# The Application of Reinforcement Materials for Earth Structures – Risk and Acceptability

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SUMMARY: Reinforcement materials for the reinforcement or stabilisation of earth structures come in many forms. The key characteristics of earth reinforcement are strength, extensibility, soil interaction and durability. In applying reinforcement materials to earth structures an assessment needs to be made of risk. Risk is defined as function of hazard, vulnerability and uncertainty. Hazard relates to the potential for loss of life or function. Vulnerability relates to the criticality of the reinforcement to the performance and stability of the structure. Uncertainty relates primarily to the ability to predict behaviour over the service life required. Application categories for earth reinforcing materials are derived which are based on an overall risk assessment of both the materials and the application. Such categories can be used for the application of material types or for the definition of appropriate safety factors.

## 1 INTRODUCTION

Since REINFORCED EARTH was invented by Henri Vidal (1966), the technology has been applied to many thousands of structures and its behaviour and application limits are well understood. In the last decade, a number of alternative soil stabilisation and reinforcement systems have been developed. Reinforcement materials are metallic or polymeric, and in strip, bar, grid, mesh or textile form. In particular, a number of reinforced soil wall systems have been promoted with varying degrees of similarity to the REINFORCED EARTH system. Reinforced soil wall systems can be applied efficiently to many structural applications where a high degree of security is required (eg bridge abutments, railway embankments, dams etc). The problem for designers and users is to understand both the similarities and the differences between these systems and to develop appropriate acceptance criteria (Arup,1990). The aim of this paper is to describe a rational basis upon which such criteria can be derived, taking into account the risk associated with both the materials and their application.

## 2 REINFORCEMENT

Reinforcement may be of different materials and form. The characteristics of primary importance in their application as earth reinforcement are:

- strength
- extensibility
- soil interaction
- durability

These characteristics differ for each of the reinforcement types presently available for earth reinforcement (Table 1). Each of these materials and forms work, but they work in different ways. It is important to understand how they work so that the appropriate design parameters and factors of safety can be applied to different applications, particularly in vertical, or near vertical, faced reinforced soil wall structures where the behaviour of the reinforcement has a direct and usually critical influence on the behaviour of the structure (Boyd,1990).

TABLE 1

Reinforcement Characteristics

| Material & Form | Strength | Extensibility | Soil Interaction | Durability Experience |
|---|---|---|---|---|
| Steel, Ribbed strip | High | Inext. | Friction + Passive | Long |
| Steel, Grid, Bar mat | High | Inext. | Passive | Long |
| PET, Strip, Mesh | High | Ext. | Friction | Medium |
| hdPE, Grid | Medium | Ext. | Passive | Medium |
| Steel, Woven Mesh | Medium | Ext. | Passive | Medium |

### 2.1 Strength

The allowable design strength per layer may be as high as 100 kN/m or more for both metallic and polymer systems whereas some polymer geotextile systems may provide less than 10 kN/m. The strength of the reinforcement must be predictable over the design life of the structure, taking into account metal corrosion or polymer ageing.

Metal corrosion and polymer ageing are different processes. Design factors must recognise this. Metal corrosion is a physical deterioration resulting in loss of material over time. Sacrificial material is usually provided to "protect" the base section required. The life of this material can be equated to known corrosion rates from the experience of such metals in similar environments for long periods. Polymer ageing is the entirety of all the irreversible chemical and physical processes over time. These processes include - weathering, construction damage, creep, structural change and chemical attack. They are influenced by temperature and may be compounded by the synergistic effects from several processes. Design factors must be applied to cover all possible processes and changes which may occur over the life of the structure based on generally short term data.

## 2.2 Extensibility

The extensibility or stiffness of the reinforcement has a fundamental influence on the behaviour and performance of reinforced soil structures. The very low working strains (<0.1%) exhibited by inextensible reinforcement promote coherent gravity block behaviour in reinforced soil wall structures, whereas the much larger working strains (>3%) exhibited by extensible reinforcements promote a tied-back wedge action. This can have a significant impact on structural behaviour.

The load/extension characteristics of metals and polymers can be quite different. For comparable strength levels, deformations can be between one and two orders of magnitude different (10 to 100 times). Even for high strength materials, there can still be a large divergence (Fig.1).

The variability of the stiffness characteristics of reinforcement types is highlighted in Fig.2, taken from data presented by Mitchell and Christopher (1990). Stiffness is shown to be function of both material and form, as steel woven mesh exhibits an extensibility closer to that of polymer materials. Default stiffness ratios for inextensible and extensible reinforcement are 75,000 kN/m/m and 2,500 kN/m/m respectively. (Christopher et al, 1990).

Strain compatibility considerations significantly effect both soil and reinforcement stresses and accordingly effect reinforcement design. The time dependency of load/deformation behaviour (creep) has the potential to alter both the state of stress (stability) and the strain behaviour over the life of the structure. For wall structures this can be critical from a serviceability viewpoint. This is recognised in the draft BS8006 (1991) which provides for strains in the reinforcement to not exceed 0.5% for abutments and 1.0% for walls. For long term structures, where the life of the structure is directly related to the life of the reinforcement, caution is required for polymer materials as there simply is no long term creep data available, comparable to such design lives.

## 2.3 Soil Interaction

The transfer of stress between the soil and the reinforcement is fundamental to an effective soil reinforcement system. Such transfer may be by way of friction or passive (anchorage) resistance depending on the form of the reinforcement and the physical characteristics of the soil.

The shear strength and dimensional stability of fine grained (cohesive) soils, are effected by moisture content. Coarse grained (granular)

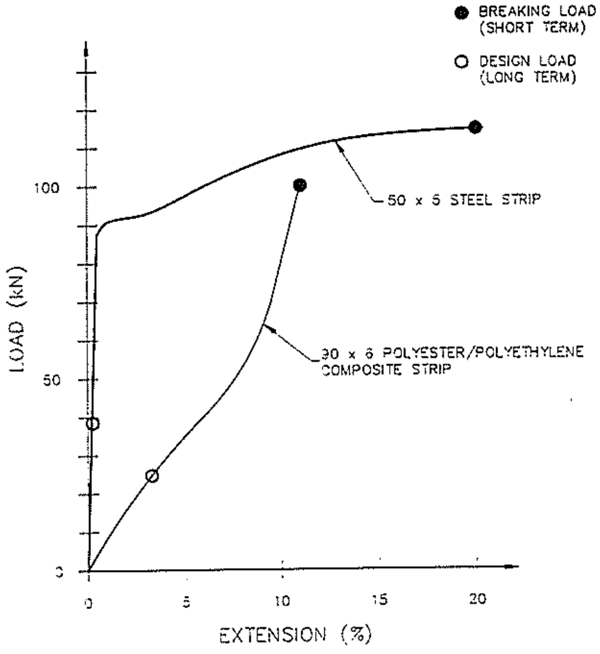


Fig. 1. Load Extension Relationship for Metal and Polymer Reinforcement

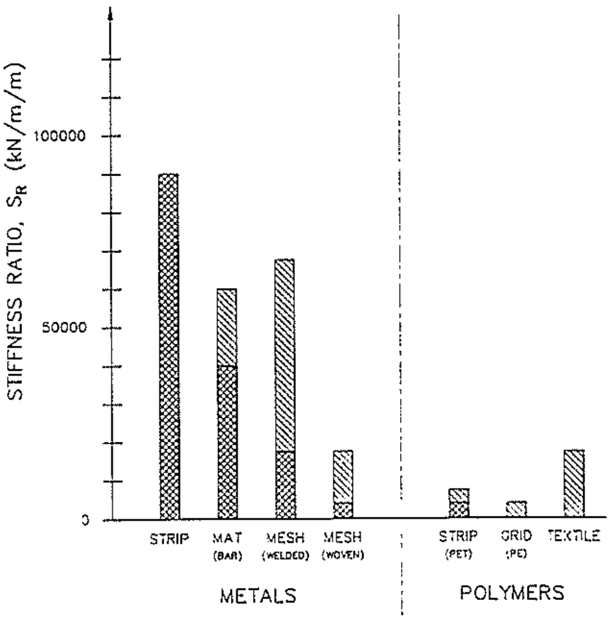


Fig.2 Stiffness Characteristics of Reinforcement (after Mitchell and Christopher, 1990)

soils promote mechanical interlock and are dilatent when sheared promoting good soil interaction with high dimensional stability. Smooth strips rely on frictional transfer. Grids and meshes rely on mechanical interlock. Inextensible reinforcement will mobilise more resistance over the length of the reinforcement, and consequently will promote more composite behaviour within the structure due to its strain compatibility with dense granular earth.

Soil reinforcement interaction factors are compared for several reinforcement types in Fig.3. The predictability and repeatability of such data is important in determining appropriate design factors.

## 2.4 Durability

All materials will lose strength and change their strain characteristics with time. The only complete method of prediction is from data taken from such materials subject to the same stress and environmental conditions as they would be in the reinforced soil structure, for the time equivalent to the service life.

The present state of knowledge of long term behaviour of materials used as soil reinforcement has been summarised by Jailloux and Segrestin (1988).

For design, the concept of partial factors applied to long-term characteristic strengths is considered appropriate to determine basic design strengths. The draft BS8006 (1991) recommends factors for:

- material variability
- test data extrapolation
- construction damage susceptibility
- environmental attack

Furthermore, it is important that not only should the reinforcement not fail in tension during the life of the structure, but also the strains in the reinforcement should not exceed a prescribed value. This approach is described in Fig.4.

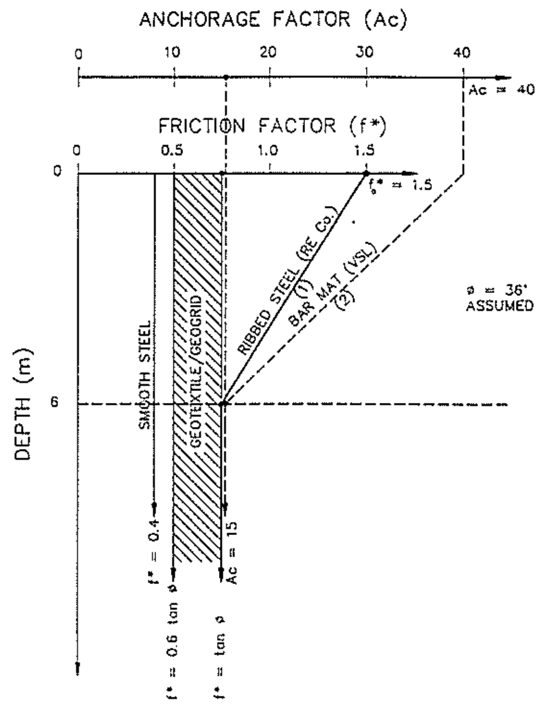


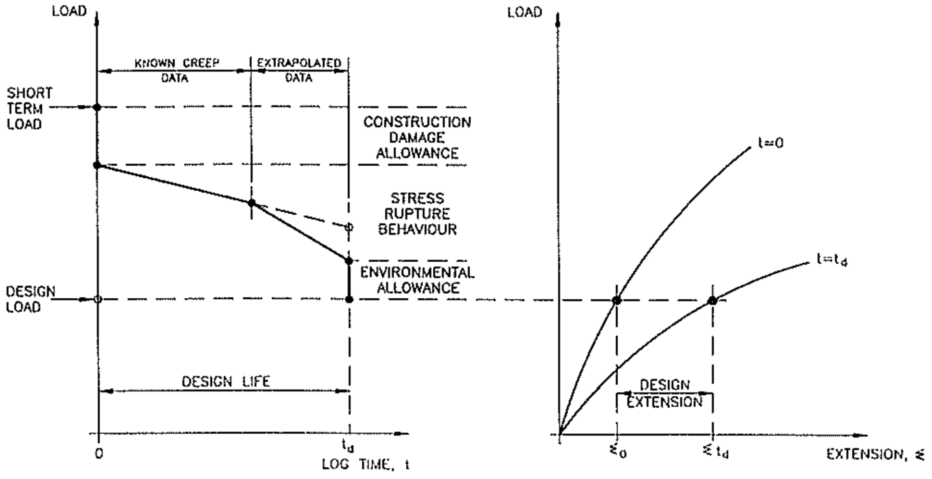
Fig.3 Soil Reinforcement Interaction Factors

Ingold (1991) emphasises the need to apply a consistent approach to both metallic and polymer materials and provides guidelines for partial factors for polymeric materials.

## 3 RISK

In order to apply reinforcement materials to structures an assessment needs to be made of risk.

Risk is a function of both the potential for failure (vulnerability and uncertainty) and the consequences of failure (hazard). The



CHARACTERISTIC STRENGTH TIME RELATIONSHIP

ISOCHRONOUS LOAD EXTENSION RELATIONSHIPS

Fig.4 Reinforcement Design for Load and Extension with respect to Design Life.

potential for failure may be increased by reinforcement vulnerability (due to reinforcement criticality) and uncertainty (due to reinforcement experience). The consequences of failure may be increased hazard from loss of life, loss of function and/or economic loss.

Variable design factors should be applied to both the potential for, and the consequences of, failure.

### 3.1 Hazard

High hazard potential exists where the consequences of failure include the potential for loss of life, excessive economic loss and loss of access on principal roads, railways etc. Low hazard potential could mean no expected loss of life, minimum structural damage and loss of access on minor routes only as defined in the Geotechnical Manual for Slopes used in Hong Kong (GCO,1984).

This differentiation of hazard is reflected in the minimum factors of safety provided for different ultimate limit states in the Model Specification for Reinforced Fill Structures, Geospec 2 (GCO,1989). These are summarised in Table 2.

TABLE 2

Minimum Factors of Safety

| Ultimate Limit States | | Risk Category | |
|---|---|---|---|
| | | High | Low |
| External | Slope | 1.4 | 1.2 |
| | Sliding | 1.5 | 1.2 |
| | Bearing | 2.0 | 1.6 |
| Internal | Pull-out | 1.8 | 1.5 |
| | Tension | 1.7 | 1.4 |

Extract from Table A1, Geospec 2 (GCO,1989)

The recommendations issued by the French Ministry of Transport (LCPC/SETRA,1979) distinguish two categories of structure based on their hazard potential:

- "Ordinary" structures
- "High security level" structures

Factors of safety for the limit state of the resistance of the reinforcing material with respect to tension and adherence resistance are summarised for the two categories in Table 3.

TABLE 3

Limit State Coefficients

| Limit State | | Ordinary | High Security |
|---|---|---|---|
| Internal | Tension | 1.50 | 1.65 |
| | Adherence | 1.35 | 1.50 |

Extract from French MoT recommendations (LCPC/SETRA,1979)

The draft BS8006 defines categories of structure depending on the ramifications of failure. This is akin to the hazard potential described above. Furthermore, these categories take some account of the vulnerability of the structure by describing examples of structures for each category which in some cases infer reinforcement criticality. Partial factors are defined with respect to the type of structure and the consequences of failure. These are outlined in Table 4.

TABLE 4

Categories of Structure depending on ramification of failure

| Category | Partial Factor | Example of structure |
|---|---|---|
| 1 (Low) | Not Applicable | Retaining walls and slopes less than 2m in retained height where failure would result in minimal damage and loss of access |
| 2 (Medium) | 1.0 | Embankments and structures where failure would result in moderate damage and loss of service |
| 3 (High) | 1.1 | Abutments, structures directly supporting motorway and trunk roads or railways or inhabited buildings, dams, sea walls and slopes, river training walls and slopes |

Extract from Table 6.2 draft BS8006 (1991)

A quantitative estimate of the consequences of failure can be made with respect to the structure geometry and the failure mechanism (TAI,1990). This provides a definition of hazard potential. Limiting clearances for loads and associated structures can be defined for different levels of security with respect to material properties and slope geometry as shown in Fig 5.

### 3.2 Reinforcement Influence

The vulnerability of the structure can be related to the reinforcement where such reinforcement influence is critical to the behaviour of the structure.

The criticality of the reinforcement depends on the relationship between the loads applied, the reinforcement forces and the earth resistance mobilised. Where the behaviour of the structure is directly related to the behaviour of the reinforcement, the reinforcement is critical. This is the case for vertical faced, load bearing structures particularly where direct permanent loads are applied to the active zone. For structures with concrete facing elements directly supported by the reinforcement, the reinforcement behaviour is also critical as the consequences of connection failure may be serious although not necessarily compromising the overall stability of the structure.

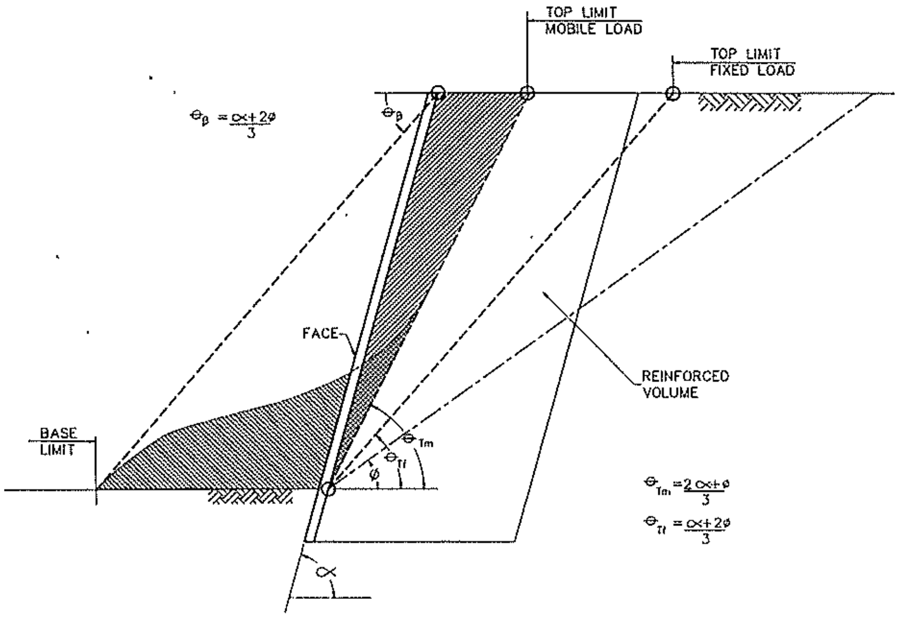


Fig.5 Proposed Clearance Limits for Low Hazard Potential

A distinction may be made between stabilisation and reinforcement in the context of criticality. Stabilisation implies improvement through an indirect influence on material properties and behaviour characteristics. Reinforcement implies direct support through primary structural action.

Rowe (1987) states that only products with sufficient strength, modulus or pullout resistance can be expected to provide significant reinforcing, however, this is not to suggest that a geosynthetic with properties less than that required to provide reinforcement will not improve performance. This could occur by, for example, their functions as separators, filters or drainage mediums.

The criticality or otherwise of reinforcement can be demonstrated by the analysis of a simple wedge in a reinforced soil wall structure as illustrated in Fig 6.

The resultant wedge force Ta, must be resisted by the sum of the reinforcement resistances mobilised across the wedge boundary. This resistance is the lesser of the frictional adherence resistance or tensile (strength) resistance of the reinforcement.

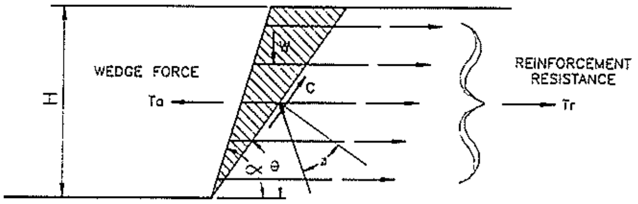


Fig.6 Simple Wedge Analysis of Reinforced Soil

The resultant wedge force can be significantly reduced by reducing the face angle ( $\alpha$ ), increasing internal friction ($\phi$) or mobilising a cohesion (C). This is demonstrated in Table 5. The acquisition of a nominal cohesion to a densely compacted granular earth in time may be sufficient to counteract the wedge force and therefore not mobilise the reinforcement resistance. A cohesion value of 10 kPa could support a vertical face to 3 metres or a sloped face ( $\alpha$ = 60 deg) to more than 6 metres. (TAI, 1990). Reinforcement in such cases may not therefore be critical in the longer term.

TABLE 5

Simple Wedge Analysis

| Wall Slope $\alpha$ (deg) | Internal Friction $\phi$ (deg) | Cohesion c (kPa) | Resultant Wedge Force Ta(max) (kN/m) | Reinf. Resist. Tr (kN/m) | Stability Factor Tr/Ta |
|---|---|---|---|---|---|
| 90 | 30 | 0 | 120 | 120 | 1.0 |
| | | 10 | 51 | | 2.4 |
| | 36 | 0 | 93 | | 1.3 |
| | | 10 | 32 | | 3.8 |
| | 42 | 0 | 71 | | 1.7 |
| | | 10 | 18 | | 6.7 |
| 60 | 30 | 0 | 41 | 41 | 1.0 |
| | | 10 | 0 | | - |
| | 36 | 0 | 25 | | 1.6 |
| | | 10 | 0 | | - |
| | 42 | 0 | 13 | | 3.2 |
| | | 10 | 0 | | - |

Assumed wedge height (H) = 6 metres and soil density ($\gamma$) = 20 kN/m3
Reinforcement resistance based on $\phi$ = 30 deg and c = 0 case for Tr/Ta = 1.0

### 3.3 Service Life

The uncertainty of behaviour is related to time and experience. Some materials and systems have only a limited experience as earth reinforcement and recourse will need to be made to predictions based on time extrapolation or experience in other applications.

Service life requirements are generally defined in the following terms:

- long term or permanent (100 +/- 50 years)
- medium term or semi-permanent (30 +/- 20 years)
- short term or temporary (<10 years)

## 4 APPLICATION CATEGORIES

On the basis of these considerations it is possible to define application categories which recognise all the elements of risk - the consequences of failure of the structure (hazard), the potential for failure of the reinforcement due to vulnerability (reinforcement criticality) and uncertainty (reinforcement experience). These are described in Table 6.

Where the risk is described as high, medium or low, the appropriate materials and systems can be defined. Furthermore, where additional security levels are required, appropriate partial (safety) factors can be defined.

TABLE 6

Application Categories

| Category | Service Life | Reinf. Influence | Potential Hazard | Risk |
|---|---|---|---|---|
| 1 | Long | Critical | High | High |
| 2 | Long | Critical | Low | Medium |
| 3 | Long | Non Crit | High | Medium |
| 4 | Long | Non Crit | Low | Low |
| 5 | Medium | Critical | High | High |
| 6 | Medium | Critical | Low | Medium |
| 7 | Medium | Non Crit | High | Medium |
| 8 | Medium | Non Crit | Low | Low |
| 9 | Short | Critical | High | High |
| 10 | Short | Critical | Low | Medium |
| 11 | Short | Non Crit | High | Medium |
| 12 | Short | Non Crit | Low | Low |

## 5. CONCLUSIONS

Earth reinforcement systems can vary considerably in material and form. The key characteristics required of earth reinforcement are outlined in order to understand the impact of their differences in structural applications, particularly for reinforced soil wall systems. A rational approach to the development of selection and application criteria is presented based on the risk assessment of both the systems and the applications.

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