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The design of MSE walls using geosynthetics in France. Present state of the art, and possible future evolution?

P. SEGRESTIN, Consultant, Former Technical Director, Terre Armée Internationale, France
J.-P. GOURC, Professor, LIRIGM, Joseph Fourier University, Grenoble, France

ABSTRACT: A standard for the design of MSE structures reinforced by geosynthetics is going to be issued in France. As a distinctive feature, it specifies an at-failure displacement mode of calculation taking into account the extensibility of the reinforcements and their progressive interaction with the fill. Questions which may still be raised regarding the validity of the model and the nature of the ultimate limit state are discussed, as well as the possibility of being sometimes less conservative for the tensile capacity of the reinforcements. Moreover a suggestion is made concerning a preliminary design based on the in-service behaviour of the structures.

1 INTRODUCTION

A new experimental standard XP G 38-064 (AFNOR, in prep.) should be finalised in France before the 7th ICG in Nice. It deals with the design of "structures reinforced with extensible and flexible reinforcing strips or sheets", which are identified in other countries as MSE retaining walls with geosynthetic reinforcement. In France, the distinction between extensible and inextensible is set by the P 94-210 standard (AFNOR).

The new standard is the outcome of years of persevering effort. A number of experts were involved in turn. Knowledge increased as work progressed and the definition of a design methodology in such a changing environment proved to be a challenging assignment… Any standard has to find a balance between contradictory requirements: confirm the state of the art, without closing the door to future evolution and developments. Therefore, it was normal while discussing the standard's prescriptions that the working group's members were aware of the hazy areas of this first edition and already pondering on questions which will have to be cleared up in future versions.

The purpose of this paper is to focus on a few of these questions, limiting itself to the topic of internal stability.

2 THE FRENCH WAY

2.1 General principles

Before discussing the precepts, let's summarise the essential. The justification of internal stability consists of analysing the ultimate limit state equilibrium (ULS) of a mass of soil along potential failure surfaces intersecting one or more reinforcing layers. It does not include at this stage any serviceability limit state analysis (SLS) nor any assessment of the deformations.

A tentative distribution of the reinforcements (lengths, spacings, tensile strengths, stiffness) needs to be selected beforehand, since the method is not a formal design method and its purpose is to verify that the proposed distribution is adequate.

The resisting actions which counter the slippage of the soil mass include the shear resistance of the soil and the forces which may be mobilised in the reinforcing layers intersected by the failure surface. For each investigated surface, equilibrium is attained when all resisting actions are greater than, or equal to all driving actions, taking into account partial load and safety factors, as specified by the Eurocodes. For the internal stability of ordinary structures, the extreme (or pessimistic) hypotheses corresponding to ULS conditions may be defined by the load and resistance factors proposed in the table 1 below:

Table 1. Load and resistance factors (ULS)

Load factors	Dead loads: 1.20	Live loads: 1.33
Resistance factors		
Soils	Friction (tan ϕ')	Cohesion c'
Specified selected fill	1.00	1.25 (or c'<5kPa)
Fill from the work site	1.20	1.50 (or c'<5kPa)
In situ soil material	1.35	1.65
Geosynthetic reinforcement	Long term strength	Pullout capacity
	1.20	1.20

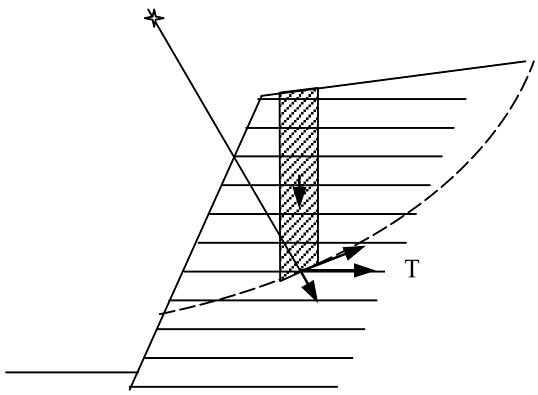

Figure 1. Equilibrium along a potential failure surface

The analysis uses a slices method. The tensile force mobilised in each layer intersected by the investigated surface is generally considered to be oriented in the direction of the layer (Fig. 1). Two methods are allowed for assessing its value:
- an "at-failure" calculation method, where a force equal to the maximum pull-out or tensile strength capacity is introduced
- a "displacement" calculation method, where a movement is imagined along the considered slip surface and the local tensile force induced by this displacement is determined; this approach has been commonly used in France since it was introduced by Gourc, Ratel & Delmas (1986).

2.2 *The "displacement" calculation method*

Here is a review of the routine used for adjusting the preliminary design, as it was set out by Gourc, Gotteland & Delmas (1989). At the beginning of the computation, a displacement (Δ) is selected for the slip line studied. When imposed at the point of

intersection of a reinforcing layer, it induces the mobilisation of a tensile force as a function of several parameters (Fig. 2):
- the anchoring length involved (L_a)
- the vertical pressure (σ) applied to it
- the reinforcement's stiffness (J)
- the interaction relationship (μ, versus the local relative displacement δ), which is assumed to be elastoplastic (Fig. 3).

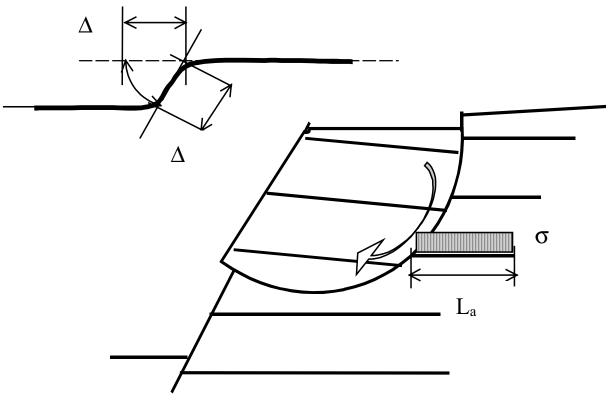

Figure 2. Principle of the displacement method

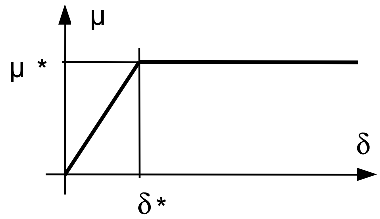

Figure 3. Soil/reinforcement interaction relationship

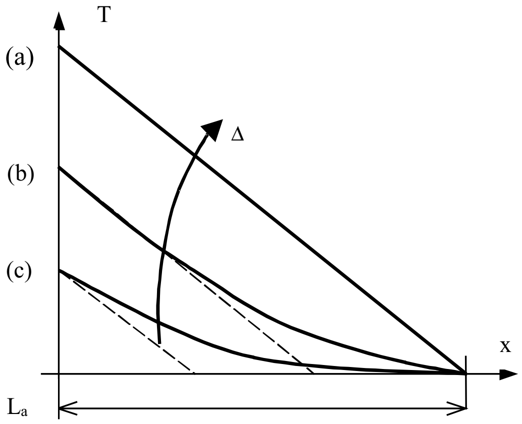

Figure 4. Different behaviours of an extensible reinforcement with an imposed displacement at head of resisting length.

The force (T) induced by the displacement and proper to each layer is obtained by solving the following differential equations (Segrestin & Bastick 1996):

$$dT_{(x)} = 2b\mu_{(x)}\sigma dx \qquad d\delta_{(x)} = \left(T_{(x)}/J\right)dx \qquad (1)$$

(b = reinforcement's width, x = abscissa along its resistant part).

Depending on whether Δ at the head, and δ_0 at the end of the anchoring length are larger or smaller than δ^*, the reinforcement will behave in either of the following manners (Fig. 4):
- either the maximum interaction μ^* is mobilised along the entire resistant length, and the reinforcement is pulled-out (a)
- or the maximum interaction μ^* is only applied on a part of the resistant length, and the overall slippage is only local (b)
- or the maximum interaction μ^* does not apply anywhere (c).

The displacement Δ is incremented until it induces a sufficient contribution from the reinforcements to ensure stability. Should the tensile force T in one layer become greater than its tensile capacity, or all the layers intersected by the slip surface be pulled out, the distribution will be altered, that is, longer, closer, more resistant, or stiffer reinforcement will be provided where it is effective, and a new calculation will be ran.

It is important to note that the limit equilibrium corresponds to a displacement proper to each potential slip line studied.

3 A FEW REFLECTIVE ISSUES

Let's now review a few issues which are still worth discussing.
- compatibility of the two methods
- theoretical nature of the displacement
- relevance of serviceability behaviour
- transition from serviceability to ultimate behaviour

3.1 Compatibility of the two methods

The first question raised is that of the choice between the "at-failure" or "displacement" methods. The norm does allow the user to select the one (i.e. the type of software) which he likes.

Validation calculations covering a large range of structures led to the findings that the differences between designs based on the two approaches are marginal (Gourc, Arab & Giraud 2001).

There is however a difference between the two. In the "at failure" method a simple assumption is that all the layers intersected by the investigated surface simultaneously attain an at-failure limit, either in slippage or tensile capacity. Conversely, only some of these layers attain such a limit in the "displacement" calculation: a few at the most in slippage and usually only one or even none in tensile capacity.

Therefore, with all things equal, an overall extra factor of safety calculated along a same potential slip line with the "at-failure" method will be equal or higher than that obtained with the "displacement" method (the latter is indeed equal to 1.0 where a displacement is needed, and strictly needed, to restore stability). It will be interesting to collect more comparative computations in order to confirm whether both methods may depend on the same definition and value of the factor of safety.

3.2 Theoretical nature of the displacement

The likelihood of the mechanism which the "displacement" method takes into consideration is another issue worthy of discussion. The problem is often circumvented by explaining that the displacement used as the basis for the calculation is a sensible way of obtaining a consistent mobilisation of all layers, although the movement does not actually take place.

The "displacement" model is indeed rational, since it makes allowance for the extensibility of the reinforcements and their progressive interaction with the fill. But, the assumed mechanism implies extreme conditions, with factored loads and reduced characteristics, as any ULS calculation. Therefore, the analysed movement only has, by definition, a marginal chance of occurring. Since the assumed displacement cannot be real unless the loads as well as the shear resistance of the soils and the tensile resistance of the reinforcements are extremely unfavourable, the method only makes sense for ULS analysis.

On the other hand, the "displacement" method does not exclude that a slippage could actually occur in such adverse circumstances. Before it finally stops once stability is restored, the movement would presumably develop along the most critical potential failure line. It might be the one where the displacement necessary for restoring stability is largest, or rather entails the greatest work, or the one which induces a tensile force closest to the resistance of the reinforcing layer.

However, one may wonder whether more than one line could possibly be activated through a same structure in such extreme circumstances. Or, how small the work needed to restore stability should be, so that no slippage can actually develop. It would be good if a rationale could explain how far from the ULS equilibrium the structure should be, i.e. which reserve of resistance it should have to prevent movement from being initiated. For the time being, let's content ourselves with essentially intuitive reasons…

3.3 Relevance of serviceability behaviour

As stated above, the "displacement" method is reserved for ULS analysis. If, anyway, the routine were used with the loads and material characteristics which are normally considered for a SLS analysis, it would of course let compute (smaller) displacements and forces. But, such displacements do not occur: no slippage is necessary to ensure the stability of a MSE structure, either during construction or under in-service conditions.

It is an other mechanism which governs the development of the forces effectively exerted in the reinforcements and the soil. The principle of passive reinforcement implies that the tensile mobilisation of the reinforcements is induced by the movement of a wedge of fill. As a matter of fact, the fill moves and the reinforcements are gradually put under tension as construction progresses. The construction procedure moreover certainly affects the tensile forces and it should therefore be taken into account, at least in the SLS conditions, if not for ULS.

So, it is acknowledged that the actual behaviour of the retaining structures is not correctly represented by the "displacement" method. Accordingly, it would probably make sense to explicitly provide for an initial calculation phase (which could be the basis for the preliminary design) based on the classical theories of soil mechanics and earth pressure, as well as on the monitoring of experimental MSE structures.

3.4 Transition from serviceability to ultimate behaviour

Let's now think about a few of the circumstances where (again under extreme assumptions) the risk of approaching the conditions leading to a slippage might occur. What was said above certainly means that something has to happen at a given moment for everything to change and be redistributed: the application of a surcharge, an unexpected event, an evolution in the characteristics of one of the materials, etc... After this event, a new equilibrium will be substituted for the pre-existing equilibrium, but it will not be superimposed to it.

There should be at this point no misinterpretation: the "displacement" method, as other conventional ones, only aims at designing the reinforcements; it does not aim at following the evolution of the behaviour of the MSE structure, depending on possible changes in the loads or the resistance of the materials.

This being said, let's discuss two of the typical reasons which could lead to the initiation of movement under ULS conditions:

- the application of a surcharge
- the progressive loss of resistance of the reinforcements.

3.5 *Application of a surcharge*

A slippage, due principally to limited pull-out capacity, may appear in the short term during or at the completion of the construction. It could be the result of the interaction taking place between the fill and the reinforcements when the MSE structure becomes too high, or when the first surcharge is applied.

The tensile forces calculated in the reinforcements as being necessary to recover stability will then be permanently exerted throughout the entire service life of the retaining structure. It is then logical to consider the long-term creep rupture strength to ensure that the tensile capacity is not exceeded. This is indeed what the norm provides for. It might yet be also logical to estimate the displacement, based on the short-term stiffness of the reinforcement, as derived from the isochronous curves of the product (Fig. 5).

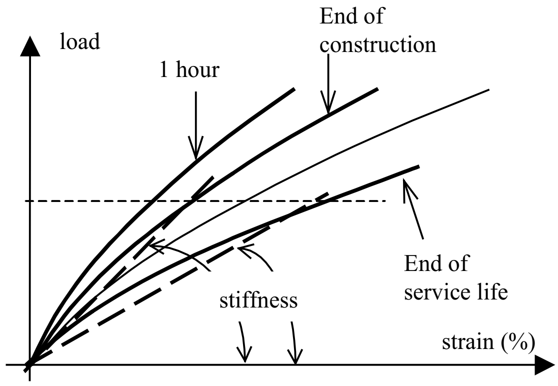

Figure 5. Isochronous curves

3.6 Loss of resistance of the reinforcements

Let's now examine another case, in which the slow ageing and progressive elongation of the extensible reinforcements might finally favour the appearance of a slip surface in the MSE structure. This is a case where the event liable to initiate the displacement is an evolution in the characteristics of one of the materials.

Under this assumption, like for the previous one, the norm recommends referring to the long-term creep rupture strength. As a matter of fact, the "displacement" method deals with the ULS condition of the structure, not with its evolution through time. Accordingly, the tensile forces calculated in the reinforcements are those which would be exerted after the displacement takes place, say shortly before the end of the service life, not those which prevailed earlier.

We may nevertheless admit that there is little likelihood that the tensile force in a given layer will be the same before and after the movement. We may even doubt that the layer identified as the most likely to break according to the "displacement" calculation, is also the one most loaded before the movement occurs. We might therefore wonder whether the creep rupture strength under constant loading associated with the duration of the service life is the appropriate reference

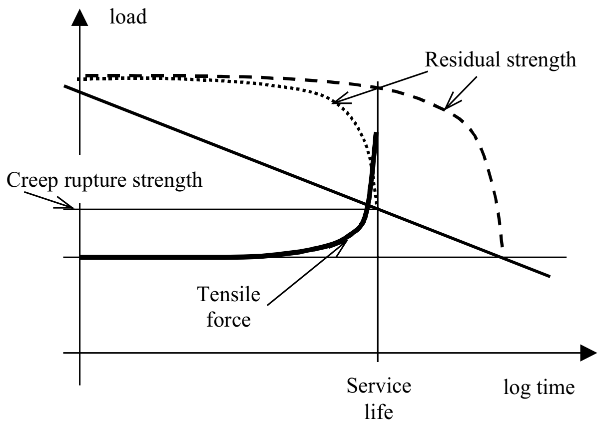

Figure 6. Residual strength

This might rather orient us toward the "residual strength", which was recently discussed in various papers, such as that of Segrestin & Orsat (2001) with respect to polyester based reinforcements. As suggested on the graph above (Fig. 6), in some cases it might indeed be possible for the tensile force to exceed the creep rupture strength corresponding to the design service life, if it is only in a last stage, after the displacement restoring stability has occurred.

As far as stiffness is concerned, it clearly makes sense in that case to rely on the long-term isochronous curve (Fig. 5).

4 FUTURE EVOLUTION?

The two cases examined above are obviously relatively simple. More complex cases could be envisaged, where the various phenomena combine and make analysis more difficult. Anyway, the questions which have been raised may open a few paths for a possible evolution in the calculation method.

4.1 Preliminary design

Firstly, it appears that we should not do without a preliminary design, reflecting both the classical theories and the observed in-service behaviour. It should be nonetheless carried it out using the ULS hypotheses, with reduced characteristics and factored loads. This is in fact the approach which is currently followed for designing structures with inextensible metal reinforcements, particularly in France according to P 94-220-0 (AFNOR, 1998).

Once the main proportions of the MSE structure are set, especially depending on its overall stability, the preliminary design would aim at estimating the tensile forces anticipated at the level of each layer of reinforcement. Since the thus-calculated forces are essentially permanent, they should be compared with the creep rupture strength for the required service life (without forgetting the other causes of degradation).

On the other hand, contrary to what is currently being done with metal reinforcements, it does not seem necessary to justify the pull-out capacity layer by layer beyond a particular line in this preliminary design phase. The "displacement" calculation along a series of potential slip lines seems more satisfactory in this respect.

4.2 Verification in displacement

We observed that the "displacement" calculation model represents in a suitable manner the failure mechanism which would be accompanied by a total or partial slippage of some layers of reinforcements. This calculation mode is no doubt to be retained for the verification of what is linked to the interaction between the soil and the reinforcements.

As we have seen, the limits to be imposed for the tensile forces in this calculation phase could lead us back in some cases to the residual strength, rather than to the creep rupture strength of the reinforcement. Of course, the difficulty is to estimate this residual strength, which depends among other things on the loading history at each point of each reinforcing layer. Another problem will be to assess whether and when this residual strength is close enough to the nominal short-term strength (as far as creep is concerned).

The reflection about the residual strength of the reinforcements reminds us about the residual strength of the soil. A possible other refinement of the "displacement" method would consist in taking into account a shear resistance varying from peak to residual as a function of the displacement, which is itself a function of the density and stiffness of the reinforcement.

This sends us back to the discussion about the reserve of resistance of the whole system, and to the idea that the movement may not start as long as enough resistance is available (and the stresses may be lower as long as the movement does not start).

4.3 Deformation calculations

We acknowledged that it would be useful, for various reasons, to better know on one hand the real behaviour of a MSE structure, on the other hand the tensile forces exerted in it at each point of each reinforcing layer. This clearly suggests that a solution might be to rather resort to numerical finite elements or finite differences models. This should obviously not be excluded, either for an estimation of the deformations to be expected in service (an issue which is not dealt with by the standard in its current state) or even for a ULS verification, with reduced characteristics and factored loads. But this is quite another matter…

4.4 Common standard

Finally, we do not see why, in a future work phase in which we are going to strive to progress in the understanding and acceptance of the mechanisms and behaviours, a common standard could not deal with both extensible and inextensible materials. After all, it is only a matter of relative extensibility. In some respects, moreover, there is possibly less of a difference between steel and polyester, for example, than between polyester and polyethylene. This might be a challenge worth tackling when the time comes to join forces on a European draft standard for the design of reinforced fill structures.

5 CONCLUSIONS

The French standard is particularly noteworthy because it introduces an innovative calculation mode, which takes into consideration the extensibility of the reinforcements. The questions we encounter when trying to imagine a plausible ultimate limit state suggest, however, that a future version should probably allow for a preliminary design based on the observation of the in-service behaviour. On the other hand, it is possible that the displacement calculation at the ultimate limit state may be performed in some cases by using the residual strength rather than the creep rupture strength of the reinforcements.

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