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A design procedure for geosynthetic reinforced soil structures

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ABSTRACT: The paper deals with the main problems related to the design of reinforced soil structures with geosynthetics. On the basis of the experience gained by the Authors through research and professional activities a scheme procedure for the design of geosynthetic reinforced soil structures is proposed.

In particular, the following points are briefly discussed: project conditions, site and fill material characterization, design of reinforced soil structure, design control and performance monitoring.

1 INTRODUCTION

Thousands of geosynthetic reinforced soil structures have been constructed in the last twenty years.

The development of construction techniques, testing procedures, design and analysis methods has allowed to increase the size and the complexity of reinforced soil structures: steep slopes, embankments and walls with height in excess of 30 m are now commonly encountered.

Design engineers can find an enormous amount of information about reinforced soil structures (BS 8006 - 1995, FHWA 1997, Jewell 1996, Rimoldi 2000, Moraci 2005), with the risk of being confused about the required parameters, the design method to select the most suitable reinforcement, and so on. Thus there is a need to organize all this information in a properly defined and organized design procedure.

On the basis of the experience gained by the Authors through research and professional activities a procedure for the design of geosynthetic reinforced soil structures is proposed.

In particular, the following points are briefly discussed: project conditions, site and fill material characterization, design of reinforced soil structure, design control and performance monitoring.

In the following Table 1 are shown the meaning of the symbols used in the paper.

Table 1. Nomenclature.

FS	Safety factor
I_D	Relative density
L_R	Specimen length
P	Tensile load in reinforcement
P_a	Allowable tensile strength
P_B	Long term tensile strength (creep limited strength)
P_F	Short term tensile strength
P_{Field}	Long term field tensile strength
P_{Field}/P_a	Material factor
T_d	Temperature
t_d	Design life
$\mu_{S/GSY}$	Soil-geosynthetic peak interface apparent
σ'	Normal stress
τ	Shear stress
ϕ'	Soil shear strength angle
ϕ'_{cv}	Soil shear strength angle at constant volume
ϕ'_p	Peak soil shear strength angle

2 PROJECT CONDITIONS

To design a reinforced soil structures the knowledge of general and specific project conditions is required.

The general project conditions include: seismicity of the area, location of the structure (e.g. slope, soft soils, etc…), environmental conditions (temperature, rain, hydrographical net, etc.), landscape conditions, territorial conditions and technical regulations in force.

Project specific conditions include: geometric characteristics of structures, permanent and accidental loads, accessibility, construction times, availability of quarries for the fill of the reinforced soil structures, and presence of other structures close to design area.

3 SITE AND FILL MATERIALS CHARACTERIZATION

First of all, the program of field and laboratory investigation for the determination of the design values of parameters of site and fill materials shall be appointed, after an accurate topographical relief of the state of fact. The investigation program shall be developed on the basis of the general and specific project conditions, after having acquired the whole existing technical documentation on the site (geologic, hydrogeological, seismic, geotechnical, hydraulic studies etc.).

The extent of any field investigation should be sufficient to allow the determination of ground conditions at the site and to enable the construction of the structures in compliance with the contract documents and design.

The in situ investigations generally consist of borings, where undisturbed soil samples are taken and seismic (cross hole or down hole) and dynamic tests (SPT) are carried out. Cone penetration and dilatometer tests shall be carried out for the mechanical characterization of granular soils. Sometimes the execution of permeability field tests may be required as well.

Laboratory tests shall be performed on the undisturbed soil samples for the physical and mechanical characterization of cohesive soils (physical and classification tests, triaxial and oedometers tests).

Moreover, geotechnical instrumentations to measure water pressure (piezometers) and the displacements (inclinometers and settlement gauges) should be set up.

If rock masses are present a detailed geo-mechanical survey for the discontinuity characterization is necessary.

Stratigraphic and geotechnical sections shall be obtained for the design area using field and laboratory tests.

Relevant geotechnical investigation shall be provided also to determine the mechanical and physical properties of the fill material coming from the nearby quarries. In particular, grain size distributions, index and chemical properties, compaction and mechanical characteristics must be evaluated. It needs to be noted that the fill material will be installed in compacted layers with the placement of geosynthetic reinforcements. Hence this material will behave as a dense granular soil for which the dilatancy effects are relevant (Fig. 1).

A geotechnical investigation shall be provided, when relevant, to determine the aggressiveness of:

– materials which can be in contact with the reinforcement or facing;
– ground water which can soak the selected fill and affect its own aggressiveness.

4 DESIGN OF REINFORCED SOIL STRUCTURE

When the project conditions, the mechanical and chemical-physical characteristics of the soil and the fill materials are known, it is possible to develop the preliminary design of the reinforced soil structure. The long term design tensile strength of reinforcements shall be evaluated referring to the design life (Fig. 2).

In particular, the long term design tensile strength (Fig. 3) shall be high enough (in static and dynamic conditions) to guarantee the required safety factors in relation to the ultimate limit states for internal and compound stability (Fig. 4).

In this phase, chemical-physical characteristics and long term tensile strength (in static and dynamic conditions), damage during installation, chemical and biological durability, and interaction properties between reinforcement and soil (direct sliding and bond coefficients) must be evaluated for the reinforcement.

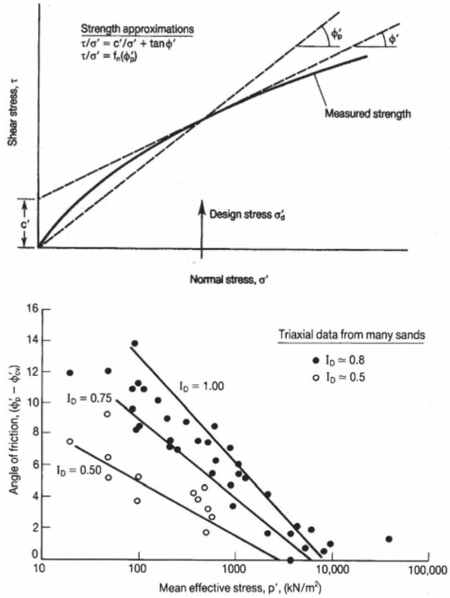

Figure 1. Shear strength of compacted soil [Jewell 1996].

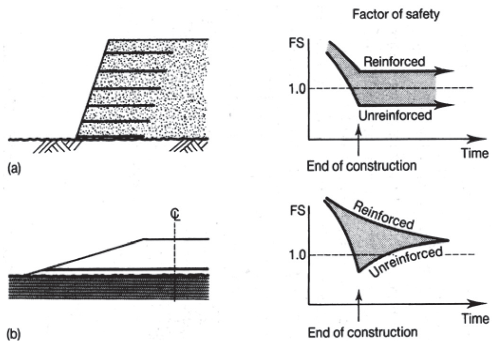

Figure 2. Variation of required reinforcement force with time [modified by Jewell 1996]. (a) Steep slope, (b) Embankment on soft soil.

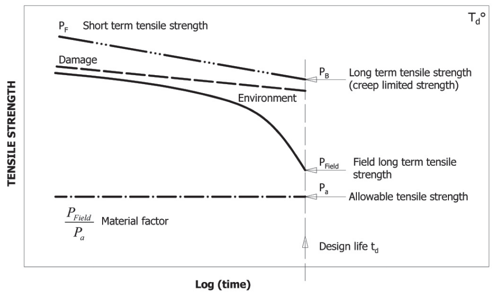

Figure 3. Scheme of the procedure used to define the design long term tensile strength [BS 8006 1995].

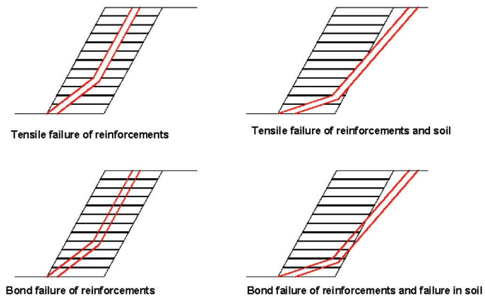

Figure 4. Ultimate limit states for internal and compound stability [BS 8006 1995].

The design analysis for reinforced soil structure is generally performed using simplified limit equilibrium methods in which the complex interaction between reinforcement and soil is reduced to an equivalent frictional parameters obtained from pullout and direct shear laboratory tests. The long term design tensile strength is evaluated by means of partial safety factors (creep, damage, environmental and material) starting from the short term tensile strength measured through the wide width tensile test according to EN ISO 10319 (Fig. 3). The length and spacing of reinforcements are also evaluated in this phase.

A recent research, based on the analysis of more than 20 full scale instrumented reinforced earth structures, has shown that the design methods based on the limit equilibrium methods are very conservative (Bathurst et al. 2004). This is due to the use of high safety factors for the definition of the long term design tensile strength of reinforcements, applied to the results of in isolation short term tensile tests (Fig. 3).

The type of reinforcement shall be selected taking into account the soil characteristics and the influence of reinforcement strength, stiffness and spacing on reinforced soil properties.

When polymeric reinforcements are used, the highest partial safety factor is the one that takes into account the creep of reinforcement. It is calibrated by in isolation creep tensile tests at controlled temperature (Moraci and Montanelli 1995), as shown in Figure 5.

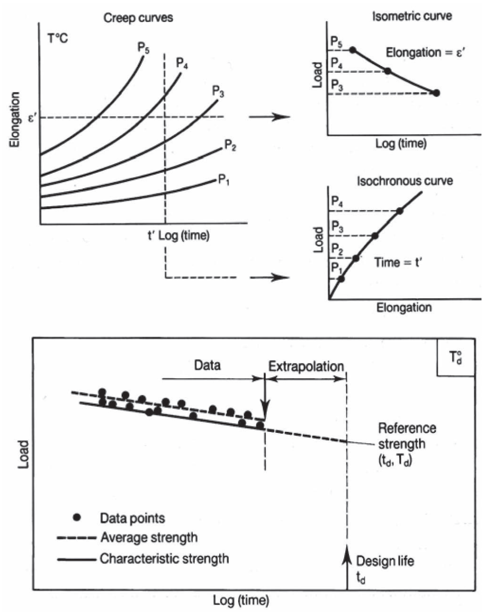

Figure 5. Creep and creep-rupture properties of geosynthetics [Jewell 1996].

In confining conditions in soil, due to different level of tensile stress acting along the extensible reinforcement, the creep effects may be different from those measured in constant stress condition as occurs in isolation tests. Such evidences have been shown in recent studies on instrumented full scale reinforced soil structures (Carrubba et al. 2000).

The over design of the structures may come from considering constant the interaction parameters for the overall reinforced soil structure. In fact recent researches have shown that the interaction parameters in pullout condition depend on the interface conditions, particularly the dilatancy which may develop along the interface (Moraci and Montanelli 2000; Moraci et al. 2003; Moraci and Recalcati 2005), and the effective bond length (Fig. 6).

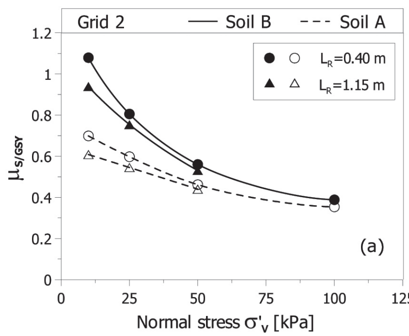

Figure 6. Influence of reinforcement length and confining pressure on interface apparent coefficient of friction [Moraci et al. 2003].

Another phase of the design of reinforced soil structures is the evaluation of the serviceability limit states. This type of analysis can be carried out through numerical calculation based on finite element models (FEM) (Rowe and Li 2002) or finite difference models (FDM). Nevertheless, these methods require the use of interface models capable to take into account the complex phenomena occurring at the contact between soil and reinforcement.

For mesh-structure reinforced elements, for example, different interaction mechanisms develop such as soil-reinforcement friction, soil-soil friction and passive bearing resistance mobilised on the transversal reinforcement elements. Moreover, such mechanisms become more complicated because of shape, length and extensibility of the reinforcements and of dilatancy effects at the interface (Moraci and Montanelli 2000, Moraci and Recalcati 2005).

The serviceability conditions can be evaluated by simplified models, such as kinematic method (or displacements method). In this method the behaviour of the active zone is assumed to be similar to a rigid block that moves on a sliding surface, retained by deformable reinforcement elements. For utilizing the displacements method (Gourc et al. 1986) it is necessary to know the stress-strain response of reinforcements when they pullout due to block movement.

The kinematic method has the advantage that it can be used for seismic analysis through the application of dynamic forces to the block movement. But the stress-strain curves and interface parameters due to cyclic pullout forces must be evaluated.

The foundation soil settlements and the overall stability of reinforced soil structure should be evaluated by means of the traditional geotechnical methods.

When the ultimate and serviceability limit state analyses have been performed and the ancillary structures (drainage and facing systems) have been designed, it is possible to work out the specification and the construction details.

Finally, the detailed project report shall include the following information:

- *Retained fill physical and mechanical properties*: unit weight; particle size distribution; shear strength and deformability parameters; water content; permeability, water and frost susceptibility, where appropriate.
- *Selected fill physical and mechanical properties*: maximum and minimum unit weight, proctor density; particle size distribution; shear strength and deformability characteristics; electrochemical, chemical and biological properties; minimum soil resistivity; minimum/maximum pH; maximum chloride and sulphate contents; maximum organic and sulphide contents, frost susceptibility, where appropriate.
- *Placement requirements*: maximum dry density; moisture content; layer thickness; installation method.
- *Reinforcement specifications*: type and configuration, laying direction, seams and connections; short term design tensile strength; long term tensile design strength; fill/reinforcement interaction factors; mechanical damage related to fill particle size and angularity; structural layout; installation of test samples; creep behaviour.
- *Facing and connections*: type and shapes; aesthetic requirements; performance level of facing; performance level of reinforcement/facing connection; maximum wind speed for erection of large panels.
- *Top soil for greened faces*: physical properties: particle size distribution; contents of organic material; chemical properties: minimum/maximum pH; hydraulic properties: capacity of water retention.

5 DESIGN CONTROL AND PERFORMANCE MONITORING

An useful checklist to control the construction of reinforced soil structures was suggested (Table 2) by FHWA (1997). To control the behaviour of reinforced soil structures during the design life it is important to check the following parameters: horizontal face movements, vertical movements of the surface, local movements or deterioration of facing elements, drainage behaviour of the backfill, performance of any structure supported by reinforced soil, horizontal movements within the structure, vertical movements within the structure, lateral earth pressure at the back of facing elements, vertical stress distributions at the base of the structure, stress in the reinforcement, relationship between settlement and stress-strain distribution, creep strains or stress relaxation in the reinforcement, aging conditions of reinforcement, pore pressure, temperature, rainfall.

According to FHWA (1997) in order to control these parameters is possible to use the instrumentation reported in Table 3.

6 SCHEME PROCEDURE FOR THE DESIGN

The information showed in more details in the previous paragraphs can be summarized with the scheme of design procedure illustrated in Table 4.

7 CONCLUSIONS

On the basis of the experience gained by the Authors through research and professional activities a procedure for the design of geosynthetic reinforced soil structures is proposed.

The present knowledge of reinforced soil structures was discussed in order to define safe design procedures in relation to ultimate limit states, in static and dynamic conditions, using limit equilibrium methods and

Table 2. Checklist to control the construction of RSS.

1. Read the specifications and become familiar with:
   – material requirements
   – construction procedures
   – soil compaction procedures
   – alignment tolerances
   – acceptance/rejection criteria
2. Review the construction plans and become familiar with:
   – construction sequence
   – corrosion protections systems
   – special placement to reduce damage
   – soil compaction restrictions
   – details for drainage requirements
   – details for utility construction
   – construction of slope face
   – contractor's documents
3. Review material requirements and approval submittals. Review construction sequence for the reinforcement system.
4. Check site conditions and foundation requirements. Observe:
   – preparation of foundations
   – facing pad construction (check level and alignment)
   – site accessibility
   – limits of excavation
   – construction dewatering
   – drainage features; seeps, adjacent streams, lakes, etc.
5. On site, check reinforcements and prefabricated units. Perform inspection of prefabricated elements (i.e. casting yard) as required. Reject precast facing elements if:
   – compressive strength<specification requirements
   – imperfect molding
   – honey-combing
   – severe cracking, chipping or spalling
   – color of finish variation
   – out-of-tolerance dimensions
   – misaligned connections
6. Check reinforcement labels to verify whether they match certification documents.
7. Observe materials in batch of reinforcements to make sure they are the same. Observe reinforcements for flaws and non-uniformity.
8. Obtain test samples according to specification requirements from randomly selected reinforcements.
9. Observe construction to see that the contractor complies with specification requirements for installation.
10. If possible, check reinforcements after aggregate or riprap placement for possible damage. This can be done either by construction a trial installation, or by removing a small section of aggregate or riprap and observing the reinforcement after placement and compaction of the aggregate, at the beginning of the project. If damage has occurred, contact the design engineer.
11. Check all reinforcement and prefabricated facing units against the initial approved shipment and collect additional test samples.
12. Monitor facing alignment:
    – adjacent facing panel joints (typically 19 mm±6 mm)
    – precast face panels: (6 mm per m horizontal and vertical; 4 mm per m overall vertical)
    – wrapped face walls: (15 mm per m horizontal and vertical; 8 mm overall vertical)
    – line and grade

Table 3. Possible methods for monitoring reinforced soil structures.

Parameters	Possible Instruments
Horizontal movements	Visual observations Surveying methods Horizontal control stations Tiltmeters Inclinometers Fixed embankment extensometers Probe extensometers
Vertical movements	Visual observations Surveying methods Benchmarks Probe extensometers Tiltmeters Horizontal inclinometers Liquid level gauges
Local movements of facing	Visual observations Crack gauges
Drainage	Visual observations at outflow points Open standpipe piezometers
Lateral earth pressure at the facing	Earth pressure cells Strain gauges Load cells
Stress distribution in soil	Earth pressure cells
Stress in reinforcement	Strain gauges Multiple telltales
Pore pressure	Piezometers
Temperature	Thermometer
Rainfall	Rainfall gauges

pseudo-static analysis. It was also discussed that serviceability state limits can be analyzed using the displacements method, which allows to determine the strains of the structure in equilibrium condition.

These methods, of common use in static conditions, need to adequate studies (cyclic pullout conditions) to be applied in dynamic conditions.

Proper construction and monitoring procedures have been presented, allowing to follow the behaviour of reinforced soil structures during construction and in the post construction period.

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Table 4. Scheme of design procedure.

PROJECT CONDITIONS	
GENERAL	SPECIFIC
– seismicity	– structure geometry
– locatio	– permanent loads
– environmental conditions	– accidental loads
– landscape conditions	– availability quarries
– territorial conditions	– accessibility
– regulations in force	– construction times
	– existing structures

FIELD AND FILL MATERIALS CHARACTERIZATION	
FIELD	FILL MATERIAL
– borings	– chemical and physical characteristics
– sampling	– classification tests
– SPT and seismic tests	– compaction characteristics
– piezometers installation	– mechanical characteristics
– settlements gauges installation	
– inclinometers installation	
– penetrometer and dilatometer tests	
– permeability tests	
– geo-mechanical survey	

PRELIMINARY DESIGN
Evaluation of design parameters for reinforcement – tensile long term in situ resistance – durability – soil-reinforcement interaction factors

Design of reinforced soil structures – internal and compound stability analysis – overall stability analysis – serviceability limit states analysis – evaluation of spacing and length of reinforcements

CHECK OF EXTERNAL STABILITY
– Sliding – Overall stability – Local bearing capacity – Settlement – Seismic

Drainage system and facing design
Specifications and construction details including the monitoring design
Design control and performance monitoring

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