SPECIAL FEATURE

Geosynthetic reinforced walls in the public sector

Performance, design, and redundancy

By Dov Leshchinsky and Fumio Tatsuoka

Introduction

Geosynthetic reinforced soil can be viewed as a subset area of slope stability. In slope stability analysis, the factor of safety signifies the margin of safety against failure. It physically means that its reciprocal value signifies the average mobilization or utilization of the shear strength of soils. Therefore, the traditional design value of minimum factor of safety of 1.5 implies that maximum strength utilization is 67%. Experience indicates that when design parameters are conservatively selected and combined with suitable stability analysis, this factor of safety produces safe earth structures, some of which are critical (e.g., high dams). However, the actual in situ value of factor of safety cannot be measured or verified. Its design value is based on many decades of worldwide experience.

Reinforced walls are inherently unstable slope structures without reinforcement and inclusion of reinforcing elements provides a means to directly assess stability. Stability now hinges on the long-term strength of the reinforcement. Measuring the actual load in the reinforcement provides a direct indication of global stability. Unlike the factor of safety of unreinforced stable slopes, measured loads enable direct assessment of the actual utilization of the long-term strength of the reinforcements, the elements on which stability hinges.

Redundancy implies inefficiency since, for example, a structure underutilizes the strength capacity of its reinforcement. Data produced by many instrumented walls indicate that the load in geosynthetic is significantly smaller than its designed long-term tensile capacity. Most often this data was collected during ordinary or normal operational conditions (e.g., not under unusual or extreme events such as heavy rainfall, flood, earthquake, and vehicular impact). Such conditions exist during most of the life span of the structure. Traditionally, safety factors or load/resistance factors are used to decrease risks due to uncertainties of material properties, loads, structural dimensions, boundary conditions, and others. Often one cannot explain the substantially low measured loads to be solely due to the factors used in design. These factors usually produce only the obvious part of the redundancy addressed in this article. It is tempting to use direct field data as a guide to producing more effective structures by eliminating conservatism as related to required reinforcement strength.

The apparent high conservatism has helped to produce structures that are safe yet economical. These structures had small residual deformations under long-term

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There have been numerous failures of geosynthetic reinforced walls. The majority of these failures occurred in the private sector.

This article does not look at the forensic of wall systems that failed due to exploited redundancy combined with ignorance or careless attempts to "economize" the structure. Instead, it explains why a common belief that the public sector's design is overly conservative is a risky generalization. It may result in significantly less redundancy in the design code used in the public sector thus allowing for substantial reduction of long-term strength of the reinforcing geosynthetic.

If accepted, a new mode of failure that has not yet been seen will likely be realized: rupture of the reinforcing geosynthetic. Oddly, this mode may be a result of a modified public sector's code. Rupture of reinforcement in the public sector may inhibit the acceptance of geosynthetic reinforced soil technology.

This article warns against a tendency to reduce the current safety of structures designed using the public sector guidelines. This may make the performance of walls in the public sector on par with that of the private sector.

–D.L. & F.T.

normal conditions although this aspect was not an explicit part of the design. Furthermore, many of these structures were capable of withstanding extreme conditions well beyond what was considered in their design. These apparently highly conservative structures were still economical, promoting the rapid acceptance and use of geosynthetics as a reliable reinforcement even in critical applications. Conversely, unconservative design, which ignores or only partially considers unusual conditions, could have resulted in failures, likely inhibiting the acceptance of geosynthetic reinforced soil walls. This apparent conservatism has been a blessing in disguise to help promote an economical and safe technology.

As any technology matures, the tendency to further optimize the structure naturally exists. The perception of conservatism implied by field measurements has fueled research aimed at producing less redundant (i.e., more efficient) structures, but often making the refinement of little or potentially even negative economic value over the lifetime cost (e.g., increased risk of failure or increased maintenance). Moreover, taking field measurements under normal conditions as a reflection of long-term reality have led some designers to downplay or belittle design rules that consider extreme conditions that may occur during the structure's life span. In lieu of "better than expected" performance, some engineers have produced careless designs that ignore the basic principles of sound engineering. Often it has reduced construction quality, counting on the "miraculous" remedial power of geosynthetic reinforcement. Consequently, in recent years there have been numerous failures of reinforced walls, primarily in the private sector, many associated with inadequate design, poor compaction, and poor drainage. These failures are a result of significant reduction—or total loss—of structural redundancy, leading to local or global/compound instability.

The objective of this article is to discuss the link between performance, design, and redundancy of geosynthetic reinforced structures. It is hoped that field data under ordinary conditions should continue to produce ample redundancy. Furthermore, under possible extreme events, unusual events, or combinations of events, a reasonable level of redundancy would still be available to ensure the continuing proper wall performance accounting for some uncertainty such as larger than expected surcharge loads imposed on the structure sometime in its life span. This article does not stem from the important forensic post-failure perspective. Rather, it addresses the increasingly accepted notion that current design is overly conservative. This notion has led some to produce negligent design while motivating others to unsafely short-cut current designs.

Reasons for large discrepancy between field data and design

Several factors may lead to a significant discrepancy between measured loads in the geosynthetic layers collected under

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Photos 1, 2, 3, 5 courtesy of the authors

Poor compaction may result in excessive residual deformation that hinders proper functioning of the structure.

normal conditions and predicted design values obtained for a specified margin of safety. Other than extreme factors explicitly considered in design, such as seismic and flood, here are some factors responsible for this discrepancy:

1. Undervalued soil strength

Existing design codes call for select backfill soil usually providing default shear strength for that backfill (e.g., AASHTO specifies default ϕ of 34 degrees, limiting its value to a maximum of 40 degrees). In practice the default value is frequently used. However, for well-compacted soil, the select fill may have frictional strength as high as 50 or even 55 degrees. The difference between assumed and actual ϕ values, using the same basic design calculations, may result in twice or even more reinforcement. While this provides substantial redundancy, it does not invalidate typical design concerned with local and global stability aspects.

2. Apparent cohesion

In most walls, the reinforced backfill contains some fines. Considering the natural moisture content of the backfill, capillary suction exists, producing an apparent cohesion. While this (apparent) cohesion is not considered in design, in many cases it may reduce the need for reinforcement substantially (i.e., it can reduce the amount of reinforcement by an order of magnitude). Design wisely ignores apparent cohesion since it is *apparent* (i.e., its value may diminish with increased soil's moisture, typically associated with a rainfall). Once more, while apparent cohesion may add redundancy by substantially reducing the load in the reinforcement, ignoring it does not invalidate typical design.

3. Toe resistance

For walls with facing, the shear resistance of the bottom facing unit may be significant. This resistance carries or counterbalances some of the lateral thrust of the reinforced/retained soil and may substantially decrease the actual load in the reinforcement. Common design ignores its impact, considering potential excavation or scouring in front of the toe during the life span of the structure. While ignoring toe resistance increase redundancy, counting on it may reduce the needed amount of reinforcement by a factor of two or more. Toe resistance adds redundancy but ignoring it does not invalidate typical design.

Need for redundancy in design

Measured field data usually indicates a high level of redundancy under long-term normal conditions. In fact, if all three factors listed above are accounted for in design, in many cases no reinforcement will be needed. For example, using medium-fine sand under normal conditions, one can build a vertical unreinforced wall **(Figure 1)**. However, measured field data is only a snapshot of reinforcement loads under normal conditions taken at a time where usually a high level of redundancy exists. Safe design must consider the life span of the structure during which conditions different from normal may exist. Here is why redundancy is needed in the context of design:

1. Undervalued soil strength

Codes limit the maximum design value of ϕ, thus not always rewarding high compaction combined with adequate backfill. In return, good performance of walls is likely if ordinary compaction (at least 95% of Standard Proctor) is achieved. The usual default design shear strength corresponds to a level of compaction that is somewhat lower than the allowable minimum value. Consequently, the actual strength of properly compacted backfill, which is usually higher than the minimum

FIGURE 1 Apparent cohesion allows for unreinforced vertical cut in medium-fine sand.

prescribed Proctor value, is significantly higher than the default design strength. The redundancy due to the low default strength value compensates for cases where actual poor compaction is achieved. Furthermore, the default value works well for practical cases where designs are made for hypothetical fill in the bidding process; rarely, the actual soil strength is tested for realistic levels of compaction or even tested at all. Clearly, when the actual soil strength is larger than assumed in design, the resulted force in the reinforcement would be lower than expected. Although there is usually no requirement for a truly high level of compaction (e.g., >95% Modified Proctor), such high compaction may become necessary for critical structures, requiring increased level of stability and limited residual deformation (e.g., tall walls or bridge abutments with footings on top to support the girders, sometimes called true bridge abutments). In such structures the redundancy will likely be even greater than for ordinary walls if default soil strength values are used in design.

The paragraph explaining the impact of undervalued soil strength should be considered in the context of "good" backfill. It addresses the practice and specifications in the public sector. In the private sector, sometimes low quality backfill is used, often poorly compacted. This backfill may have ϕ that is smaller than the public sector's default value prescribed in design. Such a case invalidates the argument stated above because in this case the soil strength is actually overvalued. Since the impact of ϕ is proportional to tan (ϕ), the smaller strength value would have relatively minor effects (typically 10–20%). However, poor compaction may result in excessive residual deformation that hinders proper functioning of the structure.

2. Apparent cohesion

While the impact of cohesion on stability is large, suction and apparent cohesion during the life of the structure cannot

APPARENT COHESION

These photos show a wall failure next to a corner. This failure occurred in an area where successive triangular sectors of geogrid layers were not installed. Failure is to be expected because reinforced walls without reinforcement should fail.

Curiously, this failure occurred about one year after the end of construction. Clearly, failure was delayed because of substantial apparent cohesion. Some change in moisture content was sufficient to trigger failure. Looking at it differently, assume that construction was properly done and the wall was instrumented. What loads would have been measured in the not-missing sectors of geogrids? Small load values, probably induced by compaction; certainly not values needed for stability as assumed in design. Normal condition in this case corresponds to an apparent cohesion producing misleadingly small force values in the geogrid. Can one assure that the water content level will remain constant during the life span of the wall? What if an earthquake has occurred? Geotechnical practice ignores apparent cohesion for good reasons. Measuring reinforcement force in the field while apparent cohesion of unknown magnitude exists leads to potentially significant underestimation of the force needed for stability during the structure's life span.

be predicted accurately. As an unusual event, heavy rain may occur, increasing the backfill's degree of saturation leading to a diminished apparent cohesion. Many failures are associated with rainfall, sometimes just because of increase in the soil moisture content or its degree of saturation. It is not unusual for an earthquake to be preceded by heavy rainfall, leading to an increased impact: loss of apparent cohesion superimposed by seismic loading. Clearly, eliminating a significant redundancy in design associated with apparent cohesion, frequently existing under ordinary conditions, may lead to a catastrophic failure during or after rainfall. In some zones this redundancy becomes more important due to an increase in precipitation intensity caused by global warming.

3. Toe resistance

Assessment of toe resistance depends on hard-to-quantify factors such as downdrag force exerted by the backfill on the back of the facing and characterization of interface properties between the bottom of a small facing unit and the leveling pad or between the narrow leveling pad and the foundation soil. Moreover, it is not clear how that horizontal load-bearing capacity of the toe will change the distribution of load among the reinforcement layers above. Because the leveling pad is rather shallow, it takes minor excavation or scouring to minimize the toe resistance. Consequently, uncertainties related to toe resistance justify ignoring its impact while its existence adds to redundancy.

Exemption from seismic design

With some exceptions, current AASHTO design does not require seismic design if a/g<0.4. Japan Road Earthwork Code does not strictly require seismic design for noncritical walls shorter than 8m, while Japan Railway Earthwork Code requires seismic design for any wall

WALL FAILURE

This photo shows wall failure during a heavy rainfall caused by a typhoon. There was no adequate internal drainage in the fine-grained backfill although water in front of the wall was collected by a concrete-paved ditch. Redundancy due to apparent cohesion disguised the lack of proper drainage for four years, holding the wall system stable. When heavy rainfall occurred—as should have been expected during the life span of this wall—the apparent cohesion vanished resulting in failure.

height considering the largest seismic load anticipated during its lifetime.

These exemptions are mainly based on limited field observations as related to structures that were properly designed for static loading, but not necessarily for seismic loading. There is ample redundancy in static design that produces, under normal conditions, an overly conservative structure. This redundancy may also produce better-than-expected seismic performance. However, as discussed, this redundancy is generally highly variable, difficult to quantify, and not reliable. In actuality, a number of conventional cantilever retaining walls and mechanically stabilized earth retaining walls, including geosynthetic reinforced walls, failed during previous earthquakes, in some cases even when $a/g < 0.4$ and height less than 8.0m. It seems that for these structures no seismic design was performed or the design was for an insufficient level of seismic load. Consequently, the redundancy under static conditions was not enough to allow the reinforced wall to survive the particular seismic loads. Reducing the existing redundancy in static design combined with no seismic design may lead to an increased failure of retaining walls, including reinforced walls. In fact, it may invalidate the apparent field observations which have led to no seismic design, relying solely on static design that has large redundancies.

It is difficult to empirically extrapolate observations made under ordinary nonseismic conditions to proper seismic design. In a sense, similar difficulty exists in trying to extrapolate experiences, or empirical data, obtained for one type of structure to a different one (e.g., from simple geometry to tiered walls or to walls with various backslopes). Adequate design calculations, compatible with those required for static conditions, should be used for any seismic loading. Simply, the precise limit on exemption from seismic analysis for all reinforced wall systems

Good construction also means good drainage so positive pore water pressure cannot be developed.

seems awkward. For example, no seismic design if a/g<0.4, or if the height of the wall is less than 8m introduces an irrational and arbitrary discontinuity in design (e.g., the design becomes considerably different when a/g= 0.39 and 0.41 or when the wall height is 7.9m or 8.1m). Furthermore, the assertion that no seismic design is needed up to a certain limit implies that *all* MSE walls systems seismically perform similarly when below that limit. Is this the case?

Redundancy associated with geosynthetic strength

The ultimate tensile strength of geosynthetics is determined by testing virgin specimens where the load is applied at a high rate: an index test. This strength is adjusted to account for installation damage and durability. It is also adjusted for creep reflecting field condition of sustained constant static load. Two aspects of conservatism are associated with this adjustment:

1. Adjustments for strength due to installation damage and durability are assumed to be the same everywhere. Hence, the adjustment (reduction) factors multiply each other. This multiplication would be justified if the two reductions occur at the same location where the actual long-term strength of the reinforcement is needed. It is uncertain whether this will happen at exactly the same place. This uncertainty justifies the multiplication of these two factors.

2. More significantly, the adjustment for creep is linked to the required force in the reinforcement that may not correspond to normal conditions; i.e., it is the outcome of design that considers this force to exist during the life span of the structure. However, for most of the wall's life span, under normal conditions, the force in the reinforcement is substantially smaller than expected. For such conditions, the reduction factor for creep is not entirely relevant; in many cases it may be close to unity (i.e., practically no reduction for creep).

Underestimated soil strength, the existence of apparent cohesion, and the toe resistance all lead to a significant overestimation of load in the reinforcement under normal conditions. This amplifies the level of conservatism as related to geosynthetic strength because it results in overestimating the required geosynthetic long-term strength: the actual long-term sustained load is significantly smaller, requiring a much smaller reduction factor for creep. It certainly adds to redundancy. Perhaps this aspect of redundancy can be reduced.

Conclusions

Generally, geosynthetic reinforced soil structures are economical, capable of carrying high loads. Their high ductility prevents sudden collapse, but may exhibit progressive development of large deformations. However, too frequently, facing units fail. This internal failure is sometimes associated with breakage of

Photos: John R. Wolosick, Hayward Baker Inc.

INADEQUATE COMPACTION

These photos show a massive remedy utilizing anchors needed for an initially inexpensive geotextile reinforced wall. One reason that necessitated this remedy is poor compaction. Also, risers collecting surface water were embedded in the reinforced soil zone. These risers were connected sequentially by a 10-in. PVC pipe located in the reinforced soil.

Differential settlement of the poorly compacted backfill sheared the PVC pipes from the risers, essentially feeding surface water into loose soil causing further densification of the soil after construction was completed. The lesson in this case has to do with eliminating two related aspects of redundancy: poor compaction and locating the risers within the reinforced soil. Good compaction might have prevented the shear of the PVC pipes.

the connection between the geosynthetics and the facing unit, including rupture of the geosynthetic at connection. Such a failure is often triggered by poor drainage, poor compaction, and little redundancy in design and construction. Under such conditions the connection capacity is exceeded resulting in facing failure and limited sloughing.

Good design should preserve rational or relevant redundancy, same as is done in standard geotechnical practice: use conservative soil strength and ignore apparent cohesion and toe resistance. It should consider connection capacity and seismic loading as needed. Good design should ensure global stability under limit state conditions using the appropriate soil and reinforcement strengths.

The objective of good construction is not to realize the conservative conditions considered in design (e.g., allowable lower-bound level of compaction, no suction/no apparent cohesion and no toe resistance), but to produce relevant redundancy. Good construction should use adequate backfill that is well compacted. Perhaps the use of realistic in situ soil shear strength could be a reward for good compaction, encouraging this practice despite a resulting reduced redundancy.

Good construction also means good drainage so positive pore water pressure cannot be developed (i.e., no hydrostatic pressures). While not used in design, good drainage will result in high suction leading to high apparent cohesion and higher redundant system. Highly redundant structures perform well under extreme conditions. The cost of this redundancy outweighs the cost of failure or increased maintenance.

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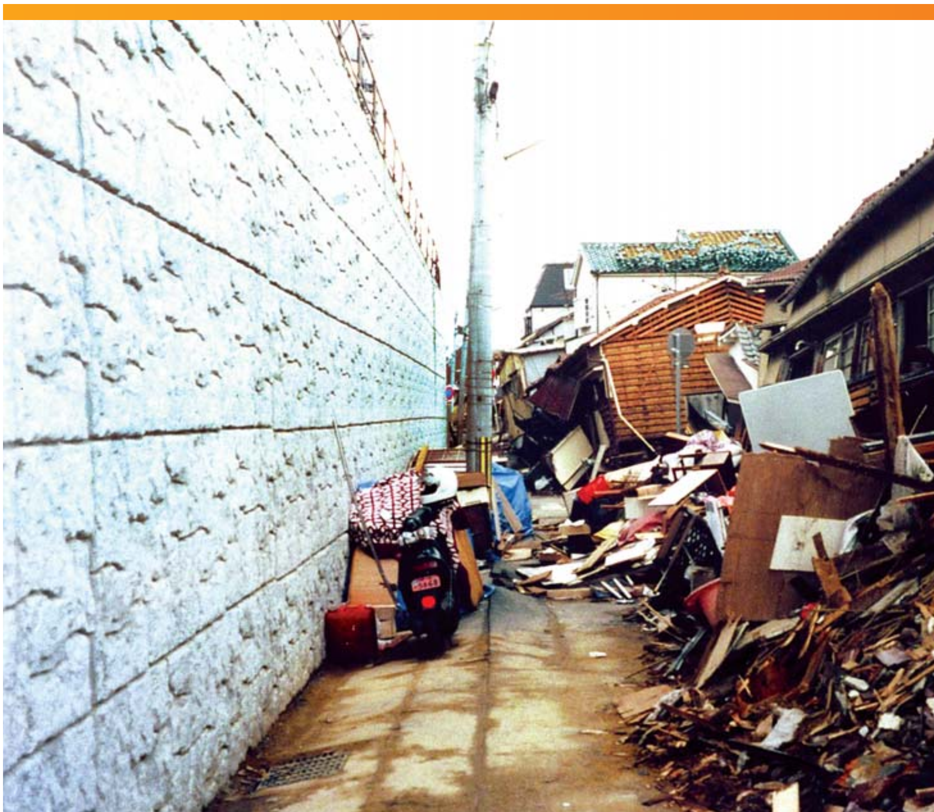

REDUNDANCY THAT HELPED A WALL TO SURVIVE AN EXTREMELY HIGH SEISMIC LOAD

This photo shows a geosynthetic-reinforced soil wall that survived a substantially higher seismic load than its designed seismic load. This resulted from redundancy due to use of soil design ϕ value lower than its actual value. Furthermore, the substantial apparent cohesion and toe resistance were also ignored.

Such a wall serves as a lifeline and its earthquake survival is critical. Note that survival of this type of MSE wall does not imply that all MSE walls would have equally survived. In fact, during the 2011 Great East Japan Earthquake, although all walls of the same type as the one shown in this photo were seismic-designed for a/g> 0.4 and performed very well, at least two different types of walls failed in ultimate state mode under seismicity of about a/g=0.30. These walls are exempt from seismic design per AASHTO, yet their existing static redundancy was insufficient.

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