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Opinions about creep rupture in soil reinforcement design

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ABSTRACT: This paper is primarily meant for the persons involved in the development and review of national or international standards dealing with soil reinforcement. It first challenges the customary definition of the creep rupture strength for design purposes and the way safety is taken into account. A rational proposal is made which generally leads to higher design values. It then points out noteworthy deficiencies in some design models based on the analysis of potential overall failure, where long-term creep rupture may not be a properly applied criterion. The need for a more realistic design model is emphasized.

1 INTRODUCTION

The present paper is an updated digest of a few suggestions which the authors already presented in various occasions and formats. It is based on the grounds of their extensive experience in the design of reinforced soil structures, using geosynthetic as well as metallic strips, and of their continual involvement in the drafting of major standards.

This paper focuses on two different issues related to creep rupture. The first one deals with the creep reduction factor, how it should be defined and how safety should be taken into account. The second one relates to at failure design models commonly used for the design of reinforced soils structures, and why creep rupture may not be a straightforward criterion.

2 CREEP RUPTURE FOR DESIGN PURPOSES

2.1 *Creep rupture and nominal tensile strength*

The long-term or, ultimate creep rupture strength R_{cru} should not be related to the short-term characteristic or, nominal or, guaranteed minimum manufacturer's tensile strength R_k. As a matter of fact the former links up with constant, long lasting static loading, while the latter is measured under constant strain, in only a few seconds. The former relates to design, while the latter pertains to quality control at the manufacturing plant. So, the difference between R_k and R_{cru} is not a loss of strength. Nor has the ratio between the two, namely the reduction factor RF_{cr}, any actual physical meaning. It basically stands for a disparity between unlike things which are measured in unlike ways. Such an ambiguity is misleading for many design engineers.

The long-term creep rupture strength R_{cru} should rather be connected with a physical property of the very same kind, that is a short-term or, "initial creep rupture strength" R_{cri} (Segrestin and Freitag 2004).

Such a reference value can be derived from actual testing, performed in compliance with the relevant ISO standards, e.g. the future CD 20433 guide. A suitable value could be obtained for $t_{cri} = 10^3$ hours as suggested on Figure 1. This initial creep rupture strength R_{cri} should be one of the characteristic mechanical properties provided by the manufacturer.

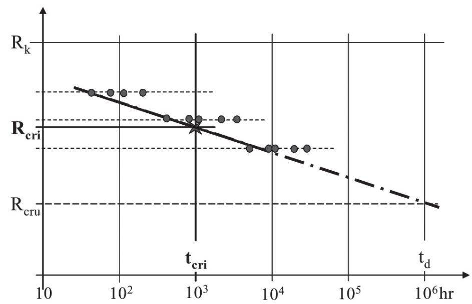

Figure 1. Proposed definition for a characteristic initial creep rupture strength R_{cri}.

This leads of course to a new definition of the reduction factor RF_{cr}:

$$RF_{cr} = R_{cri}/R_{cru} \quad (1)$$

(assuming that one abides by the erring ways of using reduction factors larger than 1.0, although the reciprocal would be simpler, make more sense and, prevent lasting confusion with safety factors).

In addition to reintroducing some logic into those concepts, the proposal results in creep reduction factors closer to 1.0 than they presently are. By the way, values of the order of 1.5 to 3.0, such as the ones commonly used today, convey a somewhat negative feeling about the long-term strength of geosynthetic reinforcements.

2.2 *Creep rupture and safety factor*

Let's come back to the present practice and present definition of RF_{cr}. When calculating the long-term design tensile strength R_d, a partial material factor of safety γ_m is commonly used for dividing the anticipated long-term strength R_u, once the effects of creep, mechanical damage, weathering, chemical and biological effects have been combined through successive reduction factors:

$$R_d = \frac{R_u}{\gamma_m} \text{ where } R_u = \frac{R_k}{RF_{cr} \cdot RF_{id} \cdot RF_w \cdot RF_{ch}} \quad (2)$$

This has an unwanted effect illustrated on Figure 2: products whose predictable decrease in strength is large are less affected than the ones which only exhibit a small decrease. This is all the less logical since a small decrease can likely be better predicted than a large one.

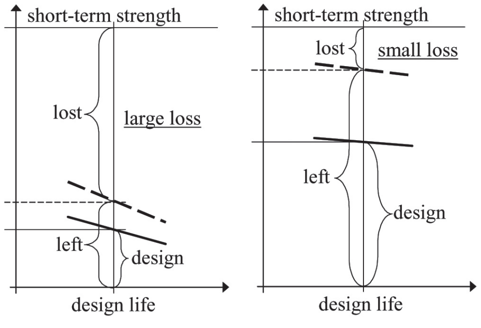

Figure 2. Disadvantage of materials with small losses.

Obviously, uncertainties affect the loss, in the very first place. Therefore, the factor of safety should reasonably multiply what may be lost, rather than divide what is likely left. We persistently advocated this way of taking safety into account for the materials whose properties diminish in the course of time (after Boyd and Segrestin 1992).

Moreover, as the uncertainties pertaining to the various effects are not identical, the factor of safety γ_m could be usefully split into a series of partial factors: γ_{mcr} for creep rupture, γ_{mch} for chemical degradation and so on. As far as creep is concerned, based on the principle that the anticipated lessening of creep rupture is the difference between R_{cri} and R_{cru}, the relationship between R_{crd} and R_{cri} can be expressed as follows, as illustrated on Figure 3:

$$R_{crd} = R_{cri} - \gamma_{mcr}(R_{cri} - R_{cru}) \quad (3)$$

or, based on equation (1):

$$R_{crd} = R_{cri}\left[1 - \gamma_{mcr}\left(1 - \frac{1}{RF_{cr}}\right)\right] \quad (4)$$

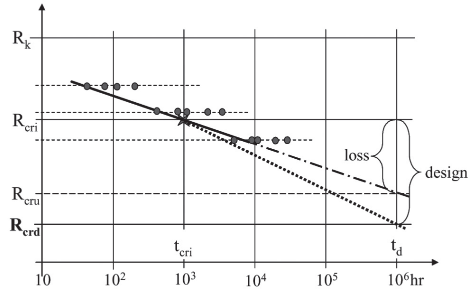

Figure 3. Proposed definition for the creep rupture strength R_{crd} for design purposes.

2.3 *Creep rupture and duration of testing*

One could even acknowledge that there is in fact no uncertainty in the creep rupture strength over a period equal to the duration of testing. Any uncertainty in the extrapolations only arise afterwards. However, that duration needs to be defined. Based on the procedure described in ISO standards, it could be the time t_{crm} where the regression line intersects the lowest level of applied load, R_{crm}, for which complete tests are taken into account, as shown on Figure 4.

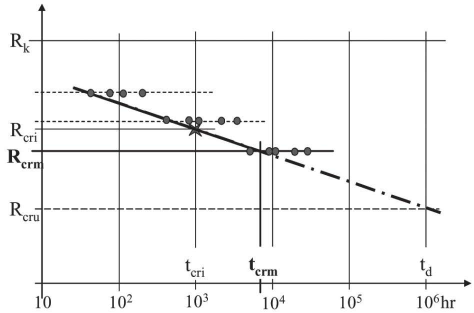

Figure 4. Proposed definition for the duration t_{crm} of creep testing.

Then, it might be justified to only apply the factor of safety to the decrease expected between time t_{crm} and the end of the service life t_d:

$$R_{crd} = R_{crm} - \gamma_{mcr}(R_{crm} - R_{cru}) \quad (5)$$

2.4 *Safety factor and duration of testing*

Assigning a value to a safety factor is nothing less than trying to quantify the unknown. Even scientific theories may end up in good enough guesstimates. In our opinion the factor of safety for creep rupture should be correlated with the span of the extrapolation (as the BS 8006 British Standard does to a certain extent). We suggest the following value:

$$\gamma_{mcr} = 1.0 + 0.5 \log (t_d/t_{cri}) \qquad (6)$$

where t_{crm} could replace t_{cri} if equation (5) is used instead of (3). This leads to a reasonable 1.5 when the extrapolation extends over a decade. It should be born in mind that this factor now only amplifies a relatively small "loss".

2.5 *Outcome*

As will be shown with a simple numerical example, our proposal generally results in larger, although safe, design creep rupture strengths for properly documented products. Let's consider a product for which the creep test regression line is defined by:

$R_{cr} = 74\%\ R_k \rightarrow t_{cr} = 4$ weeks

$R_{cr} = 70.5\%\ R_k \rightarrow t_{cr} = 9$ months

$R_{crm} = 67\%\ R_k \rightarrow t_{crm} = 7.5$ years

For a service life of 100 years it leads to:

$R_{cru} = 63\%\ R_k$

According to the present practice one would get, with a safety factor of 1.5:

$R_{crd} = 63\%\ R_k/1.5 = 42\%\ R_k$

With the proposed approach, one gets instead:

$\gamma_{mcr} = 1 + 0.5 \log (100/7.5) = 1.56$

$R_{crd} = [67\% - 1.56\ (67\% - 63\%)]\ R_k = 60.8\%\ R_k$

3 CREEP RUPTURE AND DESIGN MODELS

3.1 *Various at failure models*

Let us first remind that we stand in the context of Ultimate Limit State designs, now commonly established for designing reinforced soil structures. Three main types of design models can be identified among the ones favored by existing national codes:

- local equilibrium
- slip failure without displacement
- slip failure with overall displacement

3.2 *Local equilibrium*

Local equilibrium models are semi-empirical ones, primarily based on the monitoring of full scale structures, having more or less the same shape, slenderness and function, and built with a same type of reinforcement. The experimental data reflect the actual in service behavior of those structures and, are then used for validating similar numerical models. The routine design procedure results from the cross-checking and synthesis of both approaches.

Provided the structure under design does not significantly differ from the archetype, it can be stated that the maximum tensile loads potentially withstood by the reinforcements are reasonably known. Not one should break, since it might quickly trigger a chain reaction. Hence, the long-term creep rupture strength for design purposes R_{crd} (associated with other causes for strength losses) is the proper criterion, as far as tensile strength is concerned.

3.3 *Slip failure without displacement*

Not all types or shapes of reinforced soil structures have enough experimental data available for justifying such local equilibrium design models. Therefore, other popular design procedures are based on the analysis of potential overall slip failure.

In a first type of model, the reinforcements are expected to develop enough resistance for preventing any slippage along any potential failure line. That resistance is assumed to be equal to the smallest of either the maximum pullout capacity possibly mobilized beyond the failure line (e.g. layers 1 to 3 on figure 4) or, the long-term maximum tensile strength of every layer, derived from its creep rupture strength for the required service life (e.g. layers 4 and 5).

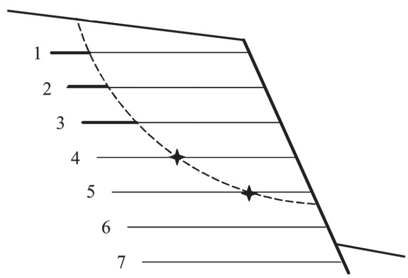

Figure 4. Slip failure analysis without displacement.

At first, the design situation may be when the structure is put into service. But, how do layers 4 and 5 know that they should not take more than what they will resist in the long-term and, restrain from taking as much as they can, as the ones working on pullout? If one of these layers does take more, it may break and prompt collapse too early.

If the design situation only occurs long after construction, the creep rupture strength which will then become available at the end of the design life depends on the history of the tensile loading of every layer, and differs from the one assumed for design.

So, relying on either full pullout capacity or full creep rupture strength is somewhat unrealistic and possibly unsafe.

3.4 *Slip failure with overall displacement*

A more complex method of analysis (known as the "displacement method") assumes that any slip failure goes with a limited overall displacement along the slip line. As the assumed displacement increases, it generates a gradual pulling out of the reinforcing layers beyond the studied line. The tensile force developed in a layer as it is dragged down depends on how much frictional interaction can be mobilized along the resisting length. It is a function of the reinforcement stiffness, among other things.

It is thus possible to calculate how much displacement is needed for the moving mass to eventually stabilize, and to assess if that mass is sufficiently reinforced.

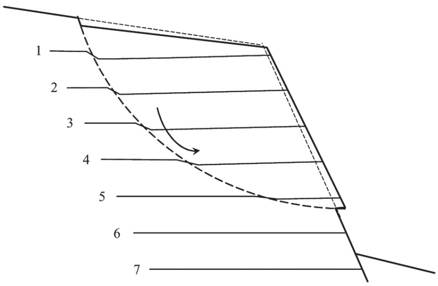

Figure 5. Slip failure with overall displacement.

Contrary to the previous one, this method allows a progressive analysis of whether or not the tensile force in every successive reinforcing layer may become equal to its long-term design strength. If it occurs before safety is insured along the slip line, more reinforcement is needed.

However, as previously noted by Segrestin and Gourc (2002), the actual development of the tensile loads in a reinforced soil structure does not result from a series of slippages along an infinity of lines, neither in the short-term nor in the long-term. So, there are little chances that the forces calculated with the displacement method match the real ones. Therefore, comparing the calculated tensile loads with the design creep rupture (combined with other factors) may not make too much sense.

Moreover, assuming that, in ULS conditions, a limited displacement might go off along one slip line possibly more critical than the other ones, the question of when it might occur would remain unanswered. So, one would still face the issues of the loading history of the reinforcements and of the relevance of their creep rupture strength for the required design life.

3.5 *Preferred model*

Not to mention numerical models, which obviously constitute a promising approach, a reliable model should first depict the actual in service distribution of the tensile loads. It is indeed the key for avoiding the long-term creep rupture of any reinforcing layer.

Such a model (which still has to be finalised) could possibly combine the two last previous ones. For every potential failure line, without displacement, the resultant of the tensile forces which are or, can be mobilized should actually counteract the resultant of the other forces. The reinforcing layers could be designed one after the other, from top to bottom. The envelopes of the required or, available tensile forces, drawn for every layer, may help visualize how the pullout capacity of the reinforcements actually affects the sharing out and the variation of the tensile loads. It could be a way of better differentiating the more or less short-term ultimate limit state, dependent on shear and pullout capacity, from the long-term one, once a risk of slip failure is dismissed, which depends on long-term tensile strength, i.e. primarily creep rupture.

4 CONCLUSIONS

As far as the long-term design creep rupture strength is concerned, it should refer to a short-term creep rupture strength instead of the nominal tensile strength. Safety should apply to what is expected to be lost over the extent of extrapolation, rather than to what is presumably left.

Regarding at failure design models, it is advisable not to rely exclusively on those which do not realistically represent the actual behaviour of the structures. A preliminary design, based at least on observations and common sense, should allow putting what is most likely needed where it is needed. As a matter of fact, what does matter in the long-term in a steady structure, is to prevent any break of the reinforcement resulting from time and ageing, i.e. mainly from creep rupture.

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