Design of reinforced slopes and embankments. State of the art

Conception de pentes et de structures en remblai. État de l'art

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ABSTRACT

The use of layers of reinforcement has proven out to be an efficient way of increasing the stability of slopes and embankments in fill. The design of this kind of structures should be based not only on a global stability analysis, but also on the application of an internal design method and the compliance with some serviceability requirements. This paper compares the existing design methods of mechanically stabilized earth structures highlighting the strengths and weakness of each one of them. The partial results of a extended parametric study currently under course will be exposed and a first sketch of new design method will be proposed.

RÉSUMÉ

L'utilisation de lits de renforcements est un moyen éprouvé d'augmenter la stabilité de pentes et de structures en remblai. Le dimensionnement de ce type de structures devrait être basé non seulement sur une analyse de la stabilité globale, mais aussi sur la mise en œuvre d'une méthode de justification de la stabilité interne et la vérification de certains critères aux états limites de service. Cet article compare les méthodes de justification existantes pour les remblais renforcés, éclairant sur leurs points forts et leurs points faibles. Les résultats partiels d'une étude paramétrique extensive actuellement en cours sont exposés et un premier aperçu d'une nouvelle méthode de justification est proposé.

Keywords : reinforced slope, reinforced earth, design method, strength reduction, AASHTO, k-stiffness, optimization, reliability

1 REINFORCED SLOPES AND EMBANKMENTS. CURRENT PRACTICE & CODES

The geotechnical activities of earth reinforcement and slope stability find a common engineering field of interest in the utilisation of layers of planar reinforcements for increasing the stability of an existing slope or to build a structure made of a composite material (soil backfill plus reinforcements and facing elements). The fact that new codes, like the new French Standard NF P 94-270, cover both the design of reinforced earth and soil nailing confirms this fact. NF P 94-270 is the first national code integrated in the Eurocode schema; it replaces NF P94-220 (reinforced earth practice) and Clouterre (nailed earth) recommendations. A detailed description of this code and its integration with other European standards (Eurocode 7 EN 1997-1:2005 and EN 14475:2007) has been given by Segrestin (2007)

There are, however, some discrepancies related to the design methods to be used for each problem:

Slope reinforcement engineers typically conduct a limit equilibrium analysis to analyse the stability of the un-reinforced slope; afterwards some reinforcement elements are added to the model and the analysis is performed again until the required safety factor is achieved; the original rupture mode cannot longer happen because of the anchoring effect of the reinforcements.

On the contrary, MSE walls and structures designers predefine the shape of the reinforced block attending to external stability and minimum slenderness code requirements, perform an internal design analysis, checking the pullout and tensile strength of each individual reinforcement layer assuming a predefined mode of rupture. This rupture mode was defined from experimental and finite element data: a line joining the position of the maximum tension points in the reinforcements (the so-called maximum tensile line) splits the R.E. block in two zones, the active one and the resistant one. It is relevant to mention that the maximum tensile line depends on the extensibility of the reinforcement; there are also a few variations on its geometry depending on the analysed code (e.g. AASHTO vs. NF P 94-270). Sloped structures are calculated following the same principle, except for the fact that a different maximum tensile line is chosen. The calculation of bridge abutments requires checking up to three different tension lines, which depend on the geometry of the beam seat. Afterwards, when the structure is built over weak ground or on a slope, a limit equilibrium analysis is to be performed to ensure that the effect of the weight increase (R.E. structure) and the modifications of the natural terrain do not reduce excessively the stability safety factor.

When checking reinforced slope stability, limit equilibrium analysis is unable to predict the exact distribution of tensile forces along the reinforcements and the amount of information is generally small (slope's statigraphy, strength and stiffness of the soil, anchoring properties of the soil- grouted nail interface). In that generally no internal design checking is carried out.

When designing reinforced walls/embankment, the fact that the designer does not usually have all relevant geotechnical data for accurately checking the global stability. This checking is then carried out by the geotechnical engineer.

None of these situations is desirable: performing an internal design allows for an optimization of the reinforcement distribution and is essential to ensure that the long term strengths of the reinforcement layers are compatible with the loads actually applied to them, while performing a global stability analysis allows for an optimized solution for the full set: structure and surroundings. The most modern codes (NF P 94-270, BS 8006:1995, Geoguide 6) emphasize the need of including both aspects in the design and make explicit mention to "compound stability" modes, in which the rupture surface crosses reinforced zones as well as zones with no reinforcement.

Serviceability limit states are essential to ensure that the structure can play its role in its environment (bridge abutments, high speed railways, etc.)

It is important to emphasize that a design method itself, as good as it may be, is by no means enough to guarantee building a structure with no problems if other aspects are not taken into

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account: adequate compaction of the backfill, adequacy of the combination of reinforcement plus facing elements, proper drainage system, adequate geotechnical information regarding the characteristics of the foundation soil and the back of the wall. NF P 94-270:2009 is for example assuming that the execution requirements of EN 14475:2007 are followed.

2 INTERNAL DESIGN OF INCLINED REINFORCED EARTH STRUCTURES

Due to brevity, the reader is referred to Grien et al (2007) for a more detailed description of the internal design of a R.E. structure.

There are several methods for the calculation of the tensile forces along the reinforcements (or, at least, the maximum value and the value at the facing). The vertical stress at a point of the backfill can be obtained:

-applying an equilibrium (Vertical forces and moments) over the R.E. mass above the level of interest and assuming a trapezoidal, triangular or rectangular (Meyerhoff) distribution of vertical pressures to reach equilibrium (coherent gravity method)

-as a function of the column of soil laying directly over the point of interest (for example Aashto simplified method)

-applying Boussinesq or other distribution rules (elastic solutions) to the model.

The horizontal stress inside the backfill is then obtained from the vertical stress applying an internal earth-pressure coefficient, K. The reinforcement max. tension is obtained from the equilibrium of horizontal stresses in the soil over an average section (known as the tributary area) and the reinforcement layer itself.

The FHWA proposes to combine a simplified coherent gravity method with a K value that depends on the batter of the structure. The advantage of this method is its simplicity; the main disadvantage is that is only gives reasonable results for a limited set of cases in which the effects of load diffusion (slope over R.E) are not of importance. The effect of concentrated loads on the top of the structure is accounted for by applying a 2:1 diffusion law.

The Reinforced Earth method, described by Segrestin et al (1992) employs the Boussinesq stress diffusion approach with some mathematical artifices to achieve equilibrium at the block level. The method is much more refined and the precision of the method is quite remarkable even for complex geometries and concentrated surcharges but its application is not straightforward and checkings are uneasy. The tension at the facing connection is adjusted according to the facing stiffness.

The K-stiffness, described by Allen et al (2004), is a semi-empirical method based on a extensive campaign of numerical modelling calibrated from the experimental data (structures built at Japan and the USA). An expression for the maximum tension at each reinforcement level is proposed by using statistical fitting. The variables that intervene on the formula as inputs are the lateral earth pressure coefficient, tributary area, reinforcement depth, global and local reinforcement stiffness, the wall batter, facing stiffness and backfill cohesion. The method, based originally on a working stress approach, can be adapted to a limit state calculation. The motivation for the development of this method was to have a better estimation of the reinforcement tension than that proposed by the AASHTO. The model is elegant and simple, but it has several drawbacks, such as the bias in the results due to some of the data included in the wall database; it does not deal with the other aspects of the internal design (position of the max. tension line, pullout checking...), accepting AASHTO dispositions. This is a big limitation and tampers the validity of the whole method, as it will be shown later.

Other methods are based on limit equilibrium analysis using different slip/failure surfaces: circular, double wedge, logarithmic spirals. They usually make strong assumption on the tensile forces on the reinforcements and on the inter-slice forces. As shown by Fidler et al (1994), some strain compatibility analysis is required in order to try to improve the accuracy of the solution, especially for the case of using extensible reinforcements. The method assumes an associated flow: this affects the volume increases when two soil masses slip along a failure surface, thus affecting the results. The quality of the solution depends not only on the selected limit equilibrium method (Bishop, Fellenius, Morgensten-Price...), but also on the choice of the type of geometry of the failure surface. Active research on this field has been being conducted for years. One may question the need of artificially improving a method that has some basic flaws that tamper the accuracy of the solution when dealing with reinforced structures. Maybe one of the most evident ways to convince ourselves is to realize that the modelling of a natural reinforced slope and a inclined reinforced earth structure may well be calculated using exactly the same limit equilibrium model (except, of course, for the definition of the reinforcements). This type of model is purely theoretical and has no foundation on actual measurement. In addition it does not take into account neither the stress strain nor the relative stiffness that may attract more or less load in the structure.

Numerical modelling methods can successfully replace limit equilibrium methods. By taking into account more or less sophisticate soil models, application of construction steps, input of initial stress conditions for the soil and the structural elements, sophisticate interfaces to model the interaction between the structural members and the soil in which they are embedded, the level of accuracy may be much higher. One of the main complaints regarding finite elements is that there's big quantity of data, usually unknowns, that is required to define the model (always in comparison with the input data needed for limit equilibrium models); this is not a valid argument; some authors, like Hammah et al. (2005) show how to easily adapt the input data of a finite element/finite difference model to reproduce the limit equilibrium model, while staying of the safe side for justification purposes:

-Set a constant value of Young modulus and Poisson ratio, set dilatancy to zero and model the soil post-peak behaviour as pure elastic perfectly plastic.

Instead of analysing a set of failure surfaces and calculating the safety factor, a technique called strength reduction is applied: The strength related parameters are reduced by a parameter until the model fails to converge or to reach a quasi-static solution. The value of the reduction parameter can be used as a factor of safety (F.O.S.) indicator. From this simple basis, every bit of additional information can be input in the numerical model to improve the accuracy of the prediction. In particular, performing parametric analysis varying some of the parameters within a reasonable range (e.g. Varying the strength and elastic related parameters of a given soil within the expected range of variation according to the engineer's experience and available data) is an excellent way for better understanding the behaviour of the structure and the influence of the elastic and strength related parameters in the solution.

A further step ahead is to resort to the reliability theory, which can be naively interpreted as an extended parametric analysis under a much more formal mathematical framework in which the variability of all the input data (inherent variability as well as uncertainty coming from the measurement method) and calculation method can be included in the problem. By applying reliability methods, we obtain an indicator of the probability of failure of the structure. It has been shown that the application of global or local safety factors to a geotechnical problem does not necessarily lead to a constant risk level. It would be desirable to make an effort to calibrate the load, material and safety factors under the scope of the reliability theory instead of doing it by direct fitting to the old codes (e.g. AASHTO ASD).

Going back to ground, reliability analysis has been applied in this specific field in conjunction with simple R.E. internal and external design models (Chalermyanont et al. 2004) and with limit equilibrium analysis. Rodriguez et al (2007) applied a reliability method in conjunction with the strength reduction calculation over finite different method for the estimation of the true bearing capacity of the footings of buried pre-cast arches. See Figure 1.

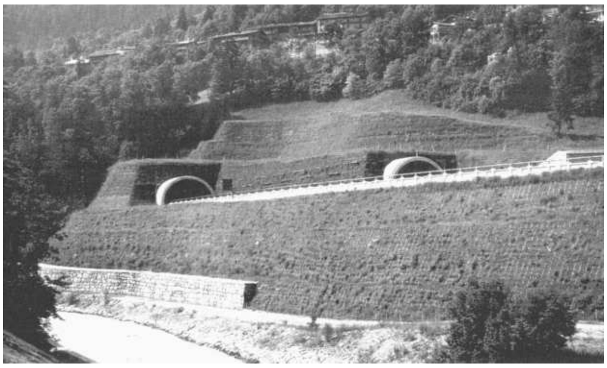

Figure 1. A sample of integration of buried precast arches and inclined reinforced earth structures.

The finite element tools and reliability analysis should be more frequently used not only for calculating the serviceability states (see Das et al, 2007) , but also the ultimate limit states of geotechnical problems. Commercial software which includes some capabilities in this sense is being developed. At the European level, the European Technical committee ETC7 is promoting the use of Numerical Methods in Geotechnical Engineering, by education, training, benchmarking; the Eurocode 7 is being adapted to make it possible to use finite element tools to be used for U.L.S. checking (allowing for the use of Design Approach 3, also called Material Factor Approach.) Please refer to Bauduin et al () for a more detailed explanation on this topic.

3 BENCHMARK. PROPOSAL FOR A NEW INTERNAL DESIGN METHOD

An extensive benchmark using finite difference sofware (Flac 2D) and strength reduction method has been started by the author. The motivation was to compare the results of vertical and inclined walls and to verify the validity of the current design model over, paying special at the definition of the maximum tension line for inclined structures and its relation with the pullout failure. More that 1000 models were calculated, varying the inclination of the facing, the slenderness ratio, the strength related parameters of the backfill, the foundation soil and the front-fill, the extensibility of the reinforcements (but within the range of the so-called “inextensible” reinforcements). and the geometry of the slope on top of the structure.. Granular backfills with low friction angle were used, but cohesive backfills were not. In order to extend the analysis to marginal backfills, it would be necessary to include other parameters in the benchmark, such as the possibility of having groundwater increasing the lateral pressure. Flac’s internal programming language was used to extend the strength reduction method already included in Flac: It is possible to perform independent/combined reduction of strength parameters of individual soil masses, the reinforcements, the interface between soil and reinforcements, the densities and the applied loads. Non conventional geometries of the R.E. block and the reinforcement distribution were also tested (trapezoidal cross section, with longer and denser reinforcements at the bottom). The benchmark is not finished yet and new models are being added to further investigate some findings, but some findings may already be exposed:

The maximum tensile forces in the reinforcement were reduced when decreasing the slope. The position of the maximum tension line before applying reduction factors was close to the one used by the Reinforced Earth method and NF P 94-270. More deviations were observed at the top of the structure than at the bottom.

The position of the maximum tension line and the maximum tension values changed significantly after performing partial strength reduction factors. See figures 2 and 3.

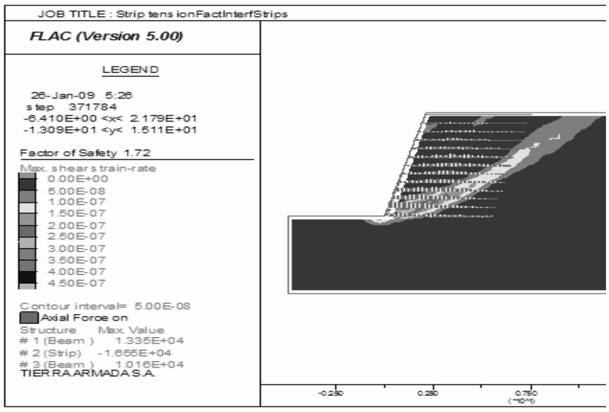

Figure 2. Strear strain and strip tension contour plot after S.R of the pullout resistance of the reinforcements.

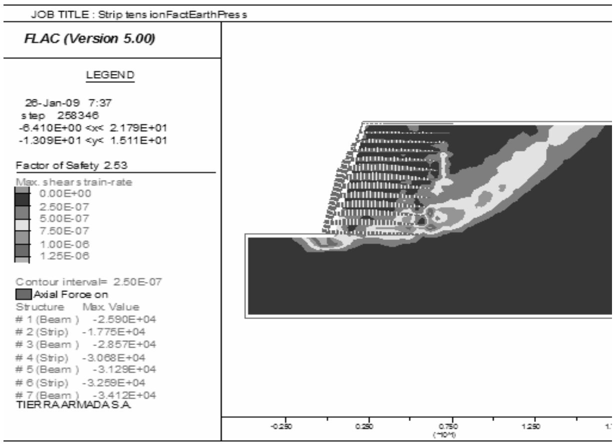

Figure 3. Strear strain and strip tension contour plot after S.R of the lateral earth pressure. Please note the thickness of the failure band.

This raises the following question: Is the use of a single maximum tension line obtained by observation of stable, well sized structures compatible with a limit states approach? Why the actual method of calculation has lead to a safe design? In the opinion of the authors, the inherent redundancy of the internal design checking (reinforcement pullout and max. tension checking at **each** level) and the adequate preliminary sizing of the external block has a lot to do with the true reliability level of these structures which is very satisfactory.

It was observed that, for inclined walls when performing a S.R. which reduced the backfill friction ratio or increased the lateral earth pressure, the maximum tension line tended to move to the facing and the values increased, specially at the bottom of the structure. This effect, which has been observed in real practice (bulging at the bottom of walls with flexible facing) should be included in a revisited design method. At the present moment, solutions to this problem include adding short reinforcements attached to the facing.

When the backfill and the foundation soil are quite weak (friction angle=30º and null cohesion for both soils), the structure is more sensitive to further reduction of foundation soil strength. The observed rupture mode is a mixed compound mode showing pullout of the lower levels. In order to reduce the sensitivity, a different structure was modelled: a trapezoidal wall having a lower mean slenderness. The reinforcement decrease at the top was added at the bottom of the structure, keeping the same amount of reinforcement in the section. The motivation was to have a lower zone stiff enough to behave as a traditional rigid footing. Due to the use of non-extensible reinforcements, the increase of reinforcement to achieve the desired result proved out to be very moderate. As shown in figure 4, the attempt was successful: the increase of pullout capacity of the lower levels is not enough to explain the observed failure "band": the stiffening effect changes the vertical stress pattern, tending to "push" the failure surface out of the R.E. block and providing with a wider "footing base". Not only the foundation soil strength ratio was improved, the same applies for all the other ratios analysed. Generally speaking, the strain rate contour plots show that the failures are not concentrated on a thin band, but there's a simultaneous failure of the whole of the block. This is interpreted as a better design in which the reinforcement distribution is much more optimized in terms of density and length.

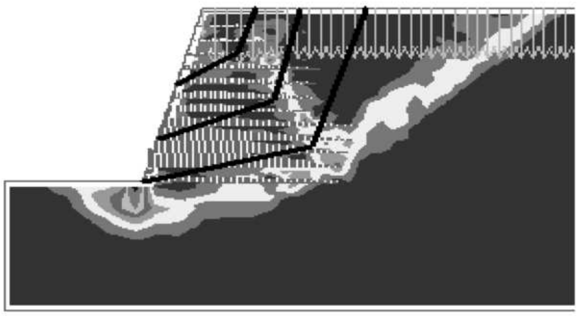

Figure 4. Foundation soil S.R.. performed over bottom over-reinforced trapezoidal structure. The failure "band" is near the back of the wall

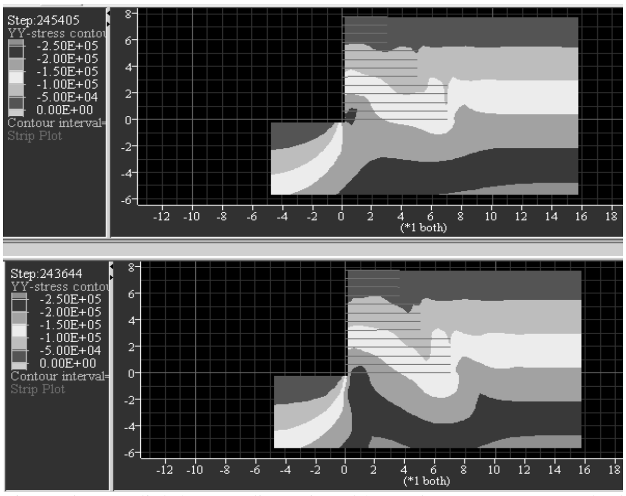

Figure 5. Up. Slightly over-dimensioned lower layers. Down: Standard reinforcement density. Vertical stress contour plots.

The same beneficial effects were observed when analysing a vertical wall, see figure 5 (significant improvement of all of the strength reduction factors under analysis and more regular vertical stress distribution under the lower reinforcement layer). It is important to know that the all the internal calculation design methods predict a pullout of the upper levels. In the opinion of the authors, this finding may be the basis of a new design method in which a slender trapezoidal wall (or similar cross section) would be acceptable. There are several approaches to be investigated:

-Definition of several maximum reference lines to check for reinforcement pullout (fig. 4). The definition of these reference lines should be calibrated from numerical methods, trying to keep, at least, the actual reliability level of these structures.

-Define a formula for a reduction factor which could be applied to our standard design methods in order to account for include the effect of R.E. block cross section shape.

The design method should also include a provision for a minimum stiffness of the lower zone ("virtual stiff footing") in order to avoid undesired failure modes and excessive deformations. The motivation for having a simple design method is to provide with an easy design/checking tool for standard cases without having to resort to the latest computational techniques.

4 CONCLUSIONS

A review of the design methods for the calculation of inclined reinforced structures have been shown, highlighting the merits and limitations of each one.

The need of a new design method, easy to follow and check, with a sound theoretical basis, will be analysed. The characteristics of the method have been outlined.

Any attempt to improve the actual design methods just by reducing the reinforcement density based on calibration of the tensile loads will overlook the simplifications involved in the other parts of the method and may seriously decrease the reliability of reinforced soil structures. Specifically, the k-stiffness method suggests that it is possible to significantly reduce the tensile capacity of the lower levels of extensible reinforcement structures, which is radically against the stiff block ("virtual footing") concept.

While the use of lower quality backfill is tempting (and in some cases a need) care should be taken about the design implications: design method modifications to avoid new failure modes, including serviceability states; when using cohesive soils, if an adequate drainage cannot be guaranteed to endure for the whole life of the structure, the effect of groundwater should be taken into account to achieve a consistent safety level.

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