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The need for standard safety factors in the determination of allowable tensile loads

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ABSTRACT : There is a lot of confusion regarding the way influential national Codes apply the concept of safety to the basic types of earth reinforcing materials. This results in quite different degrees of safety for geosynthetics and steel, which is not rational. The problem is first a question of common vocabulary and proper definitions. Then it is an issue of the fundamental safety factors which should not depend on the type of reinforcing material. This paper identifies the present anomalies and outlines a standard and consistent approach.

1 MAJOR EXISTING CODES

The major national Codes or Specifications which have been developed to date which deal with soil reinforcement and mechanically stabilized earth (MSE) are :

- AFNOR NF P 94-220 norm (France)
- BS 8006 Code of Practice, 1995 (UK)
- AASHTO Interim Specifications 1994 (USA)

The French norm only deals with structures reinforced with inextensible reinforcing strips or sheets. It will be followed by another norm dealing with extensible reinforcements, based on the same general principles.

This paper looks at the definition of the factors of safety used and the allowable tensile load set by the three major Codes or Specifications. We use for comparison, the consideration of land based retaining walls with ordinary backfills. Both the French and British rules are written in limit state format with partial factors and AASHTO is written in a working stress format. We endeavor in our comparisons to end up with an allowable tensile load, T_{allow}, consistent with a working stress approach.

2 COMPARISON OF CODES

The processes for determining "allowable" tensile loads in the three codes or specifications are summarized in Appendix 1. Although it requires careful reading, it can be seen that there are obvious discrepancies regarding safety margin and a critical need for more consistency between the European and American approaches.

2.1 *Discrepancy regarding steel reinforcements*

The first discrepancy concerns the allowable tensile load for galvanized steel strips. It is demonstrated by considering the example of a 40x5mm strip made of steel grade Fe510c ($\sigma_u > 490$MPa; $\sigma_y = 355$MPa) with 70μ zinc coating and a design life of 70 years. The allowable tensile load, T_{allow}, is determined as shown in Table 1. The result is that the AASHTO Specifications require up to 1/3 more steel than the French and British standards require!

Table 1. Allowable tensile load of a 40x5 strip, according to the three codes.

	AFNOR	BS 8006	AASHTO
Corrosion allowance for design	1.0 mm	0.9mm	1.4 mm
Allowable stress	$0.47\sigma_u$	$0.44\sigma_u$	$0.55\sigma_y$
T_{allow} (kN)	36.8	35.4	28.1
Required Steel	100%	104%	131%

The main reason for the discrepancy comes from the use of yield stress by the AASHTO Specifications instead of rupture stress. The origin of this problem comes from the incorporation of a short section about MSE walls into General Specifications for Bridges, and from the practice of using yield stress for the design of bridges.

Yield is of course relevant for bridges and other building structures where deformation of an individual element can cause instability, but it is not relevant for MSE walls with steel reinforcement where there will be very little strain in service. In addition, the sacrificial thickness for design is derived from actual corroded sample testing and calculated in relation to rupture stress. The use of yield stress with sacrificial thickness is therefore nonsense.

2.2 *Discrepancy between steel and polymers*

There is also a clear discrepancy between how the 1994 AASHTO Interim Specifications regard steel and polymer reinforcements.

First, they apply similar coefficients (0.55 and 0.56) to different strength criteria : yield (instead of rupture) for steel, and long-term rupture strength for polymers. As a matter of fact, T_l is defined in the Specifications as the highest load level at which no failure of the polymeric reinforcement can occur within the required life time. As the context shows, this designates the creep rupture strength.

Second, this creep rupture strength does not include any factor of safety accounting for the uncertainties in the extrapolation of experimental data (contrary to what BS 8006 recommends through the f_{m12} factor). Conversely, the sacrificial thickness which AASHTO specifies (like the other codes) for the computation of the allowable long-term strength of galvanized steel reinforcements, does include a large (but implicit) extrapolation factor, as will be demonstrated later on in section 7.

Moreover, although they are named "factors of safety" in the AASHTO Specifications for polymeric reinforcements (see Appendix), it should be acknowledged that FC and FD correspond to nothing more than actual losses of strength resulting from installation damages and environmental degradation or ageing. They do not incorporate any implicit factor of safety whatsoever.

The outcome is that the suppliers of polymeric reinforcements are authorized to provide much less ultimate resistance than is required from the suppliers of steel reinforcements.

3 IDEAL APPROACH

There should be no real difficulty in outlining a logical, step by step, consistent approach of the long-term allowable tensile load for any type of soil reinforcement. It merely requires, from the very beginning, clear vocabulary and rigorous definitions.

We first differentiate between the concept of "factors of safety" and "reduction factors". For all kinds of civil engineering works, factors of safety account for the uncertainties and the unknown, in order to assure long term public safety. For obvious psychological reasons, factors of safety are usually values greater than 1. Reduction factors, however, correspond to identified, well known mechanisms of loss of resistance - they are determined from measured data. Since they correspond to remaining strengths, usually expressed as a percentage of the initial strength, reduction factors are usually values smaller than 1.

4 FACTORS OF SAFETY

4.1 *Factors of safety related to applied stresses*

The first uncertainty is related to the evaluation of the applied stresses. It can be covered for clarity by two partial factors of safety (FS) :

- the "applied load factors" (FS_a) account for the variability and uncertainties concerning the effects of the applied loads, basically dead weights and surcharges (the weight of the backfill is one of the uncertain fill properties)
- the "design method factor" (FS_d) covers the imperfection or lack of substantiation of the simplified models used for the design calculations; it also accounts for the potential for local overstresses, the uncertainties in the earth pressure coefficients and the structure geometry.

It can be understood from the Appendix and from what NF P 94-220 and BS 8006 consistently prescribe for these factors :

- applied load factors : $FS_a \approx 1.25$ to 1.35
- method factor : $FS_d \approx 1.10$ to 1.15

This results in an overall factor of safety (FS_o) of about 1.50.

4.2 *Factors of safety related to materials*

The second uncertainty concerns the strength of the structural materials and gives rise to other partial material factors of safety.

Some uncertainties pertain to the variability of the manufactured dimensions or the minimum short term strength (FS_v). If it is agreed that only well defined and formally controlled "characteristic" values should be considered, then FS_v can be disregarded.

More critical are the uncertainties associated with the potential long-term losses of strength of these materials e.g. the doubts concerning the long-term degradation phenomena, as well as the uncertainties in the validity and accuracy of the extrapolations of the experimental data. It is realistic to account for all these uncertainties through a factor of safety applicable to extrapolations (FS_e).

The factor recommended by BS 8006 (f_{m12}) is very attractive since it takes into account the actual duration of the testing. However it is therefore specific to the product and subject to periodic revisions : this is not ideal from a standardization point of view.

In addition, it is appropriate for the extrapolation factor of safety to be applied to the loss of strength, rather than to the remaining resistance, as already suggested by Boyd and Segrestin (1992). Indeed, a factor applied to the remaining resistance might heavily penalize materials exhibiting only very little loss of strength, as illustrated in figure 1.

A value will be recommended for FS_e in section 7.

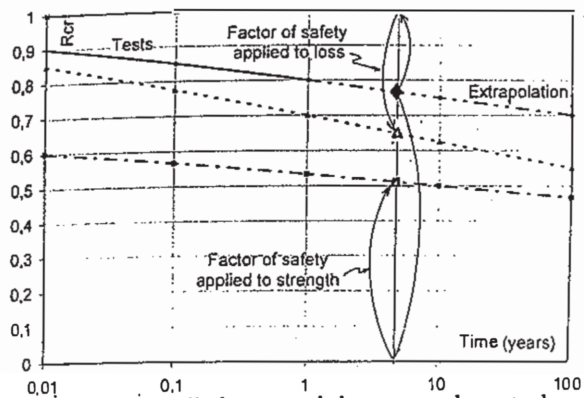

Figure 1. FS_e applied to remaining strength, or to loss of strength.

4.3 *Factor of safety related to hazard potential*

The uncertainties regarding the ramifications of failure are covered by a hazard potential factor of safety (FS_h). A major hazard potential would be considered when collapse might bar access to main roads, result in serious economic outcome or even in loss of human life. Based on BS 8006 and NF P 94-220, the following values are recommended :

ordinary structures $FS_h \approx 1.00$
sensitive structures $FS_h \approx 1.10$

4.4 *Independence from reinforcing materials*

It is essential to acknowledge at this point that none of the factors of safety reviewed here above depends on the materials used for the reinforcements. At most, the design method factor (FS_d) might be a bit larger when the computation model used for design is supported by very little monitoring results for a given reinforcing material or product.

5 REDUCTION FACTORS

Four reduction factors, expressed as percentages of the reference short term strength, need to be considered for soil reinforcements :

- a construction damage factor (RF_c)
- a creep rupture strength factor (RF_{cr})
- a chemical/biological durability factor (RF_d)
- a temperature factor (RF_t)

Each of them is specific to the reinforcing material or product.

5.1 *Construction damage factor*

This reduction factor does not depend on the design service life. It is drawn from full scale tests and does not require any extrapolation. However, since the source of the backfill material is seldom known at the design stage, RF_c should correspond to the most aggressive backfill complying with the specifications.

5.2 *Creep rupture strength factor*

RF_{cr} must be drawn from creep rupture tests where constant loads (equal to given percentages of the short term strength) are applied to samples of the product, until they break. The extrapolation of these results, provided it is valid, allows determination of the load that would bring the reinforcement to failure at the end of the required service life. It must be acknowledged that this is the only relevant criteria. The reinforcement may indeed have to withstand much more than the allowable tensile load (in the working-stress-approach sense of the word), should the calculated design load happen to be actually underestimated by a factor FS_a*FS_d. Even in this case, the reinforcement must not break.

5.3 *Chemical/biological durability factor*

A lot remains to be done (especially retrieving and scientifically monitoring samples after ten years or so in a large variety of environments) before reliable durability reduction factors can be assessed for all types of reinforcing materials. It should be noted here that a degradation reduction factor RF_d can also be introduced for galvanized steel. This will allow steel to follow the same standard "allowable tensile load" procedure as for all other kinds of reinforcements.

The reduction factor is the ratio between the long-term rupture strength after degradation and the short term rupture strength. For steel strips it is therefore nothing more than the ratio between the design thickness and the nominal thickness:

$$RF_d = (E_n - E_s)/E_n$$

provided that E_s corresponds to the maximum anticipated loss of tensile strength of the corroded strip.

5.4 *Temperature factor*

Generally creep rupture strength and chemical biological data are drawn from experiments carried out at ambient temperature. However, it is not uncommon for the temperature within the backfill of MSE walls to be well in excess of 20°C, particularly behind the facing. Since a rise in temperature principally affects creep, temperature reduction factors RF_t applicable to the creep rupture strength of various polymers were already published (Rimoldi, 1993).

It should be noted that since the effect of temperature has an exponential effect, the average temperature for the site is not the one to consider. A better approach is to refer to a mean between the average temperatures of the year and that of the hottest day of the year (Segrestin Jailloux, 1988).

6 ALLOWABLE TENSILE LOAD

6.1 *Definition*

Based on the reduction factors and factors of safety defined above, the process to determine the allowable design tensile load (T_{allow}) from ultimate short-term rupture strength (T_u) in the working-stress-approach sense can be generally described as shown in table 2.

Table 2. Chart for the derivation of T_{allow} from T_u

Input	Action	Output
Tu →	apply RF→	Tul
	↓ apply FSm→	Tu2
	↓ apply FSo→	Tallow

where:
Tu = characteristic ultimate short-term rupture strength
RF = reduction factors accounting for the anticipated losses of strength (RF_c, RF_{cr}, RF_d, RF_t)
Tul = anticipated long-term rupture strength
FSm = material factors of safety (FS_v, FS_e)
Tu2 = allowable long-term tensile strength
FSo = overall factors of safety (FS_a, FS_d, FS_h)
Tallow = allowable long-term tensile load.

The resulting equation can be expressed as follows, depending on how the factor of safety for extrapolation (FSe) is applied.

6.2 *FSe applied to remaining strength*

$$T_{allow} = T_u \frac{RF_c * RF_{cr} * RF_t}{(FS_a * FS_d) * (FS_e * FS_h)}$$

As explained in §4.2, this is not the most advisable formula.

6.3 *FSe applied to loss of strength*

It is recommended that the extrapolation factor of safety FSe be applied to the loss of strength. The equation becomes:

$$T_{allow} = T_u \frac{RF_c * RF_{cr} * RF_d}{(FS_a * FS_d) * FS_h}$$ where

$RF'_{cr} = 1 - Fs_e(1 - Rf_{cr} * Rf_t)$
$RF'_d = 1 - Fs_e(1 - RF_d)$
(assuming that temperature little affects chemical biological degradation).

7 RECOMMENDED VALUE FOR FSe

A minimum value for a standard extrapolation factor of safety FS_e can be drawn from:
- the actual knowledge regarding the loss of strength of corroded galvanized steel strips
- the present requirements of the existing codes/specifications for those strips.

7.1 *Knowledge*

The average loss of total thickness after t years is expressed by the equation:

$\Delta e < At^n$ (μ) where, in environments with resistivity > 1000Ωcm

A = 25 n = 0.65

Z being the thickness of the zinc coating, the total average loss of steel thickness for the two surfaces of the strip is:

$2\Delta a < 2(At^n - Z)$

Because of the slight unevenness of corrosion, the strength decreases somewhat quicker than the average thickness. With the notations of the Appendix and section 6, this means that the anticipated long-term rupture strength Tul of the strip is given by the equation:

$Tul > [En - 2K(At^n - Z)]w * \sigma u$
(for 40x5mm strips, we have $K \approx 1.9$).

Then, with FS_e applied to the loss of thickness

$Tu2 > [En - 2K*(FSe*At^n - Z)]w*\sigma u$ or

$$T_{allow} = [En - 2K*(FSe*At^n - Z)]w*\sigma u / FSo$$

7.2 *Comparison with Code requirements*

We run the comparison for the same 40x5mm galvanized steel strips made of Fe510c steel as above, with

En = 5mm w = 40mm
σu = 490 MPa Z = 70μ
A = 25 n = 0.65
t = 70 yrs K = 1.9

The comparison between the equation of §7.1 above and the values of T_{allow} derived from the Codes in §2.1, leads to the values (shown in table 3) of the "extrapolation factor of safety" FSe which are implicit in these Codes:

Table 3. Implicit FS_e values in the main Codes

	AFNOR	BS 8006	AASHTO
Tallow (kN)	36.8	35.4	28.1
FSo	1.40	1.50	1.78
FSe	**1.75**	**1.69**	**1.80**

We assumed for this comparison that the AASHTO Specifications should apply to steel the same overall factor of safety (1.78) which they consider for polymers.

The extrapolation factors which are implicitly required for galvanized steel look quite large, keeping in mind the long experience and the amount of long term data which is available. A value of 1.50 should be certainly conservative enough.

However, in the present state of the Codes and Specifications for galvanized steel reinforcements, an extrapolation factor of safety on the order of 1.75 is implied and should also apply to all other types of reinforcing materials, which do not benefit from the same experience.

It must be emphasized that, up to now, this kind of factor is totally ignored in the AASHTO Specifications for polymeric reinforcements. It exists in the British Code via the fm 12 factor. It is likewise expected that it will not be overlooked in the future French norm for extensible reinforcements.

8 CONCLUSION

The paper has demonstrated that there is both compatibility and inconsistency between the existing major codes on the subject of allowable tensile loads in soil reinforcements.

The two European Codes, which are each solely dedicated to reinforced soil, produce very similar results for the subjects which they both cover. However, there remains significant incompatibility between these two codes and the AASHTO Specifications.

The paper has demonstrated that imprecise definitions and even omissions of essential design factors exist. The use of the major codes extends well beyond the national boundaries of the originating country and hence basic standardization is very important. There is therefore an onus upon the writers of major codes, as well as international Institutions such as the International Geosynthetics Society (IGS) and the European Committee for Standardization (CEN), to ensure that there is a logical consistency and compatibility between national standards.

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Appendix: Internal stability of MSE highway retaining walls - land based
Allowable tensile stress (long-term limit state criteria)
Summary of main design methods (with some uniformity of notations)

AFNOR - NF P 94-220, 1992

Design philosophy

Limit state design, with load factors, method factor and material factors

General

Load factors	γ_{FIG}	applies to weight of structure and earth pressure (here $\gamma_{FIG} = 1.20$)
	γ_{FIq}	applies to live loads and resulting pressure ($\gamma_{FIq} = 1.33$)
Method factor	γ_{F3}	to account for imperfection of the practical design method ($\gamma_{F3} = 1.125$)
Material factor	γ_{mt}	applies to tensile rupture ($\gamma_{mt} = 1.50$)
Ramifications of failure		implicit (say γ_n) = 1.0 for standard structures, 1.1 for sensitive structures
Long-term base strength		R_{ck}
f_c, f_m, f_v		reduction factors for chemical degradation, construction damages, ageing
Design tensile load T_m		$\gamma_{F3} * T_m \leq R_{ck} / (\gamma_{mt} * \gamma_n)$ where T_m includes load factors
		i.e. practically: $\gamma_{F3} * (\gamma_{FIG}; \gamma_{FIq}) * T_{al} \leq R_{ck} / (\gamma_{mt} * \gamma_n)$ (width w)

Galvanized steel strip reinforcements

Design thickness	$E_c = E_n - E_s$ (nominal thickness - sacrificed thickness)
Sacrificed thickness	E_s = 1.0mm for 70 yrs service life, 1.5mm for 100yrs (NF A 05-252)
Long-term base strength	$R_{ck} = w * E_c * \sigma_u$ (σ_u = rupture stress)
Allowable tensile load	$T_{allow} \leq w * E_c * \sigma_u / [\gamma_{F3} * (\gamma_{FIG}; \gamma_{FIq}) * \gamma_{mt} * \gamma_n]$
	$\approx w * E_c * \sigma_u / (1.125 * 1.26 * 1.5 * 1.0)$ with $(\gamma_{FIG}; \gamma_{FIq}) \approx 1.26$
	$\mathbf{T_{allow} \leq 0.47 * (w * E_c * \sigma_u)}$

BS 8006, 1994

Design philosophy

Limit state design, with load factors and material factors

General

Load factors	f_{fs}	applies to weight of structure and earth pressure behind (here: $f_{fs} = 1.5$)	
	f_q	applies to traffic load and induced earth pressure ($f_q = 1.5$)	
Material factor	f_m	material factor: $f_m = (f_{m11}*f_{m12})*(f_{m21}*f_{m22})$	to take account of...
	f_{m11}	manufacturing variations	
	f_{m12}	extrapolation of data and confidence of long-term capacity assessment	
	f_{m21}	construction damage	
	f_{m22}	rate of environmental and aging degradation	
Ramifications of failure, f_n		to take account of economic ramifications of failure ($f_n = 1.0$ to 1.1)	
Long-term base strength		T_B	
Design tensile load		$T_D \le T_B / (f_m*f_n)$	where T_D includes load factors
		i.e. practically:	$(f_{fs}; f_q)*T_{al} \le T_B / (f_m*f_n)$

Galvanized steel strip reinforcements (width w)

Design thickness	$E_c = E_n - E_s$	(nominal thickness - sacrificed thickness)
Sacrificed thickness	E_s = 0.9mm for 70 yrs service life; 1.5mm for 120yrs	
Long-term base strength	$T_B = w* E_c *\sigma_u$	(σ_u = rupture stress)
Material factors ($E_n \ge 4$mm)	$f_m = (f_{m11}*f_{m12})*(f_{m21}*f_{m22}) = 1.5$	
Allowable tensile load	$T_{allow} \le w*E_c*\sigma_u /[(f_{fs}; f_q)*f_m*f_n] = w*E_c*\sigma_u /(1.5*1.5*1.0)$	
	$\mathbf{T_{allow} \le 0.44*(w*E_c*\sigma_u)}$	

Polymeric reinforcements

Long-term base strength		T_B = extrapolated tensile creep rupture strength at end of service life T_{CR}	
Material factors	f_{m11}	≥ 1.0	depending on quality control and tolerances
	f_{m12}	$\ge \log(t_d/t_t)$	depending on consistency of products tested
		where t_d = design service life, t_t = duration of real time creep tests	
	f_{m21}	to be derived from trials, plus assessment of long-term effects	
	f_{m22}	to be assessed, depending on polymer, soil chemistry, temperature, state of stress, design service life etc..	
Allowable tensile load		$T_{allow} \le T_{CR} / [(f_{fs}; f_q)*f_m*f_n] = T_{CR} /[1.5*f_m*1.0]$	
		$\mathbf{T_{allow} \le 0.67*T_{CR} / [(f_{m11}*f_{m12})*(f_{m21}*f_{m22})]}$	

AASHTO (Interim 1994)

Design philosophy

Working stresses (no load factors)

Galvanized steel strip reinforcements (width w)

Allowable stress	$0.55\ \sigma_y$	(σ_y = yield stress)
Design thickness	$E_c = E_n - E_s$	(nominal thickness - sacrificed thickness)
Sacrificed thickness	(until end of design service life)	
1/ galvanization (86μ)	15μ/side/yr for first 2 years, 4μ/side/yr for subsequent years	
2/ steel (E_s)	12μ/side/yr after zinc depletion	(i.e. 1.42mm for 75 yrs service life)
Allowable tensile load	$T_{allow} \le w*E_c*0.55F_y$	
	$\mathbf{T_{allow} \le 0.55*(w*E_c*\sigma_y)}$	

Polymeric reinforcements

Limit state tensile load T_l		highest load level at which no failure can occur within design service life
Factors	FC	"factor of safety" with respect to construction damage, to be determined by tests (1.05 < FC < 3.50)
	FD	"factor of safety" with respect to environmental and aging losses, to be based on product specific data (1.1 < FD < 2.0)
	FS	overall factor of safety to account for uncertainties in structure geometry, externally applied loads, fill properties, reinforcement manufacturing variations (FS = 1.78)
Allowable tensile load		$T_{allow} \le T_l/(FC*FD*FS)$
		$\mathbf{T_{allow} \le 0.56*T_l/(FC*FD)}$