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Evaluation of Lateral Stress Ratio (K_r/K_a) for Geosynthetic strip Reinforcements in Mechanically Stabilized Earth Walls

Evaluation du rapport de contrainte latérale (K_r/K_a) pour les bandes géosynthétiques Renforts dans les murs de terre stabilisés mécaniquement

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ABSTRACT: Soil reinforcements utilizing geosynthetic strips have been used successfully for more than four decades in the design and construction of Mechanically Stabilized Earth (MSE) walls around the world. The design of structures reinforced with geosynthetic strips have considered the reinforcement to be either inextensible or extensible, depending on the county and its design code. The AASHTO LRFD design specifications do not contain explicit guidance on the K_r/K_a or coefficient of lateral stress ratio for polymeric strip reinforcement. As such, it is necessary to correlate material properties, historic data, lab testing and numerical analysis to substantiate a comprehensive design methodology for geosynthetic strip reinforced MSE walls. Data and analysis will be presented to support the use of the Simplified Method, considering the geosynthetic strips as extensible reinforcements. A parametric study comparing the Coherent Gravity Method with a bilinear active wedge and the Simplified Method with a Rankine failure wedge will be presented. For purposes of design in accordance with the AASHTO LRFD 2015 specifications, the authors have investigated the use of the Simplified method with a Rankine Failure Wedge. The paper will provide information related to design methodologies when geosynthetic strips are classified as extensible reinforcements, including substantiating evidence for use of K_r/K_a=1.0 for design.

Résumé : Les bandes de renforcement géosynthétiques pour le dimensionnement et la construction de murs en sol renforcés ont été utilisées avec succès depuis plus de quatre décennies. Dans le dimensionnement des structures, selon les codes en vigueur dans les pays, les bandes de renforcement géosynthétiques sont considérées soit inextensibles, soit extensibles. La norme de conception AASHTO LRFD ne présente aucune recommandation explicite sur le rapport K_r/K_a ou sur le coefficient de poussée à appliquer dans le cas des bandes de renforcement en polymère. A cet effet, il est nécessaire de corréler les propriétés du matériau, les données historiques, et les essais en laboratoire à une analyse numérique afin d'établir une méthode de dimensionnement complète pour les murs de soutènement renforcés par bandes géosynthétiques. Des données et des analyses seront présentées afin d'étayer l'utilisation de la méthode dite « Simplified Method » en considérant que les bandes de renforcement géosynthétiques sont extensibles. L'article fournira des informations relatives aux méthodes de dimensionnement quand les bandes de renforcement géosynthétiques sont classifiées comme étant extensibles, incluant la justification de l'utilisation du ratio K_r/K_a=1 pour le dimensionnement.

KEYWORDS: Geosynthetic strip. K_r/K_a, Simplified method, AASHTO LRFD 2015, coefficient of lateral stress ratio

1 INTRODUCTION.

Geosynthetic strips for soil reinforcements have been used successfully for nearly 40 years in the construction of MSE walls in several countries around the world. Over the course of usage, geosynthetic strips used in systems such as Websol™, Freyssisol™ and GeoMega™ have been categorized as either inextensible or extensible, depending on the context of the particular design method, local codes, material property or structural behavior being discussed.

Due to the requirements in AASHTO for designing geosynthetic reinforcements using the Simplified Method with a Rankine Failure Wedge it is necessary to utilize a coefficient of lateral stress ratio K_r/K_a. The following paper provides the background information related to current design practice of classifying 50mm polyester geosynthetic strips as extensible reinforcements, and substantiating evidence as to why K_r/K_a=1.0 is an appropriate design value.

1.1 *Fundamental properties*

1.1.1 *Definition of inextensible and extensible*

McGown et al (1978) originally defined the differences between the relative extensibility of the reinforcement inclusions.

Inextensible inclusions are those that "have rupture strains which are less than the maximum tensile strains in the soil without inclusions, under the same operational conditions"; and "Extensible inclusions are those that have rupture strains larger than the maximum tensile strains in the soil without inclusions, under the same operational conditions"

British Standard BS8006 provides a more recent definition of extensibility for MSE reinforcements:

"Extensible reinforcement: reinforcement that sustains the design loads at strains greater than 1%. Inextensible reinforcement: reinforcement that sustains the design loads at strains less than or equal to 1%

1.1.2 *Stress Vs. Strain*

Geosynthetic strips Due to manufacturing techniques that produce a linear element without junctions or kinks, geosynthetic strips provide higher strength at lower strains than traditional full width geosynthetics

The graph below shows a polymeric strip 50mm wide and a nominal tensile capacity of 50kN achieving higher load capacity at lower strains than traditional full width geosynthetics. Although capable of very high load capacity, the stress-strain behavior during tensile test the geosynthetic strip more closely follows that of a geosynthetic.

1.1.3 *Pullout behavior and distribution of tensile force along length of reinforcement*

When compared to inextensible strips in pullout tests, polyester strips exhibit similar behavior with regard to dilation frictional behavior as presented by Lozano and Sankey in 2013 (Figure 4).

However upon review and based on figure 5 (Anderson, Gladstone & Sankey 2012), it is clear that polyester strips develop frictional resistance differently than inextensible steel strip reinforcements, and as evidenced by the lack of trailing end displacement on the polyester strip, pullout behavior more closely follows extensible reinforcement.

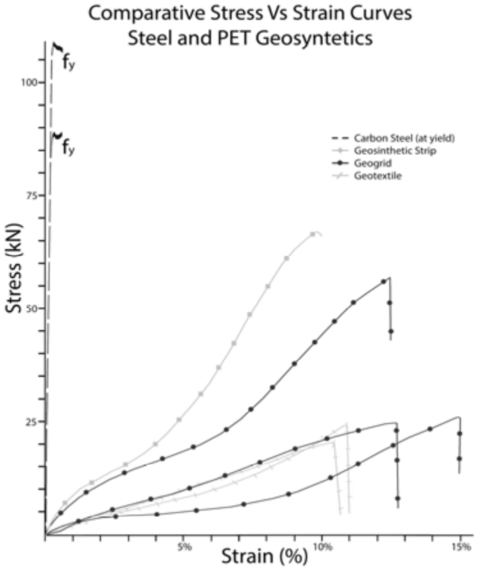

Figure 03 – Stress Strain Curves for polymeric and steel reinforcement

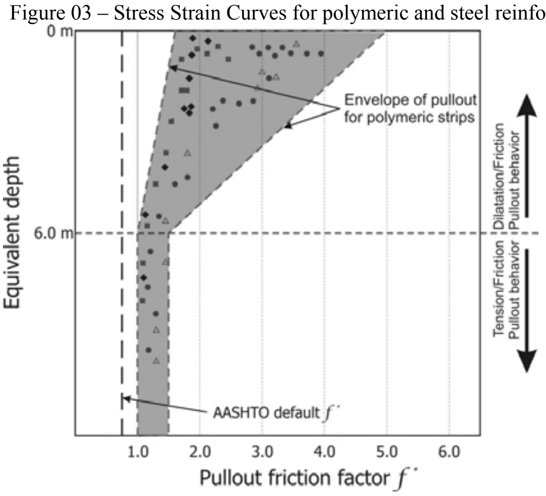

Figure 04 – Pullout envelope of f* for polymeric reinforcement (Lozano et al 2013)

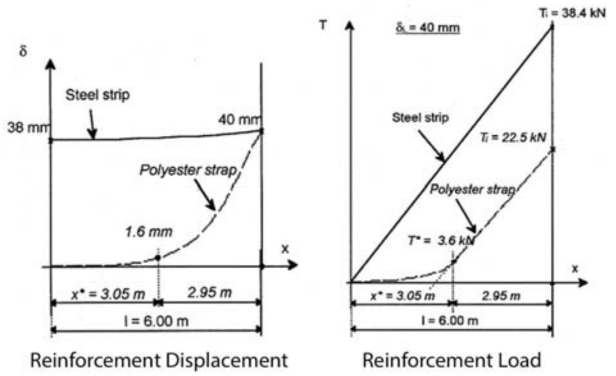

Figure 05 – Frictional resistance development for reinforcement (Anderson, Gladstone & Sankey 2012)

1.2. Instrumented structures reinforced with polyester strips discussed in the literature

Although geosynthetic strip reinforcements have been in use worldwide for decades, there is limited instrumented structure data available for comparison of design methods and in place reinforcement loads. The major reason for this is the complexity in attaching the right type of instrumentation directly to polyester fibers in the geosynthetic strip. Due to the two part composition of a geosynthetic strip (polyester fibers encapsulated in a polyethylene sheath), it has proven extremely difficult to install strain gages that can withstand the rigors of earth moving construction, without substantially altering the reinforcement geometry and stiffness properties. As such, out of the hundreds of structures constructed, there are only two relevant case histories with sufficient data in the instrumentation available in the literature. These structures will be discussed below and are referred to as (1) the St. Remy wall and (2) the Christiana wall.

1.2.1 St. Remy wall

This wall located in St. Remy France, was built in the late 1980s and reported around 1993. It was constructed with 90mm wide ParaWeb 2S reinforcements with a tensile strength per strip of 100kN. These reinforcements, which are predecessors of current generation of geosynthetic strip, are nearly twice as wide and twice as strong as current geosynthetic strips commonly used for construction of MSE structures worldwide. This wall was designed to have a trapezoidal reinforced zone with a lower zone width of 0.84H, a middle zone width of 0.95H, and an upper zone width of 1.27H. The St. Remy wall had a vertical reinforcement spacing of 0.8m typically and a horizontal reinforcement spacing of 0.5m on average resulting in a tributary area of 0.4m^2 per pair of geosynthetic strip. For reference, a typical MSE currently constructed in the US using geosynthetic strips of this height would have a vertical reinforcement spacing of 0.75m and a horizontal reinforcement spacing of 0.75m resulting in a tributary area of 0.563m^2 per pair of soil reinforcement strips.

In a paper published in Geosynthetics International titled “Soil Reinforcement Loads in Geosynthetic Walls at Working Stress Conditions” (Allen and Bathurst 2002) reports 16 fully instrumented walls were evaluated for the purpose of developing a statistical based design method called the K-Stiffness method to be used in lieu of the traditional limit equilibrium design methods. Of the 16 geosynthetic reinforced walls referenced, one (REF GW19) used a polyester geosynthetic strip.

Allen and Bathurst performed a comparison between the measured reinforcement loads and the predicted loads based on the Tieback Wedge/Simplified Method. This comparison is reported in Section 4.2 and Figure 1. The authors specifically mention the St. Remy wall and state *“the reinforcement loads in walls GW7 and GW19 [St. Remy] were predicted more accurately (i.e., with minimal conservatism) as compared to the other walls with the Tieback Wedge/Simplified Method.”* Note, the Tieback Wedge/Simplified Method uses a K_r/K_a value of 1.0 uniformly from the surface to any depth.

In order to back-calculate a K_r/K_a value for use in the Simplified Method directly from the Reinforcement Load values provided by the authors, one must use the same properties that the Simplified Method uses, specifically the soils shear strength from either direct shear or triaxial shear tests. For the St. Remy wall, an in plane strain shear strength of the soil was reported as 39 degrees by Allen and Bathurst.

For comparison purposes, the same structure is reported in the literature (Schlosser, et al 1993) as having a peak shear strength (via triaxial testing) of 37 degrees. In addition, the Schlosser paper provides a figure with higher measured reinforcement loads than reported by Allen and Bathurst. It is our understanding that the loads reported by Schlosser are based on an instantaneous Modulus of 9600kN/m, while the Allen and Bathurst reinforcement loads are based on a reduction of 75% (correlated to a creep Modulus value of 7400kN/m). Refer to section 2.13 of the Allen and Bathurst paper for additional information (Allen and Bathurst 2002).

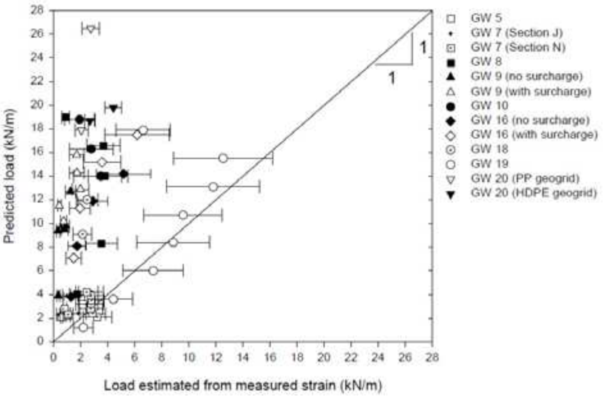

Figure 06 – Predicted versus reinforcement load estimated from strain measurements from full scale field geosynthetic walls, using the AASHTO Tieback Wedge/Simplified Method and triaxial or direct shear peak shear strength values (Allen and Bathurst 2002).

The Schlosser paper (Schlosser, Price and Hoteit 1993) provides information regarding the Maximum Dry Unit Weight (average 16.40kN/m^3), the Optimum Moisture Content, and a discussion on the effects of weather during construction. As such, the authors utilized a Moist Unit Weight of 17.55kN/m^3 (corresponding to an average moisture content of 7%) in our calculation of predicted reinforcement loads. It is noted on page 12 of the Schlosser paper that during the final stages of construction, heavy rainfall occurred and the moisture content of the completed wall is closer to 12%. The higher moisture content and effects of heavy rains may have played a part in the slightly higher than predicted measured reinforcement loads.

Based on the load data presented by Allen and Bathurst and soil shear strength of 37 degrees, the maximum K_r/K_a value at the surface is approximate 1.38. This value varies linearly to less than 1.0 at a depth of 3.0 meters. It should also be noted that due to the relatively low measured and predicted reinforcement tensions at the upper portion of the wall, small variabilities in measured vs. predicted values result in large K_r/K_a ratios. Consequently, a measured tension of 1.93kN/m vs. a predicted tension of 1.59kN/m is off by 21%, but the difference is a trivial 0.34kN/m. Per the Schlosser paper, it is noted that a pretension of approximately 0.8kN per strip is provided, which roughly equates to 1.6kN/m. Thus, the effect of pre-tensioning exceeds the measured load in the top reinforcement level. Therefore, it is possible that the uppermost level of reinforcements actually relaxed under the applied load.

Additional reasons for the increased K_r/K_a value at the surface are summarized below:

1. 37 degrees is the peak shear strength of the soil. Due to the high strength (100kN each) of the geosynthetic strips utilized, the soil reinforcement performs a larger percentage of the work, and thus the peak strength of the soil is not mobilized.
2. If a mobilized shear strength of 34 degrees is utilized to predict the reinforcement strip tension, a constant K_r/K_a value of 1.0 accurately predicts the measured tensions at the top of the wall (with an inconsequential under-prediction of 0.44kN/m at the uppermost level, while significantly over calculating the measured tensions at depths greater than 3.0m
3. The effects of compaction equipment imparting locked in compaction stresses in the upper portions of inextensible reinforced MSE walls are a common phenomenon. Although polyester strips are commonly classified as extensible reinforcements, as discussed before they have lower extensibility compared to most geosynthetics commonly used. If a 12kPa surcharge is used in the Simplified analysis to model the effects of compaction equipment, the predicted reinforcement force is in good agreement with the values presented by Schlosser and exceeds the values presented by Allen by a large percentage.

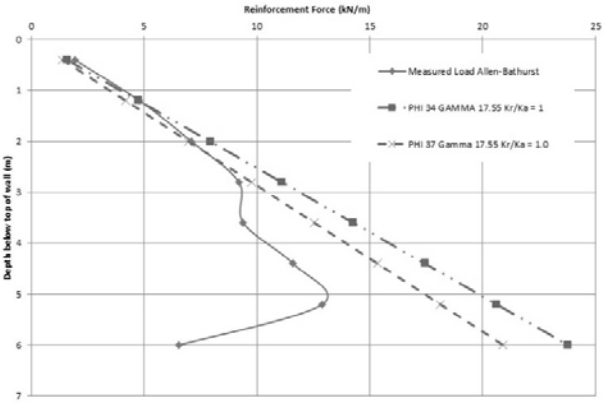

Figure 08 – Reinforcement Tension vs. Depth (St. Remy Wall)

4. The top level of reinforcements is located 400mm below grade. Typical depth of reinforcements is anywhere from 600mm to 750mm below grade. The effects of compaction stresses and small deviations in loading result in higher variability of measured results.

In summary, the variation in reported reinforcement loads between the Schlosser and Allen reports are based on different reinforcement stiffness used to convert the measured strain to reinforcement load. Based on the explanation provided by Allen in the referenced report section 2.13, along with a similar behavior of relaxed reinforcement loads measured with time in the Christiana wall discussed below, it is our opinion that the use of the Simplified Method, with a $K_r/K_a = 1.0$ adequately predicts the reinforcement loads for the St. Remy Wall.

1.2.2 Christiana wall

Recently a polyester strip wall located in Christiana, Delaware, USA, for the Delaware Department of Transportation (DELDOT) was instrumented as required by DELDOT for confirmation of design parameters/methodologies. A study of the collected data was performed by D. Leshchinsky and others and presented at the 2015 TRB Conference in Washington, DC. This wall consisted of ParaWeb™ 2D 30kN and ParaWeb™ 2D 50kN soil reinforcements with a tensile strength of 30kN and 50kN respectively. Pairs of reinforcements were placed at a vertical spacing of 0.76m and a horizontal spacing of 0.76m resulting in a tributary area of 0.578m^2.

In order to account for the apparent cohesion found in laboratory testing, Leshchinsky et. al used a secant model to determine the effective soil shear strength of 51 – 54 degrees. By back calculating a Ka value based on the recorded tensions in the reinforcements (assuming a K_r/K_a ratio of 1.0), they determined that the effective soil strength would need to be between 49 – 55 degrees. This closely agrees with the previously determined effective shear strength, therefore verifying a K_r/K_a ratio of 1.0 for this wall. The following figure was developed by the authors of the paper in order to comparing the measured tension of the Christiana wall versus the loads predicted using the Simplified Method (K_r/K_a =1.0) and various design friction angles. As shown in the figure, the use of a 50 degree design friction angle envelopes the field data.

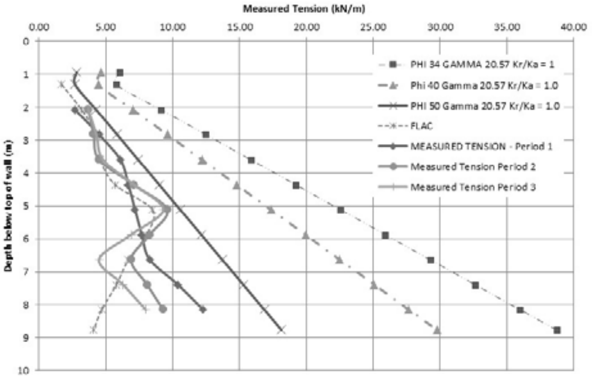

Figure 09 – Measured Tension vs. Predicted Tension (Christiana Wall)

Although it has been shown that a design friction angle of 50 degrees conservatively envelopes the field data for the Christiana Wall, a maximum friction angle for design of 40 degrees would be in accordance with the current AASHTO specifications.

Below is a figure from the Leshchinsky paper showing K_r/K_a with depth (calculated with a 50 degree friction angle).

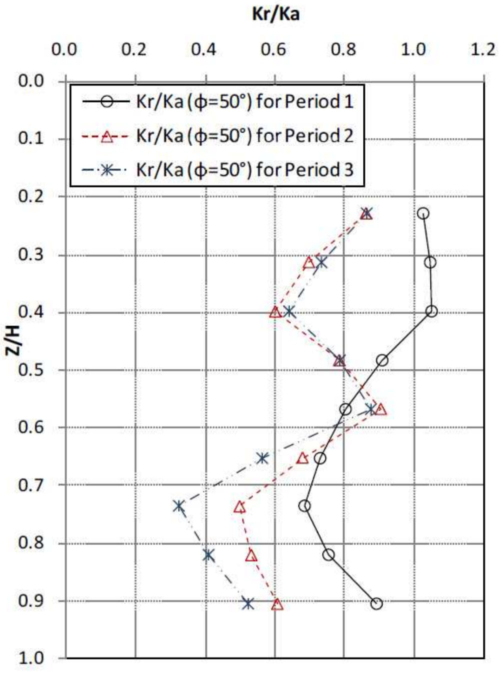

Figure 10 – Variation of K_r/K_a with depth after Lou at al (Lou, Leshchinsky, Rimoldi, Lugli, Xu 2015)

1.2.3 Comparison of design cases bilinear failure wedge with ko to ka Vs. Rankine wedge with ka top to bottom

In order to confirm that the proposed design methodology using $K_r/K_a = 1$ and a Rankine Failure wedge is appropriate for design, we have performed a side by side parametric analysis for wall heights ranging from 4.5 m to 11 m, comparing a bilinear failure wedge with K_0 to K_a (inextensible behavior) to Rankine failure wedge with $K_r/K_a = 1.0$. The results for reinforcement spacing and strength requirements are nearly the same. The use of a pair of 50 kN Geosynthetic strip s, spaced at 750mm vertically and 1000mm (max) horizontally results in virtually the same reinforcement design for either analysis method.

The inextensible design approach results in higher reinforcement tensions, but provides longer effective length against pullout at the top of wall. Below 3m, the inextensible design approach significantly over-estimates the reinforcement tensions. The Extensible design approach more closely follows the Numerical Modeling tension results, yet still conservatively predicts reinforcement tensions that are greater than predicted by numerical modeling.

The numerical modeling performed by the authors utilized FLAC. Due to required limits for the length of this paper, the FLAC study will be presented in a future paper.

2 CONCLUSION

The above information provides the basis of design of geosynthetic strip reinforced MSE walls as extensible, using the Simplified / Tie Back Wedge design method and a K_r/K_a = 1.0. Physical modeling in the lab consisting of stress-strain and pullout tests demonstrates extensible behavior. The two instrumented MSE walls were referenced to determine an appropriate design ratio of K_r/K_a for use with the Tieback Wedge/Simplified Method prescribed in the AASHTO Bridge design specifications. Finally, numerical modeling using FLAC software confirms the predicted tensions with 50 kN Geosynthetic strips are equal to or less than the measured tensions in the Christiana wall, and less than predicted by using the Simplified method and a K_r/K_a= 1.0. Thus, the proposed design methodology is reasonable.

Based on the above analysis, when using appropriate design values for reinforced soil friction angle, a constant K_r/K_a ratio of 1.0 accurately predicts the tensions at the top of the MSE wall while conservatively predicting the tensions at depths greater than 3m. For walls backfilled with high shear strength granular fill, a design friction angle greater than 34 degrees (but not more than 40 degrees) may be utilized in accordance with AASHTO specifications.

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