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Design factors and applications for reinforced or stabilised earth structures

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ABSTRACT : The primary criteria which all types of earth reinforcement systems should comply with, concerning safety of design, long term behaviour, environmental effects, hazards, are reviewed point by point. Explicit factors and precise targets for "certified products" are identified. Applications are then classified, according to four definite prerequisites, as common works, or "major structures" where only "certified products" should be used.

1 INTRODUCTION

Since it was invented by H. Vidal, Reinforced Earth ® has been applied to thousands of structures. In the last decade alternative systems have been developed, with metallic or polymeric materials in strip, grid or textile form. Users and designers need to understand their differences and to make sure that all systems abide by the same **essential requirements.**

This paper summarizes a rationale upon which common criteria can be based. It follows previous papers by CIRIA, Jewell and Greenwood, Koerner, Ingold, Voskamp, Boyd, Lawson, etc... It also refers to the elaboration of draft standards on soil reinforcement such as British BS 8006 or French NF P 94-220 and NF G 38-064. This paper describes a framework for both design and certification procedures, by considering almost all relevant aspects (except frictional characteristics and workability of backfill). It also classifies **certified** reinforcing products usable in **major structures** as well as common works.

2 DESIGN TENSILE FORCES

Tensile forces T are estimated by means of practical but imperfect calculation methods.

As recognized by most basic codes, uncertainty lies in the intensities and effects of the applied loads : weights, surcharges, earth pressure. Since these **actions** may be somewhat larger than assumed through nominal values, these are multiplied by a 1st series of partial safety factors (or load factors) $\mathbf{LF_a}$ so that unfavourable combinations are considered. Depending on the type of load and the combination, factors LF_a usually vary from 0.9/1.0 on one hand to 1.2/1.4 on the other hand before being combined with the following factor.

Subsequently, calculated **stresses** are multiplied by a 2nd partial safety factor $\mathbf{LF_s}$ covering the relative inadequacy of the calculation model. While LF_s=1.1 is logically applied to methods mainly backed up on *experimentation,* values in the range of 1.2/1.3 should be used for *theoretical* methods, such as global failure analysis.

Of course strains must be estimated on the basis of the factored tensile loads T_d.

3 ALLOWABLE DESIGN STRENGTH

T_d must be smaller than the allowable design strength R_d at the end of the required service life. As the evolution of soil reinforcing products through time is a complex matter, a step by step approach, involving successive partial and specific reduction factors (RF) and safety factors (SF) must be employed.

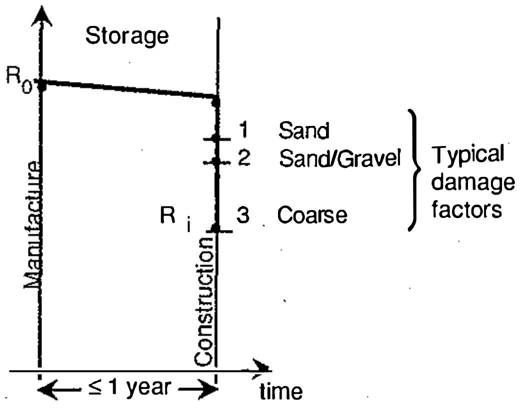

Fig. 1 : Installation reduction Factor.

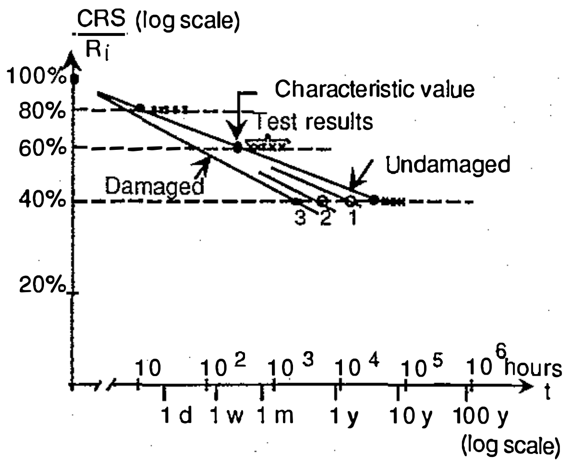

Fig . 2 : Measurement of time to creep failure.

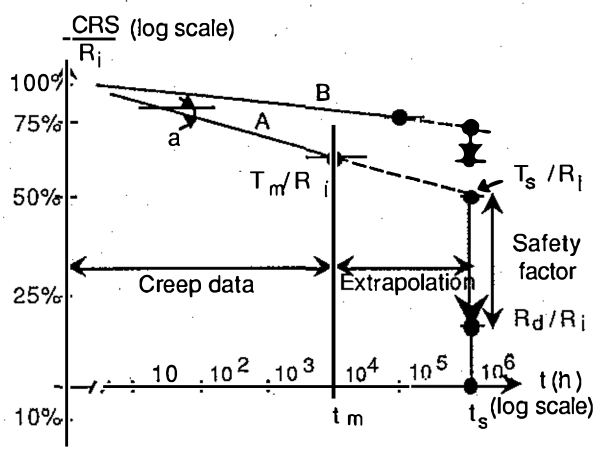

Fig. 3 : Extrapolation of characteristic creep data, in log. scales.

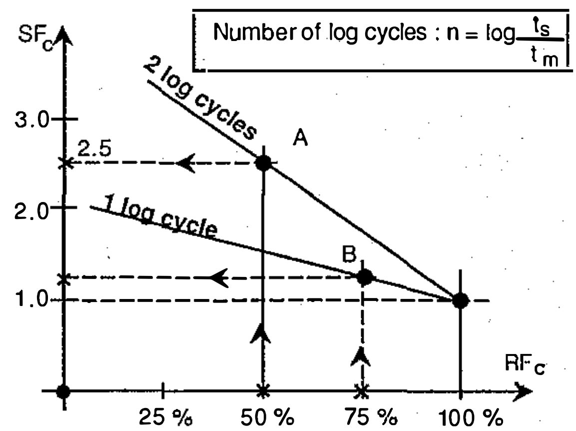

Fig. 4 : Extrapolation of creep data : safety factor.

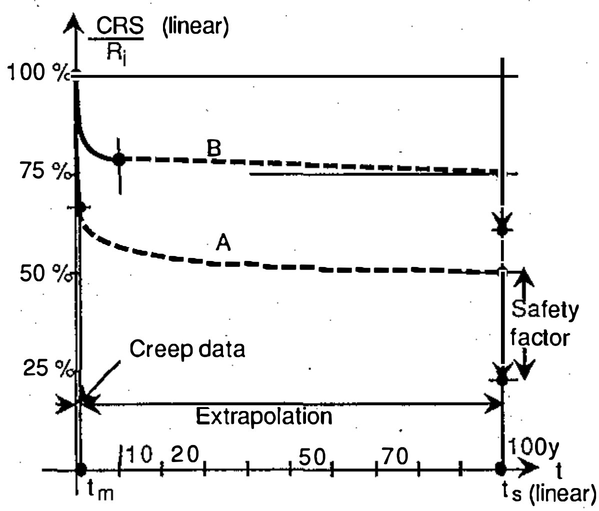

Fig. 5 : Extrapolation of characteristic creep data, in natural scales.

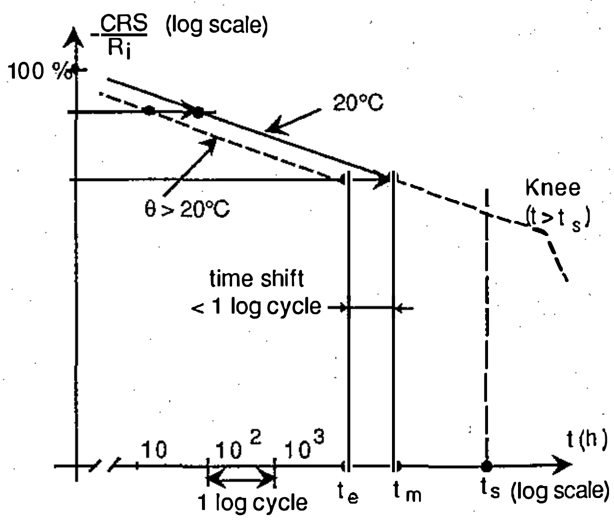

Fig. 6 : Conditions for validity of extrapolations.

3.1 *Short term strength*

Each **product** is identified by its claimed short term resistance R_{st} measured at manufacture according to standards such as ASTM D 4595-86 for polymeric materials. Depending on the degree of quality control, R_{st} must be first divided by a material safety factor $\mathbf{SF_p}$ covering possible variation in the capacity of the product. For **certified** (or 1st category) products R_{st} is either a *guaranteed* minimum (then SF_p=1.00) or a *characteristic* value (95% probability then SF_p=1.05). Other products fall in a 2nd category, where SF_p>1.20.

3.2 *Storage and construction damages*

From manufacture to installation, the product actual short term strength R_a may reduce to R_i (fig.1) due to possible :
1/- weathering during the storage period (normally not exceeding one year)
2/- damage due to backfilling and compaction. The amount of damage depends on the material and structure of the product as well as the nature of backfill, assuming reasonable compactive effort.

Installation reduction factors $\mathbf{RF_i}$, covering the whole period, must be documented for each certified product and typical backfill, based on systematic tests such as described by BS 8006. The reduction factor -defined as $RF_i=R_i/R_a$ for same batches- ranges from 100% for metal strips to 45% (Lawson) or even 33% (FHWA) for some geotextile structures.

3.3 *Creep rupture strength*

The Creep Rupture Strength CRS of a given product is derived from the time at which samples are expected to fail when constantly loaded at a certain percentage of their initial strength. It is agreed that CRS decreases linearly when both loading and time are represented in log scales (fig.2). Here initial strength is R_i and time is measured from the date of installation. For certified products CRS should be fully documented for undamaged and damaged material as suggested by fig.2, measurements being carried out at 20°C (§ 3.5 below).

The characteristic value of the time to failure associated with the smallest testing loading ratio T_m/R_i for the relevant case is called t_m. For a required service life t_s in excess of t_m it is necessary to carry out an extrapolation (bearing in mind that t_s is sometimes 100 times longer than t_m). A **creep** reduction factor $\mathbf{RF_c}$ corresponding to the slope "a" of the line has therefore to be introduced (fig.3) :

$RF_c=T_s/R_i \qquad RF_c = (T_m/R_i)(t_s/t_m)^a$

In order to cover the uncertainties of the **extrapolation** itself a safety factor $\mathbf{SF_e}$, which is a function of both the reduction factor and the range of the extrapolation, must then be applied (fig 4) :

$SF_e=T_s/R_s \qquad SF_e = RF_c+2(1-RF_c)\log(t_s/t_m)$

Contrary to factors suggested by others this does not penalize materials exhibiting very little creep. The same examples shown on fig.3, are shown in linear scale on fig.5. This emphasises the relevance of the proposed safety factor.

For certified products it must be proven beforehand that such an extrapolation is valid i.e. there is no risk of transition -or "knee"- in the rupture mechanism during the required service life (fig. 6), even for damaged samples. This can be confirmed using the U.S. Plastic Pipe Institute procedures, based on tests carried out at elevated temperatures. This methodology also provides the product specific time/temperature correlations for creep. Thus CRS can be studied at a temperature θ>20°C, provided that the time shift (fig.6) remains smaller than one log cycle.

3.4 *Degradation due to environment*

All types of reinforcing materials are affected by chemical, biological or physical actions due to the soil, its constituents, the air and water it contains. Corrosion of steel and galvanized steel buried in soils has been known for a long time and is predictable. Polyester may suffer from hydrolysis in certain cases, while polypropylene is susceptible to oxydation and polyethylene to environmental stress cracking ; this will remain however a subject of research for many years, not to mention factors of degradation such as solvents, fuels, industrial wastes, or others not yet identified.

Degradation and consecutive decrease in resistance of the reinforcement should be taken into account through 3 partial factors :

1/ A reduction factor, $\mathbf{RF_t}$, accounting for the diminishing average **thickness** or section area of material. It depends on the required service life and typically concerns steel corrosion (but also, for example, polyester in alkaline media).

2/ A reduction factor, $\mathbf{RF_s}$, accounting for the loss of **strength.** It also depends on the required service life and covers the internal alteration of the material itself as well as the superficial unevenness which makes strength decrease more than the average section area of material.

3/ A safety factor, $\mathbf{SF_r}$, providing for a **reserve.** It depends on the limitation of knowledge or experience and covers the unknowns regarding long term behaviour.

As far as galvanized steel is concerned, RF_t is related to a conventional sacrificial thickness, ordinarily 1mm over 5 for a 70 years service life, or RF_t=80%. An overall safety factor of 1.5, equivalent to SF_r/RF_s, is then applied. It virtually breaks into RF_s=85% (correlating the most pessimistic anticipated loss of strength with the sacrificial thickness) and into SF_r=1.3, although the long term behaviour of steel is presently the one which is best known (Darbin).

Even if reduction factors $RF_s.RF_t$ of 90% to 50% for service lives around 75 years are conceded to synthetic materials (AASHTO-1991) in supposedly non aggressive environments (to be defined case by case), a reserve factor SF_r>1.3 should also be applied to all materials.

Certified products references should include thorough justification of RF_s and RF_t for the long term, based on both laboratory and site investigations for periods in excess of 10 years, in a large range of representative environments.

3.5 *Effects of temperature*

All ageing phenomena are sensitive to temperature : a rise of 10°C results in the rate of corrosion to be multiplied by 1.35, the rate of hydrolysis of polyester by 4.5 while creep in polyethylene increases about 11 times.

At depths from the facing where tensile loads are maximum, temperature is still affected by seasonal and diurnal variations, as well as sun radiations. It must be admitted that the equivalent constant temperature, as regards ageing, can be as high as the mean between average and highest temperatures of the site (Segrestin-Jailloux). Three typical climates can be considered :

Cold:	0±20°C	→	10°C
Temperate:	10±15°C	→	18°C
Hot:	26±12°C	→	32°C

In temperate countries design should thus be based on reduction factors (RF_c, RF_t, RF_s) determined at laboratory ambient temperature (20°). However for projects in hot countries other sets of values, corresponding to temperatures up to 35°, must be available for certified products.

3.6 *Hazard*

High **hazard** potential exists where a failure would entail loss of life, excessive economic loss, or bar access to main roads. Differentiation of hazard is reflected in an extra safety factor $\mathbf{SF_h}$, set at 1.0 for low hazard and 1.1 for high hazard potential by both BS 8006 and NF P 94-220.

3.7 *Allowable design strength ; recapitulation*

In conclusion, the relationship between design load T_d, allowable design strength R_d and short term resistance R_{st} is expressed by the following equations, illustrated by fig.7(a,b) :

$$T_d = (LF_a.T)\, LF_s < R_d$$

$$R_d = \frac{R_{st}}{SF_p} . RF_i . \frac{RF_c}{SF_e} . \frac{RF_t . RF_s}{SF_r} . \frac{1}{SF_h}$$

4 STRAINS

The related strain is derived from the isochronous creep curves drawn from the creep tests already mentioned (and corresponding to the same case, as regard damage and temperature). Fig 7(c) shows how to calculate the strain ε_s-ε_i developing after installation, from t_i to t_s, in the example of a retaining wall. One part, ε_m-ε_i, is based on curves drawn from actual measurements, while the second part, ε_s-ε_m, comes from extrapolated results. By analogy with what has been done above, the calculated strain can be corrected as follows :

$$\varepsilon_d = (\varepsilon_m - \varepsilon_i) + SF_e\, (\varepsilon_s - \varepsilon_m)$$

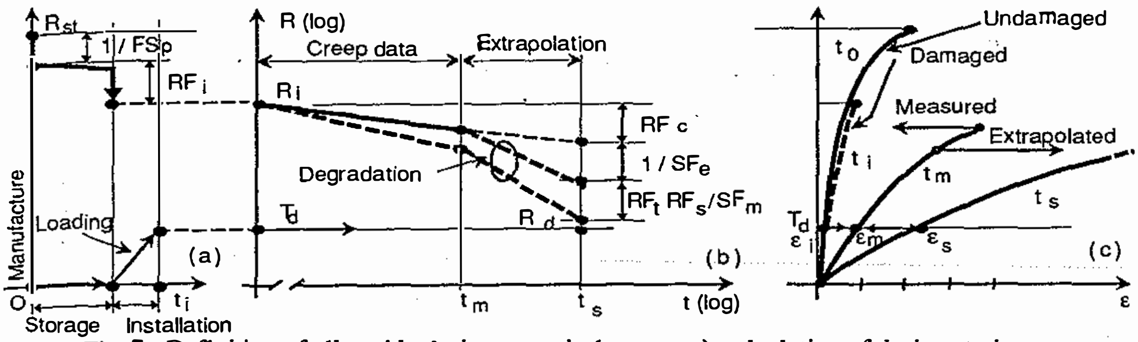

Fig. 7 : Definition of allowable design strenght (summary); calculation of design strains.

It will be compared to the specified maximum deformation (typically 1% for retaining structures). If this condition is not satisfied a lower allowable strength R_d must be considered.

5 MAJOR AND COMMON WORKS

While the information required for certified products allow to satisfactorily assess their long term behaviour and residual strength, it is not really possible to safely predict how the other ones will behave in the long term. The only reinforced or stabilised earth structures one might therefore envisage building with non-certified reinforcements are *common works*, whose collapse, should it take place, would not seriously impair the use of the structure, cause any damage to people or property. *Major works* should hence be restricted to certified products. The proposed classification depends on 4 successive criteria.

5.1 *First criterion : service life*

The question of long term behaviour does not arise for structures which are explicitely classified and managed as *short-term* structures, intended to serve for approximately 5 years. All short term structures can therefore be considered as *common works.*

On the contrary, the question of service life is relevant for *permanent* structures expected to serve -safely- for 70 to 120 years, and even for *temporary* structures, such as those in the industrial field, designed for about 30 years.

5.2 *Second criterion : height*

The second criterion is the height of the structure. It can be related to the degree of cohesion the earth fill will have acquired in most cases some 10 years after construction. This cohesion (C'), resulting from capillary effects and gradual cementation between the grains, is of the order of 10 to 15 kPa, allowing for exceptions. This small cohesion, although not considered in the structure design, could help keeping the structure stable -even if its reinforcements completely lose strength- up to a certain height which depends on the slope of the facing (α) and the angle of internal friction of the backfill (ϕ'). Based on a classical slip circle analysis, the chart below (fig 8), depicts the critical height H_c as a function of α and ϕ' for C'=10kPa.

Permanent and temporary structures whose height is above the critical height should be considered as *major structures.*

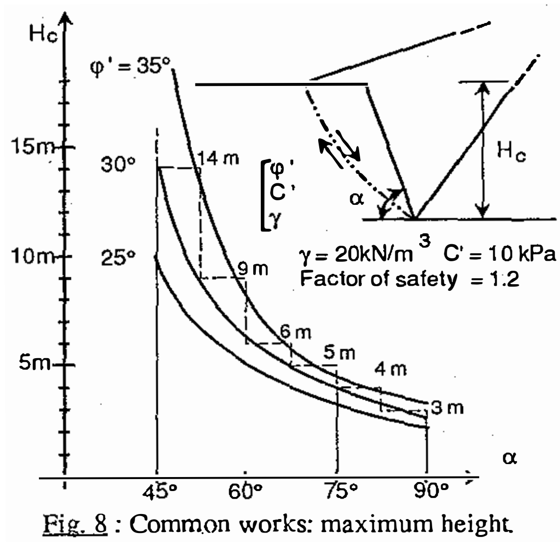

Fig. 8 : Common works: maximum height.

5.3 *Third criterion : facing*

The reinforcement behaviour is also critical for structures -even below the critical height- with heavy concrete facing elements directly supported by reinforcement. The inevitable consequences of connection failure may be serious indeed, although not necessarily compromising the overall stability. Consequently any temporary and permanent wall ($\alpha>60°$) with a facing consisting of concrete units should be regarded as a *major structure*.

5.4 *Fourth criterion : function*

In the eventuality of collapse of a whole slice of fill reinforced with second category materials, it should be ensured that the subsidence which would open on top of the structure as well as the crumbling zone forming at the toe do not risk causing any serious accident. This will exclude from the common works those carrying roads, railways, buildings located too close to the structure's edge that they risk being immediately or soon affected, encroached or de-stabilised. This also excludes those where a roadway, track, building at the bottom risks being partially covered with earth and debris in this eventuality. The limits of the critical zones can be defined as shown on fig.9, a distinction being made at the top between the mobile loads (road traffic) -which can be immediately diverted- and the fixed loads (railway tracks, buildings).

Permanent or temporary structures whose edge or toe is close to a sensitive zone should be considered as *major structures*.

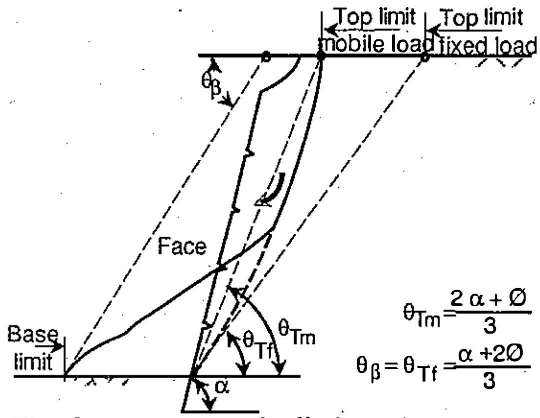

Fig. 9 : Common works: limits of critical zones.

6 CONCLUSION

Earth reinforcement systems can vary considerably in material, form and performance. The safety of the structures as well as the credit of the technique require that the industry conforms to a common basis of rational criteria regarding certification of products, selection of applications and definition of design factors. An approach is presented to meet these needs.

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