EXPERIMENTAL AND NUMERICAL ANALYSES ON THE PERMEABILITY OF REINFORCED CLAY BARRIERS

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ABSTRACT: In this paper a particular aspect of soil-geosynthetic interaction is examined, as far as the hydraulic behaviour of soil and inclusions as a whole system is concerned. The presence of geogrid layers within a vertically compacted-clay barrier and its possible influence on the hydraulic conductivity has been studied. The results of experimental tests and numerical analyses performed on soil specimens of different size, grading and nature, compacted at different energies and moisture contents, with different types of geogrids installed within as reinforcement, are reported. “Equivalent” hydraulic conductivity values have been evaluated, with and without inclusions; comparisons between the obtained results lead to useful considerations about applicability and design of this solution in works devoted to the prevention from geoenvironmental hazards. An example related to this last aspect is also briefly suggested.

1 INTRODUCTION

The use of geosynthetics in geotechnical applications has grown, in the last years, at a very rapid pace, also owing to new technological developments. If properly installed, geosynthetics offer to the civil engineers a powerful tool to solve a number of usual and unusual problems (Koerner, 2000). In designing, notwithstanding these developments, and considering the increasing demand for solutions to new problems (such as the ones related to environmental aspects) a particular care is to be taken, owing to the lack of knowledge and experience about the performance in particular cases. Typical examples are slope stability problems along low shear strength “multi-interfaces” in waste disposal facilities (Mitchell *et al.*, 1990a,1990b).

Another problem, referred to the soil-geosynthetic interaction, is examined in this paper, as far as the hydraulic conductivity of the soil and inclusion as a whole is concerned. Experimental tests have been performed to study how the presence of geosynthetic layers could influence the hydraulic behaviour of vertical compacted-clay barriers. The clay barrier in a steep slope embankment and berm, built to isolate waste landfills or contaminated lands, possibly close to rivers, could prevent from leachate propagation and/or water infiltration in case of floods (Figure 1).

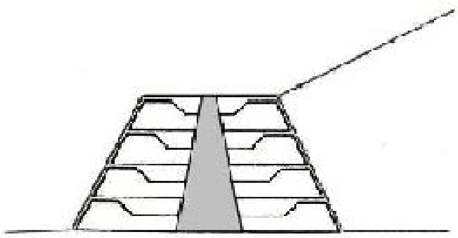

Figure 1 Example of reinforced embankment

The use of a geotextile as reinforcement element needs particular care and installation procedures in the coupling between soil and inclusion, principally owing to geotextile trasmissivity and overall performance (e.g. deformability).

On the other side, geogrids installation could cause seepage concentration along ribs, depending on soil degree of compaction and geogrid deformability.

The paper reports the results of experimental tests, performed on a 20x60x20 cm soil model, compacted at different energies and in different moisture conditions, in which various assemblies of geogrid layers were installed. “Equivalent” hydraulic conductivity values have been evaluated. The obtained results and the comparison with the hydraulic behaviour of the soil without inclusions, lead to useful considerations about the design of this kind of application.

2 EXPERIMENTAL INVESTIGATION

The experimental investigation carried out consists of:

- tests aimed at evaluating hydraulic conductivity of unreinforced soil specimens;
- tests aimed at assessing the rate of infiltration and equivalent hydraulic conductivity of reinforced soil specimens.

The testing program has been carried out in order to evaluate the mutual role played by the soil and the inclusions. With this aim, different soil mixtures and geogrid types have been used.

2.1 *Soil mixtures*

In the investigation, two different soil mixtures have been considered (Figure 2). Both of them have been prepared by blending different components (gravel, sand, silt and clay) in order to:

- obtain mixtures similar to the ones actually used in site;
- fulfil the requirements proposed by several control agencies (e.g. U.S. EPA, 1989) on the suitability of the soil mix as low hydraulic conductivity bar-

rier, in terms of grading distribution and plasticity index.

Table 1 Soil mixture characteristics

SOIL MIX	%gravel	%sand	%silt	%clay	PI [%]	U
A	35	35	20	10	18.2	400
B	30	15	45	10	15.2	275

Standard identification tests have been performed; referring to the Unified Soil Classification System, mixtures A and B can be classified as SC and CL, respectively. It is worth observing that a different fine component has been used in the mixtures A and B. Table 1 reports the main characteristics of the two mixtures, used in the experimental investigation; Figure 2 illustrates the grain size distribution.

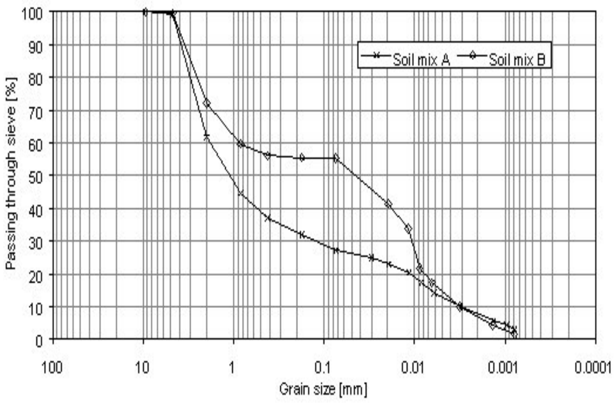

Figure 2 Particle size chart

As far as hydraulic conductivity is concerned, unreinforced specimens of the two different soil mixtures have been tested in a rigid wall permeameter, varying initial moistures and compaction energies.

Specific energies E_S have been always kept at values lower than the Standard Proctor ones, principally in consideration that:

- a lower compaction effort has to be applied for the compaction of the reinforced specimens, significantly larger than the ones in the permeameter (see paragraph 2.3);
- a low specific energy results in a more critical specimen condition accounting for its permeability.

An example of a compaction curve, relative to soil mix A, is shown in Figure 3; Table 2 reports test parameters and results for the analysed soil mixtures.

Table 2 Test conditions and results (unreinforced soil)

	w [%]	E_S [kJ/m3]	k [m/s]
Soil MIX A	~15	83	$2{\cdot}10^{-8}$
Soil MIX A	~15	109	$1{\cdot}10^{-9}$
Soil MIX B	~17	83	$2{\cdot}10^{-9}$

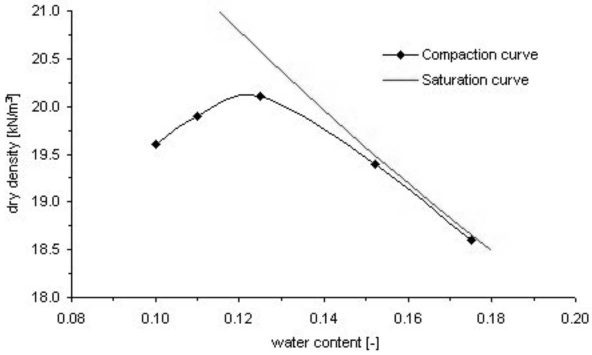

Figure 3 Compaction curve for soil mix A

2.2 *Geogrids*

In order to assess a possible influence of the reinforcement type, especially in terms of geometry and strips assembly, two different geogrids have been used.

The grid named “E” is a biaxial geogrid of polypropylene extruded strips, having a double-weft laser-bonded structure, which gives rigid connection between the strips with consistent stress-strain performance throughout the matrix. The mesh size is 44x44 mm (see Figure 4).

The grid named “F” is a flexible, high-strength polyester geogrid, with a protective polymer coating and mesh size 20x20 mm (see Figure 5).

Table 3 indicates the principal grid properties.

Table 3 Geogrids properties

	Maximum strength [kN/m]	Elongation at failure [%]	Polymer
Grid “E”	30	10	PP
Grid “F”	35	12.5	PET

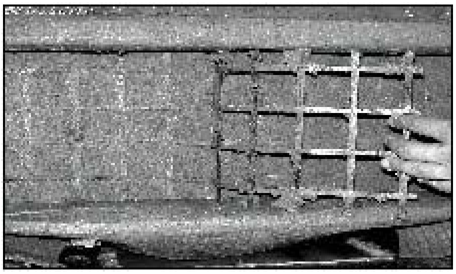

Figure 4 Geogrid “E” after a test

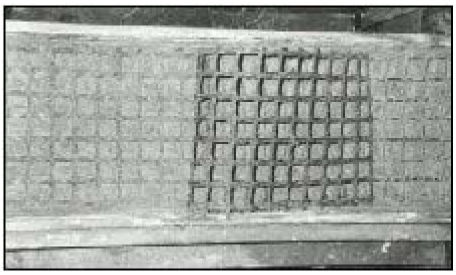

Figure 5 Geogrid “F” after a test

2.3 *Description of tests on reinforced specimen*

The tests for the assessment of hydraulic conductivity of the reinforced specimens have been performed as illustrated in the scheme of Figure 6.

The soil sample, whose dimensions are 20x60x20 cm, is constrained in a reinforced plexiglas container, put inside a basin which allows to apply a hydraulic gradient *i*. The test assembly is suited in a way that a one-dimensional flow could develop through the soil.

The reinforcement is constituted of four layers of geogrids, spaced 4 cm, inserted after having compacted the soil layers directly in the plexiglas container. Particular care has been taken to obtain good bonding between layers.

A geosynthetic filter (of known permittivity against clogging) is wrapped around the soil sample, preventing from piping effects.

The tests, run under constant head condition, have been carried out up to an almost steady state condition, in terms of flow, has been reached. At the end of each test, soil moisture has been measured in many locations within the specimens, showing a good uniformity both vertically and horizontally. Some tests have been duplicated in order to compare the results in terms of repeatability.

In Table 4 some features of the analysed tests are reported.

Table 4 Main features of the analysed tests

	Test n.1	Test n.2	Test n.3	Test n.4
Soil MIX	A	A	B	A
Grid	F	F	F	E
E_S [kJ/m^3]	209	83	83	83
i [-]	2	2	2	2
w_{init} [%]	15	15	17	15
w_{final} [%]	15.3	15.1	18	15
S_{init} [%]	~96	~90	~86	~90
S_{final} [%]	~99	~98	~97	~98
k* [m/s]	$3 \cdot 10^{-9}$	$1 \cdot 10^{-8}$	$2.5 \cdot 10^{-9}$	$1 \cdot 10^{-8}$

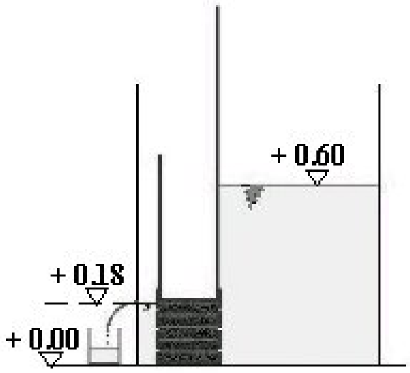

Figure 6 Scheme of the test device

3 RESULTS AND GENERAL REMARKS

This study was mainly aimed at focusing the possible influence that the presence of inclusions (i.e. reinforcement by geogrids) could have on the overall permeability, of a compacted soil barrier. With this respect, considering the composite nature of the medium subjected to seepage, it has been preferred to analyse the results in terms of infiltration rate, rather than "equivalent" hydraulic conductivity. The infiltration rate represents the flow per unit area and thus, following Darcy's law, the velocity $V=k^* \cdot i$.

As a comparison with the values obtained for the unreinforced specimens, the equivalent hydraulic conductivity *k**, assessed once reached a steady state condition, is indicated in Table 4.

It is worth considering, before discussing the gained experimental results, that, notwithstanding the low compaction energies adopted, in any test an excellent bonding between soil and grid strips has been observed (see Figures 4 and 5).

The experimental outcomes for the different tests, showed in Figures 7÷10, allow the following general remarks:

- at the beginning of the tests a well defined transient flow is always present;
- the steady state condition is reached in a very similar way in all the tests;
- the abovementioned behaviour has been observed in the test device and in the permeameter tests as well (even if in the latter case the transient is much faster);
- the hydraulic conductivity values at steady state are almost the same for the unreinforced and reinforced specimens (see Tables 2 and 4);
- the relevant and prevailing role played by the soil behaviour is clearly evident from the results in Figures 7 and 8, as the differences in the infiltration rate (and thus the equivalent hydraulic conductivity) are due to compaction energy and soil nature respectively;

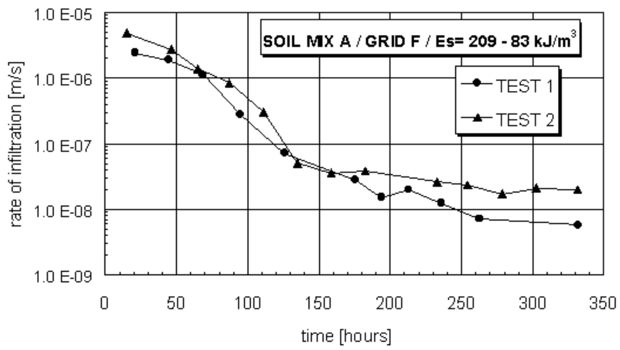

Figure 7 Test results

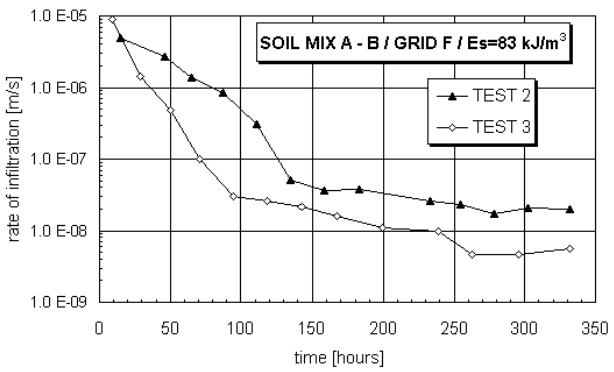

Figure 8 Test results

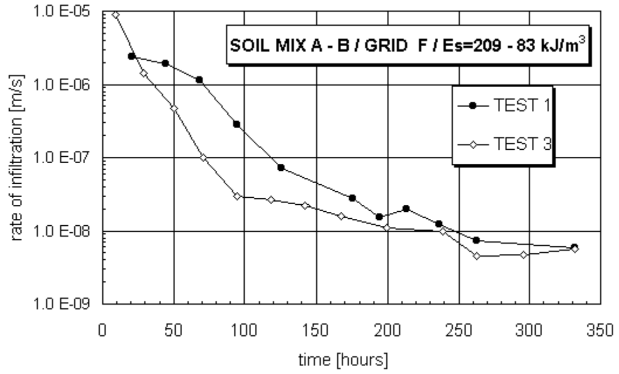

Figure 9 Test results

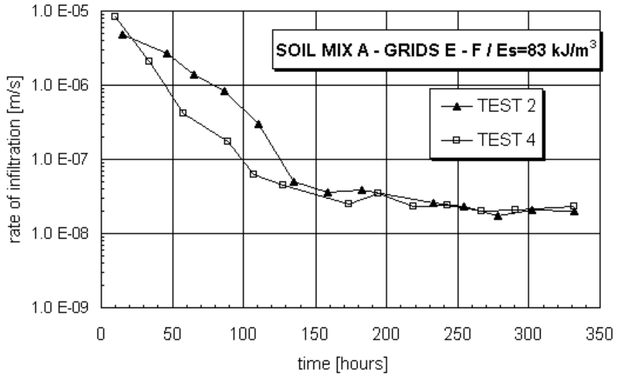

Figure 10 Test results

- the presence of geogrid layers (also of different types) does not influence the hydraulic behaviour of the compacted barrier, as illustrated in Figures 9 and 10; as far as Tests 1 and 3 are concerned (Figure 9) it is worth noting the mutual dependence of soil nature and specific energy, being the less pervious mixture (MIX B) compacted at a lower energy than the other one (see also Table 4 and Figure 2).

4 FLOW ANAYSES

The experimental tests have led to the conclusion that the hydraulic conductivity for unreinforced and reinforced specimens is not greatly influenced by the presence of geosynthetic inclusions. It is however worth recalling that the two types of specimens have been tested under slightly different boundary conditions, especially in terms of flow, which takes place in the same direction (i.e. vertical) of compaction for the unreinforced soil mixtures, whereas the vertically compacted samples are subjected, in the flow test device, to horizontal seepage.

As far as this aspect is concerned, tests performed by Boyton and Daniel (1985) have indicated that, for laboratory-compacted clay samples, with good bonding between layers, hydraulic anisotropy is essentially negligible. Differences can arise in the field, due to soil heterogeneity and poor bonding.

In order to have a complete overview of the different schemes, numerical analyses simulating an unreinforced specimen, in the same configuration of the test device, have been performed by the finite difference code FLAC® (ITASCA, 2000).

The section of the specimen corresponds to a square area (0.2x0.2 m^2), subdivided in square zones among the 400 gridpoints; the main input parameters of the model are summarised in Table 5.

Table 5 Parameters used in the flow analyses

Unit weight	γ [kN/m^3]	20
Porosity	n [-]	0.3
Conductivity coeff.	k [m/s]	$2.8{\cdot}10^{-9}$
Shear modulus	G [kN/m^2]	8000
Bulk modulus	K [kN/m^2]	13300

The conductivity coefficient *k* is an average value of those measured in the laboratory tests (see Table 4); the presence of the water head at the boundaries has been simulated by the application of the corresponding hydrostatic pressures.

Two different kind of analyses have been run, starting from the dry sample and from the saturated one.

Different parameters have been monitored during the calculation computing the trend of the incoming and outcoming flow through the boundaries of the specimen (Figure 11).

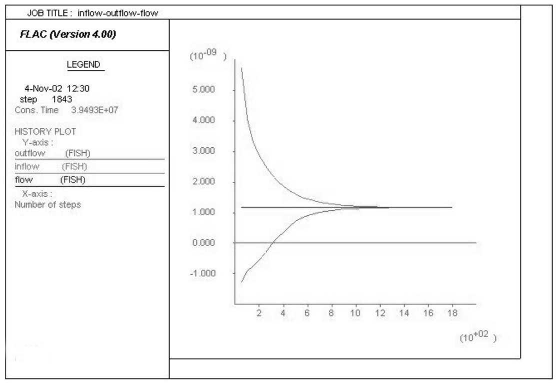

Figure 11 Trend of the incoming and outcoming flow

Figures 12 and 13 show the evolution of saturation and flow vectors in the initially dry sample; it can be noted that, at the initial stages, water seeps in through both sides of the sample but, approximately between step 250 and 350, the flow vectors in the left area change direction, seepage progressively becomes more stable, and the sample is progressively saturated until the steady state is reached.

The numerical results have shown a behaviour similar to the one experimentally observed, both as far as transient and steady state flow is concerned, and saturation phenomena as well.

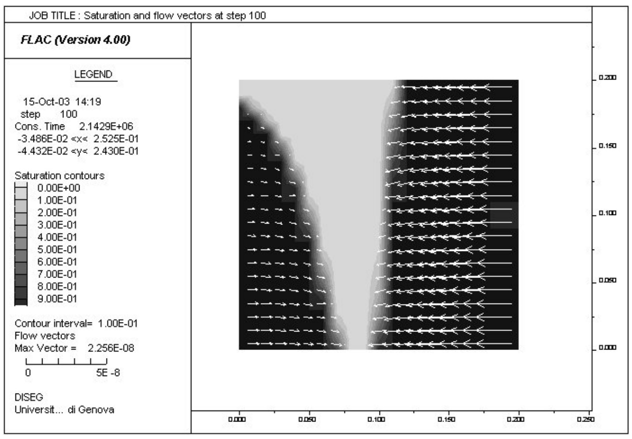

Figure 12 Saturation and flow vectors (step 100)

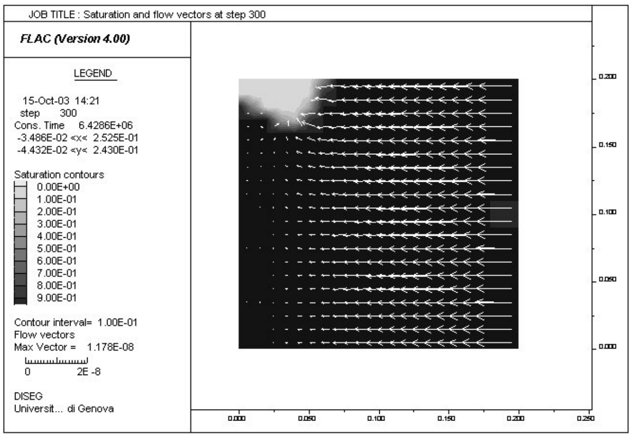

Figure 13 Saturation and flow vectors (step 300)

5 STABILITY ANALYSES

The experimental and numerical results, till now described, suggested the idea of examining a possible application of the considered technique: a 2 meter thick unreinforced/reinforced compacted-clay layer, resting on a steep slope (40°) and lying on a rock mass of rather good characteristics, expressed by RMR = 40.

This application could be encountered dealing with waste disposal facilities. As well known possible problems arise when considering clay layer stability.

Four series of analyses have been run: with unreinforced and reinforced clayey layer, both in undrained and in drained conditions; a typical geometrical scheme is shown in Figure 14.

According to Dawson *et al.* (1999), all the analyses have been performed using the strength reduction technique, aiming at the evaluation of the stability safety factor by a progressive reduction of strength parameters (s_u or c' and ϕ'); Table 6 reports the parameters of the clayey layer used in the simulations.

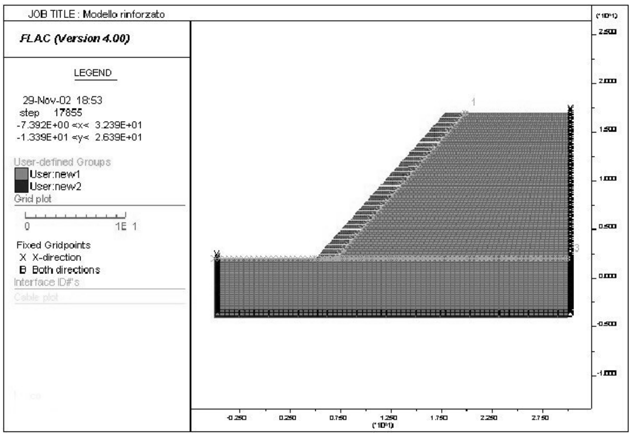

Figure 14 Considered mesh for reinforced steep slope

Table 6 Parameters used in the stability analyses

Undrained	conditions	Drained	conditions
γ [kN/m³]	20	γ [kN/m³]	20
s_u [kN/m²]	40	c' [kN/m²]	10
ϕ [°]	0	ϕ' [°]	30
G_u [kN/m²]	$1.07.10^4$	G' [kN/m²]	4167
ν [–]	0.49	ν [–]	0.2

The reinforcing elements, spaced 50 cm vertically, have been simulated by cable elements, i.e. without bending stiffness, like geogrids are, assigning them the geometrical and mechanical characteristics of geogrid "E".

In undrained conditions the resulting factors of safety are F_U = 2.2 without reinforcement and F_R = 3.5 in presence of geogrids.

In drained conditions the resulting factors of safety are F_U = 1.05 without reinforcement and F_R = 1.72 in presence of geogrids; in the first configuration the slope is already near to the limit condition at the beginning of the process and collapses after the first strength reduction.

In both cases, the failure surface entirely develops in the clayey layer without intersecting the foundation soil; moreover, good results are achieved also in term of stiffness, in fact smaller values of gridpoint displacement take place in presence of inclusions and they are confined within the surface of the reinforced layer.

The last part of the work has been devoted to the simulation of the abovementioned reinforced slope, supposed as lining system for the sides of a waste disposal.

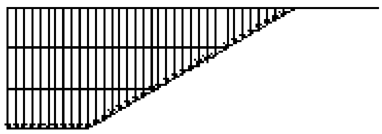

Figure 15 Loading steps

The load, in order to simulate the progressive filling, was applied in three different steps (Figure 15), considering a waste unit weight γ = 10 kN/m³.

Also in this case it can be observed that gridpoint displacement takes place in the surface of the clayey layer and along layer interface: the overall stability of slope and waste deposit is not significantly influenced but the developed displacements indicate the particular care that should be taken in designing and building this kind of structures.

6 FINAL REMARKS

In this paper an attempt of evaluating the hydraulic conductivity of soil barriers reinforced by geosynthetic inclusions has been carried out. The experimental results have shown that the presence of geogrids does not influence in a relevant way the hydraulic conductivity of the compacted soil.

The soil hydraulic conductivity, obtained by a correct choice of materials, soil moisture, compaction energy and execution procedures, continues playing a prevailing role in fluid propagation/infiltration problems; geosynthetic inclusions, correctly designed and installed, fulfil their function of reinforcement, without influencing the hydraulic performance of the barrier.

In addition, as pointed out by Bhamidipati (1996), the geogrid presence and its interaction with the soil, should reduce the possibility of cracks propagation, which could have relevant consequences on the compacted layer permeability.

In the execution of the experimental investigation other important aspects (such as the specimen dimension, the direction of flow, the hydraulic gradient value) have been considered, with reference to the influence they could have on the test results (Boyton and Daniel, 1985).

In order to couple hydraulic aspects with stability ones, a possible application of reinforced compacted-clay barriers has been simulated by a finite difference code.

From a practical point of view, the obtained information could be useful when considering the design of geotechnical works, whose functions (e.g. stabilisation, reinforcement and prevention from geoenvironmental hazards) could be fulfilled also by the use of geosynthetics. In this particular case the use of geogrids helps in realising steep and safe soil slope and embankments, also with the function of hydraulic barrier for landfills and contaminated lands.

7 REFERENCES

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