The Effects of System Components on the Deflection of MSE Retaining Walls

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ABSTRACT - This paper seeks to examine some of the technical factors influencing the deflection of Mechanically Stabilized Earth (MSE) retaining walls based on the authors' field observation of numerous structures. Excessive deflections can be unsightly and can be perceived as wall failure. Deflections can cause cracking or gapping of the facing units and general misalignment. Deflection of the reinforced backfill zone behind the wall face can result in settlement of the backfill zone and adjacent pavement cracking. Deflections can be the result of excessive movement external or internal to the reinforced soil structure. This paper only examines internal factors affecting wall deflections. External factors such as foundation settlement are not discussed.

MSE retaining walls consist of facing units, soil reinforcement material, and reinforced backfill. The type of concrete facing system seems to have little impact on deflections. However, some facing systems accommodate certain types of deflection better than others. Of the soil reinforcement factors, length and material type influence the amount of deflection. However, reinforcement material type is a more significant indicator. Empirical evidence suggests that extensible geosynthetic reinforced soil retaining walls may deflect 3 times as much as inextensible steel reinforced systems during construction and under service loading. Backfill type is an equally significant factor. Fine-grained backfills can exhibit approximately 2 to 3 times the deflection of granular backfills based on the additional movement required to develop the active earth pressure state. In addition, fine-grained soils and some coarse-grained soils with significant fine content can have an initial un-drained cohesive strength component that provides greater soil strength at first which dissipates over time. As a result, earth pressures in the upper portions of taller retaining walls can increase with time causing much of the deflection to be delayed until after initial construction. The selection of backfill materials and reinforcement type should be made based on an assessment of the allowable deflection for each retaining wall considering the unique circumstances of the site-specific application.

Construction procedures, foundation movement, backfill type, and reinforcement type & length can significantly affect MSE wall deflections. Improper construction procedures and foundation movement are omitted from this discussion. However, the reader should note that improper construction and backfilling procedures are responsible for a significant percentage of the wall movement problems observed and cannot always be isolated from technical performance issues.

I BACKGROUND

Excessive deflection and the resulting deformation of adjacent pavements and structures associated with certain MSE retaining wall installations are a leading factor in cases of unsatisfactory performance. Deflections can range from minor face distortion to significant cracks, gaps, and settlement in the wall face and in the soil, pavements, and structures behind the wall face. In addition, wall structures can vary in their tolerance of minor deflections of the wall system as walls supporting a gentle back slope may be more tolerant of minor movement than a wall supporting an adjacent roadway or building foundation.

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Wall deflection or serviceability concepts of an MSE retaining wall as a total system are not currently considered in design due to limited knowledge and criteria to evaluate such deformation. Serviceability concepts are only partially addressed by evaluating individual components of the system such as soil pullout, long term reinforcement creep and facing connections.

Unacceptable deflections can be due to internal and /or external movements. Internal deflections are within the reinforced mass itself. External deflections are associated with movement and settlement of the foundation soil or the retained soil behind the reinforced MSE mass. External factors are not discussed within this paper but must be considered when evaluating poor performing structures. This paper serves to examine some of the issues affecting internal deflections so that users and specifiers can make informed decisions concerning their use and the selection of components for these systems.

II INTRODUCTION

An MSE retaining wall is basically a reinforced soil mass with a permanent facing. The basic components are the face units, the soil reinforcement and the backfill as shown in Figure 1. The concepts of soil reinforcement are not new. The ziggurats of ancient Babylon and the Great Wall of China use similar soil reinforcing techniques.

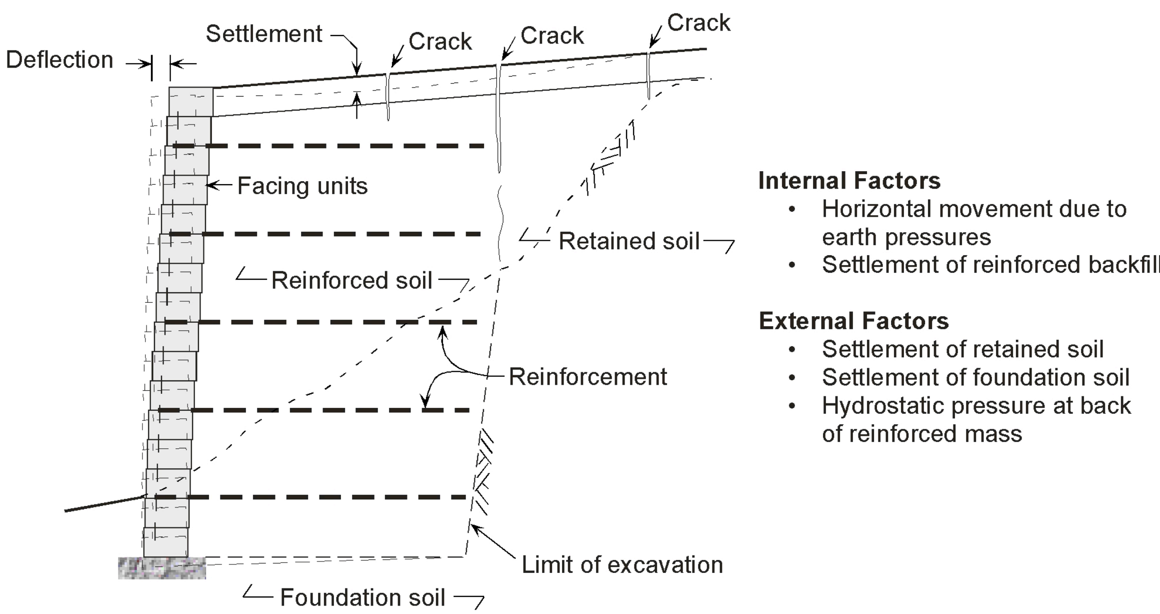


Figure 1: Typical MSE Wall Deflection Section

The first modern MSE wall construction began in the late 1960's using galvanized steel strips for reinforcement, galvanized steel or pre-cast concrete face panels, and select granular backfill. Geosynthetics were developed over a similar time period and soon were being used for soil reinforcement applications. Geosynthetics are relatively inert in a wider variety of soils than galvanized steel allowing more fine-grained or less select soils to be used for backfill. Since geosynthetics are typically used as continuous sheets as opposed to discrete strips of reinforcement, they also tend to exhibit greater pullout resistance which is another reason why lower quality backfill can be considered.

When segmental retaining walls (SRW) or modular block walls were developed in the mid 1980's, they were initially used as small gravity walls. Shortly thereafter SRW's and geosynthetic reinforcement, primarily geogrids, were matched together. The result being a retaining wall system with more versatile facing components while permitting the use of a broader range of backfill and thus reduced cost. Over time, the most common type of MSE wall type constructed has changed from large concrete panels to segmental units, from steel reinforcement to geosynthetic reinforcement, and from select backfill to onsite fill, driven solely by cost, availability, and aesthetic considerations.

The marketplace's rapid acceptance of these systems has sometimes exceeded the technical knowledge of engineering and construction community while "saving money" for many Owners. In many cases, the concepts of basic soil mechanics have been ignored or discounted. The combination of "easier to install" facing components, extensible geosynthetic reinforcement, lower quality backfills, and a lack of understanding of soil mechanics caused an increased occurrence of retaining wall installations exhibiting varying degrees of unacceptable movement. The effects of each of the MSE wall components on deflections are discussed individually.

III MSE FACING – PANELS vs. SRW UNITS

MSE retaining wall facing evolved from relatively thin (6"-7") but relatively large (24 SF) reinforced panels to relatively deep (12" to 24") but smaller (1 SF) segmental concrete blocks. The facing questions are: 1) Does a segmental block facing deflect more than a panel facing system and 2) Do thinner segmental blocks deflect more than thicker ones?

Precast panels have a different set of movement problems then SRW blocks due to being thin but the greater panel unit size tends to compensate for this movement potential. Thicker precast panels offer more construction stability than thinner panels but all sizes have been constructed successfully as construction techniques have been modified for each specific panel system.

Thicker SRW units are generally more resistant to face movement than thinner units. Current American Association of State Highway and Transportation Officials (AASHTO) specifications offers some guidance regarding SRW systems by limiting the maximum vertical spacing of reinforcement layers to 2 times the unit depth to control face distortions. This criteria attempts to address construction induced distortion of small units more than wall deflection.

We find that there are no noted performance differences to distinguish between panels and SRW's from a deflection standpoint under AASHTO guidelines. Therefore, facing type does not appear to be a direct factor in assessing deflections other than construction issues unique to each system which is consistent with the authors' observations.

IV MSE REINFORCEMENT - TYPE AND LENGTH

MSE retaining wall reinforcement can be divided into two basic material types, geosynthetic (extensible) and galvanized steel (inextensible). While each can be subdivided further into steel strips and welded bar mats or geogrids and geotextiles, those differences are subtler and are not discussed here. Other items related to the reinforcement and deflections are reinforcement length and "slack" of the reinforcement system at the connection and within the reinforced backfill mass.

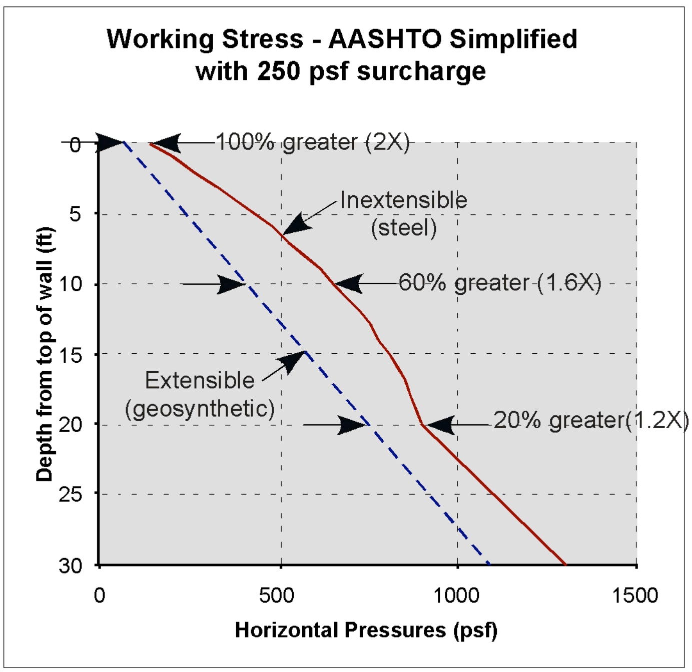
A. Reinforcement Type

The different physical property characteristics of the two types of reinforcement are:

Steel Reinforcement (Inextensible)

- Steel has a much higher modulus than geosynthetic material and carries the same load at a much lower strain. Steel is approximately 60 times stiffer than geosynthetic material and performs in a simple elastic manner (fixed modulus of elasticity).

- The strain of steel within the working stress range is instantaneous. As soon as the load is applied, all of the strain occurs. There are no creep effects to consider.



Graph Parameters-Simplified
ϕ = 34°
γ = 120 pcf
Ka = 0.283
q = 250 psf
K/Ka = 1.0 Extensible
K/Ka = 2.0 Inextensible @ Top
K/Ka = 1.2 Inextensible @ 20' depth

Figure 2: Calculated Pressure – Extensible vs. Inextensible Reinforcement per AASHTO 2001

- Due to the higher stiffness of the reinforcement, a steel reinforced wall is designed for higher earth pressures. This is somewhat analogous to designing a rigid non-yielding CIP wall for an at-rest Ko condition instead of a yielding cantilever wall designed for an active Ka condition. The lower deflections associated with a stiffer mass result in the active state not being fully developed and thus greater earth pressures. This concept is illustrated in Figure 2, which compares the calculated earth pressure of extensible and inextensible reinforcement materials. By definition, a steel system is designed for less movement based on a restrained earth pressure state.

Geosynthetic Reinforcement (extensible)

- Much lower modulus than steel reinforcement

- Strain is time dependent (creep effects). Creep is the tendency of the reinforcement to strain or stretch over time at a constant load. Different types of polymers tend to exhibit different creep characteristics.

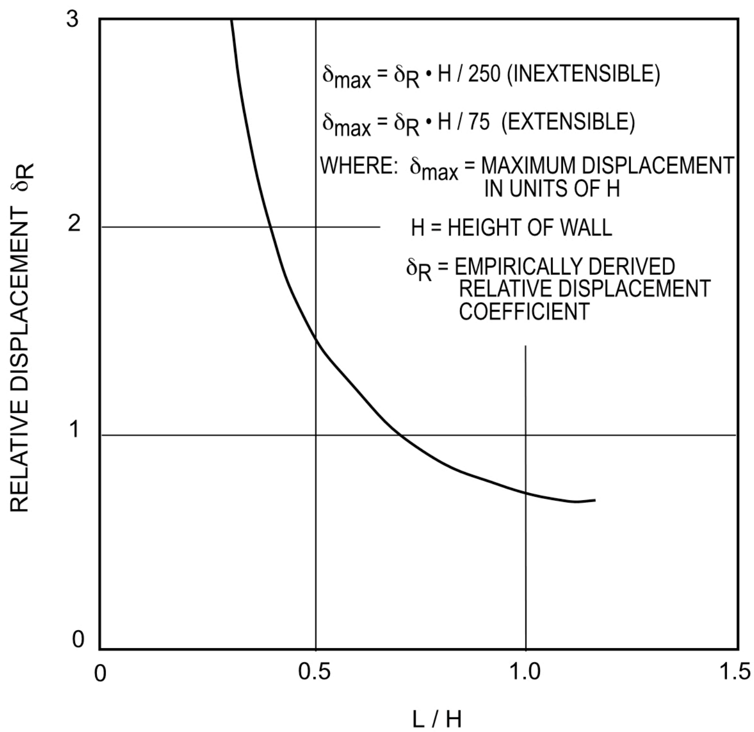
  - Polymers above the glass transition temperature, such as High Density Polyethylene (HDPE) and Polypropylene (PP), tend to plastically flow at a decreasing rate over time. For such materials, even if the load were applied instantaneously, 15 to 20 % of the creep strain would occur after a typical construction sequence.

  - Polymers below their glass transition temperature, such as Polyester (PET), tend to behave more like glass and exhibit a mechanical creep where the bulk of the creep occurs as the load is applied and less thereafter. Post construction reinforcement creep strain would tend to be less than HDPE and PP material, again assuming instantaneous load application.

- Although it is conjectured that confined creep strains (such as when the geosynthetic is surrounded by soil) are considerably less, even if they are reduced by 80 percent, the predicted strains are an order of magnitude (10 times) greater than predicted for steel reinforcement.

- Walls are designed for a lower earth pressure due to higher deflections (active rotation) allowing the active state of stress to fully develop. This is sometimes referred to as “strain compatibility” where the reinforcement will yield as much as the soil permits to maintain the minimum active earth pressure state.

The magnitude of anticipated construction deflection for the two reinforcement types can be estimated from AASHTO guidance and other research. Figure 3 suggests deflections of 0.4% (1/4˚) and 1.3% (3/4) at L = 0.70H for inextensible (steel) and extensible (geosynthetic) reinforcement under no surcharge conditions. AASHTO documents always assume a select granular backfill as specified so these values are minimums for all soils considered. Presentations by Bathurst and Simac have suggested approximately 1% deflection for a 20-foot geosynthetic-reinforced wall using granular backfill with an additional 0.5% of post construction movement for a total of 1.5% (1˚). They also suggest increasing the predicted deflection by 50% for walls greater than 25 feet in height.



NOTE: INCREASE RELATIVE DISPLACEMENT 25% FOR EVERY 20 kPa OF SURCHARGE

Based on 6 m high walls, relative displacement increase approximately 25% for every 20 kPa of surcharge. Experience indicated that for higher walls, the surcharge effect may be greater.

Note that actual displacements will also depend on soil characteristics, compaction effort and contractor workmanship.

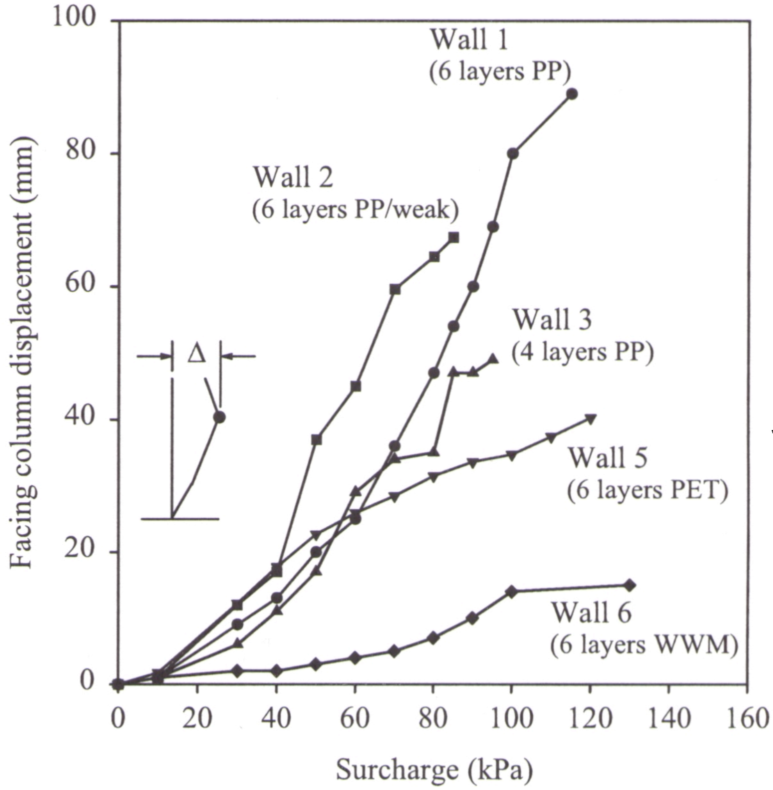
Figure 3: AASHTO 2001 Figure 5.8.10A

As an example, Figure 3 can be used to predict the magnitude of wall deflection and compare for different L/H ratios and reinforcement type with granular backfill as a relative measure:

Wall Height/Length	δ Inextensible	δ Extensible
10' at L = 50%H	3/4"	2-3/8"
10' at L = 70%H	3/8"	1-1/2"
10' at L =100%H	3/8"	1-1/4"
20' at L = 50%H	1-1/2"	4-3/4"
20' at L = 70%H	7/8"	2-7/8"
20' at L =100%H	3/4"	2-3/8"

Laboratory studies by Bathurst, et al. have measured the displacement of 12 foot (3.6m) test wall structures with different types of reinforcement and vertical spacing under surcharge conditions. The data presented in Figure 4 indicates that geosynthetic reinforcement displacement is much greater than the relatively small movement measured with welded wire steel reinforcement under large surcharge loads. All tests utilized clean granular backfill.

Therefore, reinforcement type is a significant factor in assessing potential wall deflections with expected deflections approximately 3 times greater for geosynthetic reinforcement than for steel reinforcement.



PP - Polypropylene

PET - Polyester

WWM - Welded Wire Mesh

Figure 4 - Post Construction Wall Facing Displacement - Reinforcement Material Type vs. Surcharge from Bathurst, et al. 2001

B. Reinforcement Length

Deflections are also affected by reinforcement length. As reinforcement length increases, wall deflections decrease. The relative magnitude of the change in deflection due to changes in reinforcement length is shown in the AASHTO Figure 3. A baseline of 1 X relative displacement is set at L = 70% of H, which is the standard AASHTO design criteria. Once the reinforcement length approaches 100% of the wall height (L = H), the beneficial effects of increasing length are minimal. Likewise, as the length decreases to about 0.4H, the absolute shortest possible length to mathematically meet sliding requirements in very favorable design conditions, the deflections increase dramatically. It would be impractical to lengthen geosynthetic reinforcements sufficiently to reduce deflections to the same magnitude as steel reinforcements. Therefore, reinforcement length is a significant factor, but not as significant as reinforcement type is for any given design length.

C. Reinforcement Slack

Reinforcement slack or play can also affect deflections. Slack can develop at the connection between the reinforcement and the facing units due to play in the connection system. For example, a bolt hole significantly larger than the bolt will provide significant play. Or it can be due to the tendency of the reinforcement to wrinkle in the fill or fold at the connection if the reinforcement is not relatively rigid or is not properly tensioned prior to backfill placement. Either type of reinforcement has some small amount of play at the connection, but the magnitude is very small for positively connected reinforcement. Folding and wrinkling only occurs with geosynthetics and the amount is highly influenced by construction practices. Therefore, proper tensioning and seating of the reinforcement on the connectors followed by staking of the reinforcement and careful fill placement are very important with geosynthetics to minimize wall deflection.

D. Reinforcement Effect Summary

Based on the above discussion, it is apparent that the reinforcement, and specifically the reinforcement type, can have a significant impact on the amount of deflection observed in MSE retaining walls. Deflections are potentially greater with geosynthetic reinforcement due to a variety of reasons including their lower modulus, creep characteristics, and the reduced strength of reinforcement required due to reduced design stresses predicated on active earth pressure movement.

V MSE BACKFILL

Backfill is often the most overlooked and least understood component of MSE retaining walls. Therefore, it is likely to be the component that contributes disproportionately to deflection problems with these structures. If granular material is required and not available onsite, it becomes a major cost component of the retaining wall system. As such, there are significant economic reasons to allow lower quality onsite materials to be used as structural backfill.

The key engineering properties of backfill soil for retaining wall design and construction are strength (friction angle and cohesion), unit weight, and drainage. Drainage characteristics are often not considered during design but can have a significant impact on the construction and performance of the wall system. For the purposes of this discussion, drainage characteristics include not only the permeability of the soil but also its plasticity. These drainage related characteristics are often empirically derived from grain size determinations and Atterberg Limit testing. These tests help categorize the backfill materials with respect to moisture sensitivity and water movement rates while also serving as a significant indicator of constructability.

A. Effects of Backfill Granularity on Deflection Magnitude

Compacted granular backfill materials are preferred because they typically exhibit higher friction angles with less movement and faster internal drainage characteristics. The higher friction angle reduces stresses in the reinforced mass and reduces reinforcement requirements. Rapid drainage is an indicator of less problems achieving proper compaction and obviously better drainage within the reinforced mass. The movement required to develop active earth pressure of select backfill versus non-select backfill is best described in the following retaining wall translation table adopted from Bowles (1996):

Soil and Condition	Amount of Translation	(Rotation)
Cohesionless *(granular)*, dense	0.001 to 0.002H	(0.06˚ - 0.11˚)
Cohesionless, loose	0.002 to 0.004H	(0.11˚ - 0.23˚)
Cohesive *(fine-grained)*, firm	0.01 to 0.02H	(0.57˚ - 1.15˚)
Cohesive, soft	0.02 to 0.05H	(1.15˚ - 2.86˚)

Table 1: Active Earth Pressure Translation

Making the assumption that the backfill is properly compacted and thus dense or firm, the relative deflection of the backfill needed to develop active earth pressure is approximately 10 times greater for fine-grained soils versus granular soils. Within a given soil type, the relative deflection is approximately 2 to 3 times greater for poorly compacted versus well-compacted soil. However, the magnitude of this additional deflection due to poor compaction is significantly greater for fine-grained soils, 2% for fine-grained versus 0.15% for granular.

Therefore, the type of backfill has a significant effect on the total deflection. Compaction also has a significant effect, but not as great as backfill type, particularly for granular backfill. Based on the Bowles information, the backfill component of deflection for a well-compacted fine-grained soil is approximately 3 times greater than marginally compacted granular soil.

B. Effects of Backfill Granularity on Deflection Timing

The drainage characteristics of the backfill also have a direct effect on the state of stress in the reinforced mass. Fine-grained soils with poor internal drainage can develop and retain for extended periods, cohesion or soil tensile strength that can significantly reduce apparent earth pressures initially. This effect is most significant near the top of the wall where normal pressures are low and the frictional component of soil strength is less significant by comparison to the cohesive component. Over time, as soil drainage occurs and the effective state of stress develops, most fine-grained soil's strength characteristics become more like coarse-grained soils. The friction angle increases and the cohesion decreases. This is significant because as the soil's strength values change over time so do the stresses within the soil mass. These changes can dramatically increase earth pressures in the upper 10 feet or so of the wall where the effects of the temporary reductions in stress due to cohesion are the greatest. The time it takes for the cohesion to dissipate and the stresses to increase can vary from weeks for silty sands to years for high plasticity clays.

This phenomenon is not restricted to cohesive soils. Sands and gravels with 12 to 20% fines and small pore spaces between grains can exhibit some of these characteristics, but typically for a shorter time and to a substantially lesser degree. These materials can develop an apparent cohesion due to partial saturation. As the negative pore pressures associated with partial saturation dissipate, a true drained state of stress is then achieved with a "cohesion equal to zero" condition. The time frame for this behavior is much less, with pore pressure dissipation occurring in hours, days, or weeks. The magnitude of the change in stress is significantly less since the cohesive forces are less than those observed in higher plasticity soils.

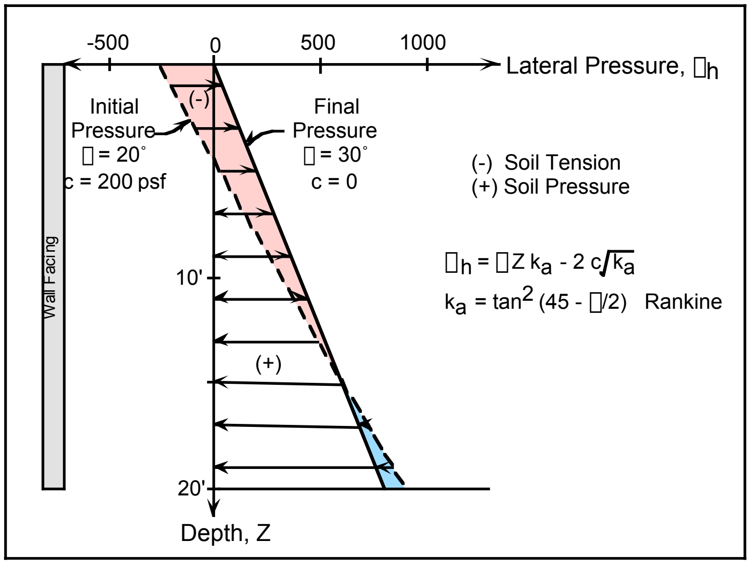


Figure 5 – Earth Pressure Diagram Including Cohesion

As can be observed in Figure 5, the increase in lateral earth pressure over time with fine-grained soils can be dramatic. In this example, the change in stresses on a 20-foot retaining wall assuming total stress (construction time period) soil strength values of ϕ = 20˚ and c = 200 psf and drained (long-term) strength values of ϕ = 30˚ and c = 0 psf are illustrated.

In this example, the following observations can be made:

- During the construction period there is very little if any earth pressure in the upper 5 feet (other than from compaction induced stresses).
- In the upper 10 feet of the wall, resultant earth force increases approximately 250% from 770 lbs to 2000 lbs over time as the soil changes from a total stress condition to an effective drained condition.
- During this time the overall resultant earth force increases from 6720 lbs to 8000 lbs or 20%.
- The earth pressures in the lower 10 feet of the wall remains about the same.

Of particular concern in deflection sensitive applications is the delay in stress development in the upper portions of the wall. With extremely free draining soils, such as ASTM #57 stone, loads on the reinforcement are instantaneous and occur during construction. With less free draining fine-grained soils, full load on the reinforcement may not be developed for years and the strain will be delayed as well. Therefore, post-construction deflections are increased. This scenario can be compounded with the use of geosynthetic reinforcements due to the greater magnitude of anticipated movement and time-delayed creep strain effects.

Also, as the backfill soil becomes more fine-grained and more plastic, the reinforced soil can exhibit creep characteristics not unlike those described previously for geosynthetic material. Soil creep can occur by exceeding the creep strength of a cohesive soil by design or error or due to changes in moisture content within the cohesive soil mass over time such as those caused by seasonal changes. Frost action can have a similar effect with high plastic soils. This can cause a progressive movement situation where seasonal soil creep increases the load in the soil reinforcement over time which in turn cause the reinforcement to creep instead of resisting the increased pressure in an elastic manner. This phenomenon is typically only a factor with higher plasticity silts and clays (PI>20 and/or LL>40) and is beyond the scope of this paper.

C. Backfill Effects Summary

The backfill soil for the MSE structure has a significant effect on the amount and timing of retaining wall deflections. Using more free draining granular soils reduces stresses on the retaining wall system which reduces deflections. Any deflection will also tend to occur more quickly during the construction period. Fine-grained soils tend to result in higher stresses and deflections and increased sensitivity to proper placement and compaction. Fine grained soils also tend to delay the stresses or loads that will ultimately reach the MSE reinforcement delaying the elastic strain of both steel and geosynthetic reinforcements and pushing the creep strain of the geosynthetic reinforcement to the post-construction period.

VI CONCLUSIONS

The basic components of MSE retaining walls are the facing, the reinforcement and the backfill.

- The facing is not a significant factor effecting wall deflections.

- The reinforcement is a significant factor with both reinforcement length and type effecting deflections. Once a minimum reinforcement length of 0.7H is used, additional reinforcement length to reduce deflections does not appear effective. For a given reinforcement length, reinforcement type is a much more significant factor. Steel reinforced systems deflect less than 1/3 that of geosynthetic reinforced systems. Additionally, due to the creep or time delayed strain characteristics of certain geosynthetics, some of this additional deflection occurs post-construction.

- MSE backfill is an equally significant factor in assessing MSE retaining wall deflections. The use of select or semi-select granular soils is preferred to reduce deflections and improve constructability. The use of fine-grained soils, particularly those of moderate to high plasticity can easily increase deflections 2 to 4 times that predicted with granular fills and can delay a substantial portion of this deflection to the post-construction time period.

VII RECOMMENDATIONS

Undesirable deflections of MSE retaining walls can be due to poor construction practices, movements outside the retaining wall (external factors) or movements within the reinforced mass (internal factors). Construction related causes can be minimized by such items as experience clauses in the project specification, contractor pre-qualification and construction monitoring programs (QA/QC). External related problems can be minimized through proper geotechnical evaluation of the subsurface conditions where the retaining wall is placed. Internal caused deflection problems can be minimized through an understanding of how MSE systems work and how the wall system components effect deflections. The purpose of this paper was to assess the internal components affecting the deflections of MSE wall systems. With this information the retaining wall owner and his engineer can then make informed decisions about the selection of MSE retaining walls by matching the project's needs and the characteristics of the available components.

- If minimizing deflections for a given retaining wall is not a significant concern, such as for a 15-foot retaining wall supporting a slope, then limits on the selection of components to reduce deflections may not be warranted. Therefore, in such a situation the use of tolerable fine-grained soils (< 65% fines, a PI < 20 and LL < 40) and reinforcement at least 60% of the wall height may be appropriate.

- As the tolerance for deflections decreases, such as for a 20-foot wall directly supporting a parking lot or roadway, limits on acceptable backfills for the retaining walls would be appropriate. Limiting backfill to semi-select AASHTO A-2-4 (< 35% fines and a PI < 10) and reinforcement lengths > 0.7H could be the first increment.

- The next increment could be for such applications as a 30-foot wall directly supporting a parking lot or roadway where unacceptable deflections and potential cracking of the pavement are typically more of a concern. Further limiting backfill to select material (AASHTO MSE backfill with < 15% fines and PI < 6) and/or limiting the reinforcement to inextensible steel might be appropriate steps.

- For the situations where MSE deflections are to be kept to an absolute minimum such as for a large wall with structural foundations within the reinforced backfill zone or supporting major roadways, limiting components to inextensible reinforcement and AASHTO MSE select backfill might be appropriate.

- In addition, the frequency and intensity of construction quality control monitoring should be increased as the sensitivity to structure deflection increases and/or as more marginal backfill material are used in more demanding situations.

Whatever choice is made, the owner and engineer should consider the impact that the components of the MSE wall system may have on deflections and whether any limits on MSE wall components are appropriate given the unique performance requirements of each structure.

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