Lessons Learned from Failed MSE Walls

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ABSTRACT: An imminent part of any new technology is failure. While failures could provide a wealth of information about improved design and construction, such events remain unpublished and poorly explored due to litigation. This paper presents briefly the results of forensic studies of two failed MSE walls. The conclusions of these studies coincide with lessons learned from other cases of failure that the author was involved with. As expected, poor compaction and improper drainage lead to serviceability issues or even to collapse. Cost of repairing failure is always more expensive than saving achieved due to poor design and construction. Redundancy in structures is important.

1 INTRODUCTION

Mechanically Stabilized Earth (MSE) walls are composite retaining structures. Three main elements produce MSE walls: soil, reinforcement, and facing. If any of these elements is not functioning, its performance would be unacceptable. In extreme cases, it will result in collapse. However, if material characterization, design, and construction are properly done, such walls will exhibit excellent long-term performance while being economical.

The design of MSE walls with respect to reinforcement and facing is usually conservative. However, the soil is often poorly considered. The end result then is either an overly conservative structure or worse, failure. Poor consideration of backfill is usually done in design by underestimating its strength. However, if in construction compaction or proper drainage is skimped, the conservatism associated with design may vanish and failure occurs. That is, the performance of MSE walls is dependent on good compaction and good drainage. This is not different from nearly any other geotechnical structure.

The objective of this article is to report two cases of failures, never published before. The cases reported are classical and, in principal, represent other cases the author was involved with. The reported cases are based on forensic studies. The forensic aspect is only briefly described. It is noted that a forensic study is similar to reverse engineering. That is, the end result is known and one then looks for plausible reasons for the failure. While usually there are several contributing factors, there is only one major likely reason for failure. This paper identifies the major reasons for failures.

2 CASE I (GEORGIA, USA)

Construction of a geotextile reinforced wall with wire basket facing was completed in late 2001 – see Figure 1. The wall's maximum height was about 16 m; the nominal height of the wire baskets was 45 cm; alternating primary and intermediate woven geotextile layers were placed every 45 cm, corresponding to the wire facing. The backfill in the front 30 cm was clean gravel and away it was random, supposedly with no more than 35% passing sieve 200, compacted to 95% standard Proctor. Following every rainfall, there was significant settlement resulting in major cracks of the drugstore building on top. This was accompanied by soil depression around surface water collectors. The owner filled these depressions with concrete to level the surface with the existing asphalt driveway – see Figure 2. In spring 2003, the drugstore was closed and repairs were done. Repair was massive using anchors (see Figure 3), basically "solidifying" the reinforced soil, costing more than four times the original cost of the wall. The case was settled out of court in summer 2004.

Figure 1: General appearance of the Georgia Wall.

Figure 2: Concrete around surface water collectors to "repair" depression.

Figure 3: Anchors remedying the problem.

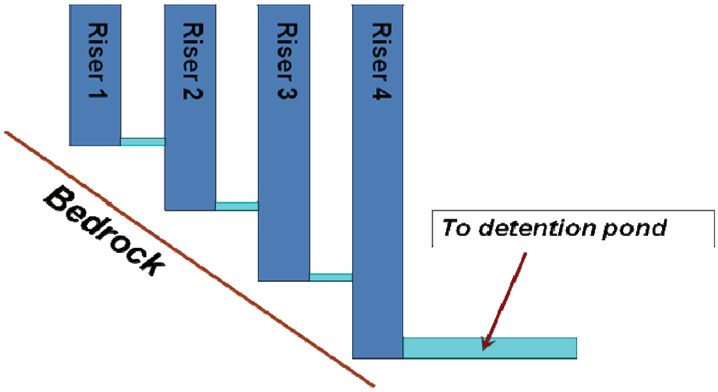

Figure 4: Schematics of risers collecting surface water and connecting horizontal PVC drainage pipes

The following observations were made during the forensic study:

1. At the end of construction the contractor had to add 25 cm of fill on top in order to reach the final grade. The foundation soil was firm and settlement could not be used to explain the need to add backfill.
2. Surveying of the face conducted before closing the area for repairs showed that all the wire baskets were shorter than their nominal height of 45 cm. Adding the cumulative deformation of the compressed wire baskets indicated total compression (including the 25 cm at the end of construction) of 70 cm. It means that while at the end of construction the backfill compressed 25 cm, about 14 months later it compressed further (70-25)=45 cm. No substantial bulging was observed that could explain the large vertical settlement at the crest. The only material that could cause this settlement is primarily the compression of the backfill.
3. The drainage system consisted of four vertical risers to collect surface water. Each riser was connected to the other by a horizontal drainage PVC pipe as shown in Figure 4. The risers were relocated by the contractor into the reinforced soil area (from the original plan placing it in the retained soil zone) since it was 'easier' to construct. The depression occurring around the risers clearly indicates that the soil there was poorly compacted.
4. While there was a supervisor to ensure proper construction, no field record of field compaction tests was found. Also, no report of quality of backfill was available.
5. Borings indicate that the fill material was truly random: over 50% passing #200, boulders 30 cm large, and some organic material.

The following conclusions were made:

1. Generally, the backfill was poorly compacted. SPT implies it was less than 90% standard Proctor (95% was specified).
2. Poor compaction around the risers resulted in differential settlement around the risers shearing the PVC horizontal pipes connected to the risers. Video inspection confirmed this conclusion. As a result, the surface drainage system worked in reverse; the water it collected was fed into the loose reinforced soil. The end result was in-service compaction, an unacceptable situation.
3. Piezometers indicated porewater pressure of about 3 m. Global stability for this situation indicated a factor of safety of about 1.1. Such low factor of safety is typically associated with large deformations. Clearly, this is an unacceptable value.

The following lessons were learned:

1. Compaction is essential to the performance of geosynthetic reinforced walls. This requirement is not different than should be imposed for all geotechnical structures.
2. Without water infiltration the structure would be stable. However, the settlements would be large enough to render a problem of serviceability. The addition of water poses a danger of collapse; it a turns serviceability issue into collapse issue.
3. If the designed grad elevation of the crest is not achieved when compacting the soil layer over the top reinforcement layer, the reason could be either excessive settlement of the foundation or compression of the backfill due to poor compaction. The exact reason should be identified before construction continues. Simple correction at the end to reach the target elevation is unacceptable as it hides a potential flaw that in the long run may result in a disaster.
4. As much as possible, drainage system should not be placed within the reinforced soil. Otherwise, if it fails, the wall is likely to fail as well. Reinforced backfill is not designed to serve as a water carrier. Furthermore, there is no simple repair of a drainage system embedded within the reinforced soil. Hence, redundancy in drainage is good.

   Cost of repairing failure is nearly always more expensive than the "saving" derived from poor construction or design.

Figure 5: Overview of the 3rd Parallel Runway.

3 CASE II (SYDNEY, AUSTRALIA)

This case is related to the construction of the 3rd Parallel Runway, Kingsford Smith Airport, Sydney, Australia. Construction utilized sand dredged from Botany Bay. This sand is uniform, fine-medium with D_{50}=300μm, 1% to 3% passing #200, and uniformity coefficient Cu=2. Initially an embankment was constructed in Botany Bay using the dredged material. Following was an excavation near the perimeter, using well-pumps to keep the phreatic surface low enough so as to enable the construction of the walls on the dry. Upon completion of the walls, the sand on the seaside was pumped away. Fig. 5 provides an aerial view of the runway, the constructed walls, and Botany Bay. Since this was a design-build project, the contractor selected to use proprietary metallic reinforced walls (Reinforced Earth) in this marine environment. Two types of walls were constructed. The first was for the Millstream canal (Figure 5) using the standard Reinforced Earth system with cruciform 1.5 by 1.5 m panels. However, the reinforcement was 10 mm thick black steel strips (not galvanized). Each side of the canal was about 1 km long. The second wall, the seawall, utilized special double-T concrete panels, 3 m long and 2 m or 1 m tall. Black steel strips, 15 mm thick, having length equal to wall height, were used. Wall height was either 5 m or 4 mutilizing the needed combinations of the double-T prefabricated concrete panels. This wall was 7 km long. Minimum relative density for compaction of the sand was specified as Dr≥80%. Ten ton roller was used at distance greater than 1 m from the back of the panels. Within 1 m from the panels, one ton handheld compactor and jumping jack were used to compact the sand next to the facing. To prevent lose of sand through joints between the panels, first no-fines blocks were stacked against the joints and then nonwoven geotextile with AOS<80 μm was glued at spots to the panel on either side – see Fig. 6. The blocks allowed passage of particles smaller than #200, should such particles pass the geotextile. The no-fines blocks were presumably placed to break water energy under wave action. Construction started in 1992 and completed in 1994, 9 months ahead of schedule.

The contractor has guaranteed maintenance-free performance of 100 years for the seawall and 50 years for the Millstream wall. Two years after construction sinkholes appeared next to some joints. In about 2002, 30% of the joints had significant sinkholes – see Fig. 7. Infilling these holes with sand could not resolve the problem. Such sinkholes accelerate corrosion – see Fig. 7. Repair was done between 8/2005 and 9/2006. Jet grouting was used from the back of the face to the rear of the reinforcement. That is, in essence a gravity wall, 9 km long with widths up to 5 m, was formed thus rendering the joints and reinforcement unimportant.

Figure 6: Facing Panels: Joints protected by no-fines blocks and nonwoven geotextile.

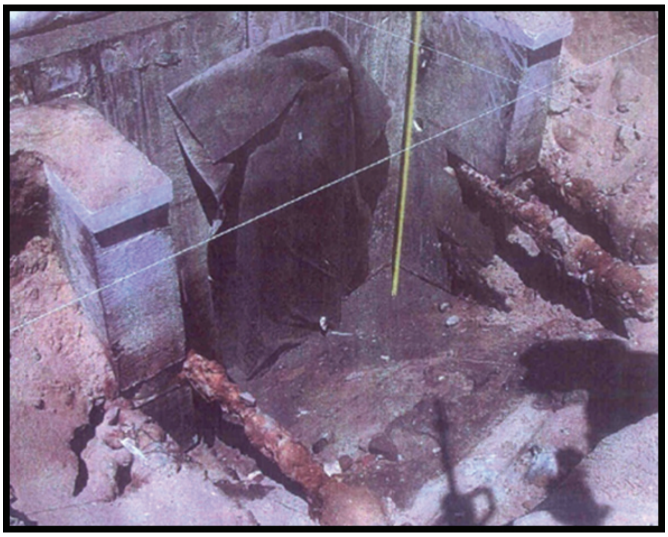

Figure 7: The problem: Sinkhole at ~30% of joints.

Figure 8: Back of Double-T Panels: Metallic strips connected to concrete buttresses (part of the concrete panels), and placement of 660 mm thick layer lift.

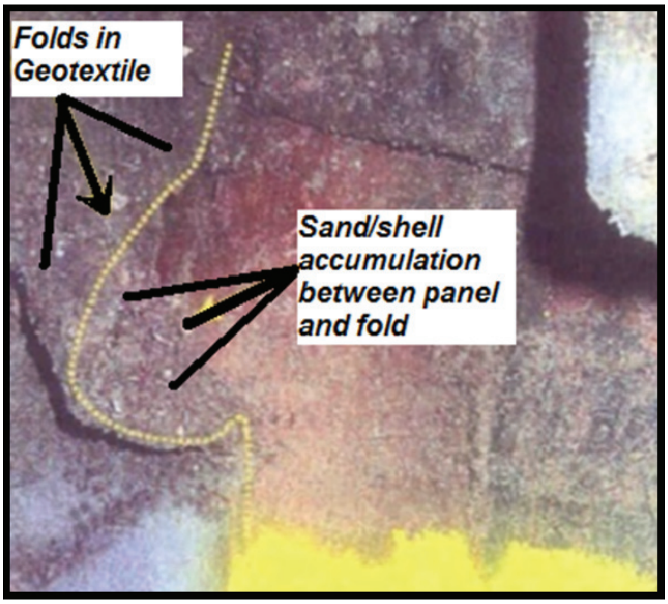

Figure 9: Folds in geotextile with sand/shell accumulation allowing sand to “flow” from the retained sand to the seaside through the joint .

The following observations were made during the forensic study:

1. The designer specified maximum 330 mm layer lift for compaction. The contractor actually used layers lift of 660 mm (generally, the vertical space between reinforcement layers). The reason for the increase was to "ease construction."
2. Quality control in the field showed that under the 10 ton vibratory roller, D_r was greater than 80%. However, within the 1 m behind the wall, there was no quality control at all. That is, even not one field compaction test was done along the seawall to ascertain that the jumping jack can effectively compact 660 mm of loose sand. It is a common practice to specify light compaction equipment is next to the facing so as not to affect the wall alignment; however, layer lift then is limited to 150 mm.
3. There was not even one test to ascertain that compaction next to the geotextile will not drag it down forming folds and creases. It also was not part of the quality control plan; no periodic verification of proper installation of the geotextile, as was specified by the designer, was conducted.
4. During construction small sinkholes ("rat" holes) were observed next to some joints. At that stage the seawall was not submerged yet (it was "on the dry"). The contractor infilled these holes with dry sand, ignoring the possibility that the joints are not properly sealed.
5. The geotextile apparent opening size was sufficient to retain the Botany Bay sand. Accelerated tests on model walls using simulated waves showed that in a period of 10 years, only a minute amount of sand would escape through the joints, certainly not sinkholes shortly after the end of construction.

The following conclusions were made:

1. It is unlikely to achieve proper compaction using light equipment when having layer lifts of 660 mm. This is even more so when many kilometers of such tedious work need to be conducted by laborers. Moreover, the space within such compaction was to be done did have difficult accessibility – Figs. 6-7.
2. Quality assurance and quality control to ensure that the geotextile was affixed properly, regardless of the thickness of a layer lift, is essential, especially in a case of where bidirectional flow exists.
3. It is apparent that the contractor considered the 1 m behind the panels as an unimportant portion the wall and therefore, spent very little effort in that region.
4. Excavations at some locations where sinkholes occurred clearly showed that the geotextile had folds filled with coarse sand and shell particles. These folds extended between the retained sand and the open joint. Slowly but surely, aided by tidal fluctuations and wave action, retained sand could escape into the seaside of the wall hence producing sinkholes – see Fig. 9. Such folds in marine environment serve as 'highway' for sand flow. It is noted that folds filled with sand/shell were observed below the low tide thus implying that the formation of folds had nothing to do with wave action or tidal fluctuations. Its formation was likely due to poor construction.
5. Folds were formed by the downdrag force occurring as the sand moves down relative to the geotextile. If the sand is loose, it will compress in-service under tidal fluctuations. Alternatively, folds could have formed during compaction, as at the face it was not done consistently using light weight compactors, thus occasionally dragging the geotextile down and creating folds. In fact, sinkholes occurred at only 30% of the joints. Random quality construction usually will lead to random results and performance.

The following lessons were learned:

1. The contractor and designer must understand the function and importance of all the elements comprising the wall. Evidently, the zone behind the facing was considered unimportant.
2. Quality assurance and quality control plans must ascertain that *all* design specifications are attainable and, indeed, achieved.
3. Problems discovered during construction should be investigated by experts. Infilling with sand the "rat" holes discovered during construction did not solve the problem; it simply 'masked' the problem.
4. Compaction is important everywhere including close to the facing. This is a fundamental geotechnical requirement in construction.
5. Redundancy in structures is needed. In the Sydney wall, the importance of the geotextile cannot be underestimated. If it ceases to function as a filter, the entire wall system would fail. There was no second front in

case filtration by the geotextile becomes ineffective.

6. One can question the wisdom of using a reinforced seawall, especially in such important project. It is doubtful if in such a project using a reinforced wall instead of traditional sheet pile wall will make much of a difference in the overall cost of the project. Uncertainties about corrosion and sand retention in marine environment imply that the risk is not worthy. The results prove this point.

Clearly, while the attempt to construct MSE wall in the Sydney airport expansion is a professional challenge, the cost saving comparing of alternative wall systems cannot be very significant, even not in hind-view. The risk associated with such application should be limited to less significant applications. Only when there is abundant experience, new and innovative application could be used in a scale such as Sydney Airport.

4 CONCLUSIONS

The briefly discussed two cases combined with experience with other failed MSE walls lead to the following general lessons:

- Compaction is extremely important. It increases the strength of soil, reduces settlement, and provides redundancy as designers tend to ignore the beneficial impacts of compaction. For example, typically designers will use shear strength that is by far smaller than the real value thus producing conservative structure. This redundancy is, in essence, an undeclared factor of safety.
- Compaction behind the facing of any MSE wall is important. It creates an integrated system of facing-reinforcement-soil. It also prevents in-service down movement of backfill against the facing resulting in parasitic load on the reinforcement at the connection.
- Drainage is essential to successful performance of any MSE wall. Water decreases the shear strength of soil resulting in excessive deformations and possibly in collapse.
- Quality control during construction is extremely important. It ensures that the design assumptions are met and that the performance meets the design expectations.
- Communication amongst all parties involved must be facilitated.