GEOSYNTHETIC REINFORCED MSE WALLS AND SLOPES WITH FINE-GRAINED FILLS: INTERNATIONAL PERSPECTIVES

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ABSTRACT

Internationally, a wide variety of reinforced fill types are used for geosynthetic reinforced MSE (Mechanically Stabilized Earth) walls and slopes. These fill types may be divided into two overall categories – frictional, or granular, fills and fine-grained fills. Fine-grained fills may be further subdivided into fine-frictional, fine-cohesive and cohesive-frictional fills. The major features of each fill type category are presented as they pertain to geosynthetic reinforced MSE walls and slopes. Considerations governing the use of appropriate fill types are also discussed in addition to special protective measures that may be required for successful long term performance when fine-grained fills are used. Finally, some comments are made concerning observed, or perceived, problems with fine-grained reinforced fills.

INTRODUCTION

In MSE walls and slopes fill material is combined with layers of reinforcement to provide a safe level of strength for stability purposes. Rational designs of MSE walls and slopes result in the reinforced fill contributing between 80% to 85% of the total strength with the layers of reinforcement contributing between 15% to 20%. If Engineers were graduates of business school, and having limited resources, they might well apply the “80/20 rule” at the design stage by concentrating primarily on the component that contributes the major strength – the fill material – to ensure effective design and performance. However, historically, Engineers have concentrated primarily on the reinforcement and given only cursory attention to the fill material.

If Engineers have “missed the plot” by concentrating primarily on the minor component of strength (the reinforcements) while neglecting the major component (the fill material) then one would expect there to have been many failures. However, overall this has not been the case, and MSE walls and slopes have proven to be safe. Some reasons for this level of safety are as follows;

- The predominant use of good quality, well-compacted, frictional fills along with overly conservative material design parameters;
- Large design factors of safety for loads, reinforcement resistance, reinforced fill resistance, etc;
- Conservative design methodologies.

More recently, new MSE systems have become available that readily lend themselves to the use of a wide variety of reinforced fill types, e.g. geosynthetic reinforced segmental block retaining wall systems and MSE fill slopes; and the MSE technique has been adopted in new geographical locations where climate and available fill types are different to those historically in use. This has lead to the adoption of a wide range of reinforced fill types - some with unexpected consequences.
Theoretically, all soils can be internally reinforced, with the poorer quality soils requiring more reinforcement in order to obtain a given stability improvement (Jewell and Wroth, 1987). Taken to the extreme this could be construed to mean that any soil type could attain any required level of internal stability provided enough reinforcement was included. In practice this is not the case. For reasons of cost and placement geometry, limits are placed on the amount of reinforcement that can be used to achieve an efficient design. This results in the selection of a complementary reinforced fill that achieves a level of shear resistance to ensure overall stability requirements are met.

Further, just as the geosynthetic reinforcement is required to maintain consistent properties over the design life of MSE walls and slopes, so too is the fill material. Suitable reinforced fills must not only maintain a consistent level of shear resistance over the design life of the MSE structure, but must do this at acceptable levels of deformation, i.e. serviceability, and negligible volume change.

A further distinction must be drawn according to the type of MSE structure when considering types of fills used. In general, MSE walls have used better quality fills than MSE fill slopes of similar heights. The reason for this has been the lower tolerances (with regard to serviceability) required of MSE walls compared to MSE fill slopes.

**FILL TYPES USED FOR GEOSYNTHETIC REINFORCED MSE WALLS AND SLOPES**

Internationally, a wide variety of reinforced fill types are used for geosynthetic reinforced MSE walls and slopes. The selection of the appropriate reinforced fill is dependent upon meeting specific strength and deformation requirements, inertness, durability and cost. Cost considerations have lead to the use of many fine-grained fills for geosynthetic reinforced MSE structures.

It is difficult to differentiate the specific characteristics of the wide range of reinforced fill types used as there are considerable overlaps of attributes. However, for the purposes of this paper it is proposed to divide the fills used for MSE walls and slopes into two overall groups – frictional, or granular, fills and fine-grained fills – according to grading. Figure 1 shows the typical grading envelopes of the two fill types. Frictional fills are composed of combinations of sand and gravel, while fine-grained fills cover a wide spectrum of gradings ranging from silty sands and gravels to silty clays. It is to be noted that there is some overlap in grading envelopes at the coarser fill fractions. It should also be noted that in addition to grading, the fill types may be further distinguished on the basis of plasticity, clay mineralogy and chemistry.

The selection of an appropriate fill material not only depends on its own intrinsic properties and its ability to interact with the layers of reinforcement in the MSE structure, but also on the environment in which the reinforced fill is placed. For example, in a warm and arid climate there is more use made of fine-grained fills in MSE structures. Further, in assessing appropriate reinforced fills the Engineer must also be cognizant that various ancillary works, e.g. drainage, may be required to ensure the good long term performance of specific reinforced fill types.
Figure 1. Typical grading envelopes for frictional and fine-grained fills

While fine-grained fills in MSE walls and slopes are the main focus of this paper, it is necessary to first consider the main attributes of frictional fills as they pertain to reinforced fills in order to compare the performance of fine-grained fills with these more traditional frictional fills.

FRICTIONAL FILLS

Frictional fills are granular materials of gravel and sand fractions (see Figures 1 and 2a) that may occur naturally or, more commonly, are mined or processed. As well as having good internal shear resistance, these fills exhibit relatively high hydraulic conductivities when compacted and thus are considered to be relatively free-draining. Typical examples of frictional fills are fine-crushed rock, gravel sands, river sands, mining sands, crushed silica-cemented sandstone, etc.

Frictional fills should be well-graded to achieve maximum density and internal stability. Further, the fill particles must be hard and chemically inert to ensure good durability.

Well-compacted frictional fills exhibit high peak shear resistances, often $\phi_p = 45^\circ$ to $52^\circ$ at low strains of between 3% to 6% under confining stresses typical of MSE walls and slopes, see Figure 2b. These fills also exhibit constant-volume shear resistances $\phi_{cv} = 33^\circ$ to $37^\circ$ at strains of 8% to 15%. Thus, to fail well-compacted frictional fills the peak shear resistance must first be overcome, which makes these materials ideal where high shear resistance at low strains is required. It is interesting to note that in a number of international design codes and organization regulations a maximum design shear resistance $\phi_{des} = 30^\circ$ to $35^\circ$ is prescribed for frictional MSE fills. This prescription yields an inherent conservatism in design due to the difference between the prescribed design shear resistance of the reinforced fill and the actual peak shear resistance attained by well-compacted frictional fills. Alternatively, this inherent conservatism may be construed as penalizing the use of good-quality, well-compacted, frictional fills as the full shear resistance of these materials cannot be utilized in design.
Historically, frictional fills were used exclusively for both MSE walls and fill slopes. Today, because of their relative high cost (c.f. other fill types), it is very rare to find them still used for MSE fill slopes. Frictional fills still remain the most commonly used type of fill for MSE walls, especially in tropical, wet climates where rainfall during construction can cause problems with fill placement and compaction. In drier climatic conditions, the use of other fill types predominate.

Figure 2. Grading envelope and typical shear resistance envelope for frictional fills
FINE-GRAINED FILLS

Fine-grained fills cover a wide spectrum of gradings ranging from silty sands to silty clays – see Figures 1 and 3a. These fills normally occur naturally insitu or may be the result of industrial processing (e.g. PFA). Fine-grained fills may be further subdivided into fine-frictional fills, fine-cohesive fills and cohesive-frictional fills. Typical grading envelopes for these fill categories are shown in Figure 3a. Fine-frictional fills and cohesive-frictional fills largely overlap, the difference being the clay component.

When compacted, fine-grained fills exhibit relatively low hydraulic conductivities (c.f. surrounding ground conditions) and thus are considered to be relatively impervious, and also can be moisture-sensitive.

Well-compacted fine-grained fills exhibit good peak shear resistances, generally $\phi'_p = 27^\circ$ to $37^\circ$ at strains of between 8% to 15% under confining stresses typical of MSE walls and slopes, see Figure 3b. These peak shear resistances are lower than that of compacted frictional fills and occur at higher strains, but are still suitable for a majority of MSE walls and slopes. However, unlike frictional fills, an inherent conservatism is not built into the design shear resistance for fine-grained fills as the actual peak shear resistance is normally used in design (compare Figure 2b with Figure 3b).

Fine-Frictional Fills

Fine-frictional fills are made up of fractions of sand and/or gravel with silt and only a little clay (see Figure 3b), and occur naturally or may be the result of industrial processes. While the granular component gives these fills their frictional characteristics and renders them suitable for reinforced fills, the fines component gives relatively low hydraulic conductivity when compacted. Typical examples of fine-frictional fills are residual and saprolitic soils, crushed clay-cemented sandstone, quarry crusher-run, silty sands, sandy silts, loess, pulverized fuel ash (PFA), etc.

In their natural state, fine-frictional fills may have natural water contents ranging from drier to near-optimum water content.

The majority of fine-frictional fills exhibit peak shear resistances $\phi'_p \geq 35^\circ$ when well-compacted, and these are generated at relatively low strains (8% to 12%). In some instances, where the percentage of fines are greater, or where plastic, the peak shear resistance $\phi'_p$ may be as low as $33^\circ$. Thus, fine-frictional fills are well-suited for MSE walls provided they are well-compacted. Fine-frictional fills are also ideal for MSE fill slopes.

One specific type of fine-frictional fill that has gained ready use in MSE walls is Pulverized Fuel Ash (PFA), which is produced as a by-product of coal-fired power stations. The material has the consistency of silty sand or sandy silt. PFA is self-hardening and its shear strength parameters are time-dependent (they can increase with time). For design, fresh samples of PFA should be prepared and tested to assess the strength parameters relevant to the construction state as this will be where the fill strength will be at its lowest. While PFA may exhibit apparent shear cohesion, this should be neglected for stability calculation purposes. The compacted unit weight of PFA is less than that of soil and can vary depending on the coal source. Therefore, a check should be made at the construction stage to confirm that the unit weight does not exceed the design value.
Figure 3. Typical grading and shear resistance envelopes for the wide variety of fine-grained fills used in MSE structures.

Fine-frictional fills are more susceptible to water ingress than frictional fills, thus good and consistent compaction of these fills is important (for maximum density and low...
hydraulic conductivity). Further, well-designed drainage measures that account for subsurface drainage and surface drainage conditions should also be provided.

**Fine-Cohesive Fills**

Fine-cohesive fills consist of fractions of silt and clay, and maybe some sand (see Figure 3a) and occur naturally. When used as reinforced fill they almost always comprise local insitu soil. When compacted, fine-cohesive fills have very low hydraulic conductivity, and fill softening occurs when exposed to water. Suitable fine-cohesive fills should not undergo volume changes when wetting or drying. Volume changes are indicative of the presence of montmorillonite clay fractions and these should be avoided for MSE structures.

In their natural state, fine-cohesive fills may have natural water contents drier, close to, or wetter, than optimum water content depending on the local climate and their location. If natural water contents are close to optimum water content then the fill can be placed and compacted with ease. If, however, there needs significant water addition or drying, then good compaction of these materials can be problematic especially in the vicinity of a reinforced soil wall face. Consequently, if fine-cohesive fills require significant working to achieve the required density and optimum water content then they should be avoided. In some instances lime has been used to treat these fill types when their natural water contents have been wet of optimum.

The low-to-medium plasticity fine-cohesive fills exhibit peak shear resistances \( \phi' \) generally in the range 27° to 37° when well-compacted, but these are generated at relatively high strains (12% to 17%). Only in a relatively small number of instances have fine-cohesive fills been used in MSE walls, but where they are locally available they have been used extensively in MSE fill slopes.

In equatorial and wet tropical regions significant engineering use is made of laterites, the so-called “red-earth” soils. These are soils that have formed insitu from volcanic rocks and have high contents of low-activity clay (which may be as high as 80%), and relatively high amounts of iron and aluminum oxides, which give these soils their red color. On drying, the iron and aluminum oxides cement the clay particles (by the process of laterization) to form a soil of relatively high shear strength and low compressibility. The cementation process can be reversed by over-compaction (the lateritic soil is broken down into its original clay-soil structure) and, with the addition of water, can result in a soft material unsuitable for reinforced fill. To prevent this reversal in engineering characteristics good control must be exerted over compaction in the field when using these soils for reinforced fills. Moreover, the fill must be allowed to dry out if rainfall occurs during construction, before further construction proceeds.

When fine-cohesive fills are used as reinforced fill in MSE structures it is imperative that subsurface drainage measures are applied extensively. Almost inevitably when fine-cohesive fills are compacted, their hydraulic conductivity will be less than that of the natural soil being retained. Consequently, to avoid pore water pressure build-ups adjacent to the reinforced fill zone good subsurface drainage measures are required.

**Cohesive-Frictional Fills**

Cohesive-frictional fills are widely graded materials made up of fractions of clay, silt, sand and gravel (see Figure 3a) and occur naturally. While the granular component gives the
fills their frictional characteristics and renders them suitable for reinforced fills, the fines component imparts low hydraulic conductivity when compacted. In some instances, if the granular fractions are large in size they may be separated out of the fill before placement, which results in a finer fill being used (which may approach a fine-cohesive fill consistency). Typical examples of cohesive-frictional fills are clay-gravels and some fine tills.

Clay-gravel fills, which are common in parts of Asia, have gravel fractions set in a low-activity clay matrix. In tropical regions these fills may have high concentrations of iron and aluminum oxides (which give them a red color) and exhibit lateritic characteristics when dry. On compaction, and on the addition of water, the lateritic characteristics can break down and the material reverts to its original clay-gravel characteristics. With the gravel fraction included peak shear resistance values of $\phi'_p \geq 35^\circ$ can be attained for well-compacted clay-gravel fills (with higher values attained for higher amounts of gravel fractions). If the cobble and coarse gravel fractions are separated out, the residual finer fractions attain peak shear resistance values $\phi'_p = 28^\circ$ to $32^\circ$.

Clay-gravel fills have been used in many MSE slopes in Asia. These MSE fill slopes have been constructed to heights of 50 m. Provided good drainage measures are included, and the compaction of the fills well-controlled, the performance has been good.

**CONSIDERATIONS GOVERNING THE USE OF REINFORCED FILL TYPES FOR MSE STRUCTURES**

The fundamental criteria for reinforced fills are that they develop a required level of shear resistance at a defined deformation over the required design life of the MSE structure. All considerations regarding the use of appropriate reinforced fill types need to be made with regard to meeting these fundamental criteria.

The selection of an appropriate reinforced fill cannot be taken in isolation without also considering the environment in which the fill will be used. Figure 4 shows the two environments that must be considered – the internal environment (within the reinforced fill mass) and the external environment (the region surrounding the reinforced fill mass). When accounting for the internal environment, considerations have to be made regarding the fill behavior (e.g. shear resistance, unit weight, deformation), fill placement quality (e.g. compaction quality and consistency), durability (e.g. maintenance of fill engineering characteristics over life of structure, fill characteristics not adversely affecting reinforcement performance), interaction with the reinforcements (e.g. fill/reinforcement bond characteristics) and the reinforced fill geometry (e.g. shape and extent of the reinforced fill zone). When accounting for the external environment, considerations have to be made regarding the effects of climatic conditions (e.g. effects of temperature, rainfall, etc. on the reinforced fill), external loads (e.g. earthquake loading, etc.), and groundwater effects (e.g. presence and extent of groundwater acting on the reinforced fill mass). In general, when fine-grained fills are used much more attention needs to be paid to the external environment in which the fill will be placed than is the case when only frictional (i.e. granular) fills are used.
The Internal Environment

Fill behavior. The reinforced fill must have a required level of shear resistance at a low level of deformation and be volumetrically stable. Further, the reinforced fill must have a well-defined, and reproducible, unit weight.

In general, if the peak shear resistance of the compacted reinforced fill is greater than or equal to 30° then an efficient, economical, MSE solution is achieved. The reinforced fills discussed previously in this paper meet, or surpass, this shear resistance requirement when well-compacted. Further, the fill deformation at which the peak shear resistance is attained must be within acceptable serviceability limits for the MSE structure. For well-compacted frictional fills, peak shear resistance occurs at around 3% to 6% strain - see Figure 2b. For well-compacted fine-grained fills, peak shear resistance occurs at around 10% to 17% strain – see Figure 3b. For the majority of situations these levels of strain are within acceptable serviceability limits for MSE structures. However, where the MSE structure is affected by ancillary structures, e.g. bridge deck foundations, pipe lines, pavements, etc., tighter control is generally required over the deformations in the reinforced fill. In these situations a frictional fill may be preferred because of its lower deformation characteristics.

Volumetric stability of the reinforced fill is also important. The reinforced fill cannot undergo volume changes that may impact the performance of the MSE structure. Volumetric stability is a function of the clay mineralogy and clay content in the reinforced fill thus, this potential problem only arises when fine-cohesive and cohesive-frictional fills are used. Only fills whose clay fraction consists of low-activity clay should be considered for fine-grained reinforced fill (i.e. at, or below, the “A-line” on the Casagrande plasticity chart).

Fill placement quality. Fill placement quality not only ensures good and consistent fill shear resistance and fill unit weight throughout the reinforced fill mass, but also prevents easy ingress of water into the reinforced fill.

Poor compaction quality allows easy ingress of water into fine-grained reinforced fills following construction. Water ingress results in soil erosion and the development of pore

Figure 4. Internal and external environments that affect the performance of reinforced fills
water pressures within the fill. As stated already, pore water pressures reduce the shear strength of fine-grained fills, and may increase fill softening.

Near the face of MSE walls high levels of compaction may be impractical because of its effect on face deformation. Thus, the fill used should be relatively easy to compact when placed in this location. For fine-grained fills the natural water content should be at, or near, the optimum water content for compaction to ensure excessive working and compactive effort is not required during placement of the fill.

Durability. There are two aspects of durability that should be considered - the durability of the fill itself and the durability of the reinforcements as a result of the fill type used. The reinforced fill used has to maintain its shear and deformation resistance over the required design life of the MSE structure. Fill durability is normally described in terms of particle hardness, but additionally, may also be described in terms of chemistry and/or mineralogy.

The reinforced fill also has to be inert so as not to affect detrimentally the durability of the reinforcements. Geosynthetic reinforcements are more resistant to fill chemistry extremes than are metallic reinforcements. Fine-grained fills can be more aggressive chemically due to their mineralogy or processing. Further, water retained in fine-grained fills may act as the catalyst for reinforcement degradation mechanisms. To prevent reinforcement degradation due to the fill type used it is best to ensure the inertness of the fill because it may not be possible to prevent water ingress over the life of the structure.

Interaction with reinforcements. The fill shear resistance, level of deformation and overburden pressure along with the surface and geometry characteristics of the reinforcements govern the bond resistance between the fill and reinforcements. Fill/reinforcement bond is the mechanism by which tensile stresses are transferred from and to the adjacent soil via the reinforcements. Bond resistance is a fundamental parameter of reinforced soil design.

Full bond resistance between the reinforcement and the surrounding fill is normally generated within a bond length of 1 m for planar geosynthetic reinforcement materials, e.g. geotextiles, geogrids. However, for strip and bar type geosynthetic reinforcements significantly longer bond lengths are required to fully generate bond resistance.

Problems of bond resistance normally only arise where reinforced fills of lower internal shear resistance are used (e.g. fine-grained fills), and where either strip or bar reinforcements are used in a reinforced fill zone of limited extent. The ingress of water into the fill and the development of pore water pressures may further reduce the bond resistance thereby reducing the integrity of the MSE structure.

Reinforced fill geometry. The reinforced fill geometry governs the stability of the MSE structure with respect to sliding resistance, bearing resistance and pull-out resistance of the reinforcements. All of these are governed by the extent of the reinforced fill zone. All of the reinforced fill types discussed in this paper can meet the required sliding resistance, bearing resistance and pull-out resistance requirements provided the extent of the reinforced fill zone is adequate and of standard geometry. Where reinforced fill zones are of unusual geometry, e.g. trapezoidal shape, then frictional fills should be preferred to ensure good resistance to sliding and reinforcement pull-out is attained over the limited reinforcement lengths.
The external environment

Climatic conditions. There are two climatic conditions that can influence the type of reinforced fill used. One is temperature and the other is rainfall.

In cold arctic climates where freezing and thawing is of concern, only highly granular (frictional) fills are used for MSE walls. This is to ensure water is not trapped in the reinforced fill which can then expand on freezing. Also, on thawing, it is best to have an insensitive, free-draining reinforced fill so that water can easily drain out of the MSE structure.

As stated previously, as climatic conditions become drier, then more use is made of fine-grained reinforced fills. In this drier environment rainfall is not a critical factor during construction and, provided the fine-grained reinforced fills can be rendered immune, is not an important factor during the life of the MSE structures. Further, in many of these drier environments fine-grained fills are much more prevalent and cost-effective than frictional fills.

In tropical, wet climates frictional fills are used extensively for MSE walls because of their relatively free-draining nature. Here, frictional fills are easy to work with between periods of heavy rainfall. After completion, the compacted frictional fill remains insensitive to prolonged periods of water ingress.

In regions of seasonal prolonged rainfall, e.g. monsoonal climates, the use of fine-cohesive and cohesive-frictional fills should be avoided unless special waterproofing and subsurface drainage measures are employed (e.g. see details in Figure 5). The reasons for this are twofold. First, when the fill is placed during the “dry” construction season adequate compaction near the wall face may be difficult with these soil types resulting in preferential drainage paths within the reinforced fill. Second, during the “wet” season water may easily penetrate these preferential drainage paths resulting in a loss of shear resistance in the reinforced fill and a loss of reinforcement bond resistance, and subsequently, a loss of stability.

External loads. There are two aspects of external loads that must be considered in relation to the type of reinforced fill to be used. First, the reinforced soil structure may have to support external loads that have to operate at defined, or limited, deformations. Second, the reinforced soil structure may be subject to unusual, and extreme, external loads, e.g. seismic loads.

Groundwater effects. The ingress of groundwater and surface water into MSE walls and slopes constructed using fine-grained fills represents the major area of performance risk. The impact of groundwater on fine-grained fills can:

- Enable pore water pressure build-ups around the fine-grained reinforced fill zone that can lead to instability;
- Penetrate, and soften, fine-grained fills resulting in reduced shear resistance and greater deformation.

Groundwater effects and control are discussed in more detail in the following section.
THE IMPORTANCE OF GOOD DRAINAGE IN MSE WALLS AND SLOPES

MSE walls and slopes should be designed for hydraulic stability as well as for structural stability. This is especially the case when fine-grained reinforced fills are used. While fine-grained fills exhibit the structural characteristics required of reinforced fills they are susceptible strength-wise to water ingress. Further, fine-grained fills have low hydraulic conductivities when well-compacted, with the result that the reinforced mass impedes the movement of groundwater and this can result in pore pressure build-ups, and instability.

Water build-ups around, and/or ingress into, fine-grained reinforced fills can lead to strength loss, deformations, and ultimately, collapse of the MSE structure. Further, the presence of water may act as the “trigger” for collapse. Thus, good drainage should be considered an integral part of the design and construction of MSE walls and slopes, especially those containing fine-grained reinforced fills.

Figure 5 shows the recommended drainage detailing for a geogrid reinforced segmental block wall utilizing fine-grained reinforced fill. Similar drainage detailing should be used for other MSE wall systems and slopes. To prevent pore pressure build-ups resulting from potential groundwater seepage from behind the reinforced fill zone, a drainage blanket should be included across the base of the reinforced fill zone and continued up the face of the retained ground. This ensures the groundwater seepage is drained off before entering the fine-grained reinforced fill (once groundwater enters compacted, fine-grained reinforced fill it is...
very difficult to remove because of its low hydraulic conductivity). The drainage blanket may consist of granular material with a geotextile filter, or alternatively, may consist of a suitable geocomposite drain. Fine-grained reinforced fills also should be protected from surface water entry due to rainfall. A geomembrane can be placed across the top of the reinforced fill at a defined slope (as shown in Figure 5) to redirect any infiltrating surface water into the vertical drainage layer behind the wall face. Alternatively, if the wall surface geometry allows, fine-grained cohesive soil can be used to prevent surface water ingress at the top of the wall. Also, if the wall is to support traffic, then the pavement layers and associated drainage system can be utilized to trap surface water and direct it away from the reinforced fill.

Specifically for reinforced segmental block walls, there is a standardized requirement to introduce a vertical granular drainage layer within the voids of the block facing and/or immediately behind the block facing (see Figure 5). The role of this vertical drainage layer is to:

- Act as a local drainage layer to prevent water seeping out through the block face, and prevent subsequent staining of the block face;
- Sometimes to act as a drainage channel to direct surface water at the top of the wall down, behind the wall face, to drainage outlets at the base of the wall;
- Increase the geogrid reinforcement/block connection capacity for some proprietary block systems.

In many instances the author has observed that designers have considered this vertical drainage layer behind the segmental block facing to be of importance in the removal of groundwater from the MSE wall when fine-grained reinforced fills are used. It should be emphasized that this vertical drainage layer can never perform this function. When utilizing fine-grained fills any groundwater present needs to be drained from the structure before it can enter the reinforced fill zone. If groundwater is allowed to first enter the fine-grained fill before it reaches the drainage layer then loss of strength and softening of the fine-grained fill can occur.

Where the geometry of the MSE structure is more substantial, subsurface drainage galleries should be included beneath each tier of the MSE structure, e.g. Figure 6. These galleries should extend all the way to the extent of the excavation. The reason for this is that the recompacted backfill will have a lower hydraulic conductivity than the existing undisturbed soil deposit, and thus, to prevent pore water build-ups along the interface of the recompacted backfill and the existing soil, effective subsurface drainage should be provided in this location.

All internal drainage systems must have well-defined exit points. These subsurface drainage exit points should connect into well-designed surface drainage lines to ensure unrestricted movement of water away from the MSE structure.

**OBSERVED, OR PERCEIVED, PROBLEMS WITH FINE-GRAINED REINFORCED FILLS**

In the vast majority of cases where fine-grained (fine-frictional, fine-cohesive and cohesive-frictional) fills have been used for reinforced fills their performance has been good, provided they have been selected appropriately and have been placed and installed properly.
However, there have been instances where the use of fine-grained fills have been reported as either been the cause of, or contributed significantly towards, the failures of MSE walls and slopes. Generally, problems that have been directed towards the use of fine-grained reinforced fills fall into three categories – “sudden” failures that occur a short time after construction, progressive deformation of MSE wall faces and loss of fill shear resistance with time.

Figure 6. Recommended drainage layout where MSE structures are substantial (After Lawson, 2001)

“Sudden” Failures a Short Time After Construction (Normally Within 6 Months)

These failures are almost always due to some problem with the original design and/or construction quality. They nearly always occur immediately following heavy rainfall – the rainfall acts as the “trigger” mechanism. Table 1 summarizes reasons for these sudden failures of MSE walls and slopes.

While fine-grained fills may be present in MSE structures subject to sudden failures, it is incorrect to assume that they are the root cause of this type of failure. As shown in Table 1, sudden failures can arise due to a number of reasons, and where these have occurred and fine-grained fills have been used, it is either poor fill placement quality or poor drainage design and quality that have been the causative factors. If the fine-grained fill had been placed and compacted to the quality required and good quality drainage measures provided, then these failures associated with fine-grained fills would not have occurred.
Table 1. Reasons for sudden failures of MSE walls and slopes

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<thead>
<tr>
<th>Nature of the problem</th>
<th>Examples</th>
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<tr>
<td>As a result of design problems</td>
<td>- Unusual geometry of MSE structure.</td>
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<td>- 3D effects not accounted for in design.</td>
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<td>- Ineffective, or no, drainage design.</td>
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<tr>
<td>As a result of construction quality</td>
<td>- Poor and inconsistent compaction of reinforced fills that allow easy ingress of water.</td>
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<td></td>
<td>- Poor drainage quality.</td>
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<td>- Water services passing through the reinforced fill that leak.</td>
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**Progressive Deformation of MSE Wall Faces**

Causes of progressive deformation of MSE wall faces may be due to one, or more, of the following:

- Pull-out bond failures of strip reinforcements. This can occur if the geometrical extent of the fine-grained reinforced fill is limited, and is normally amplified by the presence of water in the fill or a sudden extreme loading (e.g. earthquakes).
- Sliding bond failures of sheet reinforcements. This can occur if the geometrical extent of the fine-grained reinforced fill is limited, and is “triggered” by the presence of water or a sudden extreme loading (e.g. earthquakes).
- Foundation instability manifested by deformation of the wall face. While this is not a function of the type of reinforced fill used, it is included here for completeness.
- Loss of shear resistance in the reinforced fill. This can occur if the reinforced fill used does not have the shear resistance assumed in design or the reinforced fill loses shear resistance over time (see comments below).

The causes of wall face deformation listed above may result in only a loss of serviceability, i.e. initial deformation which then stabilizes, or may result in ultimate failure of the MSE wall over time. Prevention of this type of deformation really requires good design knowledge to ensure the proper reinforcement and fill type is selected for the specific application, and the extent of the reinforced fill zone is adequate for the structure.

**Loss of Fill Shear Resistance With Time**

Loss of shear resistance with time of fine-grained fills has been due to the use of argillaceous materials (e.g. shales, weathered mudstones, marls) or the continued ingress of water over time. Argillaceous materials break down during compaction and can suffer further breakdown over time due to the addition of water. Because of this degradation, argillaceous materials should not be used as reinforced fills in long term structures.

As stated already, fine-grained fills are susceptible to water ingress where they can lose shear resistance. During placement, good and consistent compaction should be carried out to maximize shear strength and minimize hydraulic conductivity. Good protection from groundwater and surface water also should be afforded the fine-grained fill if it is to perform
in the long term. The provision of a good groundwater drainage system and a good surface water protection system is just as important as the inclusion of reinforcements for good long term performance.

CONCLUSIONS

Internationally, a wide range of reinforced fill types are used in MSE walls and slopes. These fill types range from wholly granular materials to materials with significant quantities of clays. In general, as the climate gets warmer and drier, more use is made of fine-grained fills in MSE structures.

For MSE walls, frictional and fine-frictional fills are preferred. Frictional fills provide good shear resistance at low deformations and are durable provided the granular particles are hard and inert. Further, frictional fills are relatively free-draining. Fine-frictional fills also provide good shear resistance at low relatively deformations, but when well-compacted have low hydraulic conductivity. Consequently, when fine-frictional fills are used importance should be given to drainage design as well as structural design.

Much of the economics of MSE fill slopes rely on the use of the insitu, or locally available, soils as the reinforced fill. Consequently, a wide range of fill types are used for MSE fill slopes and these may be categorized as being fine-frictional, cohesive-frictional and fine-cohesive in nature. When dealing with this range of fills good and consistent compaction quality is essential. Also, the provision of good drainage measures becomes just as important as the reinforcement in ensuring a long term stable structure, especially in environments subject to heavy rainfall.

The use of durable and inert frictional fills for reinforced soil structures provides an efficient and risk-free solution. The impetus to use fine-grained reinforced fills is normally driven by cost considerations, for which there is an added element of risk. This risk must be alleviated by quality placement and compaction of the fine-grained fill and attention to the effects of the external environment in which the fine-grained fill will be placed, e.g. climatic conditions, groundwater effects, etc.

In many instances, reported problems with the use of fine-grained fills have been over-emphasized. Other than the possible problem of fill degradation with time (and these types of fills should not be used in MSE structures) problems normally arise as a result of design faults, poor construction quality, and the neglect of water ingress. It is true that fine-grained fills may be more susceptible to these events, e.g. water ingress, than other, granular, fill types, but provided these potential susceptibilities are dealt with properly then fine-grained fills perform just as well as granular fills in MSE walls and slopes.

REFERENCES
