Use of Lightweight Fill Materials for MSE Wall

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ABSTRACT
Applying lightweight fill (LWF) as the backfill for the reinforced zone of a MSE wall can effectively reduce the vertical stress imposed on the base of the wall in order to manage weak foundation soils or sensitive structures underneath the MSE wall. LWF however also reduces the available resistance to lateral earth pressure and other loads as well hence impacting the MSE wall design. This paper briefly introduces common LWF materials, analyzes in detail how LWF impacts design (failure) modes and discusses conditions, limitations and requirements of using LWF in MSE walls. Two case histories of using LWF are also presented in this paper.

RÉSUMÉ
L'utilisation de matériaux légers pour remblayer la partir renforcée d'un mur de soutènement de sol stabilisé mécaniquement (MSSM) peut réduire efficacement la contrainte verticale exercée sur la base du mur, de manière à contrer l'effet des sols de fondation peu résistants ou des structures vulnérables sous le mur. Par contre, les matériaux légers réduisent aussi la résistance à la pression latérale du sol et aux autres charges, ce qui influence la conception du mur. Le présent article décrit brièvement les matériaux de remblayage légers courants, analyse en détail leurs effets sur les modes de défaillance et expose les conditions, les limites et les exigences de leur utilisation dans les MSSM. Il présente également deux exemples concrets d'utilisation de tels matériaux.

1 INTRODUCTION

MSE retaining walls are gravity structures normally using select granular material (quarried aggregates) as the backfill for the reinforced zone. This is due to granular material's physical/engineering characteristics (density, strength, permeability) and its sound and proven interaction with the reinforcing materials (e.g. geosynthetic or metallic) to form a reliable reinforced soil mass. This provides sufficient resistant in retaining the lateral loads exerted by the earth, live, dead surcharge and seismic loads.

In some cases, however, the vertical stress at the base of the wall induced by such soil mass, governed by the height of the wall, plus other loads transferred from lateral pressure and the live/dead surcharges may cause problems if poor foundation soil (e.g. soft compressible soils), or, sensitive underground structure (such as utility lines) are present below or in the vicinity of the proposed wall.

In these cases, reducing and controlling the vertical stress within the allowed range is required. If modifying the wall geometry (reducing the wall height) is not feasible due to the structure's functionality, applying lightweight or ultra-lightweight backfill materials (LWF) becomes a natural alternative consideration.

2 COMMON LIGHTWEIGHT MATERIALS

Several LWF materials are available on the market today for such applications. They may be categorized generally into two groups, granular LWF and rigid LWF. In addition to the varying degree of lower density that these materials can all offer, different types of LWF may also provide other benefits unique to the project as well as the design challenges depending on the project specific conditions and requirements.

2.1 Granular LWF

Granular LWF are materials that have a lower density compared to normal granular materials but have similar engineering characteristics. Construction procedures and requirements (such as placement/compaction) are also similar to those of normal fill.

Furnace slag (FS) is one of the most common granular LWFs. It is a non-metallic by-product created during the process of ferrous metal smelting and cooling. The end product is granular like aggregates with the density typically around 50% of the normal fill (Table 1). The material's particle gradation (Fig. 1) ranges from coarse sand to medium gravel, which is almost in the mid-range of typical selected fill (e.g. OPSS Granular A and B).

Foamed Glass Aggregates (FGA) is another popular granular LWF. FGA is manufactured from 100% recycled glass. The production process involves crushing the glass and mixing it with foaming agent in kiln to create bubbles within the glass particles, thus achieving a lower density. This process can produce even lower densities with a density approximately less than 15% of the density of the normal selected granular fill. In addition to the Ultra-low density, FGA also has very high friction angle (due to the particles' angularity and surface roughness, and high permeability, due to the coarse grain size distribution (Fig. 1). These are the two characteristics that are desired by the backfill material for an MSE wall.

2.2 Rigid LWF

Rigid LWF means that it is in the rigid format at its final working state. Therefore, one of the unique features is that no compaction is required during the construction of applying a rigid LWF.

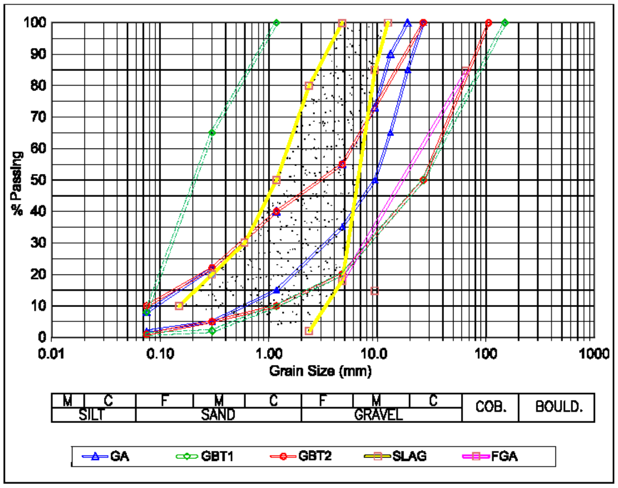


Figure 1. Typ. grain size distribution of LWF and OPSS granular fill

Lightweight Cellular Concrete (LCC) is a typical and common rigid LWF. It is primarily a foamed concrete, produced with preformed foam (small bubbles with size less than 1mm) mixing with cement slurry but contains little to no aggregates. By controlling the formation/agent of the foam (large quantity of voids), the desired density can thus be achieved.

Table 1. Major engineering properties of common LWF

Material	Density KN/m^3	Angle °	Cohesion KPa	Permeability cm/s
Gra. Fill	20-22	32-35	0	10E-1
FS	8-12	32-40	0	10E-2
FGA	1.8-2.4	40-55	0	10E1
LCC	4-6	35-45	5-20	N/A
EPS	0.2-0.4	N/A	N/A	N/A

It can attain a density as low as 20% of the density normally seen in granular fill. Due to the unique production process, the compressive strength of LCC is relatively low, typically around 0.5MPa, almost one hundred times lower than any normal structural concrete (35+MPa). It is nearly impermeable, also has low water absorption capacity and high freeze-thaw resistivity. Particularly, LCC can demonstrate some “soil-like” behavior in regarding to its shear strength. Depending on the testing method and the density, it generally has a friction angle around or greater than 35° and cohesions in the range between 5kPa and 50kPa (Tiwari et al. 2017). The weakest strength occurs at the cold joint – the joint formed between the batches of concrete pouring during the construction.

Expanded Polystyrene (EPS), or geofoam, is also a commonly used rigid LWF. EPS is primarily a closed-cell plastic foam comprising of more than 90% air due to its manufacturing process. The closed cell structure provides minimal water absorption and low vapor permanence, hence low permeability. This manufacturing process also produces a material with an ultra-low density, almost one hundred times lighter than that of normal granular fill (Table 1). It can be used as the backfill for MSE walls in some cases.

The major engineering properties of the above described LWF are summarized in Table 1.

3. APPLICATION OF LWF

Depending on the challenges faced on each specific project, primary consideration in selecting LWF as the backfill is the magnitude of the vertical stress reduction.

For poor foundation soils, low bearing capacity and/or excessive settlement may be the major concern if normal granular backfill is to be used. In such cases, selecting granular LWF can be a good idea. All other similarities with regards to engineering properties and behavior related to the normal granular fills are certainly advantages when applying granular LWF.

If the proposed MSE wall encounters not only the problematic foundation soil, but also presents any sensitive buried structures that cannot endure any vibration, such as the mechanic compaction requirements on granular LWF, rigid LWF can be considered.

Varying granular fill / LWF combinations can also be considered for some projects to achieve insignificant vertical stress reductions.

4. IMPACTS OF LWF ON THE MSE WALL DESIGN

For the purpose of discussion, a typical MSE wall with a horizontal top and live surcharge is adopted in this section as shown in Fig. 2 and Fig. 3 (assuming β = zero) with all the design criteria per the design guidelines stated in the Federal Highway Administration (FHWA) of US (2001 and 2009).

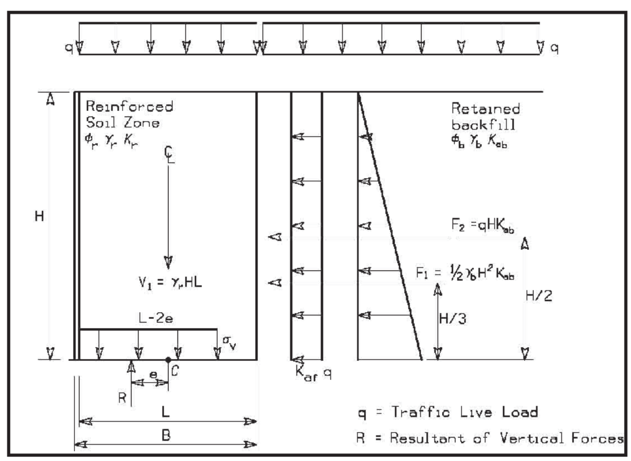


Figure 2. Typ. MSE Wall analysis model (from FHWA 2009)

Also, the total Factor of Safety (FoS) approach is used in the discussion to avoid many load and resistance factors (by LRFD method) complicating the main point of discussion, which would not affect the basic concept under the discussion. Furthermore, the geosynthetic soil-reinforcing material, i.e. geogrid, is used throughout this discussion. For more complex design conditions, such as multi-type dead and live surcharges with sloping backslope at the top of the wall, additional studies will need to be performed.

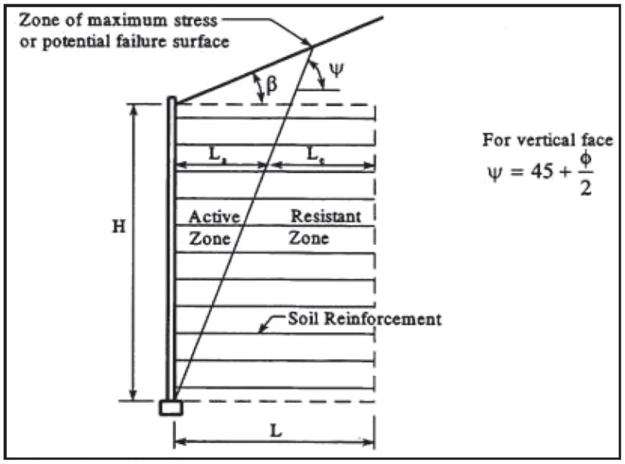


Figure 3. Location of potential internal failure surface (from FHWA 2009)

4.1 Design (failure) Modes

The Influences of reducing the reinforced fill density on five major failure modes in the MSE wall design, namely Sliding, Eccentricity, Geogrid strength, Pullout and Bearing stress are examined herein. All forces and stresses under discussion are per unit width (along wall alignment).

All notations used in the discussion are the same as shown in the Fig.2 and Fig.3, unless otherwise stated.

4.1.1 Sliding

The design criterion for checking the sliding stability, or the FoS is as follows:

$$FoS = (V_1 \text{ Tan } \phi) / [(0.5\ \gamma_b\ H^2 + (q\ H))\ K_{ab}]$$

$$= (\gamma_r\ H\ L \text{ Tan } \phi) / [(0.5\ \gamma_b\ H^2 + (q\ H))\ K_{ab}] \quad [1]$$

Where ϕ is the shear strength of foundation soil ϕ_f, when checking the base sliding, or the shear strength of reinforced fill ϕ_r when checking the sliding along the reinforced fill. The friction angle ρ between the reinforced soil and the reinforcing material (geogrid) obtained by testing, is used to check the interface sliding corresponding to each reinforced layer.

As it can be seen, the resistance (the numerator of eq. [1]) is only related to two variables, density (γ_r) of the reinforced fill material and the reinforcement length (L) for the given wall and soil conditions. The γ_r and the L have a simple inverse correlation.

If the density of the selected LWF is reduced to 50% of the normal granular fill, the reinforcement length L needs to be doubled in order to maintain the same FoS. If the LWF's density is only 10% of that of the normal fill, the L needs to be 10 times longer.

For a typical MSE wall under normal conditions, the ratio of L/H around 0.7 to 0.8 would usually satisfy the design requirements. Overly extended L will not only have cost implications but also constructability problems as most sites would not have the excavation space required. Therefore, applying LWF imposes adverse effects on the sliding stability and the impact can be significant depending on the LWF selected.

4.1.2 Eccentricity (Base Stress and Overturning)

Eccentricity e is the distance between the resultant vertical load at the base and the center along the reinforced zone (length L). "Base" herein refers to any level along the height of the wall under consideration, typically at each level of reinforcement. According to the design criteria, eccentricity shall not be greater than L/6, or, e_{max} / L < 1/6 (0.167) so that the base stress can be more evenly distributed along the reinforced zone. When eccentricity is satisfied, the overturning stability (the resisting moment over driving moment about the toe of the wall) will always be satisfied. The e is given by the following equation:

$$e = \{(H/3\ F_1) + (H/2\ F_2)\} / V_1$$

$$= \{(H/3\ 1/2\ \gamma_b\ H^2\ K_{ab}) + (H/2\ q\ H\ K_{ab})\} / (\gamma_r\ L\ H) \quad [2]$$

When checking the bearing stress acted on the foundation soil at the bottom of the wall, the eccentricity e_b, is calculated by:

$$e_b = \{(H/3\ F_1) + (H/2\ F_2)\} / (V_1 + q\ L)$$

$$= \{(H/3\ 1/2\gamma_b\ H^2\ K_{ab}) + (H/2\ q\ H\ K_{ab})\} / (\gamma_r\ L\ H + qL) \quad [3]$$

Above equations [2] and [3] can be rearranged as

$$e = \{0.5\ H\ K_{ab}\ (1/3\ \gamma_b\ H + q)\} / (\gamma_r\ L), \text{ or,} \quad [4]$$

$$e/L = \{0.5\ H\ K_{ab}\ (1/3\ \gamma_b\ H + q)\} / (\gamma_r\ L^2) \quad [5]$$

$$e_b = \{0.5\ H^2\ K_{ab}\ (1/3\ \gamma_b\ H + q)\} / \{(\gamma_r\ H + q)\ L)\} \text{ or} \quad [6]$$

$$e_b/L = \{0.5\ H^2\ K_{ab}\ (1/3\ \gamma_b\ H + q)\} / \{(\gamma_r\ H + q)\ L^2)\} \quad [7]$$

From equations [5] and [7], we note that eccentricity is related only to the density (γ_r) of the reinforced fill and the reinforcement length (L) for any given wall and soil conditions(s).

It can be further noted that the eccentricity is inversely correlated to the product of the reinforced fill's density (γ_r) and the square of reinforcing length (L). Therefore, in order to maintain the eccentricity to be within the max value of e/L, reducing the fill density will also require increasing the reinforcing length, but would be less the length due to sliding stability. Hence, applying LWF will also have adverse effect on the eccentricity and result in longer soil reinforcement.

4.1.3 Bearing Stress

The very purpose of applying LWF is to reduce the vertical bearing stress at the base of the MSE wall. The bearing stress σ is expressed as

$\sigma = V_1 / (L - 2e_b)$

$= (\gamma_r H L + q L) / (L - 2e_b)$

$= (\gamma_r H + q) / (1 - (2e_b / L))$ [8]

As reducing the density of reinforced fill γ_r (smaller numerator) will always result in increased L and better eccentricity (larger denominator), thus the vertical bearing stress σ can be reduced effectively.

4.1.4 Strength of Reinforcement

The reinforcement material (geogrid) must be sufficiently stronger to resist the maximum Tension T_{max} developed within the reinforced soil along each layer of the reinforcement. T_{max} is defined as:

$T_{max} = \sigma_H S_v = [K_r (\gamma_r Z + q)] S_v$ [9]

Where

K_r – Earth pressure coefficient calculated for the reinforced fill

Z – the depth from top of the reinforced fill to the point being checked.

S_v – the vertical spacing between reinforced layers.

Therefore, the Long Term Design Strength (LTDS) used for geogrid reinforcement in the MSE wall design shall be

$LTDS / FoS \geq [K_r (\gamma_r Z + q)] S_v$ [10]

It can be noted that under the same MSE wall configuration, loading condition and the point of consideration, T_{max} is related only to the density and indirectly to the shear strength (K_r) of the reinforced soil for the given reinforcing spacing S_v.

From Table 1, we know that all common LWFs are in general better or are equal to the shear strength of normal fill, hence, reduction of density will only result in lower tension developed on the reinforcement. In other words, applying LWF is beneficial to reinforcement and reinforcing geogrid with lower strength can be selected when using LWF.

4.1.5 Pull out Failure

Pull out check is to ensure that the effective reinforcement length L_e is adequate to resist the maximum tensile force T_{max} acting on it.

L_e is the "anchorage" portion of the reinforcement that falls in the resistant zone (Fig. 3). The pullout design criterion is expressed as follows

$FoS = (C F \gamma_r Z R_c \alpha L_e) / T_{max}$ [11]

Where C, F, and α are the factors relating to the nature of the reinforcing material. Once the reinforcement material in the MSE wall under design is selected, these factors all become constants, usually obtained by testing by the geogrid manufacturer.

R_c - coverage ratio defined as the width of reinforcement divided by width of the RSS wall under design.

If we substitute the term T_{max} with equation [9], equation [11] becomes

$FS \geq (C F \gamma_r Z R_c \alpha L_e) / \{K_r S_v (\gamma_r Z + q)\}$ [12]

By observing equation [12], one can note that the variable γ_r is present in both the resisting and driving portions of the equation. Reducing the density of reinforced soil has less impact on the pullout than that of other failure modes.

Particularly, if the live surcharge load is zero, the reinforcement length L_e is then independent from density of reinforced soil. Or in other words, the pullout resistance is irrelevant to the change of reinforced soil density.

4.1.6 Summary

Based on above discussions, the impact of using LWF on the MSE wall design can be expressed by normalized relationship between the density of the reinforced soil and the reinforcement length for each design mode discussed above. This is summarized by Figure 4 below.

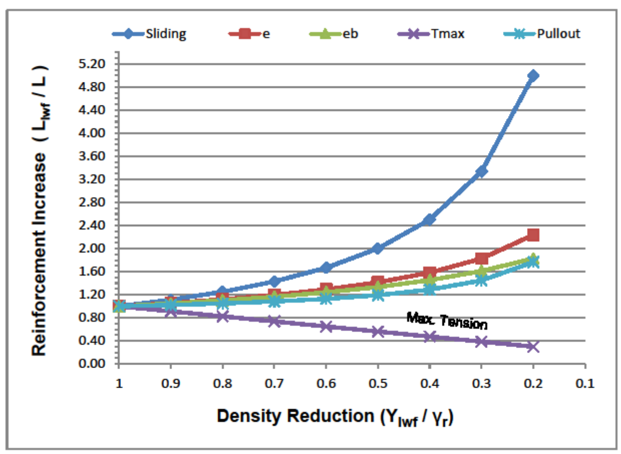


Figure 4. Normalized impact of LWF on design modes

In Figure 4, the ratio (before and after applying LWF) of reinforcement increase versus the ratio of density reduction of the reinforced soil is shown for different design modes. Each design mode is calibrated to the required safety criteria for that mode. All the correlations shown on Fig. 4 are under the assumption that the LWF has the same shear strength (friction angle) as the normal granular soil.

4.2 Drainage Considerations

As discussed in section 2, with the exception of granular LWF that has a similar hydraulic conductivity as normal fill, LWF can be less permeable or even impermeable (such as LCC) at its final working state. Under that condition, the typical assumption of "free draining" in the reinforced mass is no longer valid and groundwater or infiltration/seepage may be built up behind the reinforced soil mass imposing hydrostatic pressure against the sliding and eccentricity. Such pressure had not been considered in the stability checking for all the failure modes previously discussed.

Therefore, special (sub) drainage measures need to be designed to provide effective and reliable water passage for relieving the water pressure.

5. SUITABLE CONDITIONS OF APPLYING LWF

The above discussions show that the potential failure mode most impacted by the use of LWF is sliding resistance and the need for added drainage measures.

Some examples of how LWF can be addressed in the design of some typical MSE structures are discussed herein.

5.1 Back-to-Back Wall

Back-to-Back wall refers to two MSE walls aligned parallel and opposite to each other. This is typically the case for developing an elevated road that the MSE walls form the road embankment (Fig.5).

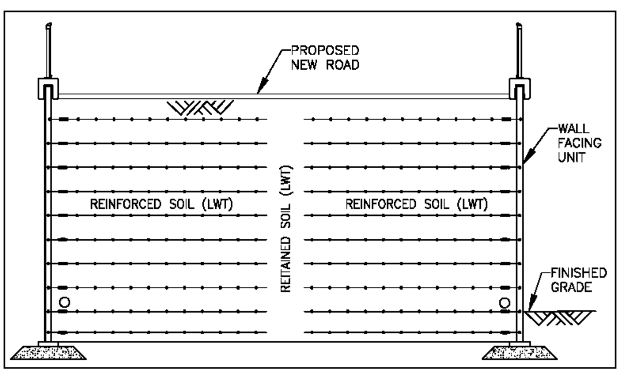


Figure 5. Typ. Configuration of Back-to-Back wall

This is probably the most ideal condition to apply LWF, as the retained soil is also mainly LWF. Therefore, the driving force from the lateral earth pressure is significantly reduced. This alleviates the need of overly extend the soil reinforcement in order provide adequate sliding resistance. Such configuration in fact enables the design to be performed back to the normal conditions, i.e. the retained soil and the reinforced soil have the same or similar density and strength.

5.2 Combination of LWF with normal fill

If the targeted reduction of vertical stress at the base of the wall allows, a compromise solution is to apply LWF (Fig. 6) partially so that the impacts discussed in Section 4 are minimized while achieving the required vertical stress reduction.

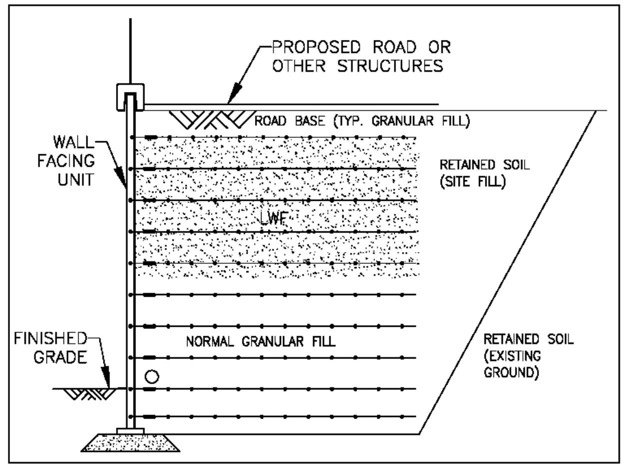


Figure 6. Typ. Configuration of LWF and normal fill combination

5.3 LWF with provision of special sub-drain

When the density of LWF is ultra-light and impermeable, measures for both reducing lateral pressure and providing sub-drain should be considered.

Similar to the concept of the Back-to-Back wall, the most effective way to reduce the lateral earth pressure is by placing the LWF in the retained soil zone as extensively as possible. This will be dependent on available site space allowed for excavation.

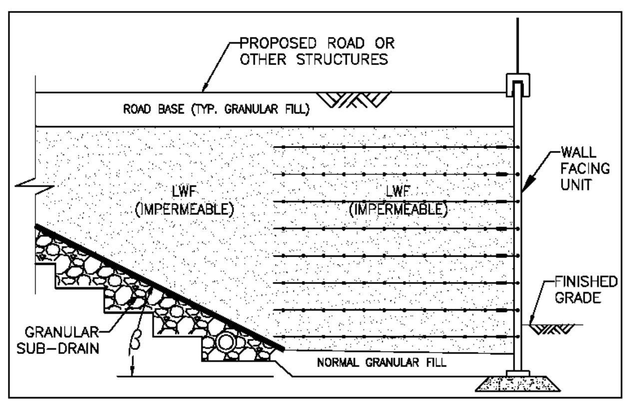


Figure 7. Typ. Configuration of LWF with subdrain system

As a minimum requirement, the back excavation should be made to an angle from horizontal (the angel β in Fig. 7) equal to or less than the angle of repose of the soil under excavation (ignoring any cohesion). In theory, the remaining soil is considered stable and will not impose lateral earth pressure on the wall. The LWF can then be applied into both the reinforced soil and retained soil zones.

6 CASE HISTORIES

6.1 Windsor Herb Gray Parkway

The Rt. Hor. Herb Gray Parkway is an 11 kilometer long new highway connecting the existing Hwy 401 in the east with the Gordie Howe International Bridge (under construction) to Detroit in the west. The highway was completed and opened to the public in 2015. Numerous bridges and (open) tunnels needed to be built along the highway hence many MSE walls were required to support the grade separations. LWF was also proposed to be used due to the weak foundation soil and settlement concerns at multiple locations.

The maximum height of the MSE walls required to use LWF was 7.6m with configuration and elevation as shown on Fig.. 8 and Fig.. 9, respectively.

The project geotechnical team had determined that granular LWF of FS with design parameters shown in Fig.. 9 should be used, They also specified the volume (the thickness) and the location of how FS should be applied based on the bearing capacity/settlement tolerance considerations.

6.6.1 Design Considerations

The design followed in general all the aspects discussed in Section 4. However, due to the partially applied LWF FS, a few more details need to be considered.

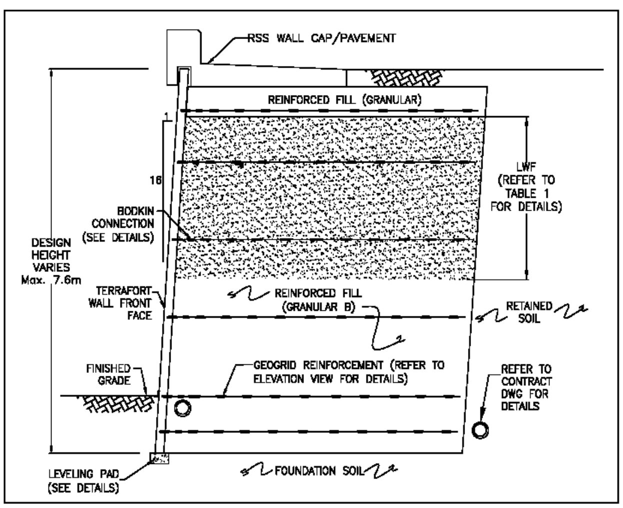
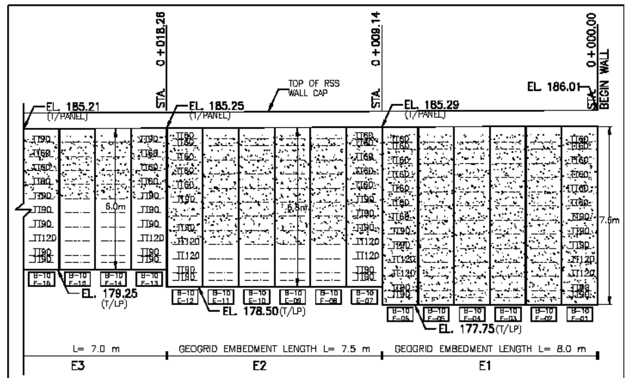


Figure 8. Typ. Configuration of MSE wall with partial LWF

First off, it was determined that the partial FS should be placed at the upper portion of the wall (Fig. 8) to minimize the overburden stress acting on it. This was due to the concern that larger particles of FS have the potential to break up under high stress.

Secondly, the Weighted-Average-Density (WAD) of the LWF and normal granular fill should be calculated when checking the base stress, sliding and eccentricity. For example, for Block E2, the WAD = (12KN/m^3 x 5m + 21KN/m^3 x 1.8m) / 6.8m = 14.4KN/m3. However, when checking all the failure modes at any other reinforcing levels subject to backfill materials with different densities above it, the WAD varies at each level and the corresponding WAD needs to be recalculated each time.



REINFORCED FILL REQUIREMENT				
BLOCK	E1	E2	E3	E4
LWF	±7.5m	±5.0m	±3.0m	2.0m
GF	±0.1m	±1.8m	±3.0m	3.2m

LWF DESIGN PARAMETERS	
DENSITY	12KN/m^2
FRICTION ANGLE	32°
COHESION	0KPa

Figure 9. Elevation of MSE wall with partial LWF

This can be a time consuming process, particularly when the LWF is sandwiched in between layers of normal fills.

As it can be observed from Fig. 9 that the ratio of reinforcement length to wall height L/H is greater than 1.0 after the partial placement of LWF, which is usually around 0.7 to 0.8 under normal fill. But such increases could be accommodated by the site conditions.

6.6.2 Construction

As discussed previously, FS has similar behaviors as the


Figure 10. FS placement behind the MSE wall

normal fill in terms of construction, hence no special measures needed to be taken. It was placed similarly by batches with lift thickness ±200mm, using hand-operated compactors for compaction. Fig. 10 shows Block E1 of the

MSE wall under construction with the placement of the FS in progress. It can be seen that normal granular fill has been placed in the adjacent Block E2 (refer to Fig. 9).

Figure 11 shows the backfill approached to the top of the wall with FS being placed across the full wall length.

Figure 11. FS backfill near the top of the MSE wall

6.2 Highway 400 Widening

Highway 400 is one of the main trunk highways in Ontario linking the city of Toronto to the northern parts of the province. The Ministry of Transportation of Ontario (MTO) decided to widen a section near the city of Barrie in 2016.

A total of 14 MSE walls had been proposed with one major MSE wall requiring LWF due to the presence of a sensitive buried utility (sanitary sewer) structures.

This MSE wall is 260m long with a maximum height of 8.1m at the south end and 2.4m at the north end to conform to the highway profile of the added new lanes. LCC was specified to be the reinforced soil in a 57m long section with a maximum height of 8m. The volume, location and position of LCC had also been specified by the MTO.

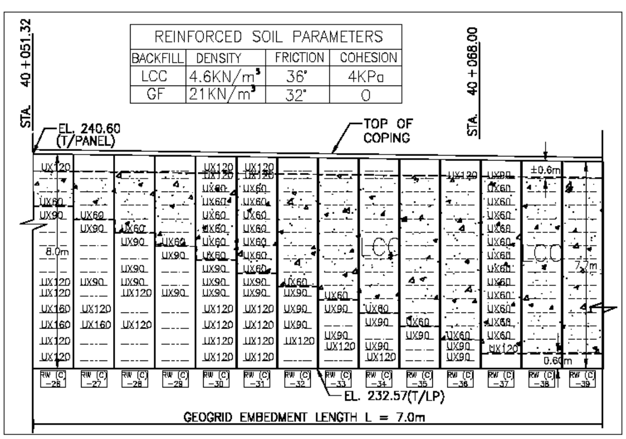


Figure 12. Typ. elevation of MSE wall with LCC

Based on those requirements, a representative section of the final design is shown on Fig. 12 and Fig. 13.

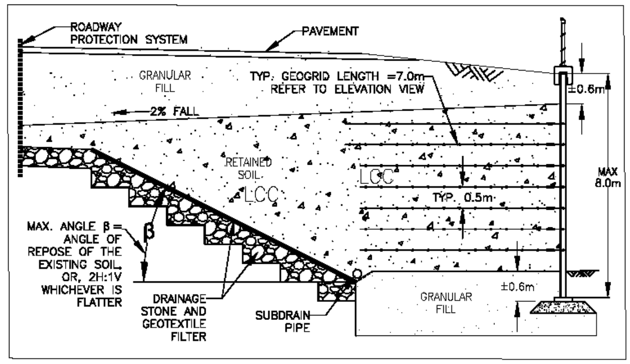


Figure 13. Typ. configuration of the MSE wall with LCC

6.2.1 Design with LCC

The design parameters of LCC were provided by the manufacturer as indicated in Fig. 12. As discussed, with such ultra-lightweight fill, reducing the lateral pressure from the retained soil side would be more cost effective than increasing the tie-back length L to compensate for the loss of gravity and the associated sliding resistance.

According to the geotechnical reports, the lower part of the retained soil is a general fill material with varying composition from silt to sand to gravelly sand with densities from loose to dense. The upper portion of the retained soil will be a new engineered fill to raise the ground to the required highway level. Based on such site conditions, the β was conservatively determined as shown on Fig. 13.

The “equalization“ of retained soil and reinforced soil has effectively reduced the external lateral earth pressure, as discussed in section 5. It resulted in a relatively short design length of reinforcement L to satisfy the sliding and eccentricity criteria, with an L/H ratio of less than 0.9 close to the ratio of normal MSE wall.

Due to the requirement of the placement of LCC to be 0.5m per pouring lift, the geogrid reinforcement is designed accordingly to be spaced at 0.5m, where cold-join is formed. The cohesion of the LCC was ignored in the design.

As it can be seen from Fig. 12 that a geogrid of UX60 (with lowest LTDS) was almost constantly assigned, regardless the design height of the wall. While nearly all the reinforcing layers falling outside of LCC required much stronger geogrid with a higher LTDS (greater UX number) under the same design height. This is due to the difference of the internal driving forces induced by ultra-lightweight fill vs. normal granular fill (as discussed in section 4.1.4).

Based on an experimental study by an LCC manufacturer using Terrafix UX geogrids, the pull-out resistance between geogrid and LCC is governed by the strength of LCC. The pull-out failure occurs when the geogrid is pulled out along the cold joint of the LCC testing block with the block cracked or split. Failure occurs at a nearly constant peak pull-out regardless of the tensile strength of the geogrid. The tested peak pull-out force is lower than the ultimate tensile strength of the lowest grade of available geogrids.

6.2.2 Construction with LCC

The excavation zone was prepared as per the design with a granular base, sub-drain layer and pipes in place ready for receiving the LCC (Fig. 14). LCC was transported to the site by concrete mixer truck in a liquid state and pumped into the prepared reinforced zone.


Figure 14. Excavation prepared for LCC placement

The LCC can be easily pumped for long distances with low pressure due to its low density. The pouring thickness was 0.5m per lift and typically poured during the daytime over a few hours and was left overnight to allow for sufficient curing.

Geogrid reinforcement was then placed and connected to the wall facing panel and pulled tight along the cured LCC surface prior to the next pouring (Fig. 15). The process repeats on daily basis until the LCC reached the designed level (Fig. 16).


Figure 15. LCC pouring over geogrid reinforcement in progress


Figure 16. LCC reached the final design level

7. CONCLUSION

Based on above discussion, the following conclusions can be drawn regarding application of LWF:

- LWF can be used partially or in full as the backfill (reinforced soil) in the MSE wall to effectively reduce the vertical stress at the base of the wall.
- The most critical impact of using LWF is on the sliding stability due to the loss of gravity mass in providing sufficient resistance.
- Using LWF as the reinforced soil reduces the internal tension acting on the reinforcing material, hence reinforce material with lower strength can be used.
- The common solutions to the sliding stability is to either increase the volume of the resisting mass by increasing the reinforcement length, or, to reduce the driving force imposed by the retained soil. This can be achieved through replacement of the existing soil with LWF within the retained soil zone partially or fully.
- Site conditions must be reviewed carefully during the planning stage, not only for selecting appropriate LWF materials, but also for checking whether the available site space can accommodate these common solutions, as in general, using LWF requires larger space than that of normal fill.
- Special or extra drainage measure(s) must also be provided if a less or impermeable LWF material is selected.

8. REFERNCES

Tiwari B. et al. 2017. Mechanical Properties of Lightweight Cellular Concrete for Geotechnical Applications, *Journal of Materials in Civil Engineering*, ASCE, 29(7): 06017007-1-06017007-7.