Advances in soil reinforcement with geosynthetics: from laboratory tests to design, practice

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Abstract

More than 40 years ago, the great impulse given by producers of polymeric materials has allowed developing new building materials, functionalizing them to many civil and environmental engineering applications (figure 1), and this has been possible even through the synergy between academic world, manufacturers and stakeholders.
The connection between geosynthetics engineering and geotechnical engineering has become inescapable. Nowadays, geosynthetics pervade most branches of the geotechnical discipline. A continuous growth of knowledge has developed over years enabling to translate research into innovation with the aim of territory development and protection.

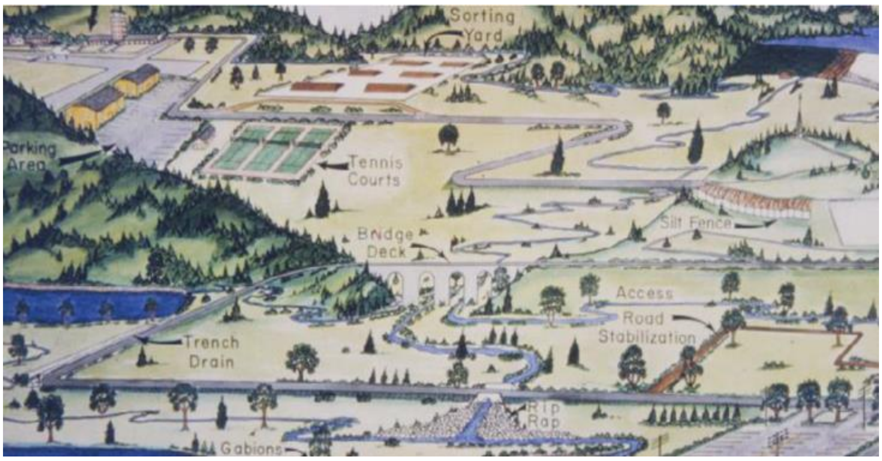

Fig. 1 Illustration from cover of Geotextile Engineering Manual (Christopher and Holtz, 1983): a visionary drawing of the 80's where geosynthetics serve developing and protecting the territory.

From a design point of view, engineering applications with geosynthetics represent nowadays a sustainable and mature technological solution. In the framework of soil reinforcement, geosynthetics may be used: (i) to build reinforced earth retaining walls, bridge abutments, embankments and steep slopes; (ii) as basal reinforcement beneath embankments over soft foundation soil (even in presence of piles); (iii) to realise geosynthetic-encased columns (GEC) in soft soil; (iv) to build passive structural barriers for landslide risk mitigation; (v) to prevent localised sinkholes; (vi) to reinforce cover systems of landfills; (vii) to reduce the seismic thrust acting on rigid retaining structures; (viii) to improve bearing capacity of shallow foundations; (ix) to reinforce roadway or railway foundations, (x) to reduce pavement cracking.

The purpose of the *keynote lecture* is reporting on the state of advancement of knowledge in soil reinforcement with geosynthetics. Considering the extent of the subject, the field will be restricted paying particular attention to applications, such as geosynthetics reinforced soil (GRS) walls and reinforced steep slopes, where the retained earth structure is built by alternating layers of compacted soil and polymeric reinforcements wrapped around the face of the slope or connected to the facing (cast-in-place concrete facing or facing assembled with precast concrete blocks or panels), according to one of the many available construction technologies.

Whether it is intended as execution of laboratory tests on the representative elementary volume or analysis of the behaviour of instrumented full-scale geosynthetic reinforced soil structures, experimentation has represented for this discipline, and still it does, the starting point and the driving force behind the continuous progresses. For these reasons, this lecture will be developed starting from the results that recent research has produced on the definition of short- and long-term design parameters, studied in the laboratory through large-scale (often prototype) test apparatus, explaining the obtained results by taking into account the interaction mechanisms actually mobilised along the geosynthetic specimen. Thereafter, the author will analyse how these research advances have or could have resulted in advancement in the design practice.

In this context, the author will try to analyse some questions still open, whose answers could have important consequences especially on two aspects: the first aspect is related to a more witting territorial development and protection, achieved in full respect of social and environmental sustainability; the second one concerns the drafting of (national) technical recommendations that can reassure and guide the designer towards the choice of these solutions.

Geosynthetics represent the winning solution in terms of sustainable development that is a "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland Commission Report*, Our Common Future*, 1983). In the coming years to reduce greenhouse gas emissions (GHGs), mainly carbon dioxide (CO_2), will be necessary and urgent. To analyse properly the environmental impact of a system or a product, generally related to the generated CO_2 emissions, it is necessary to carry out this evaluation by referring to its overall life cycle (*Life Cycle Assessment*, LCA), therefore considering the process that starts from the extraction of the raw material, then it passes through the industrial production until it can be used as a specific application; finally, a possible recycling and its waste final disposal have to be taken into account. Recently, several LCA analyses carried out on different geosynthetics applications have shown that the geosynthetics represent technological solutions that dramatically reduce the emissions of produced GHGs, compared to the traditional geotechnical structures.

Moreover, geosynthetics can intervene on adaptation to climate change in progress. Adaptation means anticipating the adverse effects of climate change and taking appropriate actions to prevent or minimise the damage they can cause. It has been shown that a well-planned, early adaptation action saves money and lives later. Geosynthetics use (i.e. passive structural barriers for landslide risk mitigation; embankments for flood protection, for the construction of dams and levees; solutions for erosion risk prevention; earth structures for re-profiling a slope; etc.) makes an important contribution in increasing the community resilience of infrastructural and geotechnical structures against, for example, earthquakes, floods, landslides and drought.

The construction methods of GRS structures allow a substantial decrease in construction time thanks to their ease of execution in comparison to traditional techniques (lower costs for skilled workers as well as the hire of vehicles and equipment). Specifically, the economic saving obtained in the short term by using geo-reinforcements in a retaining wall, compared to the more conventional reinforced concrete technologies, varies between 25% and 50%. Geosynthetics solutions ensure considerable saving even during the service life (in the long term), measurable both in the lower maintenance required and in the best performances offered, especially during seismic events. After seismic events of high magnitude, GRS walls showed a better behaviour compared to traditional walls: these evidences have been confirmed and well documented.

With regard to the design of earth structures reinforced with geosynthetics, a detailed knowledge of the mechanical, chemical and physical characteristics of these materials, as well as their durability, is very important as they influence the behaviour of these structures over time. The synthetic polymers generally used for geosynthetics production to be used in reinforced earth structures are mainly polypropylene (PP), high-density polyethylene (HDPE), polyamide (PA) and polyester (PET). For special applications, polyvinyl alcohol (PVA), aramid fibres (PAr) are usually used.

The design of GRS retaining walls or steep slopes must be performed so that it ensures adequate safety margins (in accordance with regulations or guidelines in force) against the possible ultimate and serviceability limit states for the structure and ground-structure. The possible limit states to be taken into account for reinforced soil structures are:

- the local external instability limit states (load-bearing capacity of the subsoil of the structure and slip resistance of the structure at its base);
- the general external instability limit state (by large slip along a failure line outside the rein-forced mass);
- the internal instability limit states of the mass (by failure of the reinforcements, either due to insufficient structural tensile strength or due to insufficient interaction resistance between soil and the reinforcements, and by failure of the facing, either due to insufficient strength of the facing or due to insufficient strength of the reinforcement connectors);
- the compound instability limit state (by a large slip mechanism along a failure line that intercepts reinforcing layers).

Failure mechanisms referring to the external instability can be analysed with the usually approaches adopted for traditional retaining walls.

The analysis of possible internal instability mechanisms allows determining the tensile strength and stiffness of reinforcements, their spacing and anchor length, and the structural characteristics of facing and connectors.

Serviceability limit states, which occur when the in-service deformation exceed prescribed limits, can be referred to external (foundation settlements) or internal factors (reinforced mass deformations due to creep strain of polymeric reinforcements, creep of fine grained soil fill, presence of a layer of wet fill, compression of fill; polymer degradation).

The advances in soil reinforcement with geosynthetics over years basically can be related to the advancement in knowledge about the short- and long-term mechanical behaviour of the materials used for the construction of reinforced earth structures (polymeric materials, soil, facing connection system) and about the complex soil-geosynthetic interaction mechanisms (related to the different ultimate limit states).

Geosynthetics have to be endowed with suitable mechanical characteristics of long-term tensile strength and stiffness (referred to the service life, taking into account a possible reduction in resistance as a result of mechanical and chemical attacks and tensile creep effects) as well as geometrical characteristics, shape and structure (that maximise the equivalent shear stresses mobilised by means of interaction mechanisms at the soil-reinforcement interface) in order to perform the function of reinforcement in the best way possible.

Soil-geosynthetic interaction depends on: (i) soil geotechnical characteristics, (ii) reinforcement stiffness, geometry and structure, (iii) active length and (iv) vertical effective stress. The *lecture* will analyse a model of soil-geosynthetic interface under pullout condition, capable of defining the contribution of the complex elementary interaction mechanisms mobilised along extensible reinforcements with an open mesh grid structure, embedded in compacted granular soils. The definition of similar models is very important both to improve the design and to optimise the industrial production of the geomaterials in terms of geometry, shape and stiffness, depending on the different applications for which they are designed.

The long-term tensile strength is determined reducing the characteristic tensile strength of the geosynthetic obtained with wide-width tensile tests (UNI EN ISO 10319) by means of reduction factors taking into account the damage due to mechanical attacks during construction, the tensile creep, the degradation for weathering and for chemical attacks due to the environment. Depending on which standards are considered for the design, other reduction factors taking into account the production variability of the material, the junction strength, and the type of applied load can be used.

It has been more than 40 years since geosynthetics have begun to be used in the engineering design practice, and several researches and case histories are available in the literature, leading us in opening and facing some design questions that have not been fully solved yet. The answers to those questions, once clarified and recognised by the international standards, could lead to an optimization of the design for these structures.

This *keynote lecture* will try to answer a series of these arising questions:

- ✓ Measurements carried out on several full-scale instrumented GRS walls showed stresses and strains in the reinforcements (and therefore in the structures) a lot smaller than those modelled through the design parameters, chosen in accordance with the provisions in codes, recommendations and standards. *What are the design choices that lead to a usually very conservative design practice?*
- ✓ *What still needs to be improved on the definition of short- and long-term design parameters in static and seismic load combinations?*
- ✓ *Is the polymeric materials durability a problem that can compromise the reliability of the analyses performed for the design of GRS structures?*
- ✓ *In which load combinations is it really necessary to take into account the reduction of the long-term geosynthetic tensile resistance (i.e. referred to the design life) due to the visco-plastic nature of the polymers used?* It can heavily influence the internal stability design, but the point is that it is taken into account by international codes, recommendations and standards considering results obtained by tests carried out without soil confinement. *Is creep under confined condition still an unanswered question?*
- ✓ Experimental researches performed on geosynthetic reinforcements by using different cyclic loading histories or a sustained static loading (keeping it constant over time) have allowed demonstrating that the material is not subjected to degradation, thus maintaining its short-term tensile strength. *When the reinforcement is embedded in soil could a cyclic pullout loading history lead to a degradation of the soil-geosynthetic interface and, consequently, of the design interaction parameters?*
- ✓ International codes, recommendations and standards often disagree with each other about how to design the facing-reinforcement connections. *What are we supposed to do?*
- ✓ *After this half a century's experience, what are the critical aspects of the construction practice for these structures?*

Finally, what are the challenges for the future? A first challenge is to improve the education of students, professionals and constructor companies, still often too distant from geosynthetics technological solutions that we continue to define as *innovative* almost half a century after their first applications. Another challenge, of a technical nature, is to develop innovative geosynthetics or new technologies aimed at a more aware and safe use as fill materials, such as recycled materials, industrial production waste and fine-grained soils (that may be present on site). Their use could give a further contribution to the already high economic, social and environmental sustainability of these GRS structures.