS OF STUDY

2.1 General

Basic characteristics of the nine MSE wall models used in this study are presented in Table 1. Models A, B, C, and D are intended to represent MSE wall configurations commonly designed and constructed for Utah Department of Transportation (UDOT) projects, whereas the remaining models are intended to represent MSE walls constructed with elements varying from design norms. In the context of this study, design norms consist of underlying ground which slopes at 2H:1V or less, a 4-ft wide bench at the base of a wall founded on sloping ground, and a wall embedment of at least 2 feet. Based on recent field visits to UDOT walls, a notable number of walls built on slopes do not have a full 4-ft wide bench, but have a narrower, approximately 1-ft wide bench. These narrower benches have been incorporated into models E, F, H, and I. While slopes below MSE walls are typically 2H:1V or less, sometimes steeper slopes exist, particular in the vicinity of spill slopes near bridge abutments. These conditions are reflected by models G, H, and I. A diagram showing the configuration and components incorporated into the MSE wall models is provided as Figure 1.

Table 1 Characteristics of MSE Walls Modeled

Wall Model ID	Height (ft) Above Base	Height (ft) Above Ground	Foundation Soil	Underlying Slope [Height(ft); Slope(H:V)]	Bench Width (ft)	Embedment (ft)
A	30	28	M. Dense Sand	Horiz.	n/a	2
B	30	28	Stiff Clay	Horiz.	n/a	2
C	15	13	M. Dense Sand	Horiz.	n/a	2
D	15	13	M. Dense Sand	15; 2:1	4	2
E	14	13	M. Dense Sand	15; 2:1	1	1
F	16	13	M. Dense Sand	15; 2:1	1	3
G	15	13	M. Dense Sand	15; 1.5:1	4	2
H	14	13	M. Dense Sand	15; 1.5:1	1	1
I	16	13	M. Dense Sand	15; 1.5:1	1	3

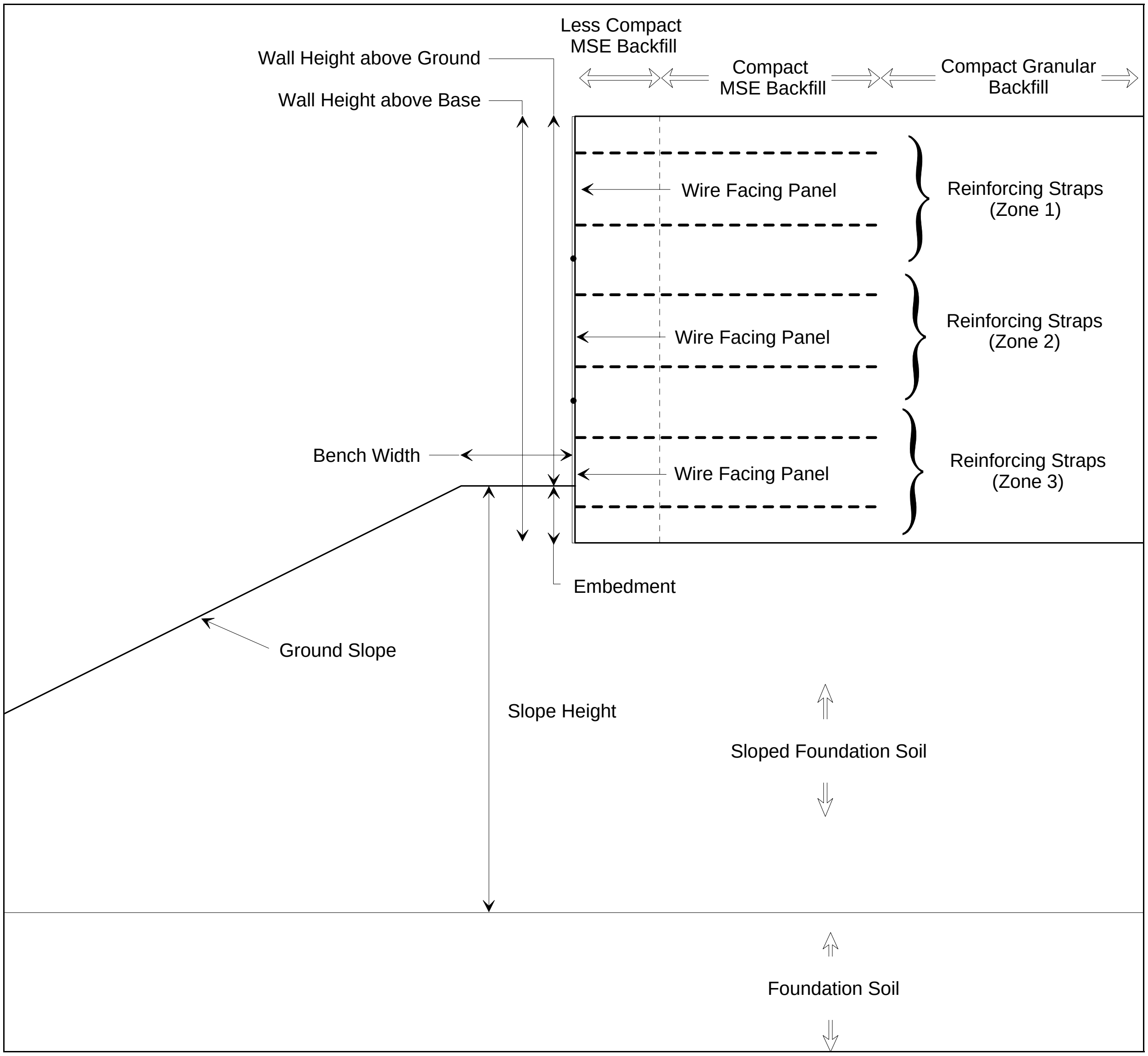


Figure 1 Diagram showing configuration and components of MSE wall models (specific case shown is wall Model D)

2.2 Finite Difference Modeling

Each of the wall models listed in Table 1 were analyzed using the computer program FLAC. Developed by Itasca (2005), FLAC (Fast Lagrangian Analysis of Continua) is an explicit finite difference computer program widely used in geotechnical engineering. Output from these analyses includes the distributions of relative deformation along both the vertical face and horizontal top surface of MSE walls, as well as factors of safety with respect to shear strength.

Again, a diagram showing the configuration and components incorporated into the MSE wall models is provided as Figure 1.

The internal MSE reinforcing system for the wall was modeled as a '2-stage' MSE wall consisting of a vertical welded wire grid facing panel (itself faced with a geosynthetic fabric facing to prevent passage of soil particles) anchored with an inextensible horizontal welded wire grid reinforcement (sometimes referred to as a reinforcing 'strap'). This particular wall system is often constructed when ground settlements are expected to be relatively large due to underlying soft ground. Concrete facing panels are attached to the wire wall face once the wall has finished settling. Since these concrete facing panels are non-structural elements, they have been omitted from the models. Properties for the soils beneath the wall (i.e., foundation soils) and the fill soils in and behind the MSE reinforced zone are shown in Table 2. The less compact granular fill was used to model a 3-foot wide zone immediately behind the wall face which is typically less compacted, whereas the compact granular fill was used to model the remaining soil within the reinforced soil zone as well as the soil beyond. The soil properties were selected based on typical design values, subsequently adjusted for construction practices, and values found in technical literature. Although undrained shear strength conditions were considered in the case of a clayey foundation soil, modeling of time-dependent consolidation processes and staged-wall construction was omitted to simplify the analyses.

Table 2 Soil Properties

Property	Granular Slope & Foundation Soil	Clayey Foundation Soil	Compact MSE & Granular Fill	Less Compact MSE Fill
Mass Density (slug/ft^3)	3.45	3.10	4.03	3.91
Elastic Modulus (lbs/ft^2)	2.8 x 10^5	2.8 x 10^5	8.1 x 10^5	3.8 x 10^5
Poisson's Ratio	0.3	0.45	0.3	0.3
Cohesion (lbs/ft^2)	100	2000	0	0
Friction Angle (°)	32	0	37	34

In modeling the reinforced soil zone, wall properties were selected to be generally consistent with 2-stage walls constructed as part of the 1997-2001 I-15 Corridor Reconstruction Project through downtown Salt Lake City. Hence the properties used are generally typical of many larger UDOT MSE walls. In the FLAC models, the wire grid facing is modeled using beam elements and the reinforcing straps are modeled as grouted cables attached to the beams.

Connections between the beam elements were modeled as being pinned. Properties of the welded wire grid facing and reinforcing straps (normalized to a unit width of 1 foot) are presented in Tables 3 and 4. A basic Mohr-Coulomb model was used to describe the soil materials.

The horizontal MSE reinforcing straps were separated into different zones to account for typical variations in the size and number of wires used. The general strap arrangement in the models was two straps per 5-foot high facing panel, with the straps extending back into the soil a distance equal to 0.7 times the total height of the wall as measured from its base. Facing and strap properties were established using a typical wall design from the 1997-2001 I-15 Corridor Reconstruction Project through downtown Salt Lake City together with information presented in Mitchell and Villet (1983) and (Elias et al., 2001). Each zone in Table 4 corresponds to the height of one panel (i.e., 5 ft), with zone numbers increasing with depth below the top of the wall. As seen in Table 4, the cross-sectional area increases with depth, which is reflective of progressively heavier straps being used at greater depths. The tensile strength similarly increases with depth, while the bond strength increases with increasing overburden pressure.

Table 3 Structural Properties for Wire Grid Facing

Property	Value
Cross Sectional Area (ft^2/ft)	3.12×10^{-2}
Moment of Inertia (ft^4/ft)	1.07×10^{-7}
Modulus of Elasticity ($lb/ft^2/ft$)	4.18×10^{9}

The modeling grid was established such that elements (or zones) in and near the MSE wall itself were generally 1-foot square and becoming larger with increasing distance away. In each model, the MSE wall was constructed in a single stage upon existing foundation soil. Consequently, the calculated amount of vertical displacement (settlement) is greater than the amount of post-construction settlement that would be observed since placement of fill material during staged construction would fill in and offset most of the settlement experienced below the working grade elevation. The general pattern of settlement, however, should be reasonably accurate.

Table 4 Structural Properties for Reinforcing Straps

Property (per strap)	Zone 1*	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Cross Sectional Area (ft^2)	7.69×10^{-4}	7.69×10^{-4}	9.17×10^{-4}	1.11×10^{-3}	1.11×10^{-3}	1.39×10^{-3}
Modulus of Elasticity (lbs/ft^2)	4.18×10^{9}	4.18×10^{9}	4.18×10^{9}	4.18×10^{9}	4.18×10^{9}	4.18×10^{9}
Tensile Strength (lbs)	7196	7196	8581	10394	10394	12992
Bond Strength (lbs/ft)	187	491	832	858	984	1503
Bond Stiffness (lbs/ft^2)	8.97×10^{3}	2.36×10^{4}	4.00×10^{4}	4.12×10^{4}	4.72×10^{4}	7.22×10^{4}

*Zone 1 corresponds to the top of the wall with successive zones at increasing depth

2.3 Limit Equilibrium Slope Stability Analyses

In addition to the finite difference modeling performed using FLAC, global stability was analyzed using the computer program SLOPE/W (Geo-slope, 2002). Limit-equilibrium based factors of safety were calculated using Spencer’s method of slices with circular and non-circular (i.e., left- and right-block defined, or “tri-linear”) failure planes. These planes were constrained by the back of the MSE wall’s reinforced zone (i.e., the MSE wall zone is modeled as having an extremely large amount of cohesion, thus preventing the critical surface from being located within the zone). In these analyses, soil properties were the same as shown in Table 2.

2.4 Bearing Capacity Analyses

In addition to the finite difference modeling performed using FLAC, the bearing capacity of walls founded on slopes was analyzed using the methodology of Shields et al. (1990), where the reference capacity for walls founded on flat ground with no embedment was determined using Meyerhof’s equations (1963). Since the method was derived from theoretical considerations and a number of centrifuge and small-scale tests conducted in cohesionless sand, the granular foundation soil was assigned a friction angle of 34 degrees and cohesion of zero (the nominal cohesion of 100 pounds per square foot was previously assigned, in part, to prevent infinite slope-like failures along the face of the sloping ground). These strength properties are somewhat different than those used in the other analyses, but since the focus of the analyses is the relative reduction in bearing capacity due to parameters such as the proximity to the slope, slope angle, and embedment, the properties need not be exactly the same as those used in the other types of analysis (besides, the factors of safety against bearing failure are not directly comparable to factors of safety with respect to shear strength). In the bearing capacity analyses, it has been assumed that the material beneath the sloped foundation is at least as competent as the material comprising the slope itself. The base width was taken being equal to 0.7 times the total height of the wall as measured from its base. No constraints were placed upon the bearing capacity results as to limit settlement; thus with granular foundation soil, relatively large factors of safety were produced.

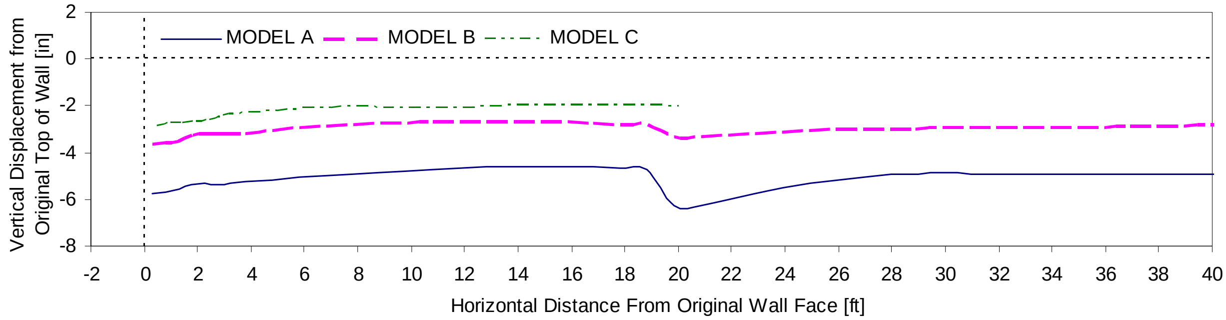
3.0 RESULTS AND INTERPRETATION

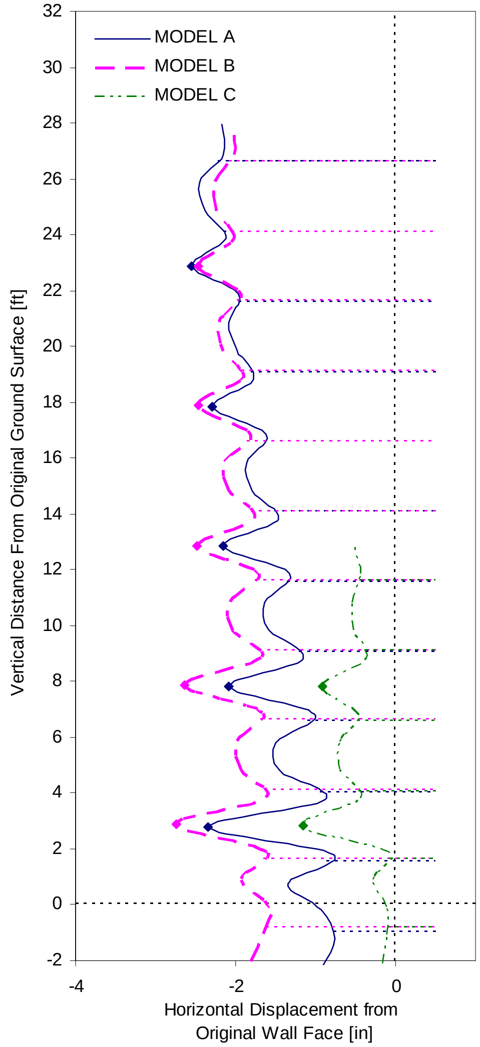
3.1 Deformations

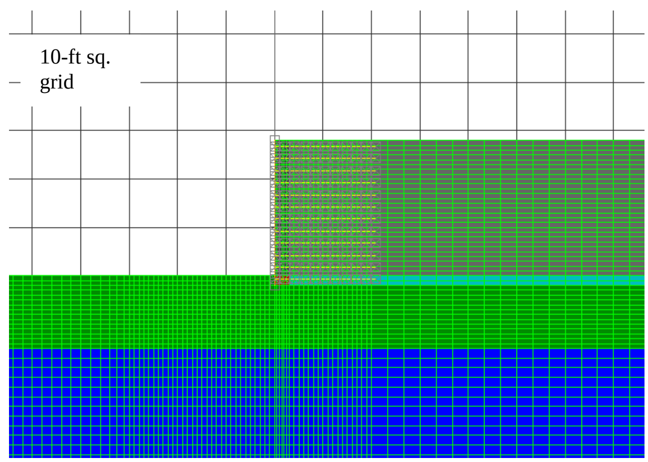
To help visualize the relative performance of each MSE wall configuration, the patterns of horizontal deformation along the vertical face and vertical deformation along the horizontal top surface of the wall have been plotted in Figure 2 through Figure 5. In the vertical profiles, the locations of reinforcing straps are shown by short, dashed lines and pinned connections between facing panels are shown by a small diamond-shaped marker. In the figures, localized bulging of the wall's grid facing panel between straps is readily seen. Each figure is accompanied by an image of a FLAC model for the typical wall configurations represented by the plots. In these images, boundaries at the extents of the models have been cropped to facilitate viewing. For reference, the grid spacing in the background of the images is 10-ft by 10-ft, and wall heights are from the top of the wall to the bottom of the embedded base.

Figure 2 presents a comparison of relative displacements of the two 30-ft high wall models (Models A and B) and the 15-ft high wall model (Model C), all of which are founded on flat (i.e., horizontal) ground. As expected, the taller walls exhibit greater amounts of displacement with an average outward displacement of about two inches at the top, as compared to a displacement of about ½ inch at the top of the shorter, 15-ft high wall. In comparing Models A and B with granular and clayey foundations soils, respectively, one can see that with a granular foundation present, the vertical face of the wall tends to tip out, whereas with a clayey foundation, the overall outward displacement of the wall is more uniform along the height of the wall. Vertical differential displacements along the top of the MSE wall also accompany the greater outward tilting when the granular foundation is present. As a result, there is an area of notable differential settlement located some distance back from the face of the wall near the end of the MSE wall straps. This behavior is indicative of the greater rigidity of the MSE reinforced zone as compared to the fill soil beyond and foundation soil underneath, and suggests a potential location of distress in overlying pavement, more particularly in taller walls.

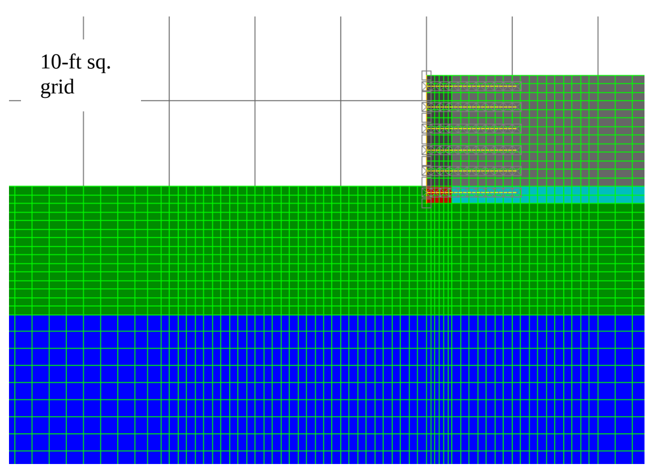
The deformation of the welded wire grid facing can readily be seen in the vertical profile of horizontal displacement. Because the facing is flexible, differential displacements on the order of up to an inch and a half exists between points where the horizontal reinforcement







FLAC models A and B (30-foot high wall with flat ground, 2-ft embedment)



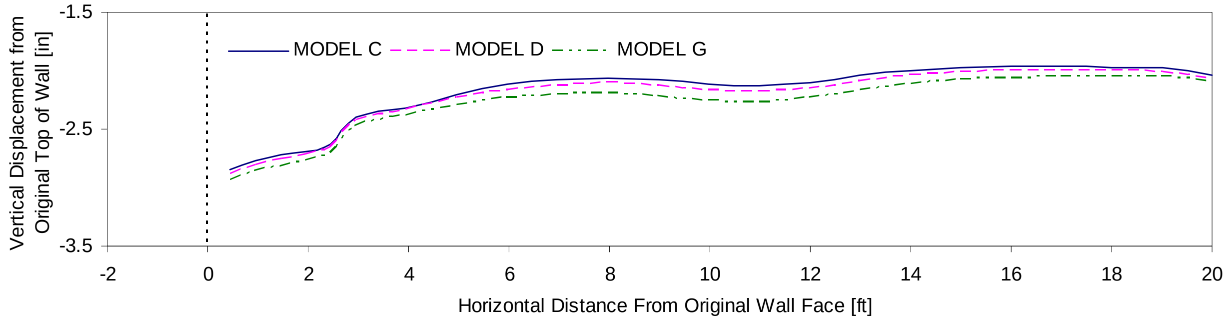
FLAC model C (15-foot high wall with flat ground, 2-ft embedment)

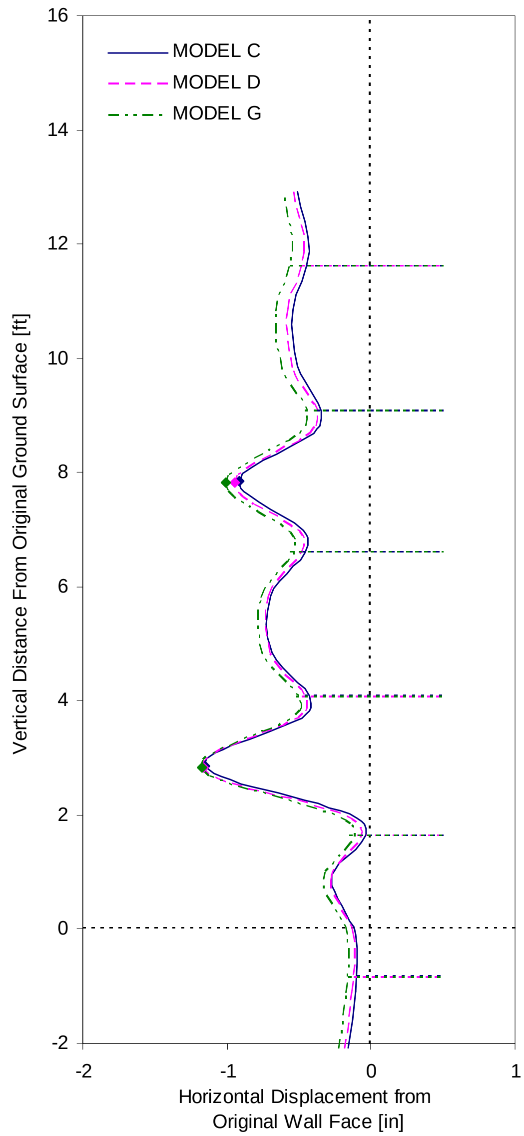
Figure 2 Comparison of relative displacements along MSE wall face and top surface for walls on flat ground (Models A, B, and C) connects to the facing panels and the mid-/end-points of the facing panels. These differential horizontal displacements can potentially signal yielding of the wall facing material and cracking of corrosion-resisting galvanization. The presence of the less compact zone with its lower moduli tends to increase these deformations as the backfill material settles downward and its effect is more pronounced as wall height increases.

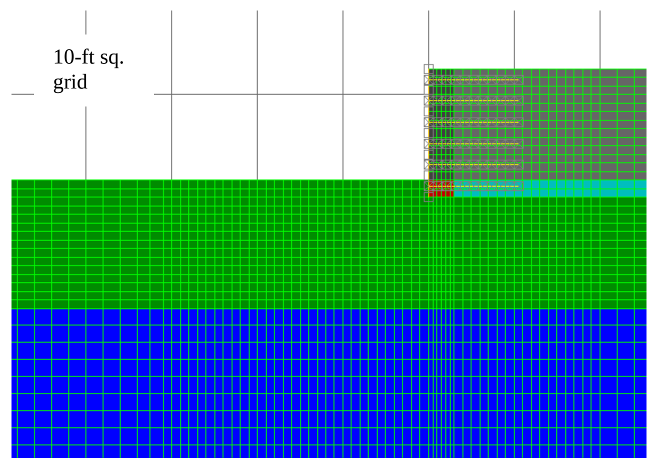
Associated with this horizontal, near-face behavior is an increase in vertical displacement right near the wall face. This displacement is associated with the presence of less compact material typically located within a few feet of the wall face. The implication for design is that there may be greater settlement near the wall face and hence less support for any overlying slabs. This zone appears to be about the same width as the width of less compact material, which is typically about 3 ft.

Figure 3 presents a comparison of relative displacements along the wall face and top surface for the 15-ft high MSE wall model on horizontal ground (Model C), the 15-foot high MSE wall model on 2H:1V sloping ground with a 4-ft wide bench and 2-ft embedment (Model D), and the 15-foot high MSE wall model on 1.5H:1V sloping ground with a 4-ft wide bench and 2-ft embedment (Model G). The two models on sloping ground represent conditions that may exist at some bridge approaches where MSE walls are 'perched' on sloping ground. Common practice suggests that slopes of 2H:1V or flatter are preferred, although 1.5H:1V slopes sometimes occur.

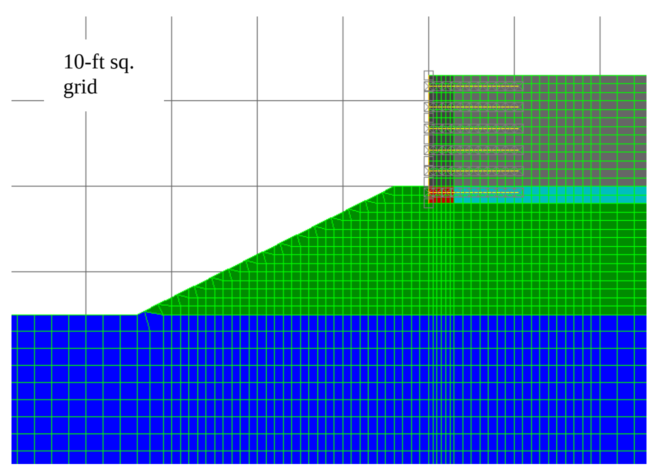
In comparing Model C with horizontal ground to Model D with sloping ground, it is seen that the presence of 2H:1V sloping ground in front of the MSE wall increases outward horizontal displacement of the wall face by only a fraction of an inch. This seems consistent with the idea that the 4-ft setback of the wall from the slope (i.e., the bench width) is intended to be of sufficient distance such that the presence of the slope does not significantly alter wall behavior. Horizontal displacements increase about one-tenth of an inch when the slope increases to 1.5H:1V. The trends in vertical displacement along the top of the wall are similar, with wall Models C and D showing very similar behaviors while there are greater displacements for Model G. The greatest differential displacement along the top of the wall occurs 2 to 3 ft behind the wall face, which is the extent to the less compact MSE wall backfill material. Because overall







FLAC model C (15-foot high wall with flat ground, 2-ft embedment)

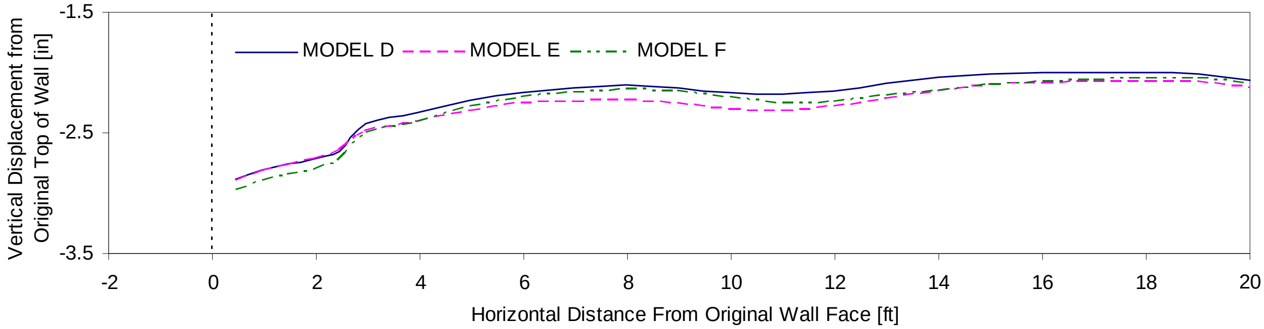


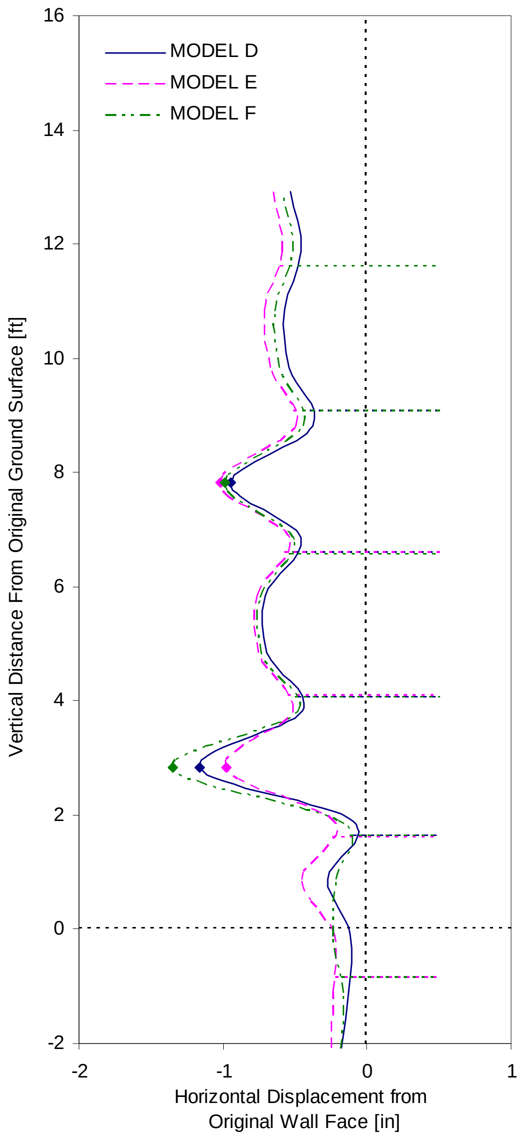
FLAC model D (15-foot high wall with 2:1 slope, 4-ft bench, 2-ft embedment)

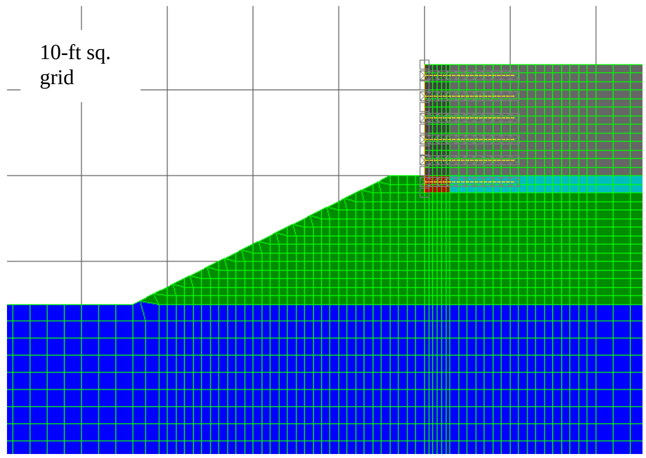
Figure 3 Comparison of relative displacements along MSE wall face and top surface for 15-ft high walls on ground with varying slopes (Models C, D and G [flat, 2H:1V, and 1.5H:1V slopes, respectively]) vertical settlement is less in the shorter walls as compared to the taller walls, the differential appears to be more pronounced. In comparing these results with those in Figure 2, the shorter walls do not exhibit as large of displacement differentials near the end of the wall straps. This suggests for shorter walls that, globally, the block of soil reinforced by the straps interacts more integrally with the soil behind the reinforced zone and/or there is less movement within the foundation soil underlying the reinforced MSE wall zone.

Figure 4 presents a comparison of relative displacements along the wall face and top surface for three MSE walls on 2H:1V sloping ground: one with a 4-ft wide bench and 2-ft embedment (Model D); one with a 1-ft wide bench and 1-ft embedment (Model E); and one with a 1-ft wide bench and 3-ft embedment (Model F). All three models have the same 13-ft exposed wall height. For the design norm of a 4-ft bench and 2-ft embedment (Model D), the horizontal deformation near the top of the wall is approximately a half inch. Decreasing the bench width and embedment to 1-ft each causes the horizontal displacement to increase by about 0.1 in. This amount of additional displacement can be reduced in half by increasing the embedment from 1 to 3 ft. With respect to vertical displacement along the top of the wall section, Model E exhibits behavior similar to Model D near the wall face with displacements decreasing with distance away from the wall. Model F shows contrary behavior, with increased settlement near the face and unchanging settlement at greater distances. These trends indicate that the greater the effective height of the wall is (as in Model F), the more settlement near the wall face due to the greater height of the less compact soil located there. Also, the less the wall embedment, and hence the less the base width (as in Model E), the greater the vertical displacement is towards the back of the wall (due to the overall lower amount of stability on the slope provided by this configuration).

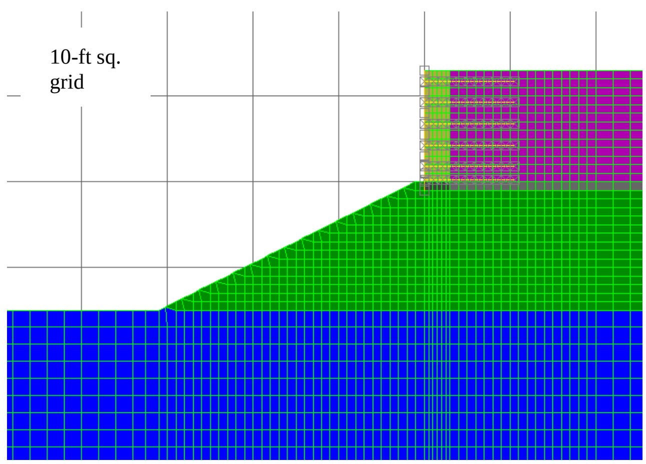
Figure 5 shows results similar to those in Figure 4, except for a steeper 1.5H:1V slope. Model G represents the design norm of a 4-ft bench and 2-ft embedment (but on a 1.5H:1V slope). Models H and I represent walls with a 1-ft wide bench and a 1 and 3-ft embedment, respectively. It can be seen that reduced embedment has a marked effect on horizontal displacements, with displacement near the top of the wall increasing about 0.3 in between Models G and H. Increasing the embedment to 3 ft relative to 1 ft does decrease horizontal displacements, but the change is less than that occurring in situations involving 2H:1V slopes.





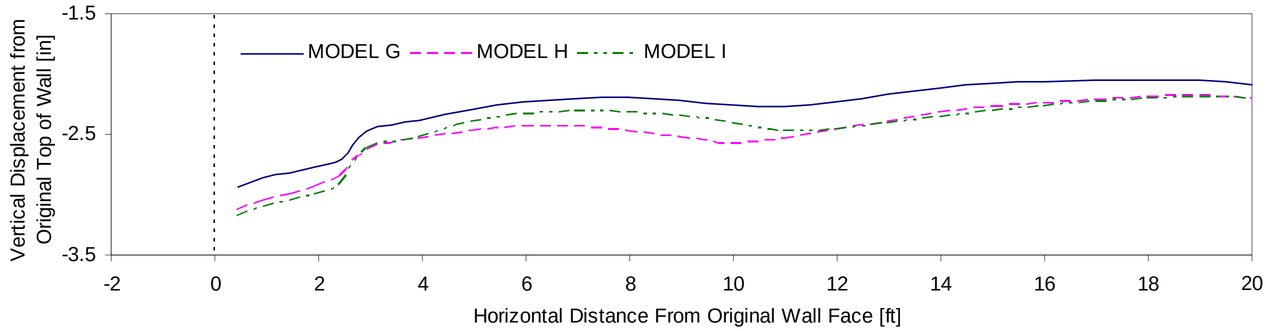


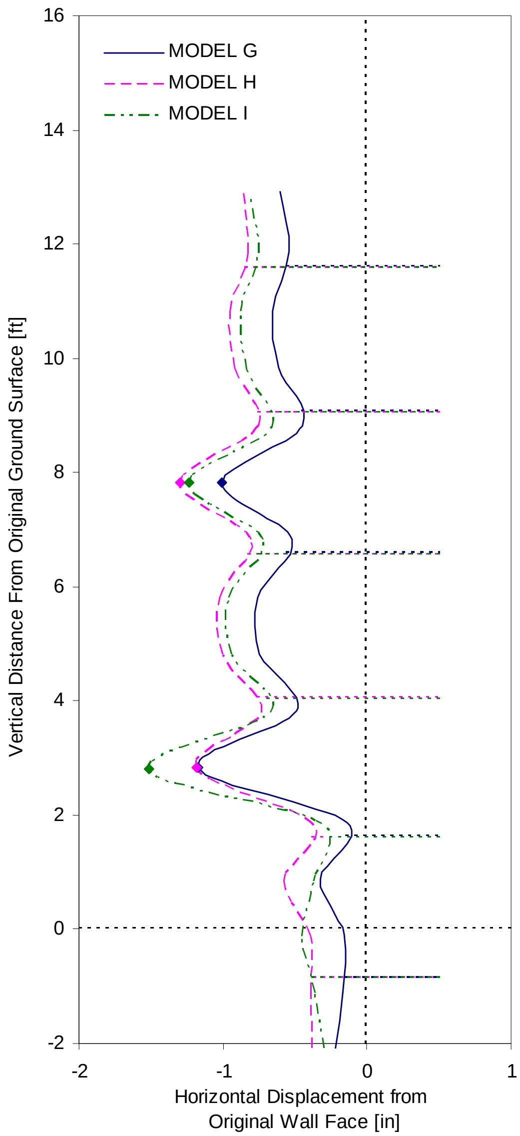
FLAC model D (15-foot high wall with 2:1 slope, 4-ft bench, 2-ft embedment)

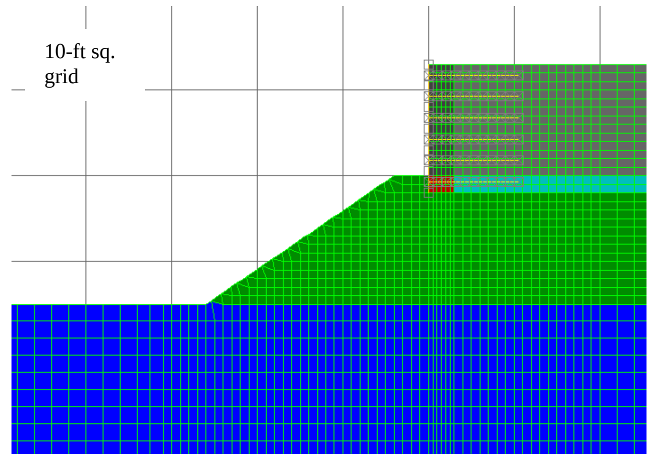


FLAC model E (14-foot high wall with 2:1 slope, 1-ft bench, 1-ft embedment)

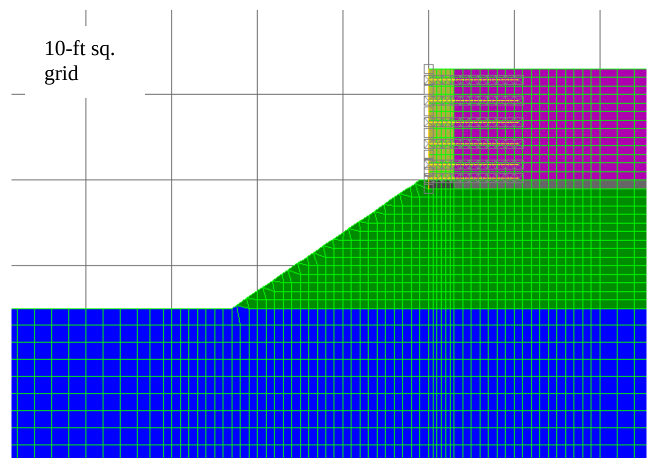
Figure 4 Comparison of relative displacements along MSE wall face and top surface for 14 to 16-ft high walls on ground with 2:1 slope and varying bench width and embedment depth (Models D, E and F)







FLAC model G (15-foot high wall with 1.5 slope, 4-ft bench, 2-ft embedment)



FLAC model H (14-foot high wall with 1.5:1 slope, 1-ft bench, 1-ft embedment)

Figure 5 Comparison of relative displacements along MSE wall face and top surface for 14 to 16-ft high walls on ground with 1.5:1 slope and varying bench width and embedment depth (Models G, H and I)

Hence, greater embedment is required when 1.5H:1V slopes are present in order to compensate for smaller bench widths. Trends in vertical displacement along the top of the wall are similar to those observed with the MSE walls founded on 2H:1V slopes.

3.2 Factors of Safety

Factors of safety with respect to shear strength, slope stability, and bearing capacity were calculated for each wall model. Since each factor of safety (FS) is defined differently and represents a different type of potential failure mode, the different factors of safety determined for one particular wall model are not directly comparable to each other. However, the trends in each type of factor of safety do provide meaningful insight into the effects of sloping foundation soils, wall setback, and wall embedment on the behavior and performance of MSE walls. Changes in stability due to changes in embedment is a compound effect of the changed embedment itself as well as the changed base width (i.e., reinforcing strap length) for the wall since the wall height (as measured from the base) to base length ratio is treated as being a constant value of 0.7. Otherwise, changes in stability due to changes in embedment would be less pronounced. A summary of the calculated factors of safety for each wall model is shown in Table 5.

Table 5 Summary of Calculated Factors of Safety (FS)

Wall Model ID	FLAC-based Strength FS	Slope Stability FS*	Bearing Capacity FS
A	1.62	1.97 (c)	9.3
B	1.96	2.35 (c)	2.7
C	1.91	2.27 (c) 2.10 (nc)	9.3
D	1.44	1.49 (c) 1.54 (nc)	4.4
E	1.29	1.37 (c)	3.4
F	1.38	1.44 (c)	4.2
G	1.25	1.32 (c)	3.6
H	1.12	1.19 (c)	2.7
I	1.20	1.25 (c)	3.3

* (c) = circular failure surface; (nc) = non-circular failure surface

In order to better quantify the relative effects of sloping foundation soils, wall setback, and wall embedment, margins of safety were calculated from the factors of safety (where margin of safety equals factor of safety minus one). Since wall model D represents what can be considered a normal, adequate wall design, the margins of safety have been additionally normalized relative to this wall model, thus providing a simple measure of how “safety” varies from acceptable norms due to the differing conditions present in each model. Hence, a margin of safety of 1 indicates a state at the point of failure, whereas a normalized margin of safety of 1 indicates a state comparable to that present in wall model D (and the actual margin of safety is not explicitly specified but readily calculable). The normalized margins of safety are presented in Table 6.

Table 6 Margins of Safety Normalized Relative to Wall Model D

Wall Model ID	FLAC-based Strength	Slope Stability	Bearing Capacity
A	1.41	1.98	2.4
B	2.18	2.76	0.5
C	2.07	2.24	2.4
D	1.00	1.00	1.0
E	0.66	0.76	0.7
F	0.86	0.90	0.9
G	0.57	0.65	0.8
H	0.27	0.39	0.5
I	0.45	0.51	0.7

The factor of safety calculated in FLAC is based on a strength reduction method, and wall “failure” is not limited to a single particular mode. In some instances, the wall models show more of a traditional bearing capacity failure mode (see Figure 6, noting the log-spiral shape at the toe of the wall) while other models show more of an overall, global type of failure, or even a combination of the two combined with overturning (see Figure 7). In Figure 6 and Figure 7, the potential failure “plane” is delineated by contoured zones of high shear strain rate. The shear strain rates and velocity vectors are relatively small since the factors of safety are relatively large, and it is the pattern rather than the magnitude of these parameters that is most meaningful. It should be noted that the failure zones calculated in the wall model do not generally extend to the base of the slope as suggested by a more traditional, limit equilibrium slope stability analysis. Rather, the failure zones indicated by the FLAC models show a composite failure mechanism with elements of both global stability and localized bearing capacity failure, as influenced by the deforming wall.

The FLAC-based strength factors and margins of safety indicate that a 15-ft high wall founded on a 2H:1V slope with a 4-ft wide bench and 2-ft embedment (wall Model D; also referred to as the baseline case) has a margin of safety against slope-like failure that is only about 48% of that for a similar wall founded on flat ground (wall Model C). For an MSE wall founded on a 2H:1V slope, a reduction in bench width from 4 to 1 ft and a reduction in embedment depth from 2 to 1 feet reduces the factor of safety by 0.13, from 1.44 to 1.31 (corresponding to a 30% reduction in the margin of safety). Interpolation of data from wall models E and F indicates that for a 1-ft wide bench, each foot of additional embedment contributes approximately 0.10 to the normalized margin of safety. Hence, a wall configuration on a 2H:1V slope with a 1-ft wide bench and 3-1/3-ft embedment depth would have approximately the same stability as a wall with a 4-ft wide bench and a 2-ft embedment depth. In the context of the MSE wall configurations analyzed, these results are generally consistent with the concept that combinations of bench width and embedment depth which result in the same horizontal distance between the base of the wall and the face of the slope produce a similar degree of safety.

The factors and margins of safety with respect to slope stability show trends similar to those calculated using FLAC. As a point of reference, the factors of safety computed for the 2H:1V and 1.5H:1V sloped foundations by themselves without MSE walls present are 2.11 and 1.70, respectively. (These values correspond well with FLAC-computed factors of safety of 2.12 and 1.72). Figure 8 and Figure 9 illustrate both the critical circular and non-circular failure planes calculated for wall models C and D, respectively. (The failure planes in these figures can be compared to the FLAC-based potential failure zones shown previously in Figure 6 and Figure 7). The accuracy of the slope stability factors of safety depends upon the applicability of the assumptions made in the methodology (e.g., that the factor of safety is uniform across the failure surface and that the interslice forces are oriented in a pre-defined way) and do not incorporate the effects of wall deformation.

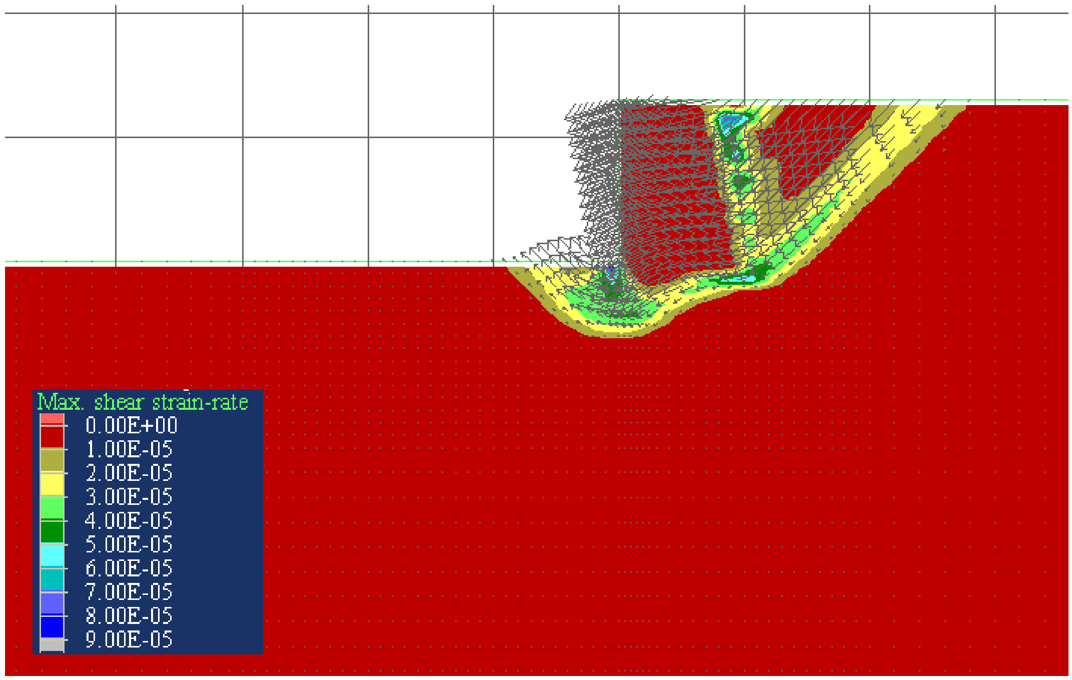


Figure 6 Plot of shear strain rate contours and velocity vectors, highlighting the potential failure zones for wall Model C (FS = 1.91)

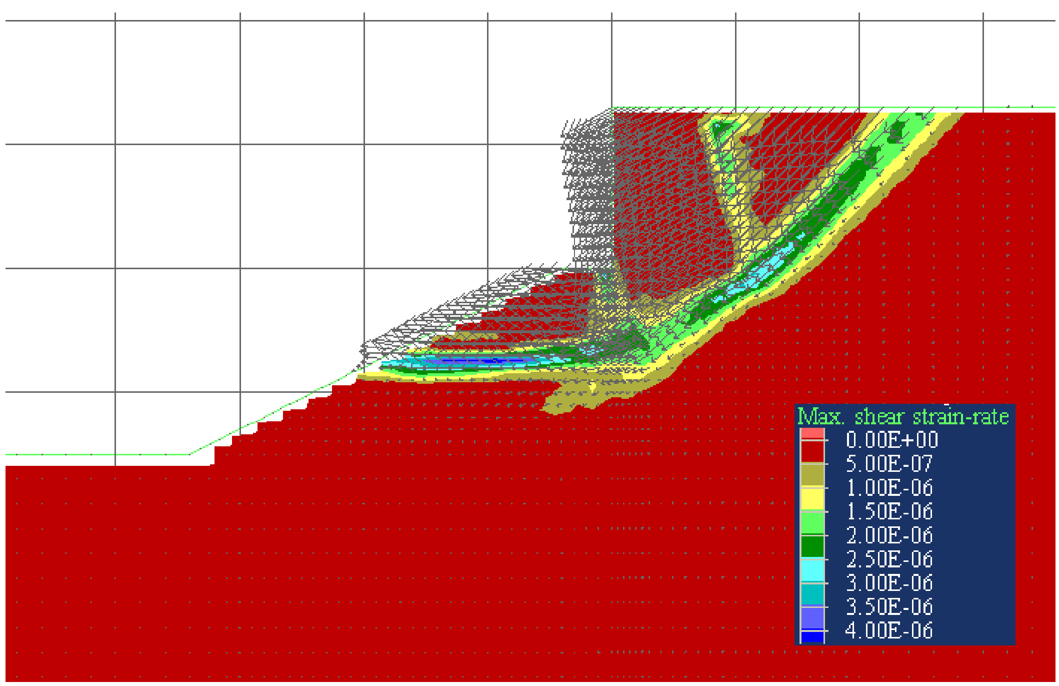
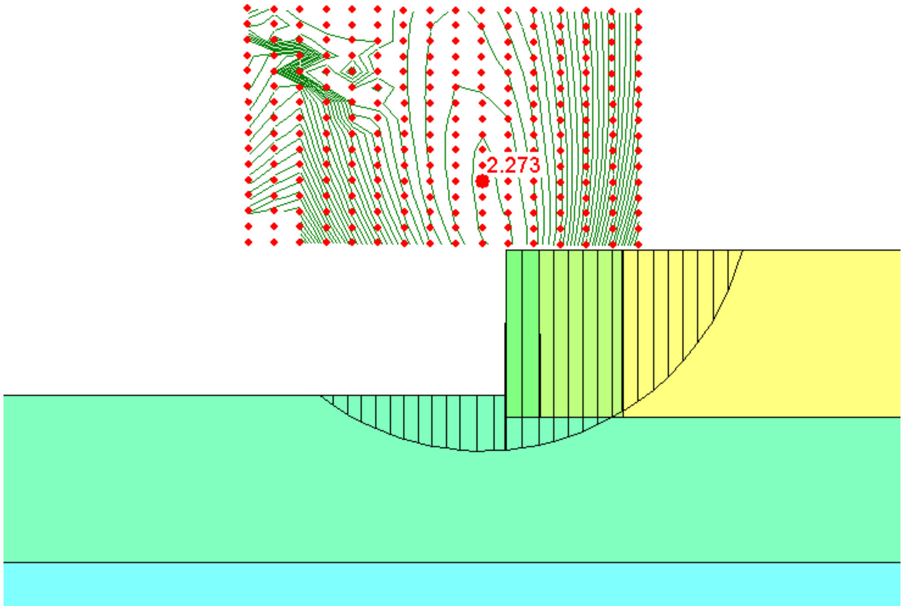


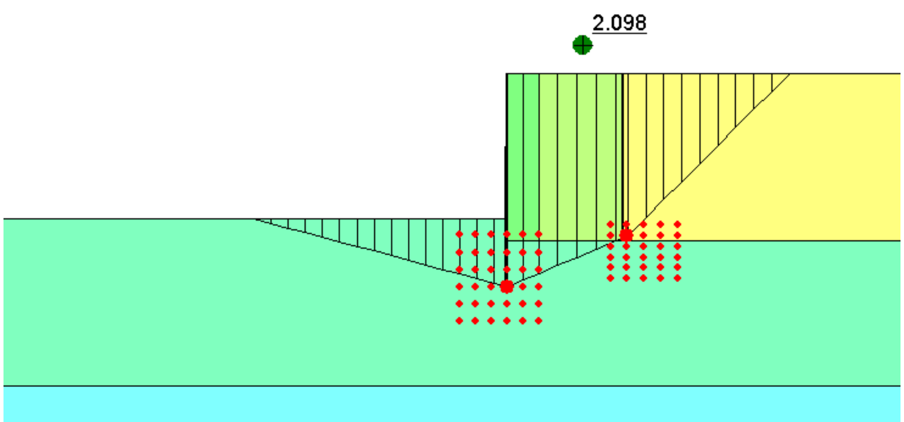
Figure 7 Plot of shear strain rate contours and velocity vectors, highlighting the potential failure zones for wall Model D (FS = 1.44)

The factors of safety with respect to limit equilibrium slope stability shown in Table 5 suggest that a 15-ft high wall founded on a 2H:1V slope with a 4-ft wide bench and 2-ft embedment (wall Model D; also referred to as the baseline case) has a margin of safety against slope-like failure that is only about 45% of that for a similar wall founded on flat ground. For an MSE wall founded on a 2H:1V slope, a reduction in bench width from 4 to 1 ft and a reduction in embedment depth from 2 to 1 feet reduces the factor of safety by 0.12, from 1.49 to 1.37 (corresponding to a 24% reduction in the margin of safety). Additionally increasing the slope to 1.5H:1V decreases the factor of safety another 0.13 relative to the baseline case (corresponding to a cumulative 61% reduction in the margin of safety). Wall Models F and I indicate that increasing wall embedment when bench width is minimal does improve the factor of safety, however, in order to produce a factor of safety comparable to the baseline case, more than 1-ft of extra embedment (closer to 2 ft based on an extrapolation of the data) is required to offset a reduction in bench width from 4 to 1 ft when the slope is 2H:1V. However, such a conclusion is based on failure planes existing near the base of the slope, which is different from the locations of the more realistic planes of weakness indicated by the FLAC modeling.

The calculated factors and margins of safety with respect to bearing capacity failure show trends generally similar to those calculated using FLAC. To more clearly present the effects of the steepness and proximity of sloping ground on the stability of a wall, a series of parametric charts (see Figure 10 through Figure 12) was developed in which bearing capacity is expressed in terms relative to the bearing capacity existing for walls founded on flat ground. While the factor of safety against bearing capacity failure for a wall founded near a slope by itself may be high enough to be acceptable, a low ratio indicates that the effects of the slope are significant. The value of the factor of safety itself depends on the value of the soil's friction angle whereas the bearing capacity ratio is largely independent of the friction angle. On these charts, a ratio greater than 1.0 is possible since the reference condition (as established by Shields et al. (1990)) is based on no embedment; hence, a wall that is embedded and located such that the effects of the slope are negligible would have a bearing capacity ratio greater than 1.0.

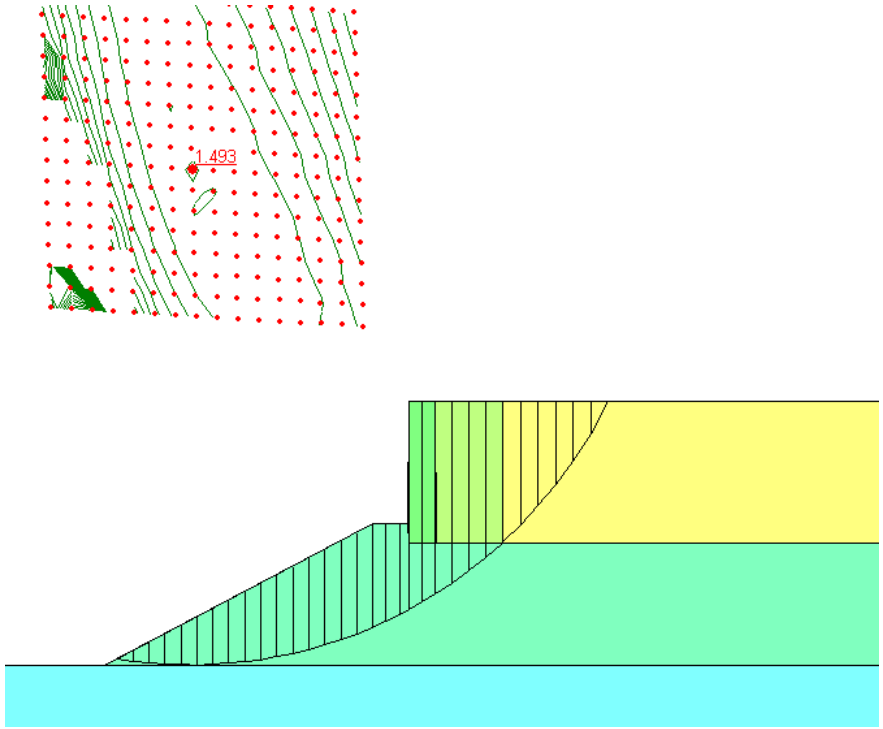


(A)

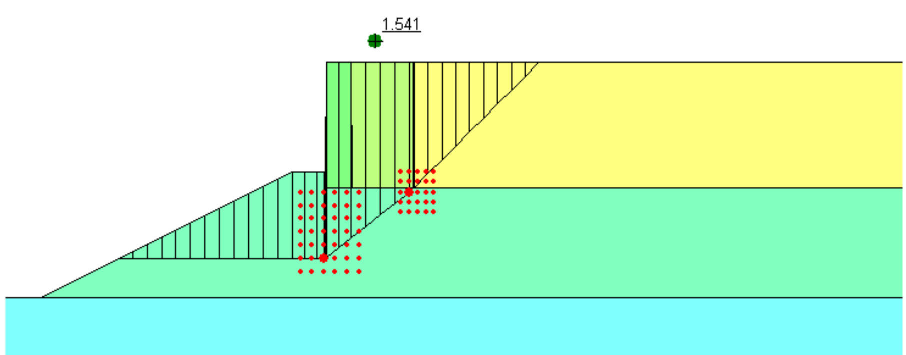


(B)

Figure 8 Plot of slope stability analysis results for (A) circular and (B) non-circular failure surfaces for wall Model C



(A)



(B)

Figure 9 Plot of slope stability analysis results for (A) circular and (B) non-circular failure surfaces for wall Model D

In Figure 10 through Figure 12, the relative effects of ground slope, bench width, and embedment are quantified. As seen in Figure 10, the effect of slope becomes more pronounced as the base width of the wall increases (which is the same as the wall becoming taller since the two are proportionally related). Further reductions in capacity occur as the slope becomes steeper, and the setback (i.e., bench width) and embedment depth both decrease. In general, the relative effects of embedment depth and bench width are controlled by the slope of the ground (and hence the horizontal distance between the base of the wall and the face of the slope). The capacity of a 15-ft high wall founded on a 2H:1V slope with a 4-ft wide bench and 2-ft deep embedment (wall Model D) is seen to be about half that of a similar wall founded on flat ground.

Combinations of bench width and embedment depth which result in the same horizontal distance between the base of the wall and the face of the slope generally produce similar bearing ratios, and hence bearing capacities. This behavior can be seen in the curves shown in Figure 11 for a 2H:1V slope. The bearing ratio for an MSE wall with a 4-ft wide bench and 2-ft embedment (i.e., wall Model D representing the design norm) is shown by the solid line. For a wall with a 1-ft wide bench to have approximately the same degree of stability, it would need to have an embedment slightly more than 3 ft, as shown in the figure by the most elevated dashed line. (For the wall with the 4-ft wide bench and 2-ft embedment, the distance from the wall base to the slope face is 8 ft. For the wall with the 1-ft wide bench and 3-ft embedment, the distance from the wall base to the slope face is 7 ft). In a different scenario in which the embedment for a 15-ft high wall is maintained at a constant 2 ft, reducing the bench width from 4 to 1 ft reduces the bearing capacity ratio from 0.47 to 0.40, meaning that the reduction in bench width reduced the bearing capacity 15% relative to the normal design conditions represented by wall Model D. While a 15% decrease may not appear to be significant, this is comparable to reducing a factor of safety from 3.0 to 2.55, or from 2.5 to 2.13 (which corresponds to a 22 to 25% reduction in the safety margin, respectively). Figure 12 is similar to Figure 11, but addresses 1.5H:1V slopes. On these steeper slopes, even more embedment is required to offset reductions in bench width.

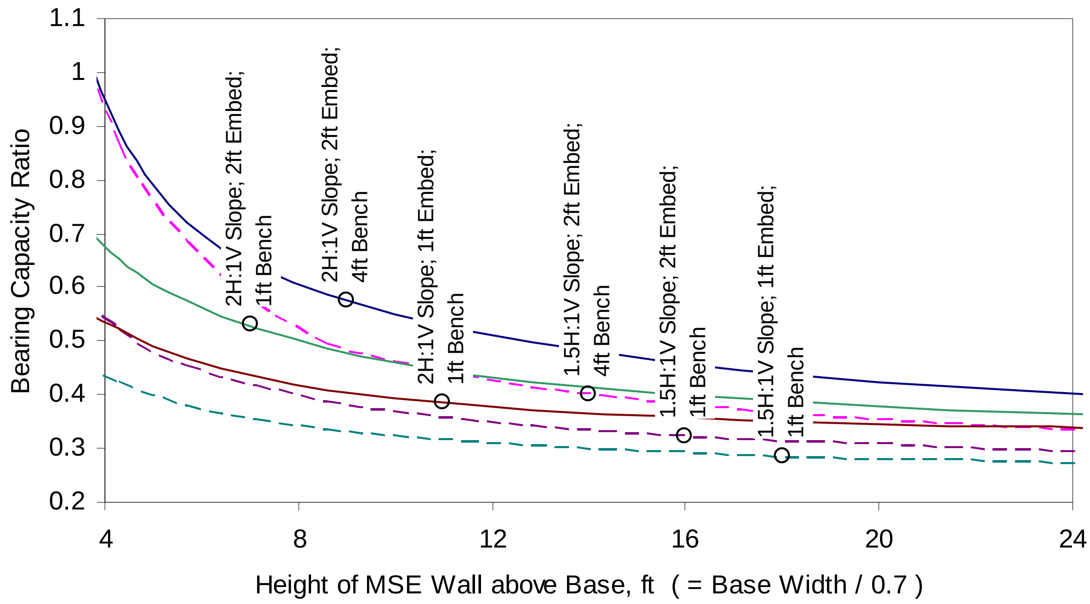


Figure 10 Chart of bearing capacity ratio for MSE walls founded on 2H:1V and 1.5H:1V ground slopes with varying bench widths and embedment depths

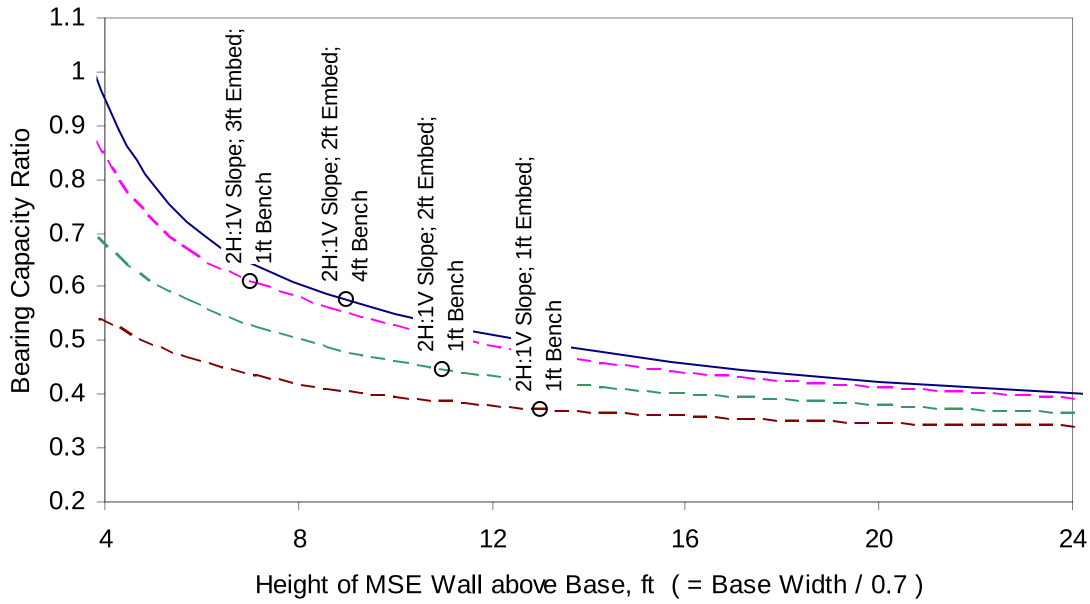


Figure 11 Comparison of bearing capacity ratios for MSE walls founded on 2H:1V sloping ground with different embedment depths

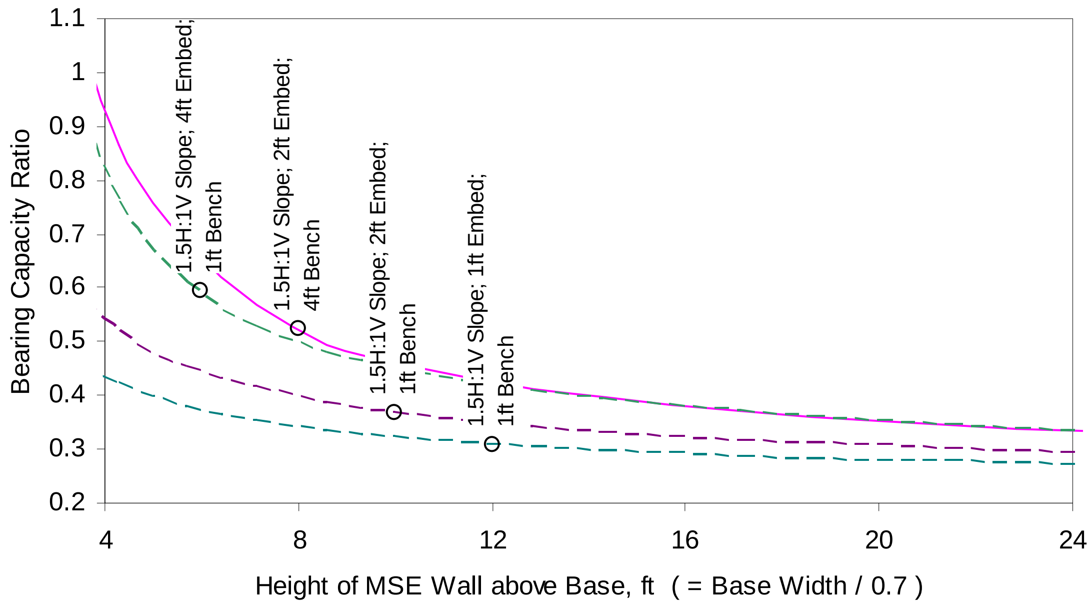


Figure 12 Comparison of bearing capacity ratios for MSE walls founded on 1.5H:1V sloping ground with different embedment depths

THIS PAGE LEFT INTENTIONALLY BLANK

4.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the work presented herein, the following conclusions are made and recommendations presented:

1. Wall height plays an important role in MSE wall behavior, with vertical and horizontal deformations increasing non-linearly with increasing wall height.

2. Wall deformations are greater for walls founded on slopes than for walls founded on flat ground.

3. Both bench (i.e., slope setback) width and wall embedment play important roles in MSE wall behavior; deformations in walls founded on relatively steep slopes increase markedly when bench width and/or embedment depth is reduced; factors of safety similarly decrease.

4. In general, combinations of bench width and embedment depth which result in the same horizontal distance between the base of the wall and the face of the slope produce similar factors of safety with respect to shear strength and bearing capacity.

5. The failure mode of an MSE wall founded on a slope may be a combination of slope stability, bearing capacity, and overturning mechanisms. The factor of safety determined in a full constitutive model may be lower than those calculated with simple procedures like equilibrium slope stability which address only one failure mode.

6. Relative to an MSE wall founded on a 2H:1V slope with a 4-ft wide bench and 2-ft embedment, if the bench width is decreased to 1-ft, an embedment increase of 1.3 to 1.5 ft (with an accompanying increase in strap length due to the increase in effective wall height) will produce a comparable degree of performance; greater embedment would be required for 1.5H:1V slopes.

7. A notable zone of differential vertical displacement coinciding with the presence of less compact MSE wall backfill soil can exist immediately behind the face of MSE

walls; the design of overlying slabs and structures should not rely on support from this typically 3-ft wide zone of MSE wall backfill.

8. Design consideration should be given to potential differential vertical displacements along the top of the wall section at the transition zone between the back of MSE wall straps and adjacent, unreinforced fill.

REFERENCES

Elias, V., Christopher, B.R., and Berg, R.R. (2001). *Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, Design and Construction Guidelines.* FHWA-NHI-00-043. Nat'l. Highway Inst., Federal Highway Admin., U.S. Dept. of Transportation, Washington, D.C.

Geo-slope. (2002). *SLOPE/W (Version 5) User's Guide*. Geo-slope International, Ltd., Calgary, Alberta, Canada.

Itasca. (2005). *FLAC (Version 5.0) User's Guide.* Itasca Consulting Group, Minneapolis, Minnesota.

Meyerhof, G.G. (1963). "Some recent research on the bearing capacity of foundations," *Canadian Geotechnical Journal.* 1, 16-26.

Mitchell, J.K. and Villet, W.C.B. (1983). *Reinforcement of Earth Slopes and Embankments.* National Cooperative Highway Research Program Report 290. Transportation Research Board, National Research Council, Washington D.C.

Shields, D., Chandler, N., and Garnier. (1990). "Bearing capacity of foundations in slopes," *Journal of Geotechnical Engineering*, American Society of Civil Engineers. 116 (3), 528-537.