

Geosynthetic Reinforced Retaining Walls
Murs De Soutenement Renforces Avec Des Geosynthetic
Geosynthetisch Verstaerkte Stuetzmauern

The performance and economic advantages of geosynthetic reinforced retaining walls are analyzed. Geosynthetic reinforced retaining walls are categorized by height and criticality of the application. The physical property requirements for geosynthetic reinforced materials are analyzed with respect to design and construction parameters. Optimum geosynthetic properties are suggested. Instrumentation results from two geosynthetic reinforced retaining walls are reviewed. Comparison of calculated versus measured values of stress and strain are presented. The comparison verifies the conservative wall design achievable through geosynthetic reinforcement and the tie-back wedge analysis for reinforced retaining wall design.

GEOSYNTHETIC VS. STEEL REINFORCEMENT

While the true origin of earth reinforcement using tensile stress resisting materials can be argued, the first commercial successful application of this concept was Reinforced Earth. (1) Since 1968 thousands of reinforced earth structures have been constructed using the patented design which calls for galvanized steel reinforcing strips in exclusively granular soils.

One of the primary concerns with steel reinforcement is its susceptibility to corrosion that can lead to loss of reinforcing strength and catastrophic wall failure. Nearly half of a steel reinforcing strips' cross-sectional area is provided to allow for corrosion. This sacrificial portion of the steel is not considered to contribute tensile reinforcing strength. Because of its corrosion potential even galvanized steel is restricted to reinforcement in cohesionless, granular, free draining backfills to reduce the potential for water and chemical attack. Slow draining and chemically aggressive soil backfills present a potentially corrosive environment that prohibits their use with steel reinforcement.

The advent of geosynthetic reinforcement materials has brought a new dimension of efficiency to design and construction of earth reinforced retaining walls due to their corrosive resistance and long term stability. The polyethylene and polypropylene polymers used in the majority of geosynthetics today are of the most chemically inert and nonbiodegradable materials commercially available to the construction industry. (2) The chemical inertness of these polymers make them ideally suited for use in even the most chemically aggressive environments, e. g. polyethylene membrane linings for hazardous waste containment. In addition to inertness, polymer technology provides the ability to produce thin and light weight planar structures with the tenacity of steel.

Die Durchfuehrung and wirtschaftlichen Vorteile geosynthetisch verstaerkter Stuetzmauern werden analysiert. Sie werden nach Hoehe und Anwendungsschwierigkeitsgrad klassifiziert. Die physikalischen Eigenschaften des geosynthetischen Verstaerungsmaterials werden in Hinsicht auf Design and konstruktions Parameter untersucht. Empfehlung optimaler geosynthetischer Eigenschaften.

Instrumentations Ergebnisse von zwei geosynthetisch verstaerkten Stuetzmauern werden besprochen. Vergleich von gerechneten and gemessenen Werten von Spannung und Verformung werden vorgestellt. Der Vergleich bestaetigt das die Stuetzmauerkonstruktion mit geosynthetischen Verstaerkungsmaterial und die Keilfoermige Rueckverankerung fuer die verstaerkte Stuetzmauerkonstruktion ein Konservativer Rechengang ist.

Geosynthetics combine these features to yield elements suitable for earth reinforcement in a variety of soil backfills.

For equivalent reinforcement value the cost of steel versus geosynthetic materials is comparable. But the ability to use low cost nonselect wall backfill and the ease of transport and handling due to lower material weight provide tremendous incentives to consider geosynthetics as an alternative to steel reinforcement.

RETAINING WALL CATEGORIES

The wall systems shown on Figure 1 all incorporate geosynthetic soil reinforcement to support a variety of wall facing systems. The utility of geosynthetic reinforcement with a variety of wall facings reflects the reality that the wall facing element will commonly represent a greater expense than the geosynthetic reinforcement. It is interesting to note that the use of geosynthetic reinforced soil techniques promise to correct the principal application fault traditionally associated with conventional masonry walls, that is, failure due to overturning.

Each of the wall facing systems shown in Figure 1 will have an economic advantage for a given wall geometry or height. Retaining walls can be divided into three distinct categories based on height as follows:

- o Low Walls: less than 3 meters in height
- o Medium Walls: 3 to 7 meters in height
- o High Walls: greater than 7 meters in height

Commercial and design details of these three distinct wall categories are given in Table 1.

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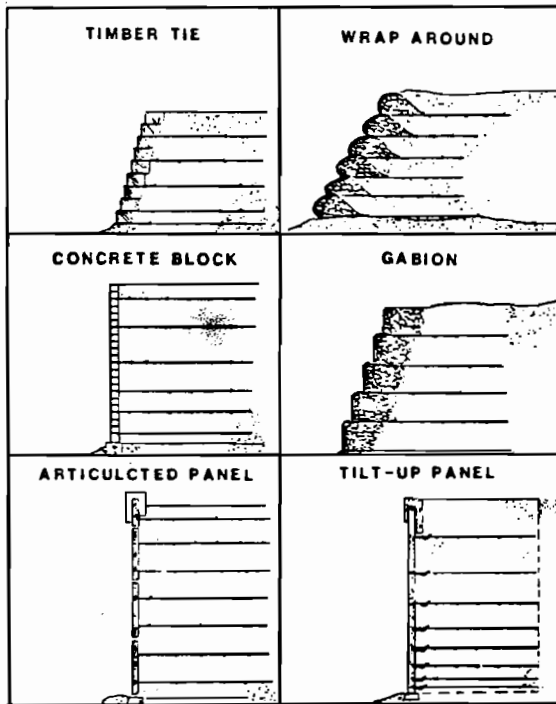


Figure 1 Geosynthetic Reinforced Retaining Wall System

Low walls are dominated by landscape type walls that are seldom designed and are typically constructed of salvage treated timber or concrete and nonselect backfill. Geosynthetics' future role in low wall construction will lie in their ability to be incorporated in both landscape and masonry wall systems such that the poor performance of these conventional walls can be improved. For a marginal increase in wall cost geosynthetic reinforcement can provide insurance against wall failure. Even with the additional cost of the geosynthetic, landscape and masonry walls will still provide a significant cost advantage over the reinforced concrete alternative.

Medium height walls are commonly constructed by both private and government bodies. This category is currently dominated by concrete or metal bin walls, cantilever concrete walls and reinforced earth type walls. Walls in this category typically require structural facing elements that are aesthetically appealing. Geogrid walls in particular should dominate this category because their high reinforcing strength offers the potential for a significant reduction in the number of layers of reinforcement required. To utilize this advantage, however, geogrid walls must provide structural face panels that can bridge the greater unsupported lengths between reinforced layers.

High walls are almost exclusively built for government highway agencies. All high walls require durable facing elements. In the United States it is expected that the vendor will provide and be responsible for the complete design of earth reinforced walls. Geosynthetic walls in this "high" category will require both a standardized facing system and a new generation of higher tensile modulus materials such as geogrids to compete against reinforced earth type structures.

The predominant forces of resistance to the use of geosynthetic reinforced retaining walls are lack of time proven experience and fear of wall failure and its consequences. This resistance, however, is almost directly proportional to a wall structure's perceived level of criticality. Of course, all walls are critical structures to the design engineer who is liable for their performance. However, from a practical point of view, walls can be classified as either noncritical or critical.

The noncritical wall is typically a low to medium height structure and can be defined by the following conditions:

- o wall failure does not result in significant damage to adjacent structures or property;
- o evidence of potential failure appears well in advance of failure allowing time for corrective measures to be implemented;
- o cost of corrective measures or repairs are less than the original wall structure cost; and
- o political ramifications of wall failure are negligible to those liable for wall stability.

In contrast, critical walls are typically medium to high structures that do not comply with all the noncritical criteria above.

Currently the greatest potential market for geosynthetic reinforced retaining walls is in the low to medium and noncritical wall category. Time proven experience must be gained through design and construction of these wall types in order to gain acceptance and use for higher more critical wall structures.

OPTIMUM DESIGN PROPERTIES

Selection of geosynthetic reinforcement materials should be first based on performance criteria and second on material costs. Performance requirements are typically controlled by the material properties that impact internal and external stability according to the design analogy. In addition, properties that influence construction procedures and wall aesthetics must be considered.

Design methods for geosynthetic reinforced earth walls are not newly developed. In fact, the analogies used are the same as those developed over 15 years ago for use in steel reinforced earth structures, i.e. tie back-wedge and cohesive gravity procedures. Of the two, the tie back-wedge analysis is the most appropriate for geosynthetic reinforcement because its assumptions most closely correspond to the conditions of soil strains required to mobilize tensile strength in extensible reinforcements (3). In brief, the design must assure both external and internal stability of the wall.

External stability of retaining walls is verified using the three postulated modes of failure shown in Figure 2. These modes include failure due to sliding, overturning, and foundation bearing capacity failure at the toe of the wall. External design forces used to calculate factors of safety for these modes of failure are shown in Figure 3. Overall stability should also be checked.

Geosynthetic - Soil Friction

It should be noted that sliding is the only mode of external failure that is directly influenced by properties of the reinforcing media. The factor of safety against sliding is defined as follows:

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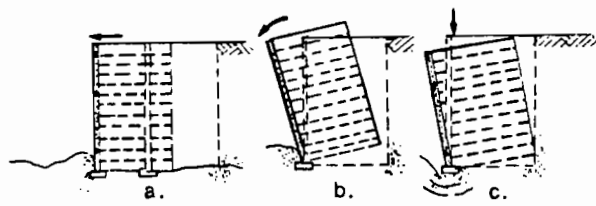


Figure 2 Modes of Wall Failure: a) sliding, b) over-
 turning, and c) bearing.

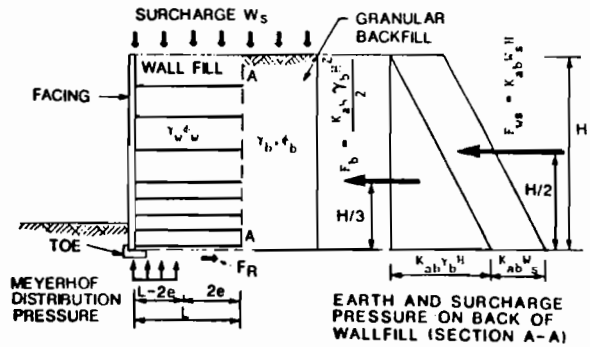


Figure 3 External Design Forces

TABLE 1: General Characteristics of Wall Types

Wall Category	Wall Type	Components	Designer/Methods	Fill Types	Performance	Component Cost, \$/ft ²
Low Wall (3 m)	Landscape	Railroad ties, concrete salvage	Typically no engineered design	All types	Poor	\$2 - \$3
	Masonry	Press block, brick	Not recommended for earth retention by ACI	All types	Poor	\$4 - \$8
	Cantilever	Reinforced concrete	Clients designer provides internal stability per ACI and ensure external stability	Granular	Very good	\$10 - \$16
	Geosynthetic	Geogrid or geotex- tile with wrap around, tie, block or gabion face	Clients designer provides internal stability per tie-back analogy and ensures external stability	Granular	Very Good	\$2 - \$11
Medium Wall (3 to 7m)	Gravity	Gabion, bins, cribs	Internal stability per vendors specs, external stability per clients designer	Granular	Good	\$3 - \$7 (gabion) \$11 - \$22
	Cantilever	Reinforced concrete	See low wall cantilever	Granular	Good	\$13 - \$35
	Reinforced Earth	Concrete face panels with steel strips or grids	Complete design provided by vendor	Select Granular	Very good	\$12 - \$18
	Tie-Back	Concrete face anchored with steel tendons	Complete design provided by vendor	Granular	Good	\$10 - \$16
	Geosynthetic	Geogrid or geotex- tile with wrap around, tie, block or gabion face	Vendor or clients designer provides internal stability per tie-back analogy and ensures external stability	Granular	Good - Very Good	\$4 - \$12
High Wall (7m)	Counterfort	Reinforced concrete	Clients' designer provides internal stability per ACI and ensures external stability	Granular	Good	\$30 - \$55
	Reinforced Earth	Concrete face panels with steel strips or grids	Complete design provided by vendor	Select Granular	Good	\$15 - \$36
	Geosynthetic	Geogrids with face	Complete design provided by some vendors	Granular	Good	\$12 - \$32

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$$F.S.SL = \frac{\text{resisting force}}{\text{sliding force}} \quad (\text{Equation 1})$$

The minimum factor of safety against sliding is typically greater than or equal to 1.5. Federal agencies in the U.S. and Great Britain require a minimum of 2.0.

The resisting force for wall systems using sheets of geosynthetic reinforcement is directly influenced by the apparent friction that develops between the soil and the reinforcement sheet. The influence of this apparent friction coefficient on the sliding factor of safety is shown on Figure 4. With horizontal backfills it is apparent that walls having aspect ratios for the reinforced zone (the ratio of wall height to the effective depth of reinforcement) greater than 0.7 have a minimum sliding factor of safety of 2.0 even if the friction angle between the soil and the reinforcement falls to $0.6 \tan \phi$, where ϕ is the internal angle of friction of the soil. On the other hand, sloping backfills above the wall have dramatic impact on the reinforcement-soil frictional requirements. For a backfill slope of only 3:1, a minimum sliding factor of safety of 2.0 for an aspect ratio of 0.7 can be obtained only if the effective friction angle equals the full soil friction angle. For optimum stability against sliding failure, the geosynthetic-soil friction should be equal to the soil's internal friction ($\tan \phi$).

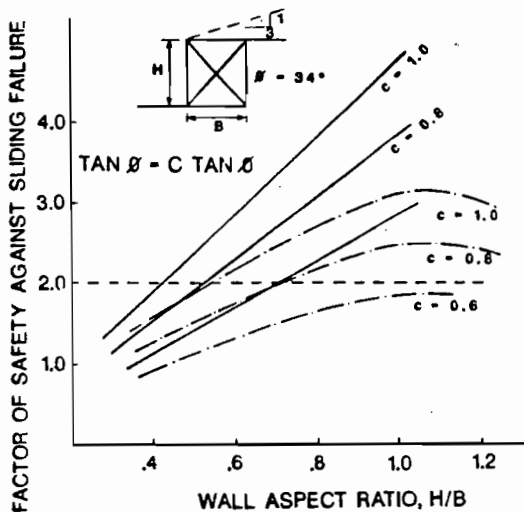


Figure 4 Sliding Factor of Safety is controlled by wall geometry and geosynthetic - soil friction.

The value for geosynthetic-soil friction can be evaluated by pullout tests. Figure 5 shows the typical results of pullout tests using TENSAR Geogrids SR2 and a woven polyester geotextile embedded within sand. (4) The geogrid tested demonstrates an apparent friction angle greater than or equal to the internal angle of friction of the soil. The geotextile's apparent friction angle is considerably less. These results highlight the importance of pullout resistance testing to establish the design value for soil-geosynthetic friction.

Having assured that the reinforced soil mass is stable due to external loading, it is now necessary to confirm that the components comprising the reinforced soil mass are also stable. The design lateral earth pressure at a layer of reinforcement can be calculated as the product

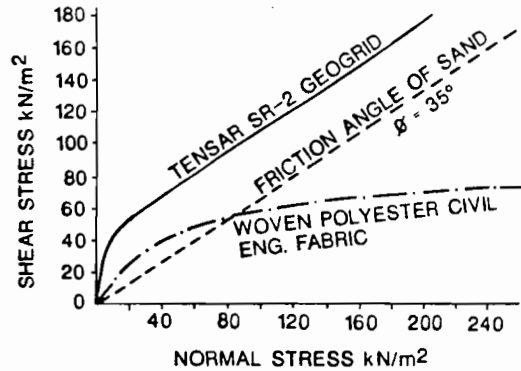


Figure 5 Geosynthetic - sand friction measured by pullout tests (Reference 4)

of the trapezoidal or Meyerhof vertical pressure multiplied by the lateral earth pressure coefficient (3). The design force in each layer of geosynthetic is calculated as the product of the lateral earth pressure on the wall face multiplied by the face area tributary to the geosynthetic layer.

The above procedure results in a maximum tensile force per unit length in each layer of geosynthetic. Two modes of failure must then be investigated for each layer of geosynthetic reinforcement: (1) pullout failure due to insufficient bonding or embedment within the soil, and (2) tensile failure due to design tensile forces.

Evaluation of potential pullout failure of a given layer of geosynthetic requires assumptions for the effective embedment length of the reinforcement and the apparent friction angle defining the bond between the soil and the geosynthetic. The effective length of a given layer of geosynthetic is dependent upon the shape of the failure wedge assumed to develop within the reinforced soil. The failure surface assumed in the design of most geosynthetic walls is either the Rankine failure wedge or a modified Rankine surface (3). The length of geosynthetic lying within the assumed failure zone is neglected in defining the effective length or the depth of the reinforcement. Additionally, the failure zone boundary is assumed to define the locus of the points of maximum stress in the reinforcement.

Design pullout resistance of a given layer of geosynthetic is calculated by the product of the effective area of the geosynthetic and the tangent of the apparent soil-geosynthetic friction angle, i.e. $\tan \phi'$ discussed earlier with respect to external stability. The $\tan \phi'$ value for geosynthetics is often assumed to be some value less than the $\tan \phi$ of the reinforced soil. This is a valid assumption for geotextiles that can only interact with soil particles through surface friction. This is not, however, the case for geogrids as illustrated in Figure 5. The openings within the geogrid geometry allow interlocking of soil particles and result in formation of micro-soil anchors at the face of the grid's cross elements.

For optimum pullout resistance as well as sliding stability the optimum geosynthetic reinforcement should have $\tan \phi'$ equal to the $\tan \phi$ of the reinforced soil.

Geosynthetic Reinforced Retaining Walls
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Creep Limited Design Stress

Traditionally, tensile failure is prevented by limiting the design stress in the reinforcement to some percentage of its ultimate load capacity. For steel reinforcement, the ultimate load capacity is significantly reduced by corrosion considerations. For geosynthetic reinforcements, the ultimate load capacity may be significantly reduced by creep potential of the geosynthetic. All polymers exhibit some level of creep deformation. Therefore, it is imperative to limit the design loads carried by geosynthetic reinforcement to prevent excessive creep deformation.

The maximum design load based on the strain limit will vary depending on polymer composition and construction of geosynthetics. Creep analysis is therefore a critical requirement for defining design limits of all geosynthetic reinforcement.

Creep behavior of geosynthetics have been evaluated in isolation to predict the long term deformations that can be expected in geosynthetic reinforced earth structures. (5, 6). Typical creep strain versus time results for geosynthetics can be analyzed to show the creep rate versus total strain for a given load as shown in Figure 6 for Tensar SR2 Geogrid. This analysis can be used to predict the maximum allowable design load and strain limit for geosynthetics.

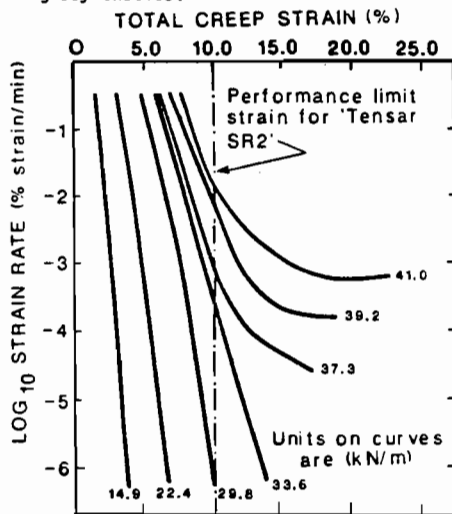


Figure 6 Creep Rate versus Creep Strain for Tensar SR2 Geogrid (Reference 6)

Tensile Modulus

It is ironic that this tie-back wedge analysis does not consider the strength versus elongation character of the reinforcing media. Nowhere in the analogy is there reference to or need for a modulus value in the reinforcement. When this design analogy was developed, steel was the commercially available reinforcement. It is intuitively obvious that the tensile modulus of steel is orders of magnitude greater than the compressive modulus of soil. In theory, even the slightest soil strain will mobilize steel's tensile reinforcing strength. This is not the case with geosynthetic reinforcements.

The strength versus elongation behavior of geosynthetics span a broad range. For example, geogrids that claim ultimate tensile stress equivalent to steel reach peak strength at relatively low extensions (less than 20%

elongation). Geogrids therefore demonstrate a relatively high initial tensile modulus and generate high reinforcing strength at the low deformation or strain levels normally experienced in the soil mass before failure, i.e. working strain level. Nonwoven geotextiles on the other hand typically do not reach their peak strength before elongating to 50 to 100%. As a result, nonwoven geotextiles have very low initial moduli and therefore generate only a small percentage of their peak strength at the working strain levels of soil masses. Woven geotextiles typically have tensile moduli within the range between geogrids and nonwoven geotextiles.

Note that it may be impractical to use many geosynthetics in conjunction with wall facing elements because of the high anticipated strains during construction. As a result, certain moderate to low modulus geosynthetics may be restricted to wrap-around wall face techniques where relatively high deformations can be accommodated without sacrificing wall stability or where wall aesthetics are not critical.

DESIGNED VS. MEASURED STRESSES

In 1985, two TENSAR Geogrid reinforced retaining wall projects were constructed and instrumented for post-construction monitoring (7). Both walls were built using concrete facing panels with TENSAR SR2 geogrid reinforcement and granular backfill. The maximum heights of the walls were 4.7 and 6 meters. Instrumentation included load cells and strain gauges at selected elevations and distances behind the wall both within the wall backfill and on the geogrid. Results from this instrumentation are being used to compare calculated versus measured stresses.

The two most commonly used techniques for calculating vertical stresses within the reinforced zone of an earth reinforced wall are to assume a trapezoidal stress distribution or a Meyerhof stress distribution for eccentrically loaded footings (3). Both methods predict maximum vertical stress at the wall face and minimum vertical stress at the back of the reinforced soil mass. The trapezoidal stress distribution technique was used in designing the two reinforced walls referenced here.

Horizontal and vertical stresses in the reinforced soil mass of these walls were measured using load cells. The measured values of horizontal stress approached the calculated values near the toe and near the top of the wall. However, the measured values were substantially lower than the calculated values at intermediate elevations. Figure 7 is an example of the measured values of horizontal stress compared to calculated values. It is important to note that measured values of horizontal stress are conservatively bounded by the calculated stress distributions using the trapezoidal, as well as the Meyerhof and Rankine lateral pressure distributions.

Figure 8 provides an example of the vertical stresses measured along with the calculated values. Measured vertical stresses were lower near the wall face than in the center portion of the reinforced soil mass. This is contrary to the tie-back wedge analysis which predicts maximum vertical stress at the wall face.

Geogrid strains were also measured for one of these walls using resistant strain gauges. Figure 9 illustrates the magnitude of these strains at selected elevations. The actual peak strain values are very small compared to those predicted based on the calculated tensile forces expected within the geogrid reinforcement. This indicates that any wall deformation observed is most likely a result of geogrid-panel connections and backfill compaction rather than load induced strain of the geogrid.

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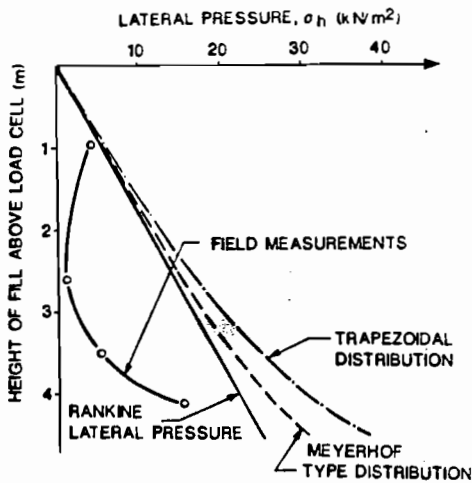


Figure 7 Horizontal Soil Pressure - Tensar Wall (Reference 7)

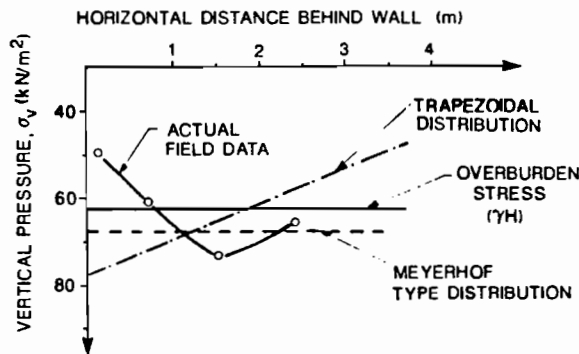


Figure 8 Vertical Soil Pressures - Tensar Wall (Reference 7)

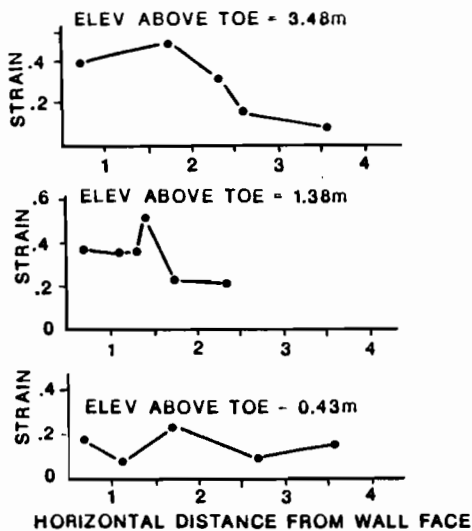


Figure 9 Geogrid Strain Tensar Wall (Reference 7)

Conclusions

- o Geosynthetic reinforcement can provide significant economic advantages over steel in earth reinforced retaining walls because geosynthetics are noncorrosive and can be used in conjunction with nonselect backfills.
- o The predominate near term market for geosynthetic reinforced retaining walls is in medium to low height, noncritical walls.
- o Of all commercially available geosynthetics, geogrids offer optimum stability against wall sliding and reinforcement pullout failure due to their high frictional bond with soil backfills.
- o Maximum allowable design strengths for geosynthetic reinforcements may be controlled by creep. Creep analysis will identify the critical performance limits of geosynthetics under sustained loading.
- o The role of reinforcement modulus is not defined in the current wall design procedures. Design methods predicting working stress states are required to properly incorporate the role of reinforcement modulus.
- o High tensile modulus geosynthetics are preferred for earth reinforced retaining walls to minimize wall face deformation during and after construction.
- o Instrumentation results from geosynthetic reinforced retaining walls suggest that vertical soil stresses and strains in the reinforcement are significantly smaller than predicted by the tie back-wedge design analysis.

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ACKNOWLEDGEMENTS

Special thanks to R. Berg, R. Bonaparte, P. Crenshaw, R. Johnson, B. Hutcheson, D. Campbell and K. Pottinger for assistance and guidance.