ABSTRACT: The lecture considers the environmental aspects related to the many uses and functions of geosynthetics (including biodegradable natural products) in large man-made structures, like landfills and dams, having a prevailing containment function for both solids and fluids. For landfills, the applications of geosynthetics are illustrated with reference to the different structural elements: subgrade, bottom and side lining system, leachate collection system, biogas extraction system, waste body, reinforced soil embankments, top capping and final reclaimed top surface. For dams, the applications of geosynthetics are reviewed according to the performed functions (barrier, drainage, protection, filtration, reinforcement and surficial erosion control), in relation to the different types of dams (embankment, concrete, masonry and roller compacted concrete), both for new construction and rehabilitation purposes. Geosynthetics can contribute to reduce or minimize some negative impacts on the environment.

(This version of the lecture has not to be considered as definitive)

1. INTRODUCTION

Environmental protection from the negative impacts of Man's activities (land urbanization; large construction works; improper agricultural practices; excessive exploitation of natural resources; air, soil and water pollution) is going to become more and more important to the welfare of human communities and dramatically essential to the survival of Life itself on the Earth.

On the other hand, the growth of Mankind and the technological development of human societies cannot be arrested, and the primary causes of the previously remembered negative impacts cannot be removed; therefore, the scientific and technical disciplines concerned with interaction problems of construction work and natural environment, i.e. Engineering Geology and Geotechnical Engineering, require increasing consideration (Jesenàk, 1987). In particular, the last twenty years have seen the development of new disciplines, e.g. "Environmental Geotechnics" (Sembenelli and Ueshita, 1981).

Probably it was not a pure temporal coincidence, but the same times have also seen the rapid development of many kinds of synthetic materials, in the form of manufactured sheets or strips, and by their applications in contact with foundation soil, rock, or earth to the solution of multifarious geotechnical problems: for this reason, they were comprehensively named "Geosynthetics" (Fluet, 1983, apud Giroud, 1986).

A list of currently used geosynthetic products and proposed related abbreviations, is reported in Table 1; a more detailed description of the products is given in Appendix (Terminology of products). Bearing in mind the increasing importance of environmental aspects, the list includes also biodegradable natural products (from now on defined as "Bioproducts").

Before entering into details of the engineering applications and the environmental aspects to be dealt with, it seams also convenient to recall the main functions performed by geosynthetics and related natural products (Table 2). The main functions could be briefly defined as follows:

A) Absorbtion: the process of fluid being assimilated or incorporated into a geotextile (Frobel, 1987) or a bioproduct (Ranganathan, 1994). This function, even if not usually mentioned, has to be emphasized essentially for two specific environmental aspects: water absorption in erosion control applications

Table 1. List of currently used geosynthetic and biodegradable natural products, with related abbreviations (modified after IGS, 1993 and Rimoldi et al., 1993).

Abbreviation	Geosynthetic / Bioproduct
GT	Geotextile (generic)
GTW	Woven geotextile
GTN	Nonwoven geotextile
GTK	Knitted geotextile
GG	Geogrid (generic)
GGE	Extruded geogrid
GGB	Bonded geogrid
GGW	Woven geogrid
GN	Geonet
GS	Geospacer
GA	Geomat
GL	Geocell
GM	Geomembrane (generic)
GMP	Plastomeric geomembrane
GME	Elastomeric geomembrane
GMB	Bituminous geomembrane
GC	Geocomposite (generic)
GCD	Geocomposite drain
GCR	Geocomposite reinforcement
GCL	Geocomposite clay liner
GCM	Geocomposite membrane liner
BT	Biodegradable natural textile ("biotextile")
BA	Biodegradable natural mat ("biomat")
BL	Biodegradable natural cell ("biocell")
BC	Biodegradable natural composite (generic)
BCD	Biodegradable natural composite drain ("biocomposite drain")

(typical of bioproducts) and also recover of floating oil from surface waters in occasion of ecological disasters (typical of geotextiles).

B) Barrier (to fluid): the ability of a geosynthetic to prevent migration of fluids (both liquids and gases).

C) Cushion: the ability of a geosynthetic to control and eventually to damp dynamic mechanical actions (Jappelli and Cazzuffi, 1991). This function, even it is not usually mentioned, has to be emphasized particularly for the applications in canal revetments and in shore protections incorporating geotextiles (dynamic loads induced by waves) and also for the applications in geosynthetic strip layers as seismic base isolation of earth structures (dynamic loads induced by earthquakes), as illustrated by Kavazanjian et al. (1991).

Table 2. Main functions with related abbreviations (modified after IGS, 1993) and typical geosynthetic and biodegradable natural products.

Main function and abbreviation		Typical products (see also Table 1)
A	Absorption	GT, BT, BA, BL
B	Barrier (to fluid)	GM, GCL, GCM
C	Cushion	GT, GN
D	Drainage	GT, GN, GS, GCD, BCD
E	Surficial Erosion Control	GT, GA, GL, BT, BA, BL
F	Filtration	GT
I	Interlayer	GT
P	Protection	GT, GN, GS
R	Reinforcement	GT, GG, GCR
S	Separation	GT, BT

D) Drainage: the ability to collect and carry off fluids (water, leachate, gas) within a geosynthetic or, eventually, within a biodegradable natural composite drain (Lee et al., 1994).

E) Surficial erosion control: the complex function carried out by a geosynthetic or by a bioproduct to prevent ground surface soil particles from detachment and transport.

F) Filtration: the ability of a geotextile to retain soil particles while being crossed by flowing water or, eventually, leachate.

I) Interlayer: the ability of a geotextile to improve shear resistance between two layers of geosynthetic products and/or earth materials.

P) Protection (of geomembranes): the ability of a geosynthetic to prevent local damage to a geomembrane due to concentrated mechanical stresses.

R) Reinforcement: the result of stress transfer from soil to a geosynthetic.

S) Separation: the ability of a geosynthetic or, eventually, a bioproduct to prevent intermixing of adjacent soils and/or fill materials.

It appears evident that the variety of products, functions and applications is so large, that some restrictions have to be put to the subject of this keynote lecture.

First of all, the environmental aspects will be considered in a preminent way. This subject can be approached on EIA (Environmental Impact Assessment) basis, according to the different procedures that have been proposed and developed in the Western World since the beginning of the 70's; in Europe, official Directives concerning EIA for important, public or private constructions were issued by ECC (European Communities Council) on 27 June 1985, and National Codes were conformed accordingly.

As far as the scope of this paper is concerned, the basic environmental components (and factors) are the following:

a) Atmosphere: meteoclimatic parameters and characterization; air quality (pollutants, suspended particles); meteorological hazards;
b) Hydrosphere: from one side, surface water (rivers, lakes, marshlands, see), in terms of regime, movements, solid transport, quality, uses; on the other side, ground water flow, piezometry, quality and uses (both waters to be considered as environmental components and also as resources); hydrogeological hazards;
c) Lithosphere: pedologic horizons (soil), in terms of genesis, physico-chemical and biotic composition, evolution and use; subsoil (soils and rocks) nature, structure, physical, hydraulic and mechanical properties; geodynamic processes (endogenous and exogenous) and geological hazards; surface morphology; geomorphic processes and land stability (to be considered also as non-renewable resources);
d) Biosphere: vegetation, flora and fauna; floral formations; animal associations; significant, protected natural areas; protected species; grasslands and forests; wild-fires hazards;
e) Anthroposphere: distribution of population and land use; human activities; urban and industrial development; agriculture and related activities; transportation routes and lifelines; public health, including hazards from pathogenic micro-organisms, chemical and biochemical substances, noise, vibrations, radiations, and so on.

The aforementioned components have to be intended as both active and passive elements; different combinations of physical, chemical and biological factors, each other interacting and interdependent, can form the environmental systems ("Ecosystems"). A datum ecosystem (e.g. a lake, a forest, a river, a hillside, a sea) is a unique system and can be defined and identified by proper structure, operation processes and temporal evolution. Another important environmental system, requiring adequate protection, is the landscape: in its widest sense, the term includes not only the natural morphological aspects, but also the results of human activities (agricultural, residential, industrial, recreational) and the cultural heritage of the Man's presence on the territory.

As a second "boundary condition" to this keynote lecture, only large man-made structures, all having a prevailing containment function for both solids and fluids, will be considered:

1) Landfills, as containment structures for solids, and also for fluids (liquids, gases); to this aim, landfills could be classified depending on what kinds of waste are deposited (Stegmann, 1989a):
   a) municipal solid waste (MSW), and municipal solid waste after separate collection;
   b) inorganic mass waste (IMW);
   c) industrial waste, or hazardous and toxic waste (HTW).

2) Dams, in which the containment function is limited to liquids, mainly water (tailings dams will be not considered); therefore dams could be divided into:
   a) embankment dams, both earthfill and rockfill(E+R);
   b) concrete and masonry (C+M) dams;
   c) roller compacted concrete (RCC) dams.

The approach on EIA (Environmental Impact Assessment) basis includes formal and "ad hoc" methods; in turn, the former may be grouped in the following four classes (Andreottola et al., 1989):
- the "overlapping map" methods;
- lists of questions and controls;
- correlation matrices;
- networks.

The validity of the different methods and their applications to the many kinds of human works and structures are beyond the scope of the present lecture. A possible way to approach the problem is reported in Table 3, where the range of the impact level of the considered large man-made structures on the basic environmental components and on the landscape is summarized according to a four-level ordinal scale (negligible, low, moderate, high impact). The impacts on the other derived, complex environmental components (like ecosystems) require to be evaluated case-by-case.

Anyway, within a single structure having a containment function, the variety of functions carried out by geosynthetics and related products can be much more articulated; these materials not only play different roles within barrier systems, but can also be used with multiple functions in foundation layers, drainage systems, reinforced structures, cover systems, and so on. According to the role, performed function, place of

Table 3. Range of the impact level (H high; M medium; L low; N negligible) on the environmental components of large man-made structures with containment function.

	Landfills			Dams		
	MSW	IMW	HTW	E+R	C+M	RCC
Basic:						
Atmosph.	L-H	N-M	L-H	L-M	L-M	L-M
Hydrosph.	L-H	N-L	M-H	H	H	H
Lithosph.	L-H	L-H	L-H	M-H	H	H
Biosph.	L-M	N-M	M-H	M-H	M-H	M-H
Antroposph.	L-H	L-M	M-H	L-H	L-H	L-H
Derived:						
Landscape	M-H	M-H	M-H	M-H	H	H

Legend: MSW : municipal solid waste
IMW : inorganic mass waste
HTW : hazardous and toxic waste
E+R : earthfill or rockfill
C+M : concrete or masonry
RCC : roller compacted concrete

application and life of the structure, the use of geosynthetics and related natural products can result beneficial or adverse as for the impact on the environment.

A few examples of negative impacts on the environment could be:

- the immission of non-natural materials into a natural ecosystem, in case of geosynthetic products (this is not the case of bioproducts);
- the permanent presence of a continuum structure, even if no more necessary (the remembrance of it, if buried, could be lost within a few years, and also in this case the use of putrescible natural materials instead of imputrescible synthetic ones could be desirable);
- the release of toxic substances in case of unforeseen accidents (e.g. fire) or lining systems failures.

On the contrary, many more are the examples of positive impacts on the environment. Among them, the following are common to most of the aforementioned large man-made structures having a containment function:

- the possibility to use low quality earth materials for compacted, reinforced earth fills (e.g. A4, A5, A6, A7 instead of A1, A2, A3, according to AASHO classification);
- the reduction of the overall quantities of required, natural earth materials;
- as a consequence of both, the reduction of the quantity of unrenovable resources to be exploited.

Another positive impact, typical of the manufacturing process, is the use of recycled plastics for the production of geosynthetics: this technology became recently very popular, above all for specific Directives issued by EPA (Environmental Protection Agency) in the United States (EPA, 1994). Of course, in this case, particular attention has to be addressed to the characteristics of the "new" geosynthetic products, that in any case have to satisfy the technical requirements according to role, performed function, place of application and life of the structure.

Other positive impacts are typical of the different engineering structures and of the specific performed function. In general terms, geosynthetics applications to landfills allow to reduce pollution hazards, while, for dams applications, the most typical positive impact of geosynthetics is to reduce flood and erosion hazards in the downstream hydrological system. More specifically, there are several potential advantages typical of each performed function: for example, in relation to the reinforcement function, geosynthetics allow to increase the final slope profile of a landfill or eventually of an embankment dam, thus permitting to increase the available volume of waste or, eventually, water to store.

2. LANDFILLS

2.1. Landfilling as an environmental problem

From the ancient times to the present, landfilling, recycling and combustion have been the classical means to dispose wastes. Of course, their relative importance and the technological level of disposal processes have been evolving up-to-date and are continuously changing, depending on many factors (geographical, geological, hydrological, technological, economical, cultural, social, political, etc.), but in any case landfilling will play an important role also in the future, within an integrated solid waste management. Future trends will require lower volume for landfilling, but at the cost of increasing environmental problems, due to pre-treatment techniques concentrating potentially hazardous elements; adopting high quality standards for landfill design and construction will be essential to face successfully such environmental problems (Cossu, 1989). A new concept of "dry" landfill has been recently proposed by Stegmann (1991), where waste unloading, biological pre-treatment and baling of the residue should take place in-house before landfilling, so giving no leachate and only a small amount of gas, but such a technique is still quite uncommon.

At the present state of the art, the landfilling techniques depend primarily on the kind of waste to be disposed. In turn, wastes may be classified as follows (Stegmann, 1989a):

- municipal solid waste, the composition of which (e.g. the organic content) may change from place to place and in the time, due to separate collection of biowaste and/or recyclable materials;
- mass waste (e.g. residues from gas treatment activities, mine waste and also industrial sludges that are produced in huge amounts);
- demolition waste (or residues from demolition waste recycling plants);
- soil and rock from excavation;
- waste water sludges;
- bulky waste.

The differences lie in origin, chemical composition, organic and water content, physical state, short and long-term properties, all that influencing the degree of hazard for the environment. Therefore, as already said, the prevailing opinion in the highly developed countries leads to a classification of landfills into three categories:

a) landfills for municipal solid waste (MSW) and municipal solid waste after separate collection; stabilized sewage sludges are also co-disposed in these landfills;
b) landfills for inorganic mass waste (IMW), primarily demolition rubble, soil and rock excavation waste;
c) landfills for industrial waste, or hazardous and toxic waste (HTW); in turn, this category can be furtherly subdivided according to the different concentration level of some toxic and hazardous substances (the legal constraints can be different from one country to another).

By the way, it has to be remembered that some researchers disagree with this classification, and above all with definitions of some wastes as "hazardous" or "toxic", that they judge to be misleading, especially to the public and to the waste regulators, so leading to design criteria based on concepts of a "complete (and some infer eternal) containment". In their opinion hazardness and toxicity should strictly apply to the "impacts" arising from how the wastes are managed, and not to the origin of wastes. The consequence of these opinions are design criteria based on the "controlled release of contaminants within predeterminated standards over defined time periods", provided that permanent monitoring of landfill facilities be ensured (Campbell, 1991; Joseph and Mather, 1993).

The antithesis between the two design philosophies may be resumed in a simple question: "permanent storage of wastes and uncontrolled pollution hazard transmitted to our descendants" or "controlled return of waste contaminants back to the environment"? The answer to this question should be prioritary to a correct environmental policy, but the debate is still live, because each of the two design criteria could have both positive and negative impacts on the environment.

In any case, when dealing with landfilling environmental impact, the following sequence of phases during the landfill life cycle has to be considered (Christensen, 1989):

i) planning phase (including site investigation and design - "flirt, love and conception"); the environmental impact is practically nil;
ii) construction phase (preliminary earthwork and preparation of the fill area, including bottom liner and drainage - "prenatal life and birth"); the environmental impact during this phase is still relatively low, and not dissimilar to that of other engineering works;
iii) operation phase (filling with waste layers, from the bottom to the uppermost one - "active life"); during this phase, typically lasting from 5 to 20 years, the impact on the environment attains its maximum;
iv) completed phase (including top covering, monitoring of the environmental emissions, and final reclamation of the area - "death and 'post mortem' state"); the environmental impact can remain at very high level for longtime (up to several decades) and decreases slowly, depending on the size of the landfill and the type of wastes;
v) final storage phase ("burial state"), when the landfill is going to be (hopefully) integrated into the environment, even if a certain level of impact still remains.

The main portion of the negative impact of a landfill is directly due to its environmental emissions (wind-blown litter and dust, noise, biogas, leachate, surface run-off; birds, vermin and insects attracted by the operating landfill; contaminated crops and offense to landscape - Fig. 1). Other indirect impacts (not all necessarily negative) are: induced traffic, effects on environmental policy and education, effects on surrounding economical activities and occupation, permanent limitations to any kind of land use, and so on.

National codes (besides common sense) require

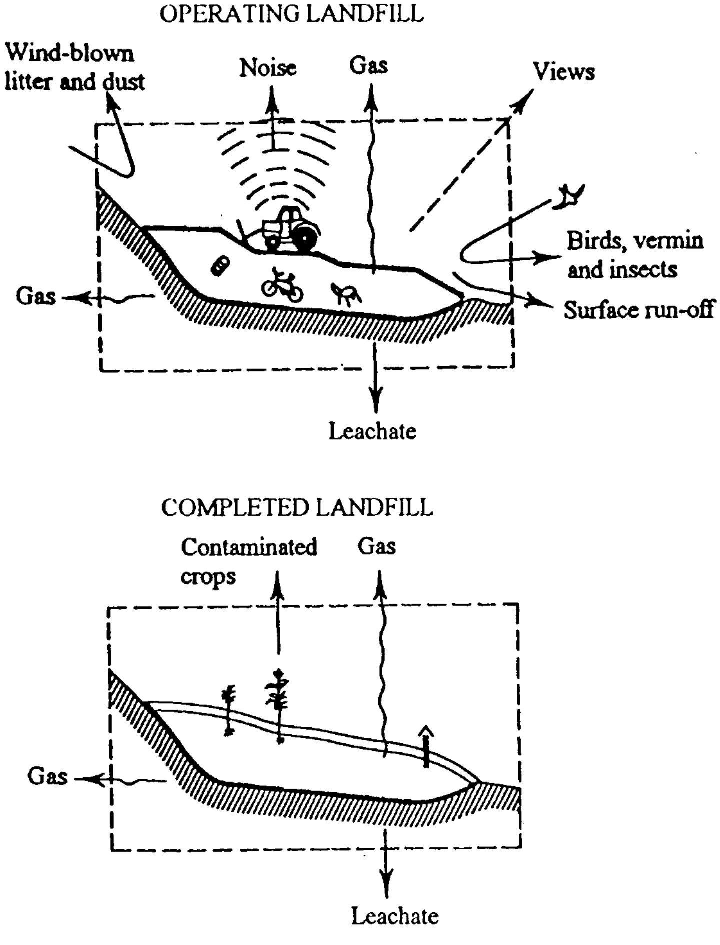

Fig. 1 Sketch of the major environmental aspects related to sanitary landfilling (re-drawn after Christensen, 1989).

hydrological, hydrogeological and engineering geological, preliminary criteria to the site selection. The landfill should be sufficiently distant from lakes, rivers, and especially from drinkable water supplying points; landslide areas and compressible foundation soils should be avoided. Hydraulic, geotechnical and environmental design criteria should allow to ensure surface and ground-water protection from pollution, stability of the landfill and of the landfill plus foundation soil ensemble, biogas collection (and possibly re-use), surface water drainage and final reclamation and land use of the area.

2.2. Structural elements of a sanitary landfill and related problems

Bearing in mind the geotecnical problems of sanitary landfills, it is convenient to classify them according to the site morphology (modified after Cancelli, 1989):

1) "depression" landfills, into natural gullies, shallow man-made trenches, or abandoned quarries and open pit mines;
2) "area" landfills, as embankments on relatively flat natural ground;
3) "slope" landfills, adjacent to natural slopes or to man-made cut-slopes;
4) "underground" landfills, into subterranean, abandoned mine tunnels and caverns.

Underground landfills present many geological, geotechnical and structural problems, highly different from the problems that are currently encountered for surface landfills, and for this reason they are not treated herein; as for as the other categories (1-2-3), slope landfills are representative of the most complex problematics, generally including all the problems of both depression and area landfills.

The main structural elements (at the same time functional elements from an environmental engineering point of view), forming a typical MSW landfill on a slope are synthetically sketched in Fig. 2; their essential requirements, and related geotechnical problems, are summarized as follows.

2.2.1. Subsoil and subgrade

It could seem superfluous to remember that the essential requisites of a sanitary landfill foundation soil are to perform as a natural hydraulic barrier and to possess sufficient bearing capacity and low compressibility.

The former involves geological and hydrogeological problems in the preliminary phase of site selection: the best "natural" solution is possible only in the presence of very thick, overconsolidated, homogeneous clay formations, like in the case of Imola landfill in Italy, lying on several hundreds meters of marine, Lower Pleistocene silty clays (Cancelli, 1989). Unfortunately, such a highly favourable geological situation is very uncommon and in the large majority of cases artificial hydraulic barriers (including geomembranes) are truly necessary.

The latter problem is of both geological and geotechnical nature; siting a landfill on soft, normally consolidated clays or organic silts should be preliminarly avoided on the basis of adequate geological investigations; surprisingly, such a design practice is not always respected, as demonstrated by numerous examples (from different parts of the world) of base failures due to the low undrained cohesion of foundation soils (the example of Finale Emilia landfill in Italy is illustrated in Fig. 3). Serious foundation problems, in terms of stresses and consequent intolerable deformations and also failures in the overlying lining system, can also be given by unforeseen voids of various origin (tension cracks,

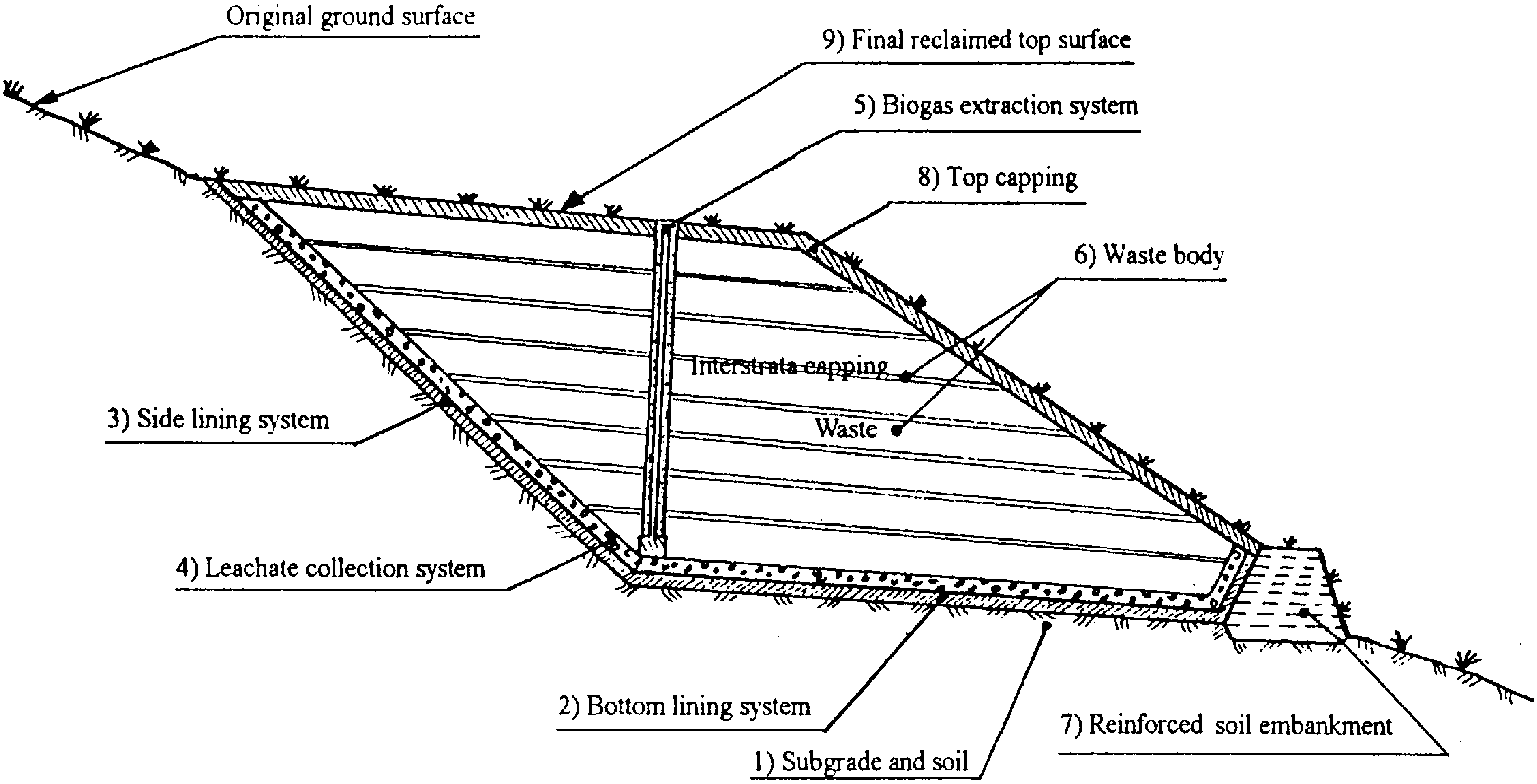

Fig. 2 Structural elements of a typical MSW landfill on a slope (the numbers are referred to subparagraphs from 2.2.1 to 2.2.9 and from 2.4.1 to 2.4.9).

sinkholes, dissolution cavities) or by depressions due to differential settlements (Giroud et al., 1990).

Similar problems are encountered when an existing landfill has to be expanded vertically with addition of new waste. Two cases are possible:

- if the existing waste accumulation is an old, uncontrolled landfill, the espansion has to be intended as a completely new waste landfill, requiring all the structural parts of a well conceived, modern sanitary landfill, including the realization of a new improved subgrade on the existing waste accumulation;
- if the existing landfill is already provided with the all the bottom facilities of a modern sanitary landfills, the expansion has to be intended as a stability problem of the overall waste body (see paragraph 2.2.6 in the following).

In any case, a large variety of geotechnical solutions to create an artificially improved subgrade is available, also involving the application of reinforcing geosynthetic products, with the result to increase the ultimate bearing capacity and, at the same time, to reduce the overall settlement to values tolerable by the deformability of the overlying lining system.

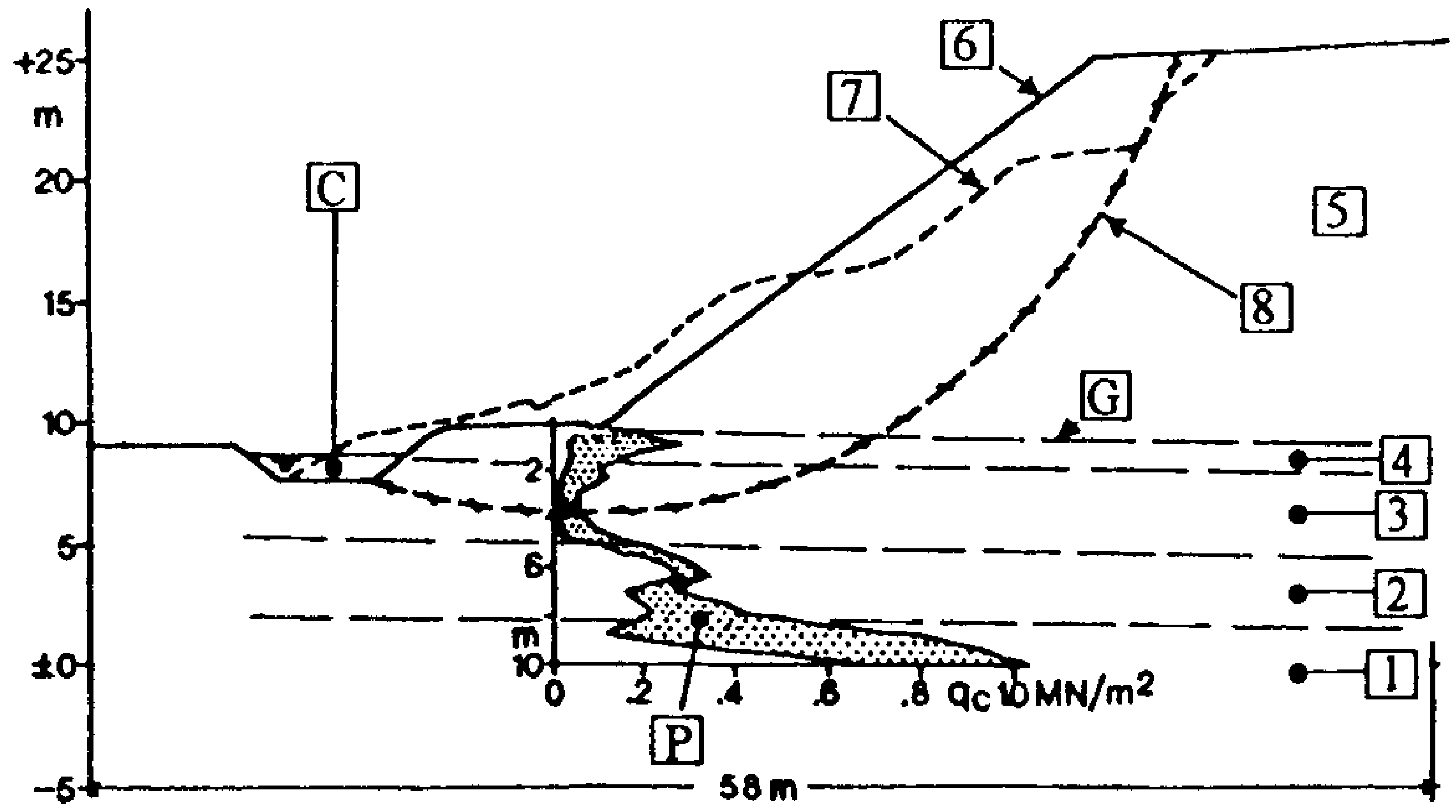

Fig. 3 Example of base failure induced by undrained loading at Finale E. landfill in Italy (after Cancelli, 1989).

1. Alluvial sand.
2. Sandy silt and silt.
3. Very soft, high plasticity, silty clay.
4. Sandy and clayey silt.
5. Lightly compacted refuse.
6. Ground surface before failure.
7. Ground surface after failure.
8. The most probable slip surface.

G. Original ground level.
C. Canal.
P. Results of 4 static cone penetration tests: range of measured values of the cone resistence q_c.

2.2.2. Bottom lining system

Regional and site hydrogeological conditions, and particularly the piezometric surface of the underlying aquifer, govern the preliminary design option and the function itself of the landfill bottom liner. Two opposite situations are analyzed by Rowe (1994a), who considers a system formed by a double liner with an intermediate highly permeable layer:

a) in the case of deep-seated aquifer, an outward hydraulic gradient is imposed across the primary liner and the permeable layer is intended to allow detection and collection of leachate escaping through the primary liner; attenuation within the underlying unsaturated zone should ensure further pollution control (Fig. 4-a);

b) in the case of high piezometric level in the aquifer, an inward hydraulic gradient is imposed from the intermediate permeable layer across the primary liner; this solution form a sort of "hydraulic trap", preventing leachate from flowing out of the waste body into the aquifer (Fig. 4-b).

Advantages and disadvantages of the two approaches are discussed by Rowe (1994a) in terms of advective transport only; the role of (carefully investigated) hydrogeological site conditions should be discriminating in the preliminary selection of the design option, so to minimize the landfill impact in terms of groundwater pollution hazard. Anyway, it has to be remembered that, due to the uncertainties regarding diffusive transport of contaminants, many national codes and environmental policies do not accept the idea of the hydraulic trap design solution; the case a) is by far the most common and will be the only one to be dealt with in the following.

All this considered, the essential requirement of a lining system is, of course, to act as a hydraulic barrier against the leachate, so protecting groundwater from pollution. Due to the particular nature of leachate, the hydraulic barrier should be effective against both seepage and diffusion phenomena: the consequences of the latter are often underestimated, but it has been demonstrated that diffusion may be an important transport mechanism, particularly in clay liners (Quigley et al., 1987; Daniel and Shackelford, 1989; Rowe, 1994b).

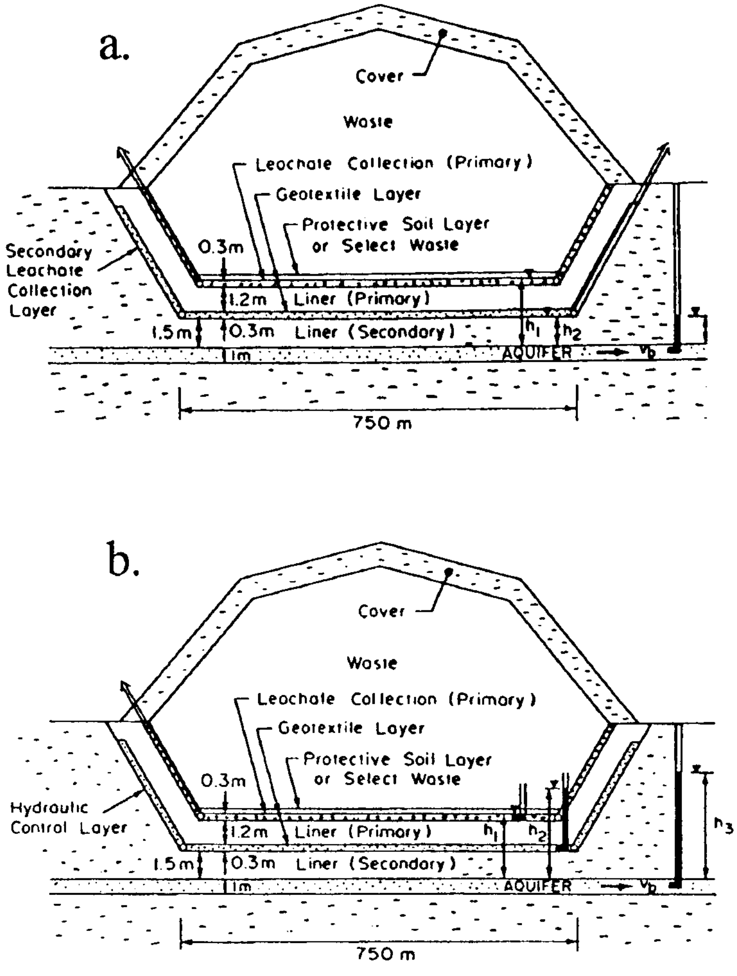

Fig. 4 Schemes showing the two possible hydrogeological situations and consequent design solutions for the bottom lining system of a landfill (after Rowe, 1994a):

a. advective flow outward through the primary liner;

b. primary liner underlaid by a hydraulic control layer; the landfill is conceived as a "hydraulic trap" with inward advective flow into the landfill.

Leachate production starts in a short time after the waste disposal and continues for many years, also after the completion and final capping of the landfill. Appreciable effects of pollutants on the hydraulic conductivity of barriers have been demonstrated, both for clay liners (Quigley et al., 1987; Daniel and Shackelford, 1989) and for geomembranes (Haxo, 1989; Haxo and Haxo, 1994); therefore, the barriers should also be long-term, chemically resistant to leachate. In addition, resistance of barrier-forming materials to high temperatures is needed (Collins, 1993).

Bottom lining systems should also possess mechanical resistance (in general terms, to both shear and tensile stresses); the importance of a good long-term performance is emphasized by Koerner (1990), in relation to the fact that repair works on buried liners are possible only at enormous costs, especially for already completed landfills.

All these requirements can be satisfied only by a composite, multilayered barrier system, including natural materials and different kinds and combinations of geosynthetics.

2.2.3. Side lining system

Strictly speaking, hydraulic barriers on the side of a depression or slope landfill should respect the same requirements as bottom barriers. On the other hand, in well designed and well operated landfills the leachate is collected and drained away, so the maximum height of the leachate level on the bottom should be constantly kept very low (less than one meter). In addition, due to the steepness of landfill sides and resulting high mobilized shear stresses, internal stability and mechanical resistance are relatively more important than long-term chemical resistance, so requiring appropriate design criteria and selection of materials.

For these reasons it is generally admitted, especially for steep cut slopes where construction of compacted clay liners is difficult, that the composite lining system be designed and realized differently from the bottom liner.

2.2.4. Leachate collection system

A continuous leachate collection system, on both sides and bottom of the landfill, is a necessary condition for every modern sanitary landfill. Moreover, in most landfills where the low hydraulic conductivity of interstrata capping layers does not allow a full drainage of the produced leachate, vertical drainage wells are also required, connected to the bottom drainage system; such wells must have a deformable structure, in order to adapt themselves to vertical settling and horizontal deformations of the waste body. The vertical drainage is often combined with the biogas extraction system (Cossu, 1994).

In-plane transmissivity is the essential requisite, together with good performance as a filter. Besides, due to the need to maintain the hydraulic head of leachate on the bottom liner at an acceptably low level, long-term performances are also of primary importance: they include non-susceptibility to clogging, and resistance of the materials to chemicals and to high temperatures.

Internal stability and resistance to shear are supplementary requisites for leachate collection layers, especially on the steep sides of the landfill.

Due to the many requirements, leachate collection systems are conceived and realized as composite layers, always including one or more types of geosynthetics; excess leachate production has to be evacuated, by gravity or by pumping.

2.2.5. Biogas extraction system

Landfill gas is generally extracted by means of vertical gas wells, connected at the top with horizontal gas transportation pipes (the application of a vacuum is necessary); additional, or alternative, extraction systems based on horizontal ditches and pipes are by far less used and lesser experience is available (Stegmann, 1989b). Peculiar aspects of geotechnical design are related to the presence of these vertical structures within a compressible waste body, in that they are subject to the negative skin friction induced by the all-around settling wastes; consequently, the supplementary load applied on the base of the vertical shaft can be a cause of high stresses in the bottom draining and lining systems, eventually inducing failure in the geomembrane. Different technical solutions for biogas and for combined gas/leachate extraction systems, together with some performance results, are reported by Leach (1991).

In any case, high permittivity and transmissivity to gas are essential requisites for any material surrounding the (vertical and/or horizontal) extraction pipes; this implies that also water and leachate, if present within the waste mass and not adequately drained off, can penetrate into the gas extraction system, eventually stopping extraction. The possibility of interactions between biogas and leachate extraction systems should be taken into consideration.

The other requirements are the same previously reported for all technological systems incorporated in a waste landfill: for all materials, including geosynthetics, long-term resistance to chemicals and temperature and, for filters, non-susceptibility to clogging.

2.2.6. Waste body

This comprehensive term includes the properly said compacted waste layers, the interstrata cappings and also the internal gas and leachate extraction systems (Jessberger, 1991).

Geotechnical stability, during all phases from the construction to the final storage one, is the most important requirement of the waste body. Stability should be intended in terms of the following two basic aspects, as pointed out in the Technical Recommendations on Geotechnics of Landfill Design and Remedial Works issued by the ISSMFE European Technical Committee

No. 8 (ISSMFE-ETC 8, 1993; Jessberger et al., 1993):
a) external stability;
b) internal stability.

The former depends on the strength and deformation behaviour of the waste mass, influencing potential failure zones for all slopes and in the adjacent natural soils. Three typical failure mechanisms have been recognized and have to be investigated in terms of factor of safety:

- slope failures, along curvilinear surfaces crossing both waste layers and interstrata cappings;
- planar failures (by spreading induced stresses), mostly along slip surfaces within the bottom lining system;
- ground (or base) failures, along slip surfaces passing also into the foundation soil (see 2.2.1).

The external stability depends on many factors: the pre-treatment, compaction and unit weight of wastes; the shear strength of compacted wastes (strain-dependent and also time-dependent); the shear strength of interstrata cappings; the performance of leachate and biogas extraction systems; the lowest shear strength along the bottom lining system; bearing capacity of foundation soils (Cancelli, 1989; Jessberger and Kockel, 1993).

The internal stability concerns the problems deriving fron the placement of particularly low strength wastes (as sludges) in zones sufficiently distant from the external stability zones and from the surface of the waste body, so limiting within acceptable levels differential settlements and consequent excessive stresses on the top capping system (ISSMFE-ETC 8, 1993).

Technical solutions to improve both for external and internal stability conditions cover a wide spectrum, including waste pre-treatment or enhanced compaction, co-disposal wastes with different mechanical properties, subgrade soils improvement, internal cover layers reinforcement, and so on; reinforcing functions are typically carried out by geosynthetics.

2.2.7. Reinforced soil embankments

Reinforced soil embankments are often realized at the toe of waste embankments (as schematically shown in Fig. 2), in order to improve the stability of the landfill slopes. As these structures must resist the horizontal actions applied by the waste mass, their essential requisite is mechanical strength, in particular to shear stresses.

An important outcome of constructing reinforced soil embankments along the base of a landfill is the increasing of the average steepness of the landfill and, consequently, the waste storage capacity, with evident advantages also from an environmental point of view. This is true also if the embankment is directly founded as a flexible structure on compressible and dishomogeneous materials, as pre-existing wastes: it is the case of a geogrid reinforced embankment realized in order to dispose additional material in the MSW disposal facility in Modena, Italy (Cazzuffi et al., 1988).

2.2.8. Top capping

The top capping system is an important element of a modern landfill, having a number of different functions: firstly, it serves to avoid the transfer of contaminants into the atmosphere and the biosphere, keeping disease transmitting animals (rats, insects, birds) off the waste; a second important function is to control water infiltration into the waste, in order to optimize the water balance and to minimize the production of leachate (Melchior et al., 1993). To prevent from blowing away dust and light plastic waste materials and to provide growing conditions for the vegetation are the other important functions of the top capping (Hoeks and Ryhiner, 1989).

Due to the many functions to be performed, the top capping of a landfill is a multi-layer system, including different materials; besides, the design criteria vary from one country to another, depending on: the site hydrogeological conditions; the availability of natural of soils suitable both for the engineering and the agronomic points of view; the climatic regime (rainfall parameters); the dimensions of the sanitary plant, different from the small village landfills to the great landfills of large cities, and the duration of the operating phase; the legal constraints of the country. Anyway, the technical requirements are numerous and all important: stability against slope failures (in turn dependent on the long-term general stability and settements of the waste body); stability against slumping and cracking; shear resistance along the different layers; ability to perform as barriers (to both liquids and gases), or as semi-permeable layers; transmissivity of the drainage layers; long-term resistance to chemicals (though actually the top layers should not be in contact with leachate); resistance to disruption by animals and plants; resistance to water erosion; resistance to wind erosion (see also Saarela, 1993).

2.2.9. Final reclaimed top surface

The top surface is generally considered as a whole with the underlying final cover composite system and, from a strictly technical point of view, it should fulfil the same requirements as indicated in the previous paragraph.

Actually, the final reclaimed top surface has also the function to hide the waste from sight and, together with its connections with the original ground surface at the borders of the lanfilled area, it has to be inserted into a true "landscaping project", in both environmental and architectural terms (Fabris and Mandelli, 1991).

Of course, the land-use of such reclaimed areas is generally limited to green recreational areas and related facilities, although other public facilities, such as schools (Matsufuji et al., 1991), have been constructed in reclaimed areas in some densely populated regions.

Also, it is important to recall that the main technical requirements for the upper horizon of the top cover are represented by agricultural soil use, slope stability and resistance to water and wind erosion.

2.3. Geosynthetics used in landfills and performed functions

As it appears from the discussion in the previous paragraphs, the functions to be performed by the different elements of a landfill are many and widely diversified; therefore, no wonder that so many different technical solutions have been proposed and implemented to solve specific landfill construction problems.

Till the 60's, in agreement with the inconsiderate "dilute and disperse" approach to waste disposal problems, sanitary landfill technology had been at a very primitive level, or practically inexistent. But with the growth of population, the development of the industrial society, the increase of the average individual economic possibilities and consequently of the primary (and superfluous) needs, the enormous volumes of wastes being accumulated on the Earth surface made the problem prioritary (Sembenelli and Ueshita, 1981).

In the meantime, the parallel development of many kinds of synthetic materials has lead to an increasing use of geosynthetics in landfill technology, in cooperation with, or in partial or total substitution of the traditional earth materials. The different products can be used, individually or as components of an assembled structure (geocomposite), depending on the different functions required by the previously described landfill elements, and also on the material properties, short- and long-term performances, and costs; the level of applicability of the different materials that can be used to satisfy the required functions is summarized in Table 4 (modified after the original idea by Christensen et al., 1994).

As it can be seen in the table, all the main functions of geosynthetics (except function C - cushion) are present in the landfill technology, and for every function there is at least a geosynthetic (or a bioproduct) that can be used eventually in concurrence with earth materials.

Table 4. Level of applicability (H high; M medium; L low) of different materials used in landfills with regards to the required function: the evaluation is given on the base of material properties, performances and costs (modified after Christensen et al., 1994).

Types of	Functions											
materials	A	B	D_W	D_L	D_G	E	F_W	F_L	I	P	R	S
Earth material:												
GV	-	-	H	H	H	-	L	-	-	-	L	L
SD	-	-	L	L	H	-	H	M	M	H	-	M
CL	-	H	-	-	-	-	-	-	-	H	-	-
SB	-	H	-	-	-	-	-	-	-	M	-	-
Geosynthetic/Bioproduct:												
GT	L	-	L	-	L	L	H	L	M	H	M	H
GG	-	-	-	-	-	-	-	-	-	-	H	-
GN	-	-	H	H	H	-	-	-	-	M	-	-
GA	-	-	-	-	-	H	-	-	-	-	-	-
GL	-	-	-	-	-	H	-	-	-	-	-	-
GM	-	H	-	-	-	-	-	-	-	-	-	-
GCD	-	-	H	M	H	-	-	-	-	-	-	-
GCR	-	-	-	-	-	-	-	-	-	-	H	-
GCL	-	H	-	-	-	-	-	-	-	L	-	-
GCM	-	H	-	-	-	-	-	-	-	-	-	-
BT	H	-	-	-	-	H	-	-	-	-	-	M
BA	H	-	-	-	-	H	-	-	-	-	-	-
BL	M	-	-	-	-	H	-	-	-	-	-	-

Legend: D_W: drainage of water
D_L: drainage of leachate
D_G: drainage of gas
F_W: filtration of water
F_L: filtration of leachate
GV: gravel
SD: sand
CL: clayey soil
SB: soil/bentonite mixture
For geosynthetics and bioproducts see Table 1
For functions see Table 2

2.4. Applications of geosynthetics in landfills and related environmental impacts

Applications of geosynthetics, or eventually bioproducts, are here described with reference to the different structural elements of a typical landfill, as sketched in Fig. 2 and previously described in paragraphs from 2.2.1 to 2.2.9. For each landfill element, the applications of geosynthetics and bioproducts are illustrated by means of examples. Only brief references are made to design methods, while construction details are beyond the scope of this paper. The function performed by geosynthetics in the different applications and the main environmental impacts (both positive and negative, if any) related to the use of such manufactured products instead of natural earth materials are resumed in Table 5.

Table 5. Main environmental impacts related to the use of geosynthetics and/or bioproducts instead of natural earth materials in landfills (for abbreviations related to products and functions see Tables 1 and 2).

Landfill structural elements	Essential requirements of the structural element	Geosynthetics and bioproducts typically used, with performed functions		Main environmental impacts related to the use of geosynthetics or bioproducts instead of natural earth materials	
		Products	Functions	Positive	Negative
9) Final reclaimed top surface	Stability, resistance to erosion, aesthetics	GT,GA,GL BT,BA,BL GCD,GN,BCD GG	E,F E,A D R	Re-vegetation Surface runoff control Surficial stability Landscape project	Permanent buried structure at low depth Release of toxics in case of accidents both only for geosynthetics
8) Top capping	Barrier to gas, gas venting, water infiltration control, isolation from animals, stability	GM,GCL GN,GCD GT GG,GCR	B D S,F,P,R R	Biogas emission control Saving earth materials Waste extra-storage Reducing quarry activities Decreasing traffic Leachate production control	Permanent buried structure at low depth Release of toxics in case of accidents
7) Reinforced soil embankments	Stability, contrast to waste pressure	GG,GCR GT	R R,S	Waste extra-storage Landscape projecting Optimizing use of the site Improving external stability	Modification of natural morphology
6) Waste body	Internal stability, external stability	GG,GT GN	R,S D	Waste extra-storage Optimizing use of the site	
5) Biogas extraction system	Gas drainage, long-term performance	GN GT GG GCL	D S,R R B	Saving earth materials Reducing load on the bottom barrier Prevention from gas uncontrolled outcome	
4) Leachate collection system	Leachate drainage, long-term performance, internal stability	GT GN,GCD	S,F,I D	Saving earth materials Reducing quarry activities Decreasing traffic Increasing stability	Increase of hydraulic head in case of clogging
3) Side lining system	Barrier to leachate, external stability, long-term performance	GM,GCL,GCM GN,GCD GT	B D I,S,F	Increasing available sites Saving earth materials Reducing quarry activities Reducing damage to landscape Decreasing traffic Controlling lateral pollution	Groundwater pollution in case of failures
2) Bottom lining system	Barrier to leachate, long-term performance	GM,GCL GN,GCD GT	B D S,F	Increasing number of available sites Saving earth materials Reducing quarry activities Reducing damage to landscape Decreasing traffic	Groundwater pollution in case of failures
1) Subgrade and subsoil	Bearing capacity, low compressibility	GG,GCR GT	R S	Minimizing bottom failure hazard Increasing number of available sites Decreasing traffic	Increasing construction times

2.4.1. Subsoil and subgrade

As already mentioned, bad subsoil conditions should be avoided since the preliminary phase of site selection. Should low bearing capacity foundation soils be encountered, geotechnical investigations must be carried out, in order to assess the nature (non-cohesive, cohesive, or organic), the main geotechnical properties and the thickness of the weak soil horizon.

All this known, traditional soil improvement techniques are available (weak soil substitution with granular earth material, surface compaction, heavy tamping, etc.), that are not to described herein. Among these techniques, acceleration of settlements due to rapid loading of soft cohesive, or organic, foundation soils, in order to reduce the hazard of base failures as described in 2.2.1, can be seen as a field of application of geosynthetics also under landfills. These results can be obtained by installing vertical drains; the traditional "sand piles" are, in fact, widely substituted by geocomposite strip drains (Akagi, 1994); the same possibilities are offered by biodegradable natural composite drains, as the biocomposite strip drain described by Lee et al. (1994), were the biodegradability is a supplementary advantage from an environmental impact point of view (being in this case the drainage function only for a temporary process).

For low to moderately thick deposits of loose soils, a reinforced subgrade aiming to homogenize settlements and to reduce tension stresses in the overlaying bottom lining system is highly recommended. Bioriented geogrids can be used as reinforcing elements cooperating with medium to coarse grained soils, within a multilayer subgrade, according to the scheme reported in Fig. 5. Alternatively, geocomposite reinforcements, or twin layers of mono-oriented geogrids disposed with their preferential directions transversal each to other, can be used to the same scope.

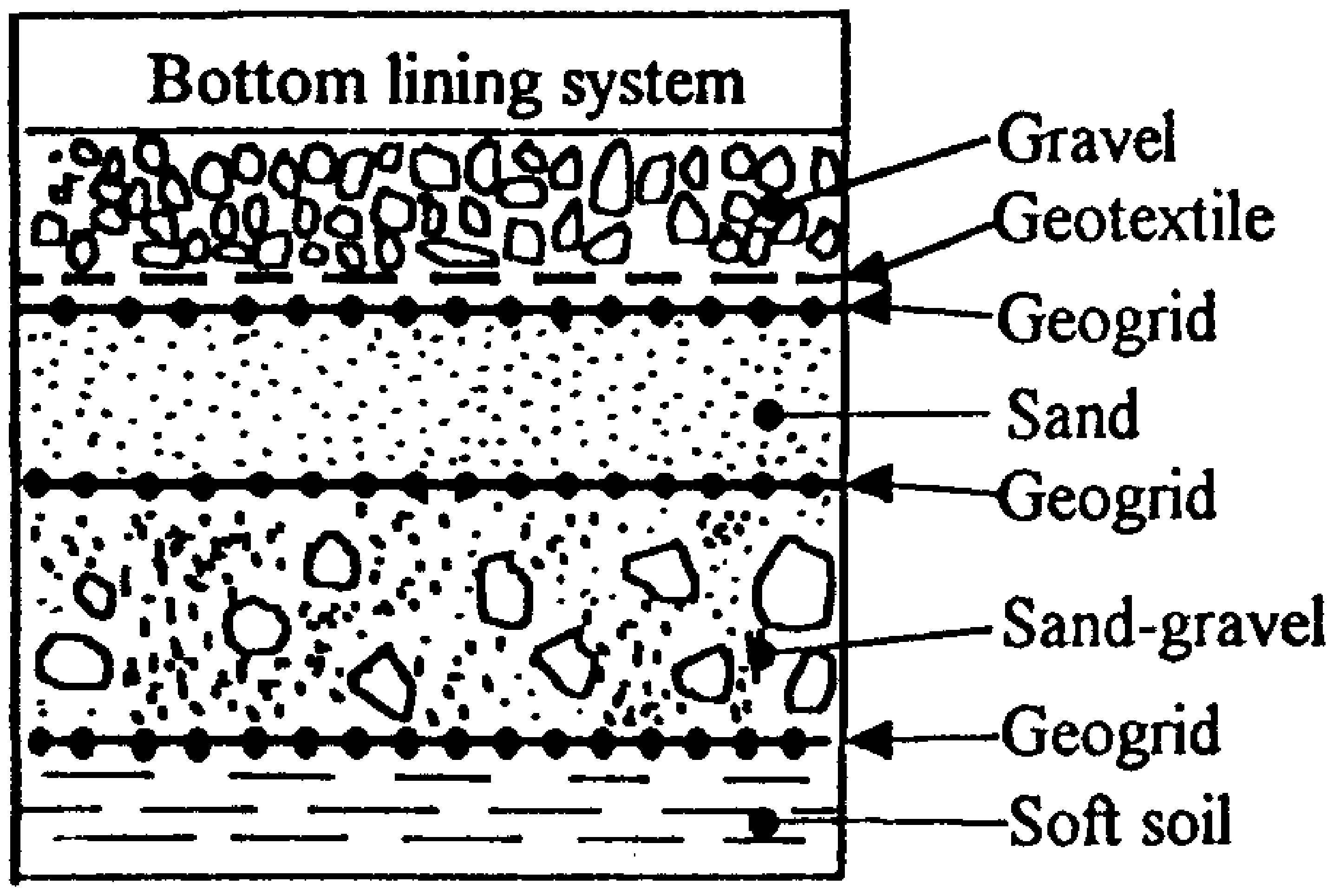

Fig. 5 Example of use of bioriented geogrids to improve the bearing capacity of soft soil, at the bottom of a landfill (modified after Rimoldi and Togni, 1991).

The case of landfills to be realized on geological formations susceptible to cracking or sink-hole generation has been analyzed by Giroud et al. (1990); some charts, in parametric form allow for designing the overlying bottom lining system. Geogrid-based reinforcement is reported by Fox (1993) for the solution of problems due to the presence of cracks in the foundation soil.

In terms of environmental impact, a reinforced improved subgrade compensates major costs and time required for preparation works by minimizing the hazard of failures in the bottom liner, increasing the number of available landfills sites in areas characterized by difficult geological and geotechnical conditions, and also decreasing transportation costs and traffic intensity.

2.4.2. Bottom lining system

A compendium of the types of barrier systems is reported in Fig. 6 (from Cossu, 1994); the different solutions are briefly analyzed in the following.

The single clay liner (case a) is a very simple solution, going back to the history of landfill technology, but still in use in favourable hydrogeologic site conditions, or for inorganic mass waste (IMW) landfills. Many researchers put in evidente the main defects of such a solution, due to many causes, e.g. after-compaction dessiccation before covering with other material (Mitchell and Jaber, 1990), and long-time effects of leachate contaminants percolation (Quigley et al., 1987). In the past, sand/bentonite or silt/bentonite mixtures have also been used in substitution of natural clayey soils, but such a solution is no more economically advantageous for the required minimum thickness. As for the single geomembrane liner (case b), directly posed on the subgrade, it has problems of damage due to unfair contact, unless the subgrade be formed by uniform clay soil; Giroud and Bonaparte (1989) have calculated the unitized leakage rates through a geomembrane liner due to many causes (permeation, pinhole, small and large holes). Nowadays, also this barrier solution has been practically abandoned; alternatively, geocomposite clay liners or geocomposite membrane liners are used with some success for particular site conditions.

The single geomembrane/clay composite liner (case c) is the typical solution adopted for MSW landfills. In Italy, 1 m-thick compacted clay, with hydraulic conductivity

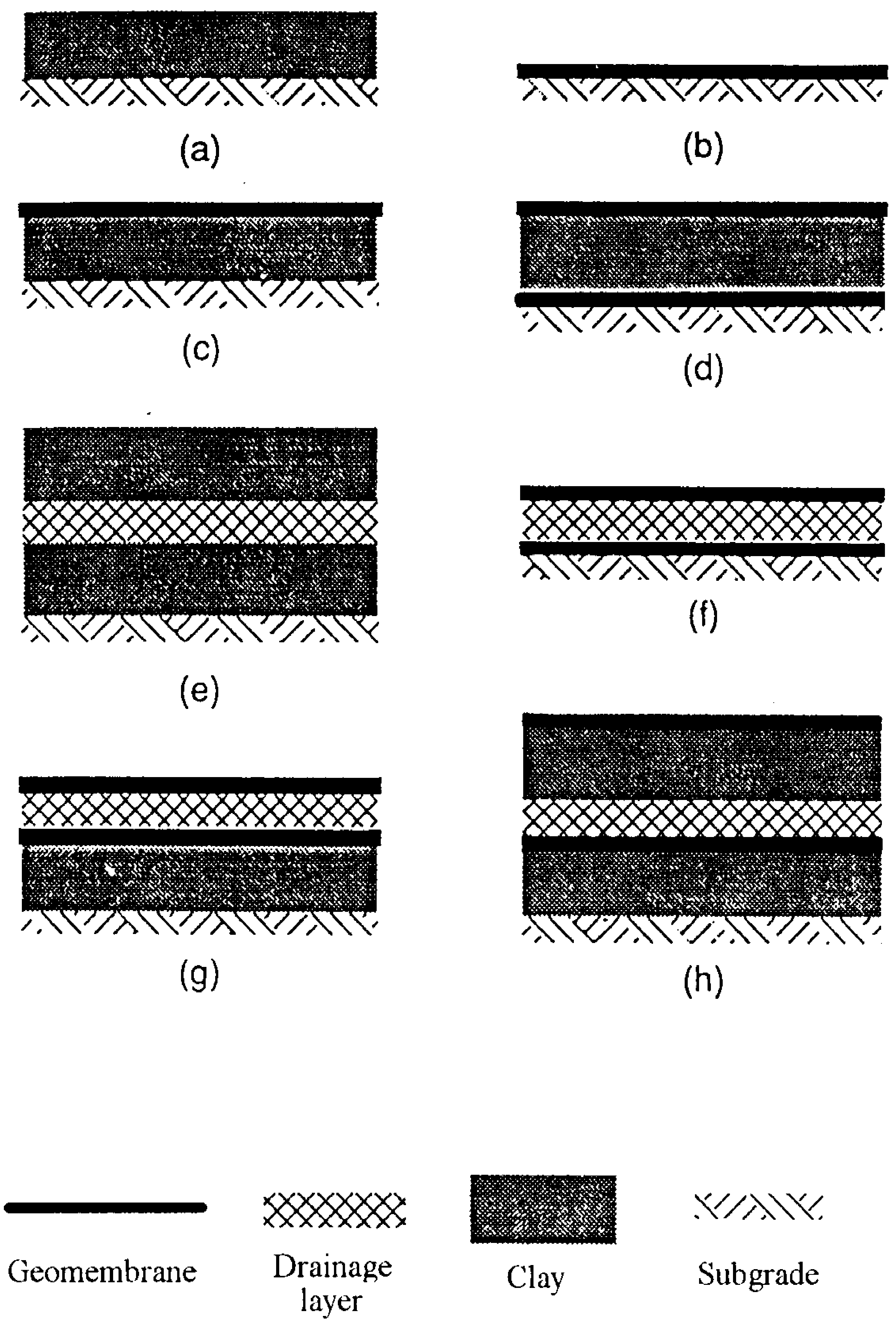

Fig. 6 Types of barrier systems (redrawn after Cossu, 1994).

a. Single clay liner.
b. Single geomembrane liner.
c. Single geomembrane/clay composite liner.
d. Sandwich composite liner.
e. Double clay liner.
f. Double geomembrane liner.
g. Double semicomposite liner.
h. Double composite liner.

lower than 10^{-9} m/s is generally required, overlied by a geomembrane (generally of HDPE). Advantages and disadvantages of such a technique, together with the computation of flow rates due to the many defects, have been investigated in the field and in the laboratory (Giroud et al., 1989; Bonaparte and Gross, 1990; Gross et al., 1990; Giroud et al., 1992). Direct contact between geomembrane and the compacted clay layer, without interposition of any geotextile, is highly recommended to reduce flow in case of imperfections by Giroud and Bonaparte (1989). Alternatively, a geocomposite clay liner can be used in substitution of the compacted clay layer, where natural earth materials are not economically available, with the further advantage of saving extra volume for waste disposal. One of the first applications of the latter solution was realized at Seveso, Italy, for the safe storage of materials contaminated by TCDD-dioxin: a sand-bentonite layer (0.20 m-thick) was put in place instead of the conventional compacted clay (Piepoli et al., 1984).

The sandwich composite liner (case d) represents a safer solution with respect to the previous one (as limiting the damages due to the clay layer dessiccation), but more expensive and with problems of contact with the subgrade. Its use is uncommon.

The schemes from e) to h) represent the evolution of barriers including a double barrier with an intermeadiate drainage layer, which has the function to collect and drain away the leak passed through the primary liner, and also for putting in place inspection pipes. The use of geotextiles as separators is necessary for all problems of contact between drainage material and compacted clay (cases e, h), and in any case for protecting the geomembrane (cases f, g, h). The drainage layer is generally formed by earth materials (sand to fine gravel), but the use of geonets with the same function can be advantageous, both to the economy and to the environmental impact (where natural drainage materials are not available). Solutions e) and f), based on the use of only one type of barrier (respectively, natural earth materials and geomembranes), can be unsafe for "hazardous" waste landfills and are uncommon; the present tendencies for industrial HTW landfills privilege solutions g) and especially h).

An example of double composite liner of type h), conceived for the HTW landfill at Barricalla, Italy, is reported in Fig. 7. The sequence of the barrier-forming materials, attaining an overall thickness of 3.5 m, is (from the top):

- a 0.30 m thick drainage layer, in turn including a gravel layer, a nonwoven geotextile as a separator and a 5 mm-thick HDPE geonet (μ = 750 g/m²);
- a primary geosynthetic liner formed by a 2.5 mm-thick HDPE geomembrane;
- a 1.00 m-thick compacted clay layer (hydraulic conductivity not higher than 10^{-9} m/s);
- an intermediate drainage layer, 0.20 m thick, again including a gravel layer, a nonwoven geotextile as a separator and a 5 mm-thick HDPE geonet, besides a pipe for telecamera inspection;
- a latter, 2 m-thick mineral layer, formed by compacted clay with the same hydraulic requirements as the primary one.

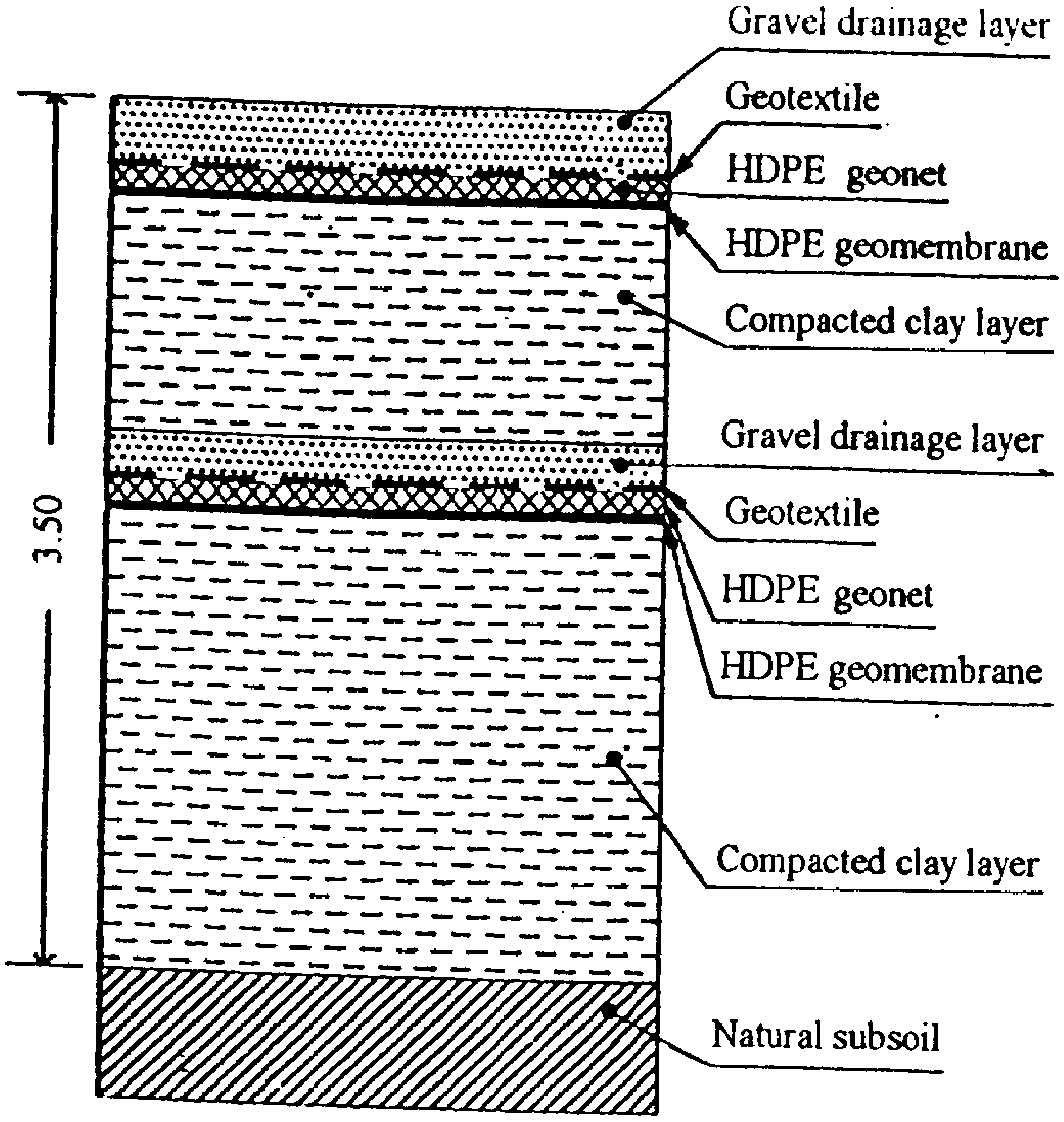

Fig. 7 Composite lining system of the Barricalla HTW landfill in Italy (modified after Di Molfetta, 1993).

As for geosynthetic materials used within barrier systems, the main concern is by far the long-term durability of geomembranes. Field investigations by Rollin et al. (1991) on various sites confirmed that appreciable ageing occurred after seven years of contact of geomembranes with contaminated soils; of course, the ageing intensity was more severe on the bottom than on the slopes. The minimum required tests for geomembranes to be put in place below wastes are listed by Koerner (1990), including chemical resistance (by immersion), index strength tests (tensile, puncture, tear, impact), performance strength tests (wide width friction, anchorage), seam strength tests (shear, peel) and hydraulic tests (water vapor, solvent vapor). In addition, the effects of temperatures higher than 40°C (values up to more than 60°C have been measured into waste landfills) should be taken into account for design (Collins, 1993). The essential design elements for geomembrane selection and dimensioning, in terms of a design-by-function approach and based on the concept of minimum required factor of safety, are given by Koerner (1990, 1994). Results of recent studies on different liners, including compacted soil layers, single composite liners and different types of geosynthetics (geomembranes, geocomposite clay liners) make it possible to evaluate the rate of leakage of leachate, also demonstrating the effectiveness of a composite liner including a geocomposite clay liner in comparison with other more classical solutions (Giroud et al., 1994).

Environmental impacts related to the use of geosynthetic products within bottom barrier systems are numerous and mostly positive. The use of geomembranes, or other geosynthetic composite liners, allows to realize landfills in a wide number of sites that would require long-distance supply of large quantities of natural clayey soils, so decreasing traffic impact due both to clay transportation (in the site preparation phase) and to waste transportation to disposal (in the operation phase); the same could be said for the use of geonets in partial substitution of natural earth drainage materials (gravel, sand); the consequence is an increasing of the available total volume that can be used for disposal. A related, further environmental advantage lies in the reduction of damages to the landscape in the quarry areas. As for as the pollution hazard (and related risk) is concerned, the use of geosynthetic liners is certainly beneficial in the short-term, while some doubts still remain about the long-term performances of geomembranes and consequent risk of time-delayed, unforeseen release of toxic substances into the environment.

2.4.3. Side lining system

Differently from the bottom, the realization of a lining system on the sides of a depression or slope landfill presents, despite of the common hydraulic requirements, some peculiar aspects and difficulties.

Due to the steepness of the cut slopes (at least 30°, unless excessive reduction of the available volume be tolerated), it is quite impossible (or in any case operatively difficult) to put in place adequately compacted clay layers; prefabricated products, as geomembranes, geocomposite clay liners and geocomposite membrane liners, are largely preferred as barriers, while geonets and geonet-based geocomposites are used instead of natural gravel or sand as intermediate drainage layers. Therefore, with reference to the barrier typologies reported in Fig. 6, solution c) (with the variant of a geocomposite clay liner instead of the compacted clay liner) for MSW landfill, and solutions f) and g) for HTW landfills are commonly used.

The previously described HTW landfill at Barricalla gives an example of side barrier and side-bottom connection, as reported in Fig. 8. The system includes, within the intermediate layer, a couple of 300 mm-diameter HDPE pipes, the former for periodic telecamera inspection and the latter for samples taking and for installing an alarm system (Di Molfetta, 1993).

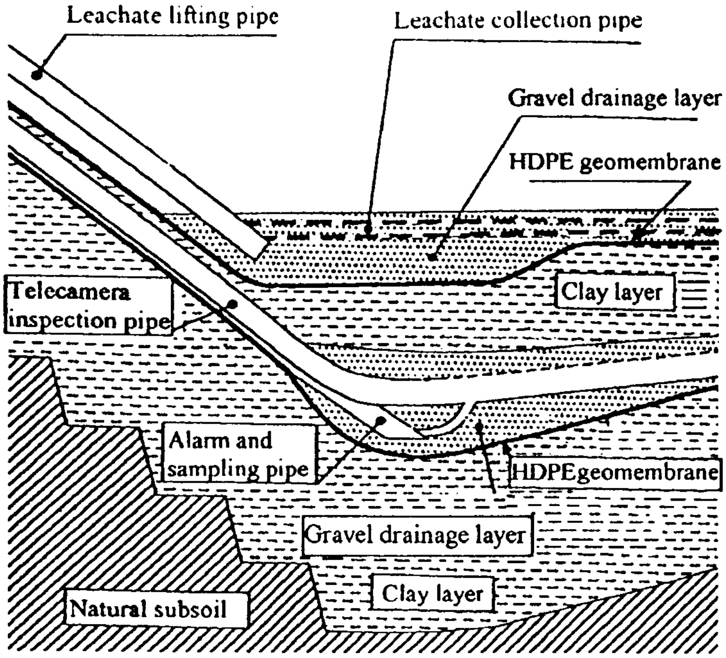

Fig. 8 Barricalla HTW landfill in Italy: example of connection between side and bottom lining systems, including leachate collection lifting pipe and lining monitoring system (modified after Di Molfetta, 1993).

For a multilayered side barrier systems, both external and internal stability require particular attention; the shear resistance along each interface has to be evaluated (Koerner, 1990, 1994); values of shear resistance parameters, also expressed in terms of pure friction angle, are available from literature (e.g. Bonaparte et al., 1985; Lopes et al., 1993).

By the way, for side lining systems supplementary problems can be associated to external groundwater infiltrations (Bonaparte and Gross, 1990). This water has to be intercepted along the side barrier; two different solutions are possible (Cossu, 1994):

a) an external drainage layer is integrated in the barrier system, between the geomembrane and the natural soil (in this case, a geonet can advantageously substitute a gravel layer);
b) a drainage trench within the soil mass, not in contact with the geomembrane (also in this case, the use of geocomposite sheet drains, including a geonet, can be used instead of traditional earth materials).

Geomembranes (and geocomposite membrane liners) are also used as essential components of vertical cut-offs, used for additional barriers at the external of a depression landfill: examples of applications of a composite structure, where the geosynthetic is placed, centrically or excentrically, within a concrete diaphragm wall ("composite cut-off wall"), are described by Brandl, 1990. Nowadays, this solution is still unusual for new landfills, while its applications are rapidly growing in number as lateral containment of already contaminated sites. This latter application has, no doubt, very positive environmental impact, though requiring the careful assessment of site hydrogeological conditions.

The other environmental impacts due to to uses of geosynthetics in side barriers are the same as for bottom barriers.

2.4.4. Leachate collection system

A continuous drainage blanket (0.3-0.5 m-thick, or more), overlaying the bottom liner. forms an essential part of every leachate collection system. Generally the landfill bottom is gently sloping and roof-shaped; collector pipes are placed along the most depressed lines, according a regular or irregular layout; trenches of split gravel, at regular intervals, convey leachate from wastes to the underlying continuous blanket and/or directly to the collector pipes.

A schematic section of the bottom leachate collection system, according to a proposal by Ramke (1989), is shown in Fig. 9 (of course, the clay liner can also be a different, more or less complicated, type of bottom barrier - see Fig. 6). The geotextile has here only a separation function vs. the clay; if the draining blanket is placed on a geomembrane, the geotextile (or a

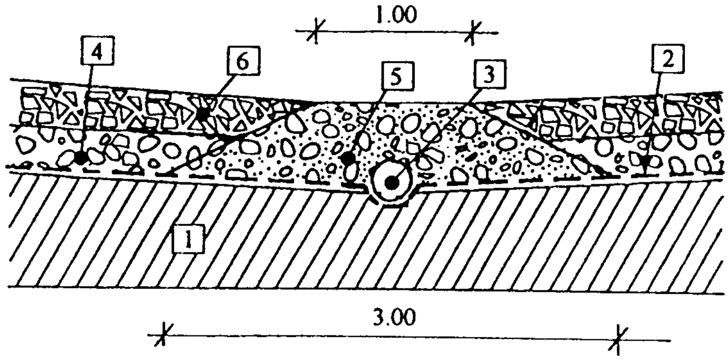

Fig. 9 Example of leachate collection system (modified after Ramke, 1989).

1. Compacted clay liner.
2. Geotextile.
3. Collector pipe.
4. Uniform gravel layer.
5. Gravel casing.
6. Trench of split gravel.

geocomposite) acts as a protection. For the pipe casing and the continuous drainage blanket, uniform coarse gravel (grain size 16÷32 mm and coarser), or alternatively well graded gravel with a diameter D_{15} greater than 10 mm are suggested by Ramke with regard to filter stability.

Naturally, variations to this scheme are almost infinite. For instance, Cossu (1994) proposes a smaller size diameter gravel for the continuous blanket and coarse gravel only all-around the collector pipe; he also suggests a supplementary local protection of the geomembrane, to be placed under the coarse gravel strips, formed by a geocomposite clay liner plus a sandy-loamy soil layer. Moreover, a layer of raw compost (about 0.5 m-thick) is also suggested at the base of the waste, forming a sort of protection of the drainage blanket.

Drainage-forming materials in contact with leachate present incrustation problems, particularly serious in the initial operating phase of landfilling, when highly-loaded leachate is produced Under similar conditions, coarse uniform drainage materials perform better and mantain their permeability longer than finer, well graded drainage materials and should be preferred (Ramke, 1989; Brune et al., 1994). By the way, it has to be noted that the most part of incrustations is formed by calcium carbonates, but determining the lithological composition of drainage materials is well far to be a routinary design practice. Calcareous gravel should be avoided; if siliceous gravels are not available, an alternative solution could consist in the use of crushed glass from differentiated waste recover, with undeniable advantage in environmental terms.

Many suggested modifications include a more general use of geosynthetics. The continuous gravel blanket can be substituted by a geonet (lying on the primary geomembrane), overlied by a geotextile (as a filter), in turn covered with a soil protective layer and finally with wastes. This solution is especially valid for the landfill sides, and a double layer of geonets was proposed to compensate for the reduction in transmissivity due to the partial penetration between of the geonet into the geotextile (Bonaparte et al., 1985). Other alternatives include the use of different types of prefabricated geocomposite drains, all including a geonet. The minimum required tests for geonets to be used in a leachate drainage system include chemical resistance (by immersion), index strength tests (compression), performance strength tests (creep, friction), and naturally transmissivity tests (Koerner, 1990). Design indications for dimensioning geonet-based drainage systems are also available in the literature (Cancelli and Rimoldi, 1994; Koerner, 1994).

Geotextiles are used both as separators and as filters. In the latter case, their performance with regard to leachate is a matter of contest. For instance, good performances of geotextiles as filters to particulate have been assessed by Kisskalt and Gartung (1990), but provided no biological processes acted during the tests; on the other hand, remarkable biological clogging of geotextiles has been found in laboratory tests (Cancelli et al., 1988; Cazzuffi and Cossu, 1993). According to Koerner (1990), both particulate and biological clogging have to be considered, and field simulation tests using the site specific materials should be required; the possibility of a periodic maintenance of the drainage system via backflushing should be included in the design.

Positive environmental impacts due to the use of geosynthetics in drainage systems are: as said elsewhere, reduction of the quantities of natural earth materials to be exploited in quarry and reduction of the related traffic and offense to the landscape; increase of the available volume for waste disposal in the same site. The uncertainties on the long-term performances of synthetic materials as drains (but only if compared to truly excellent earth materials) constitue the only doubtful aspect.

2.4.5. Biogas extraction system

Applications of geosynthetics in the gas extraction system are relatively less than the other structural parts of a landfill. For pipes (both vertical and horizontal), non-corrosive materials have to be selected; the alternative is between HDPE and carbon steel, though other materials are still used (Stegmann, 1989b).

The horizontal (perforated) pipes within the waste body are generally embedded into a gravel-filled ditch (grain size 32÷64 mm); the ditches have to be realized just under the daily intermediate cover, therefore the use of a geotextile as a separator is highly recommended (Motzo, 1994). As a possible alternative, the use of HDPE geonets all-around the perforated pipes should be taken in due consideration for performing drainage function.

As for vertical wells, the common practice is to realize large diameter (about 1 m or more) structures, externally lined with perforated concrete rings and filled in with gravel (Leach, 1991). The problems deriving from the presence of rigid vertical structures within a settling waste mass have been already reported in 2.2.5; therefore an alternative solution, in which most of the concrete rings are substituted by HDPE geogrid rings, more deformable than concrete ones (Fig. 10), should be preferred.

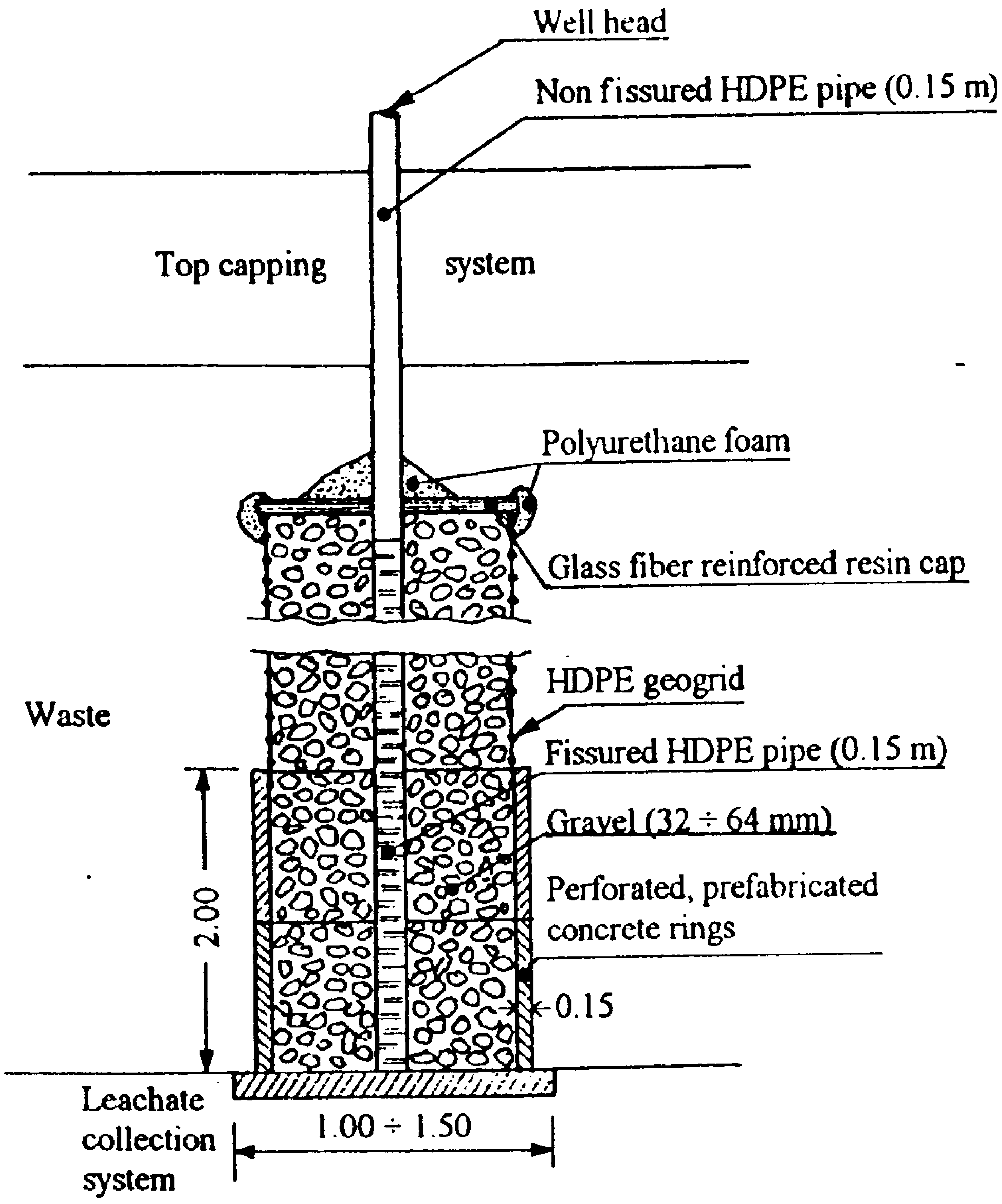

Fig. 10 Scheme of vertical well for biogas extraction, showing the use of geogrids for the well gravel containment (after Motzo, 1994).

An example of unusual, geocomposite clay liner application was the sealing of the outcoming upper portion of gas extraction wells for a MSW landfill; the geocomposite has been applied on a truncated cone of compacted clay all-around the wells extremities and in turn covered, accordingly with the general scheme of the top capping system, with a 0.3 m-thick layer of compacted clay (Fig. 11).

Although sporadic, applications of geosynthetics in gas extraction systems have the following positive environmental aspects: possibility to save gravel when geonets are applied in the horizontal system; reduction of negative skin friction on vertical wells and of the consequent overloading of the bottom liner, when geogrids are used for constructing deformable vertical wells; repair works all-around the upper portion of gas extraction wells and prevention from uncontrolled gas outcoming and from the occurrence of contaminated crops.

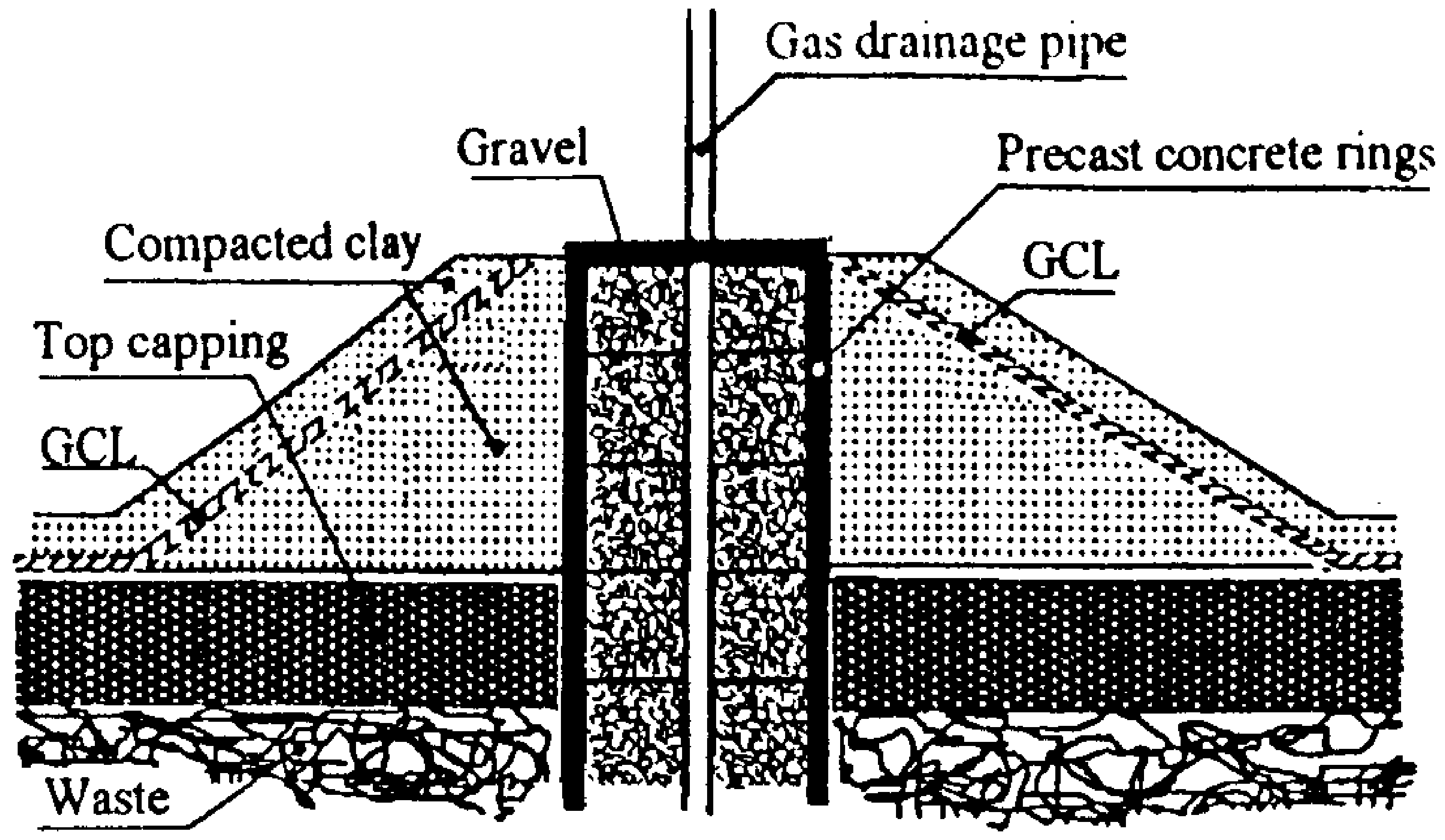

Fig. 11 Application of a geocomposite clay liner to the upper sealing of a vertical well for gas extraction (modified after Scotto, 1991).

2.4.6. Waste body

Leachate vertical drainage and biogas extraction systems, as related in the previous paragraphs, are not the only applications of geosynthetics within the landfill body. When the (external or internal) stability requirements are not satisfied, reinforcement with geogrids can become necessary for different reasons.

A first example is represented in Fig. 12, where the scheme of the solution that has been adopted to expand vertically an existing waste landfill is represented; the general problem has been already discussed in 2.2.1. Due to the extremely low beaaring capacity of the old waste body, also subject to further settlements, a "structural lining system" has been realized, according to the sequence reported in the figure. The reinforcing element was a bioriented HDPE geogrid (Chouery-Curtis and Butchko, 1991). It has to be noted that this application was effective in creating a new reinforced subgrade, preventing from a possible base failure, analogously to the example reported in 2.4.1 and sketched in Fig. 5, with the only difference of the presence of unstable waste instead of natural soft soil.

A second example is also shown in Fig. 13. The left part of the section represents the geogrid reinforcement of the waste in adjacency to the landfill slope, by means of 4-m long monoriented HDPE geogrids put in place in layers at height difference of 0.6 m (Rimoldi and Togni, 1991). This application allowed to increase the outer slope of the waste body, preventing from any slope failure. The soil surface was completed with the application of geocells for erosion control.

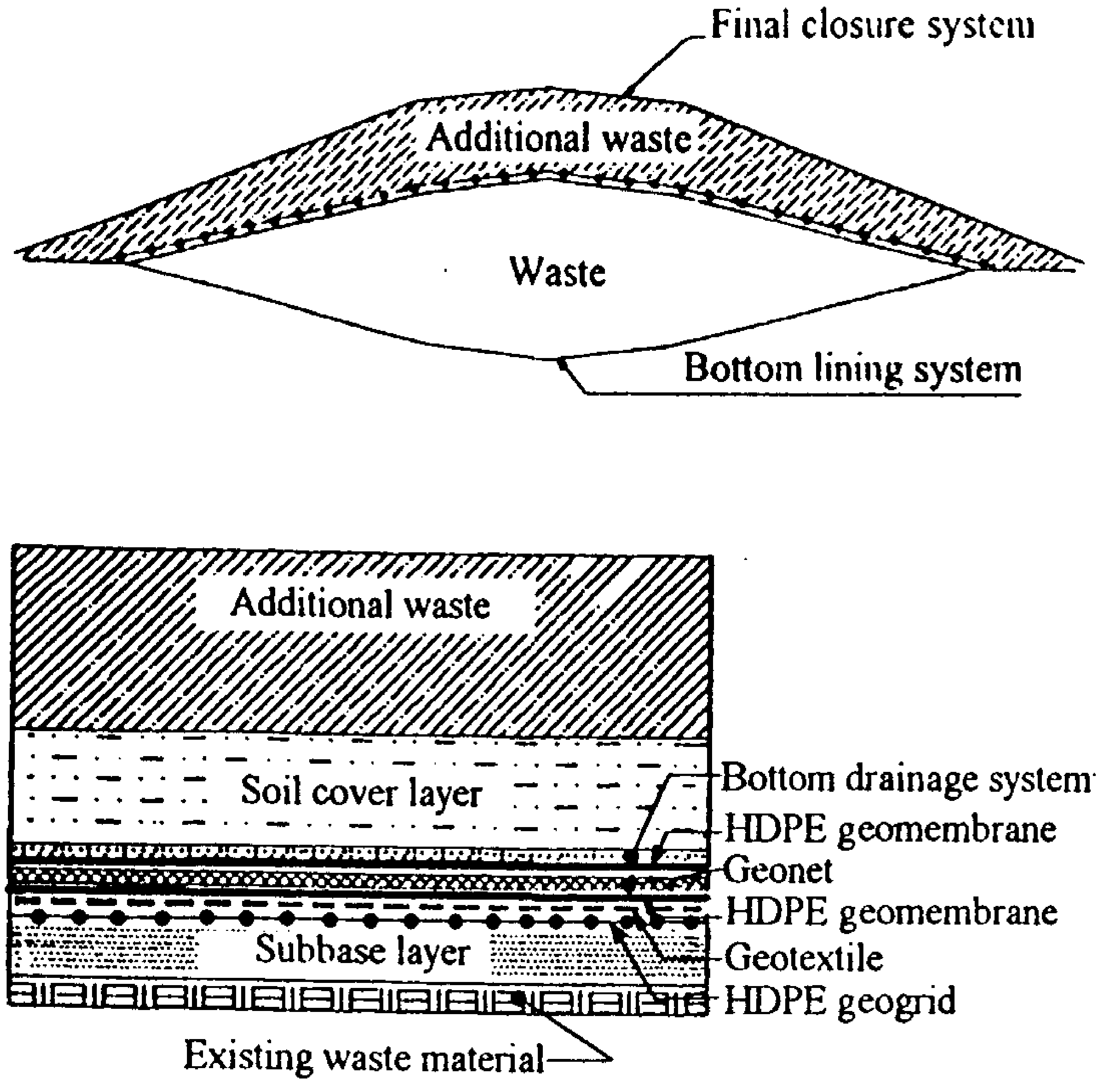

Fig. 12 Vertical expansion of a landfill and schematic section of the new geogrid-reinforced bottom liner and subbase (modified after Chouery-Curtis and Butchko, 1991).

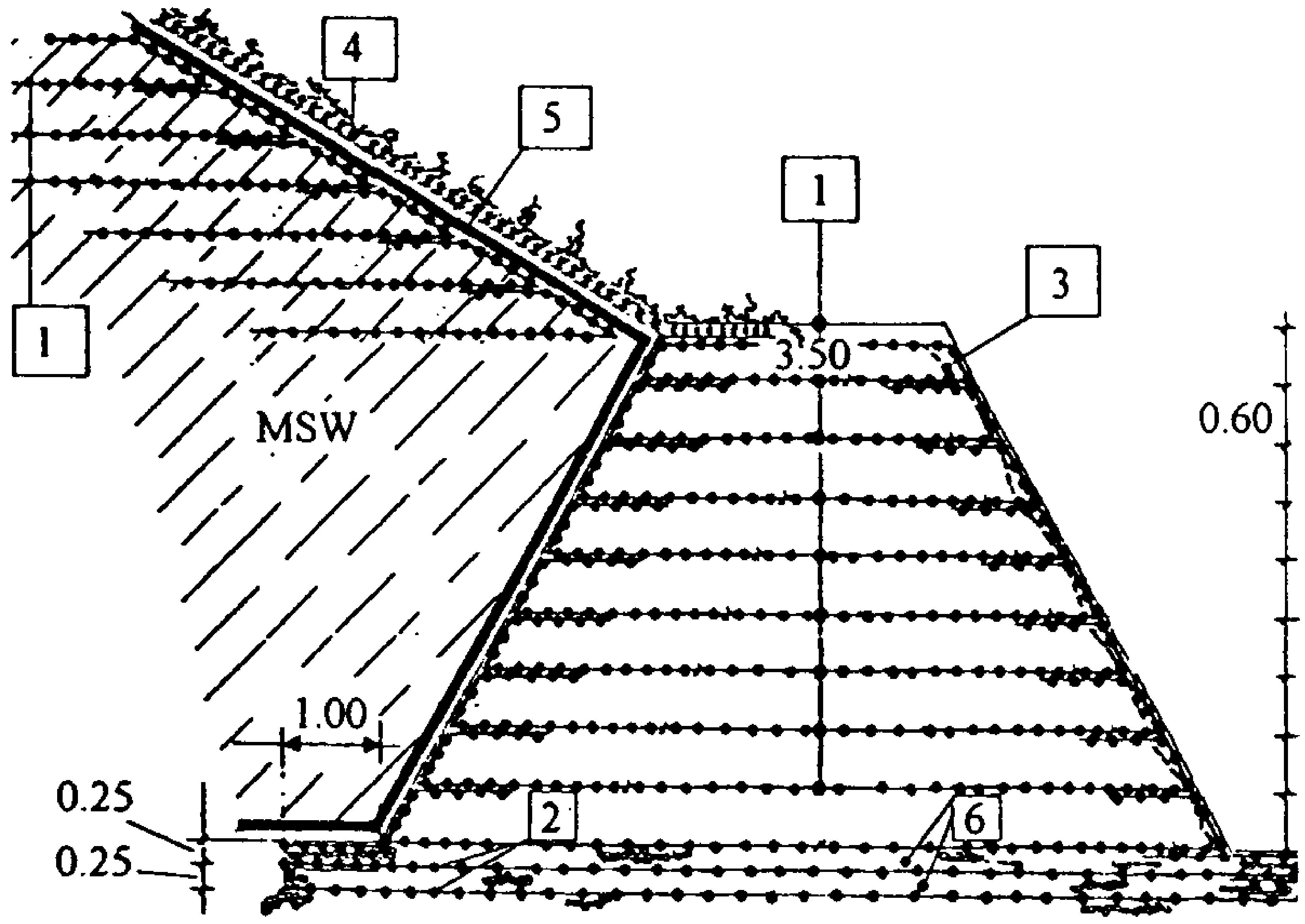

Fig. 13 Example of realization of geogrid-reinforced waste slope and soil embankment (modified after Rimoldi and Togni, 1991).
1. HDPE monoriented geogrids.
2. HDPE bioriented geogrids.
3. Biomat.
4. Geocells.
5. HDPE geomembrane.
6. Sand and gravel.

Design criteria to create reinforced earth and reinforced waste structures descend from the same basic principles, apart the obvious differences in strength and deformability parameters; reference can be made to Jewell (1990), for design methods and soil parameters, and to Jessberger and Kockel (1993) for waste parameters.

The two examples lead to the same kind of highly positive environmental impact: both applications favoured the increase of the total volume available for waste landfilling in the same site, without any negative consequence on the landfill stability and without requiring occupation of new land to be landfilled.

2.4.7. Reinforced soil embankments

Reinforced soil embankments at the foot of a waste body are becoming a relatively common solution to increase the disposal capability of a waste landfill. An example can be seen in the right portion of the same previously commented Fig. 13. The embankment, 5.4 m-high, has been realized in 9 layers; a monoriented HDPE geogrid was used for the overground part of the structure, while the foundation was realized in two layers, each 0.25 m-high, reinforced with bioriented geogrid. The work has been completed by revetting the outer slope with a biodegradable natural mat, to favour the growth of vegetative cover (Rimoldi and Togni, 1991).

Well assessed general design criteria and methods are reported in the literature by Jewell (1990) and Koerner (1994).

An unusual application of reinforcing soil embankments is described by Wilson and Thomas (1991): the scope was to protect particularly important geological exposures in the cut slopes of a quarry to be landfilled. The reduction of the site volume capability was adequately compensated by the conservation of an unvaluable public good.

2.4.8. Top capping

The section of a typical landfill top capping is shown in Fig. 14. As such a system should perform a barrier function in both directions, the properly said liner (a single geomembrane/clay composite liner, 0.6 m-thick, including a minimum 5 mm-thick geomembrane) is limited by two drainage blankets (each 0.3 m-thick as a minimum): the lower one as a vent layer for the biogas produced by wastes and the upper one as a drainage layer for rainfall water infiltration. The system is completed by the cover soils, which can vary in composition and thickness from one country to another, essentially depending on the climatic regime and on the national regulations; anyway, due to the stability requirements of the top cover a minimum thickness of 0.75 m is recommended.

Design constraints include the external stability of the waste body, the stability of the cover system itself (interface friction between the different layers should be properly evaluated, as for side barriers), the erosion of cover soils and, of course, the hydraulic behaviour of the lining materials. Experimental data on gas permeability are relatively rare in comparison with the extended literature concerning water or leachate permeability of both natural and synthetic liners; results of detailed investigations on field and laboratory, gas permeability tests on a compacted clay liner are given by Figueroa and Stegmann (1991). As for as synthetic liners are concerned, according to Koerner (1990), the minimum required tests for geomembranes to be put in place above wastes should include index strength tests (tensile, puncture, tear, impact), performance strength tests (wide width friction, anchorage, axisymmetric strength), seam strength tests (shear, peel) and specific hydraulic tests (water vapor, methane vapor). Design criteria for top capping systems including a geomembrane are given by Koerner (1994).

Anyway, in terms of required performances as barrier, gas permeability represents the critical design constraint of a top capping; to this aim the presence of a geosynthetic liner within the system is recommended.

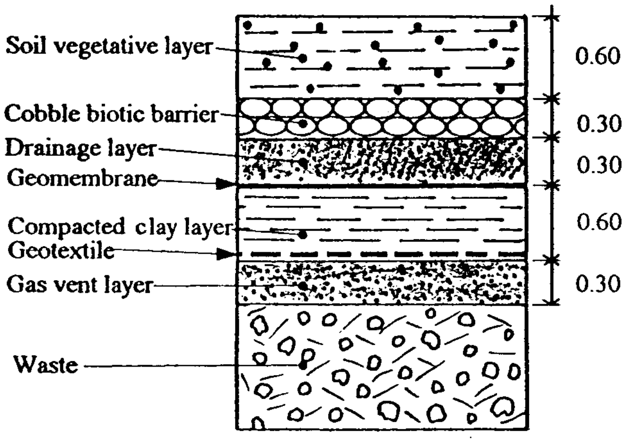

Fig. 14 Typical cross-section of the top capping system (modified after Wallace, 1993).

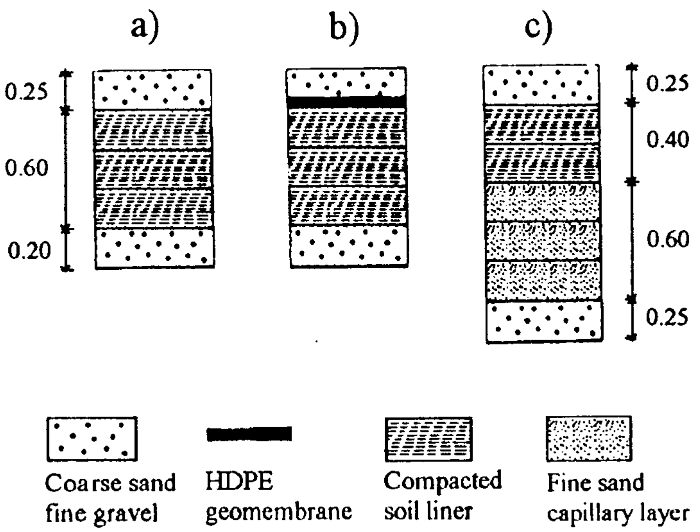

Fig. 15 Schematics of three different types of top capping systems: a) compacted solid liner; b) composite liner; c) extended capillary barrier (modified after Melchior et al., 1993).

Melchior et al. (1993) report the results of field comparison tests (water balance and long-term performance) conducted on three different top capping systems: respectively, a compacted soil layer, a composite liner with geomembrane, and an extended capillary barrier (Fig. 15). The compacted soil liners lost their efficiency due to desiccation and shrinkage, while both the composite liner and the extended capillary barrier performed very well. However, if the environmental impact of such alternatives is analyzed:

- composite liners including a geomembrane generally require a lower thickness than extended capillary barriers, and for this reason they allow to save volume for waste disposal; moreover, as already said for other landfill structures, the use of geomembranes allows for saving natural earth material (fine sand in this case);
- on the other hand, capillary barrier systems do not have the negative impacts connected to the introduction of non-natural material (permanent presence of an imputrescible barrier at low depth and possible release of toxic substances in case of accidental fire).

Saarela (1993) presents an interesting comparison between six different schemes of top cover systems. Although based only on Finnish technical experience and economic situation, the costs of a multilayer system including a geomembrane are lower (by 20% to about 80 % less) than the costs of similar multilayer barriers, having the same functions and requisites but including only natural earth materials.

A comparison between compacted clay liners and geocomposite clay liners, based on the analysis of 25 equivalency items (in turn deriving from design, construction and performance issues), demonstrates the many advantages of the use of GCL instead of natural clay barriers (Trauger and Stam, 1993).

In terms of positive environmental impact, the substitution of natural earth materials with a complex multilayer geosynthetic system (including a combination of geomembrane, geonets and geotextiles with different functions) can induce beneficial extra-storage for waste landfilling (see, for example, Fig. 16).

2.4.9. Final reclaimed top surface

Up to now, the final reclamation of the top surface has been paid relatively less attention by researchers and designers than the other structural and functional parts of a waste landfill. In most descriptions and regulations, the top surface is incorporated into the general top capping multilayer system, although performing well definite and separate functions, as it can be seen in Fig. 16.

As in the large majority of cases the land-uses of the final reclaimed top surface require the presence of vegetative soil, the main problems are the surficial stability with regards to slope failures and to wind or water erosion processes. To this aim, important results can be obtained by an appropriate use of the many geosynthetics and/or bioproducts (see Tables 1 and 2).

Results of large-scale laboratory tests on the performances of different products (both geosynthetics and bioproducts) when subject to artificial rainfall and/or runoff are reported by Cancelli et al. (1990). General design criteria for preformed erosion control systems have been proposed by Ingold and Thomson (1990). The selection of the most effective product should depend on rainfall and runoff parameters, infiltration characteristics of soils, slope length and inclination, foreseable land use.

Many different applications are reported in the literature and only a few examples are illustrated here. The surface protection of steep slopes by high shear resistance geocomposites, including a PA geomat and a PET woven geotextile, also allowing to increase the storage capacity, has been suggested by Hoekstra and Berkhout (1991). For soft armor erosion protections, a turf biomat with geosynthetic reinforcement can be applied to a rapid vegetation growth also on the steepest slopes of a landfill (Carroll and Theisen, 1990). The original applications of woven geotextiles in form of wattling for runoff control on steep slopes in the French Alps (Faure et al., 1993) could be efficacely applied also to the long steep slope of a completed waste landfill. The same kind of application, but with the alternative use of biotextiles (like jute products), is widely used in many countries, especially in South East Asia (Ranganathan, 1994).

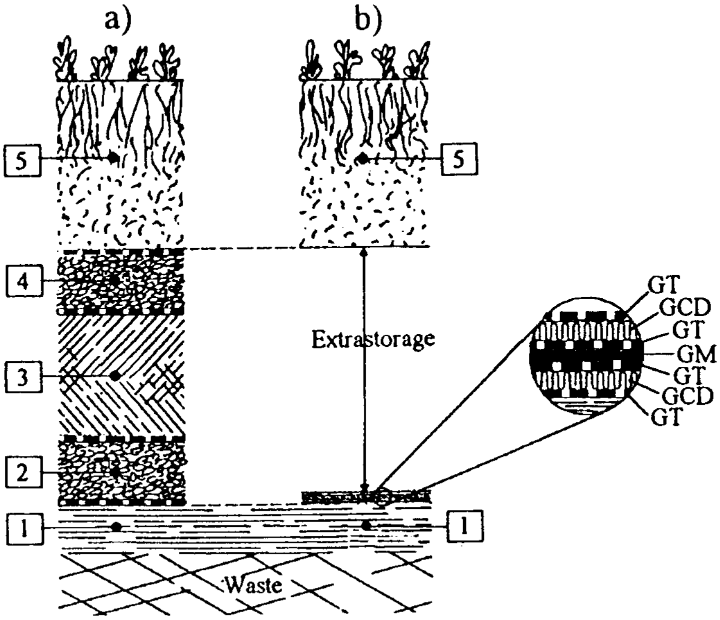

Fig. 16 Comparison between two top capping systems: extra-storage for waste allowed by the use of geosynthetics instead of natural earth materials (modified after Hoekstra and Berkhout, 1990).

1. Supporting layer over the waste (0.30 ÷ 1.00 m).
2. Gas vent gravel (0.30 m).
3. Compacted clay layer (0.30 ÷ 0.60 m).
4. Gravel drainage layer (0.30 m).
5. Cover soil (0.60 ÷ 1.50 m).

Coming to the environmental implications, from the many experiences it appears evident that all products for erosion control (both geosynthetic and bioproducts) have positive effect on the more or less rapid growth of the vegetative cover on slopes, therefore drastically reducing detachment of soil particles due to rainfall drop or to surface runoff.

Further considerations regard the crucial selection between biodegradable natural products (which cannot survive for more than two years) and synthetic products (practically eternal). The presence of the latter, at the ground surface or at low depth, could become undesired in a future and has to be intended as a possible, long-term negative impact.

3. DAMS

3.1 Dams as an environmental problem

Among the various types of large man-made structures (with containment function), dams have surely the most important impact on the environment, due not only to the size of the structure itself, but also to the creation of water storage reservoirs, often of very large size.

In the past, the main concerns in dams design and construction were safety issues, while recent public awareness has leaned towards greatest attention also to ecological problems and, more generally, to any aspect of a dam scheme which may appear as a threat to the environment. Since 1985, the International Commission on Large Dams stated that "it must be possible to take advantage of natural resources without destroying nature" (ICOLD, 1985); this concern has to pervade all the phases of the dam life, i.e. both before and during the implementation of works (planning and construction phases -"flirt, love and conception" and "prenatal life and birth", if the same life cycle of landfills is adopted) and also during the entire operation of the structure (operation phase - "active life"). Actually, the completed phase ("death and 'post mortem' state") and the final storage phase (" burial state") typical of landfills are not specific of dams, but on the contrary these two phases have sometimes represented the negative impacts induced by dams on the surrounding environment: variuos past experiences have shown, in fact, that neglecting environmental aspects linked to the planning and construction of large dams, for example in tropical forests, can easily lead to ecological disasters.

However, modern engineering science and technique could provide the capability to plan, design, build and operate dams with safety and, in the same time, with minimum unexpected or unacceptable environmental impacts.

From a global point of view, the general question is to clearly assess the balance between impacts on the environment and the benefits expected from a dam: the answer to this question has to consider the physical needs and the economic situation of the concerned country. For example, nation starving for energy with
answer to this question has to consider the physical needs and the economic situation of the concerned country. For example, nation starving for energy with
water power as the only available or practicable source, is certainly more inclined to modify the environment of an endangered species than another which has the choice between several viable power alternatives.

3.2 Geosynthetics used in dams and performed functions

In the past 35 years, a wide variety of geosynthetics have been used, with different functions, in virtually all types of dams, both for new construction and rehabilitation purposes (see Table 6).

Table 6. Main functions and typical geosynthetic or biodegradable natural products, in relation to the type of dam and the type of work.

Main function	Typical products	Dams		
		E+R	C+M	RCC
B	GM,GCM	NC,RB	RB	NC
D	GT,GN,GCD	NC,RB	RB	NC
P	GT,GN	NC,RB	RB	NC
F	GT	NC,RB	-	-
R	GT,GG,GCR	NC,RB	-	-
E	GT,GA,GL,BT,BA,BL	NC,RB	-	-

Legend: E+R: earthfill or rockfill
C+M: concrete or masonry
RCC: roller compacted concrete
NC: new construction
RB: rehabilitation
For geosynthetics and bioproducts see Table 1
For functions see Table 2

The next paragraphs are dedicated to a review of geosynthetic applications in dams, according to the performed functions, i.e. barrier (to fluid), drainage, protection (of geomembranes), filtration, reinforcement and surficial erosion control; in the frame of each function, the review will consider the different types of dams in which geosynthetics have been used, i.e. embankment dams (both earth and rockfill), concrete and masonry dams, and roller compacted concrete dams, respectively.

3.2.1 Barrier (to fluid)

Embankment dams

A geomembrane was first used as the waterproofing element of a dam in 1959 at Contrada Sabetta dam in Italy (Cazzuffi, 1987). This rockfill dam, 32.5 m high, has performed successfully to date: two sheets of a polyisobutylene geomembrane (2 mm thick), protected with concrete slabs, were installed on the 1V:1H upstream face of the dam during initial construction (Fig. 17). Since then, a number of embankment dams have been realised with geomembrane waterproofing (ICOLD, 1991): in the most of cases, geomembranes are externally protected from atmospheric agents by the superposition of a cover layer, like concrete slabs, precast concrete elements, geosynthetic-reinforced gunite, and so on.

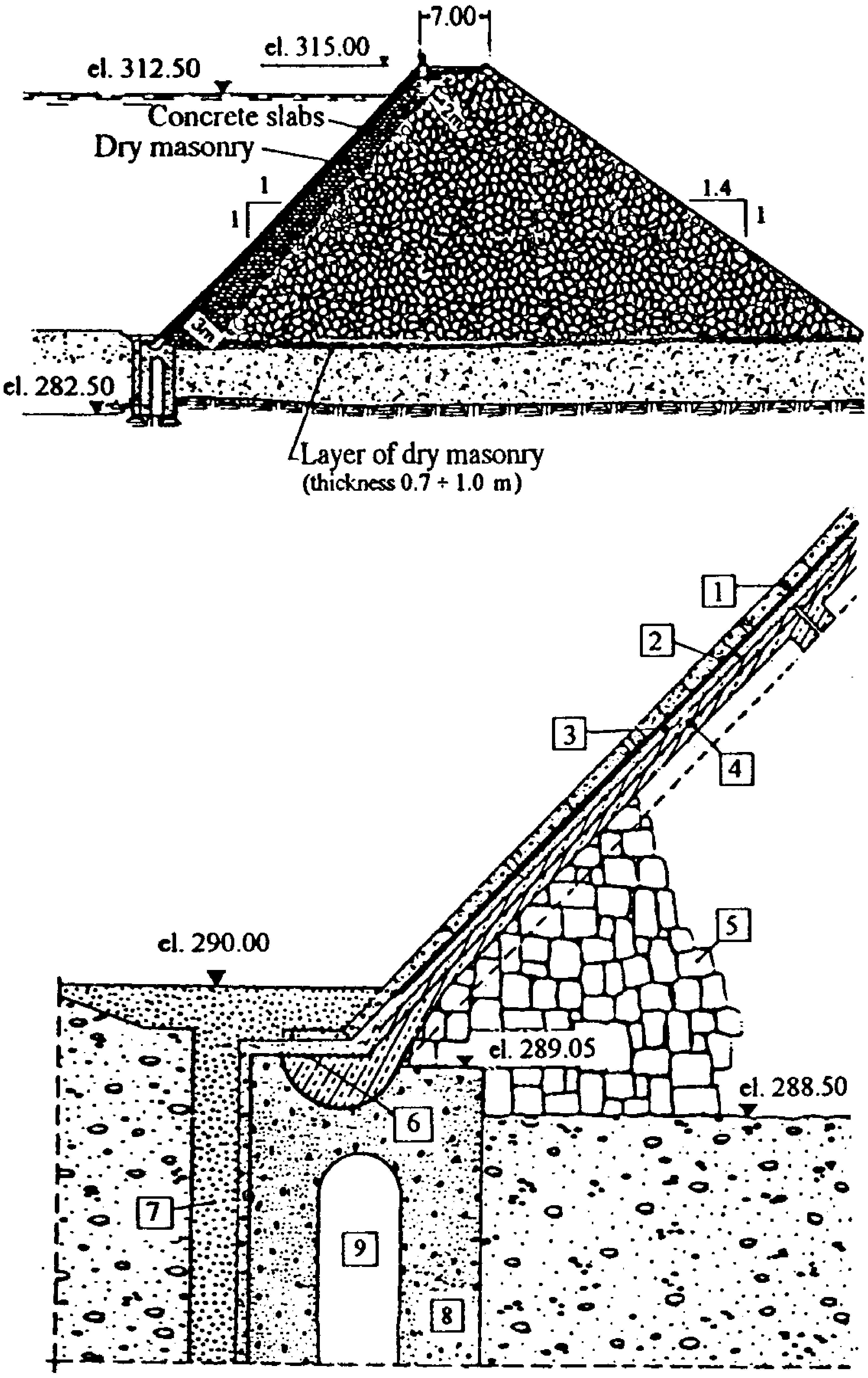

Fig. 17 Contrada Sabetta rockfill dam in Italy, 32.5 m high (modified after Cazzuffi, 1987 and ICOLD, 1991).

1. Concrete slab (0.20 m thick).
2. One sheet of bituminous paper-felt + two sheets of polyisobutylene geomembrane (2.0 mm thick) + bituminous adhesive.
3. Porous cement concrete (0.10 m thick).
4. Reinforced concrete slabs (0.25 m thick).
5. Dry masonry (thickness ranging from 2.00 to 3.00 m).
6. Joint betweeen plinth and upstream facing.
7. Plastic concrete diaphragm wall.
8. Concrete plinth.
9. Inspection and drainage gallery.

Geomembranes have also been used to rehabilitate embankment dams, particularly in order to minimize seepage through the upstream face: different cases of geomembrane applications to repair both bituminous concrete upstream facings and concrete-faced rockfill dams have been reported (Giroud and Bonaparte, 1993).

Finally, a number of cofferdams have been waterproofed with geomembranes: for example Bilancino dam, under construction in Italy, consists of a zoned embankment, 42 m high, including a cofferdam, 15 m high (Fig. 18). The cofferdam upstream face has been waterproofed using a PVC geomembrane (t_{GM} = 1.2 mm), with a PP nonwoven geotextile (μ = 350 g/m²) as mechanical protection towards the eventual damage due to puncturing of the underneath rockfill (Baldovin, 1993).

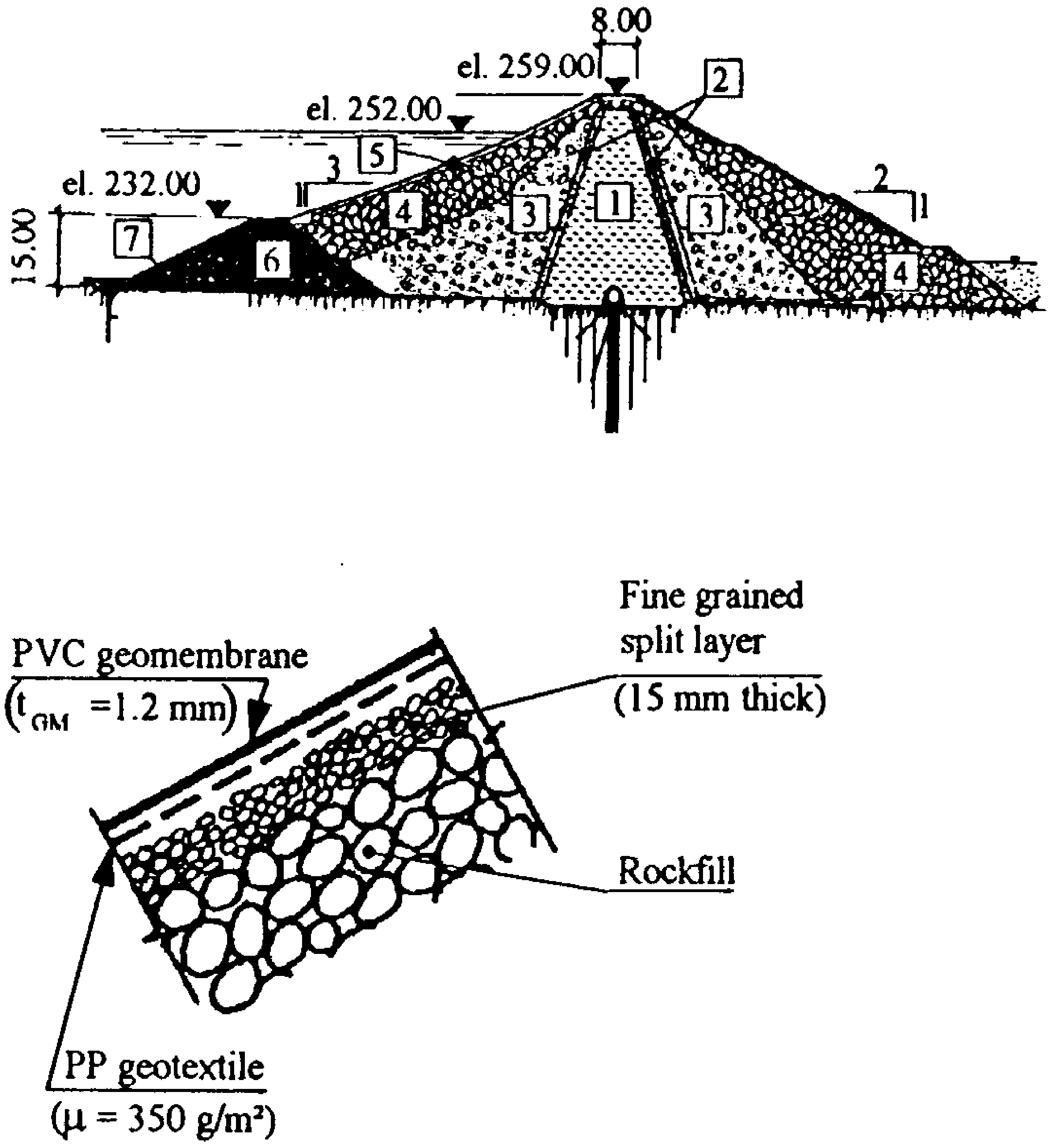

Fig. 18 Bilancino zoned embankment dam in Italy, 42 m high (modified after Baldovin, 1993).

1. Clayey silt core.
2. Filters.
3. Transitions.
4. Rockfill.
5. Rip-rap.
6. Cofferdam (with upstram face 1V:2H and downstream face 1V:1.5H).
7. PVC geomembrane (t_{GM} = 1.2 mm) and PP geotextile (μ=350 g/m²).

Concrete and masonry dams

In the last 25 years, geomembranes were used to rehabilitate approximately 40 large concrete and masonry dams, in order to reduce leakage phenomena that typically appear on these structures after 30 ÷ 40 years of operation, depending on the accuracy of construction and on conditions of the damsite.

The first dam in which a geomembrane was used for waterproofing rehabilitation was Lago Baitone masonry dam in Italy, 37 m high, constructed from 1927 to 1930 and rehabilitated from 1969 to 1971 using a polyisobutylene geomembrane, 2.0 mm thick (Cazzuffi, 1987).

The most popular rehabilitation technique, developed in Italy and used up to now in about 25 applications around the world, consists of fastening a PVC geomembrane to metallic ribs anchored in the upstream face: usually the PVC geomembrane is thermocoupled in factory to a PET nonwoven geotextile (thus forming a geocomposite membrane liner - GCM) and, after application, the GCM is not externally protected from atmospheric agents.

The first large dam rehabilitated with this technique was Lago Nero concrete dam in Italy (Fig. 19), 40 m high, constructed from 1924 to 1929 and rehabilitated from 1980 to 1981 (Monari, 1984): in this dam a GCM, formed by a PVC geomembrane ($t_{GM} = 2.0$ mm) thermocoupled in factory to a PET nonwoven geotextile ($\mu = 350\ \mathrm{g/m^2}$), was used. After more than ten years since application, the general behaviour of the GCM is satisfactory: regular inspections have ensured that no yielding of the GCM nor any other detectable alteration has taken place (Cazzuffi et al., 1993).

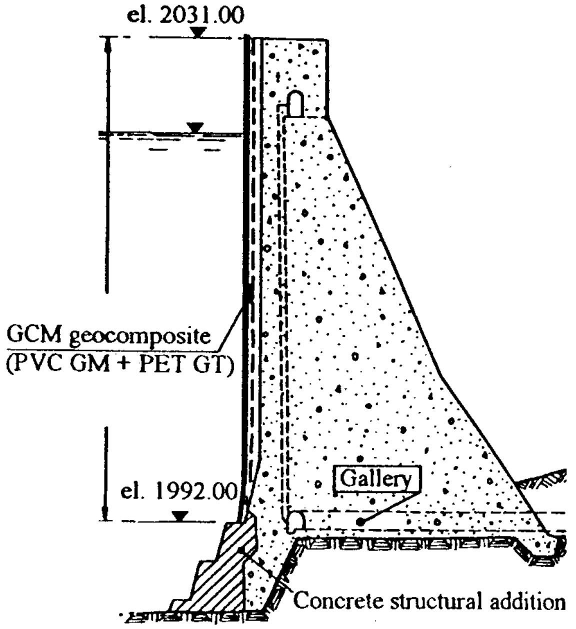

Fig. 19 Lago Nero concrete dam in Italy, 40 m high (modified after Cazzuffi, 1987).

A recent case of new rehabilitation technology has also to be reported, in which a multilayered PVC geomembrane ($t_{GM} = 2.5$ mm) thermocoupled in factory to a PET nonwoven geotextile ($\mu = 400\ \mathrm{g/m^2}$) was glued with special adhesives to the upstream face of Zolezzi dam, in Italy, 22 m high, constructed in 1923 and rehabilitated in 1992 (Cazzuffi and Sembenelli, 1994).

Roller compacted concrete (RCC) dams

While it would be of course unnecessary to add a geomembrane to waterproof a new concrete dam built by conventional methods, the emerging roller compacted concrete (RCC) technology has favourite to make use of geomembranes for new constructions (ICOLD, 1991).

In fact, using this technology, where the main mass of RCC is insufficiently impervious, extra cement is usually added to the mix towards the upstream face of the dam or, in alternative, conventional or prefabricated concrete is used in this area: to reach the same result, geomembranes were also adopted, both protected and exposed. Among the first applications of exposed geomembranes on RCC dam upstream facings, are Riou dam in France, 22 m high, and Concepcion dam in Honduras, 70 m high, both completed in 1990.

In particular, at Concepcion dam (Fig. 20) a geocomposite membrane liner (GCM) formed by a PVC geomembrane ($t_{GM} = 2.5$ mm) thermocoupled in factory to a PET geotextile, was placed by mechanical fastening over the upstream face, using essentially the same technology commonly adopted in Italy for rehabilitation of concrete and masonry dams. The GCM was manufactured and shipped in rolls 2 m wide and was pre-assembled on the ground into sheets 4 m wide, which were positioned using a platform supported by a small portal crane moving over the crest of the dam (Giovagnoli et al., 1991).

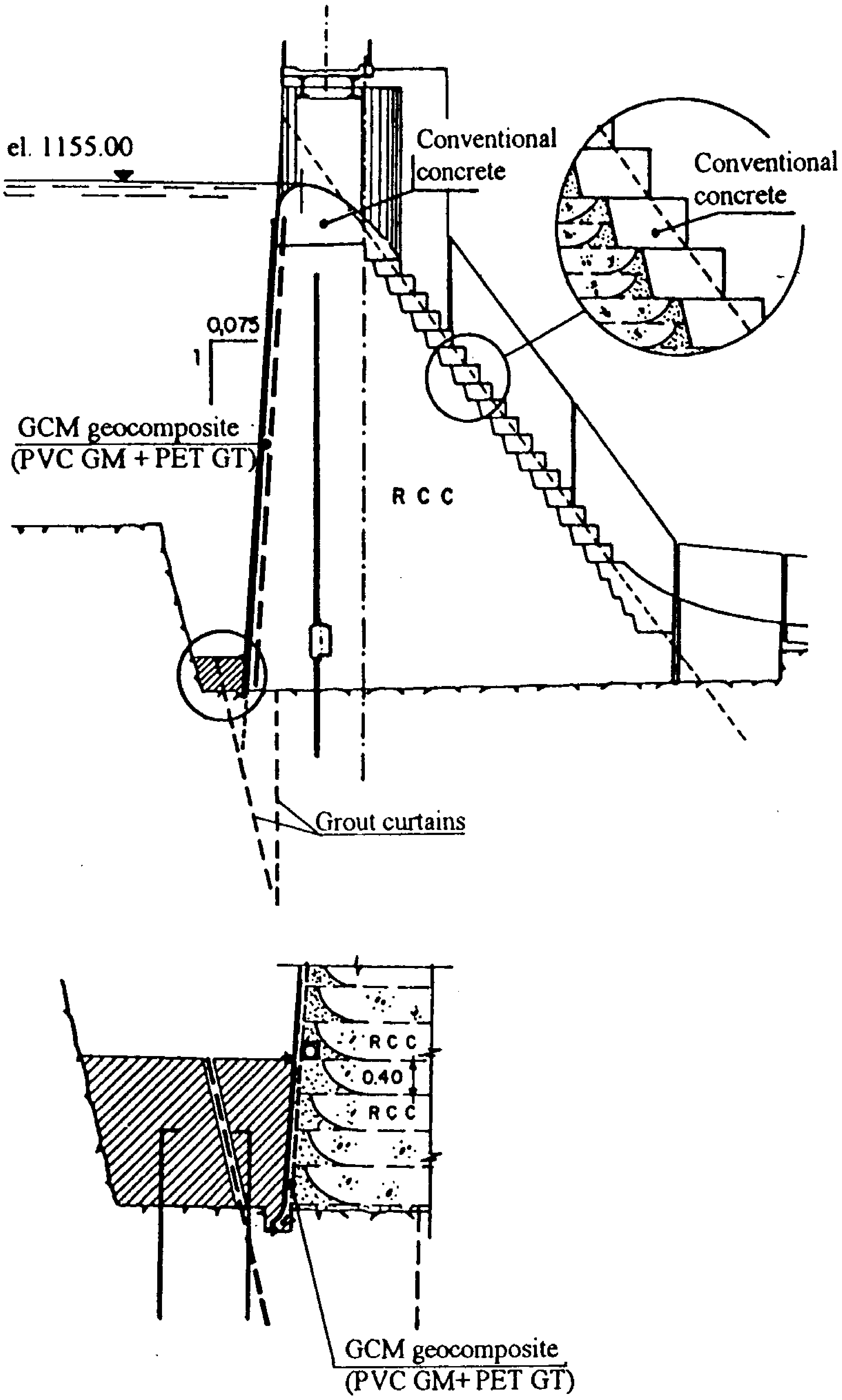

Fig. 20 Concepcion RCC dam in Honduras, 70 m high (modified after Giovagnoli et al., 1991).

3.2.2 Drainage

Embankment dams

For new constructions, the first application of a geosynthetic as chimney drain was at Brugnens earth dam, in France, 11 m high, constructed in 1973: the drainage geosynthetic used in that dam was a thick PET needle-punched nonwoven geotextile (Giroud, 1992).

Other more recent French applications of drainage geosynthetics have been reported by Navassartian et al. (1993); since 1987, a geocomposite shaft drain (including a PP nonwoven geotextile draining core between two PP nonwovens geotextile filters) has been used instead of granular drain for the construction of a number of homogeneous earthfill dams about 10 m high: the geocomposite drains have been set down gradually with the alternative earth layers (Fig. 21).

The chimney drain concept could be used also for rehabilitation purposes: in the case of embankment dams that exhibit seepage through their downstream slope, the construction of a drainage system in the downstream zone is required. A solution consists of using a geocomposite drain (GCD) placed on the entire downstream slope or only on the lower portion of it and covered with backfill: the GCD must be connected with the new toe of the dam with outlet pipes or with a drainage blanket. This technique has been used, for example, at Reeves Lake dam in United States, 13 m high, which was repaired in 1990 by placing a GCD (including a PE geonet core between two PP thermobonded nonwoven geotextile filters) on the downstream slope relatively steep, of the order of 1V:2H (Wilson, 1992).

Concrete and masonry dams - RCC dams

In the most of the cases of concrete and masonry dams upstream facings rehabilitation and also of RCC dams construction, a thick nonwoven geotextile has been used between the geomembrane and the dam, to perform the double function of drainage and of mechanical protection of the geomembrane itself. Usually, the geotextile is thermocoupled in factory to the geomembrane, thus forming a geocomposite membrane liner (GCM), and, in some rehabilitation cases, where important quantity of water is expected to be drained from the body of the dam,

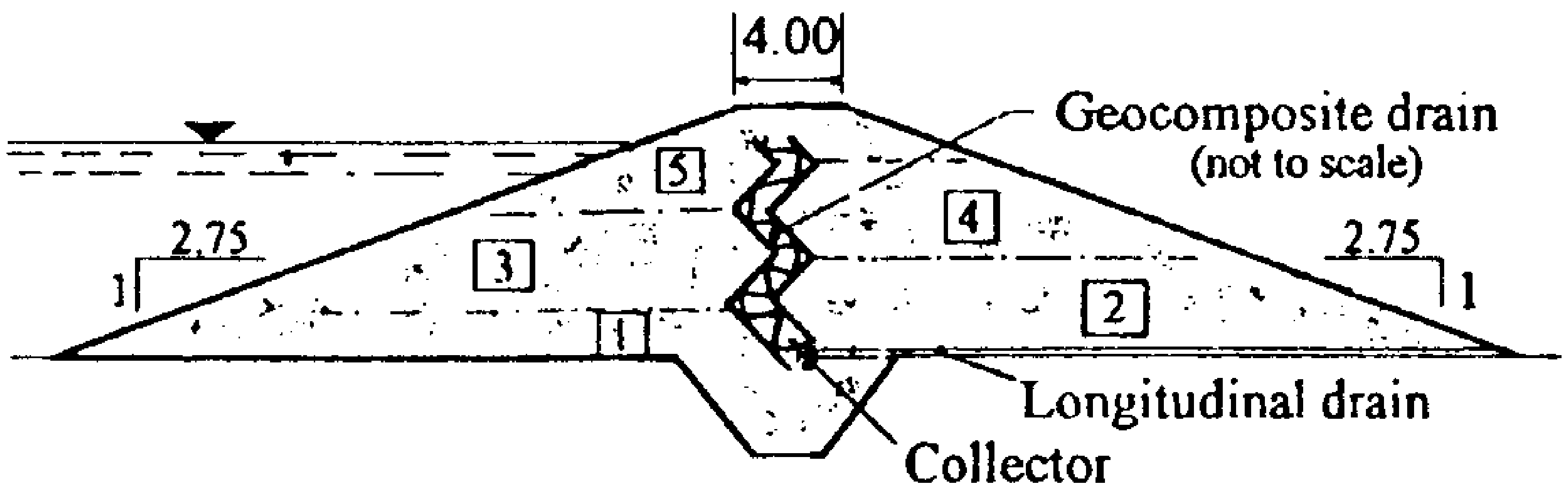

Fig. 21 La Parade homogeneous earthfill dam in France, 10 m high (modified after Navassartian et al., 1993).

1. First compacted layer.
2. Second compacted layer.
3. Third compacted layer.
4. Fourth compacted layer.
5. Fifth compacted layer.

an extra geosynthetic (like a geotextile or a geonet) is added between the geocomposite membrane liner and the dam itself. As far as construction details are concerned, it is important that the geosynthetic is connected to a related collector pipe at the toe of the dam. Particularly, in the case of rehabilitation of concrete dams, the concrete of the dam body, which has been saturated with water over the years, is allowed to drain, because of the presence of the drainage geosynthetic itself, thus contributing to slow down the mechanism of concrete deterioration, due also to the presence of water. A lot of concrete dams have in fact recently suffered the effects of AAR (Alkali Aggregate Reaction), which is influenced remarkably by the presence of water: some of these dams have been rehabilitated using the GCM technique.

3.2.3 Protection (of geomembranes)

Embankment dams

In many embankment dams where a geomembrane was used as barrier (to fluid), a thick geotextile was placed on one or, more often, on both sides of the geomembrane itself, to protect it from potential damage by adjacent materials, typically the granular layer underneath and the external cover layer. For example, at Codole dam in France, 28 m high, constructed in 1983 (Fig. 22) and also at Jibiya dam in Nigeria, 23.5 m high, constructed in 1987 (Sembenelli, 1990), two thick geotextiles were placed on both sides of the PVC geomembrane: in both dams, the lower geotextile was factory-bonded to the geomembrane, while the upper geotextile, independently placed, was positioned between the geomembrane and the external protection, made by cast-in-place concrete slabs.

The same technique could be exactly applied also for rehabilitation purposes. For example, at Goronyo secondary dam in Nigeria, 13 m high, constructed in 1982 and rehabilitated in 1987 with a geocomposite membrane liner (GCM) application, two different layers of geotextile were laid, both having a protection function: the lower geotextile, bonded in factory to the geomembrane, was glued to the original bituminous concrete facing, while the upper geotextile was independently placed between the PVC geomembrane and the cast-on-place concrete cover layer (Sembenelli, 1994).

Concrete and masonry dams

As already mentioned, thick nonwoven geotextiles, eventually associated with geonets, have been used not only for drainage function, but also for mechanical protection of geomembranes, in the frame of the techniques adopted for rehabilitation of concrete and masonry dam upstream facings.

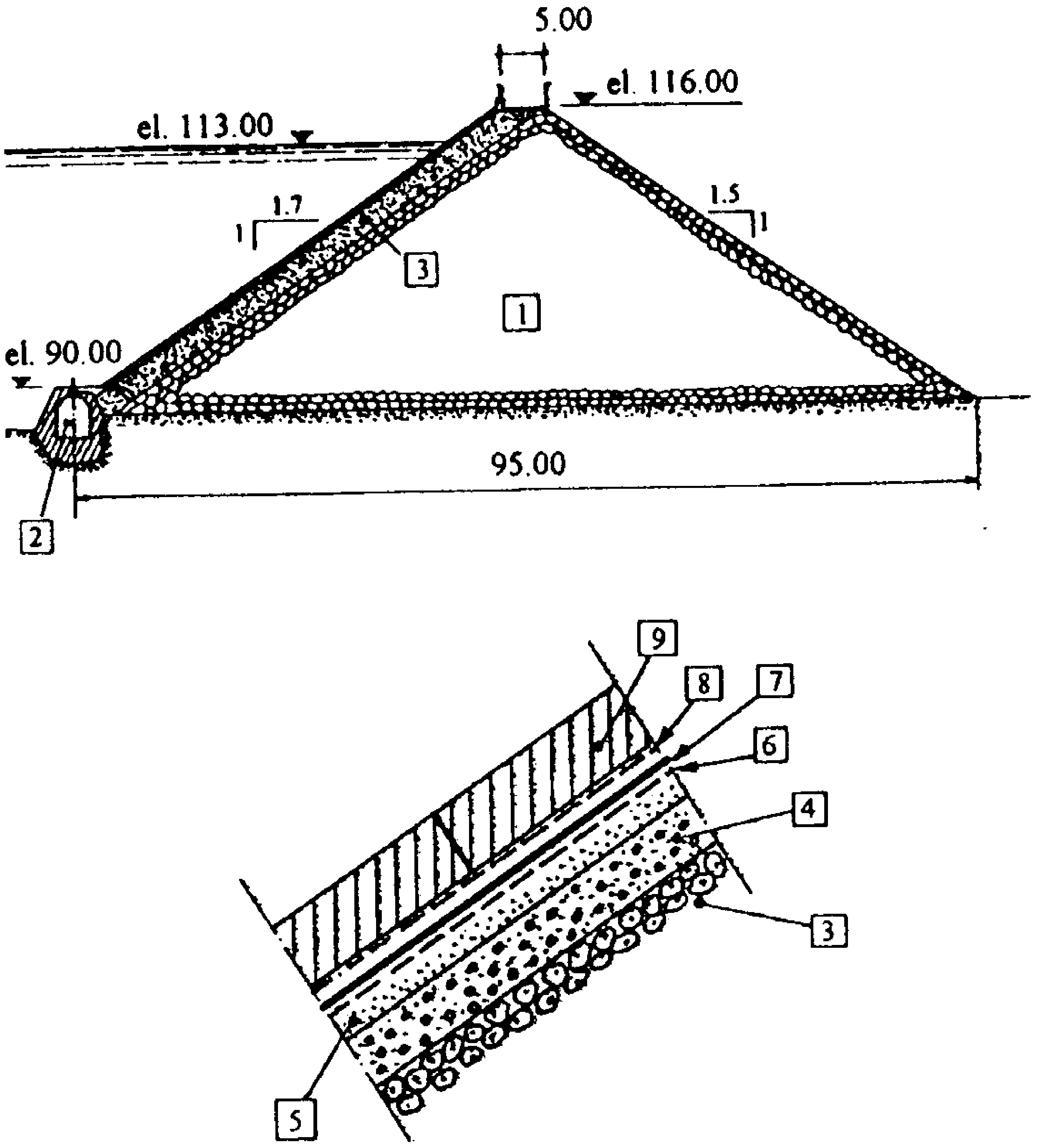

Fig. 22 Codole rockfill dam in France, 22 m high (modified after ICOLD, 1991).

1. Rockfill (up to 1.00 m size).
2. Inspection and drainage gallery.
3. Sand and gravel layer (2.00 m thick, 25÷120 mm grain size).
4. Gravel layer (0.15 thick, 25÷50 mm grain size).
5. Cold premix layer (50 mm thick, 6÷12 mm grain size).
6. Geotextile ($\mu = 400$ g/m^2) bonded to geomembrane.
7. PVC geomembrane ($t_{GM} = 2.0$ mm).
8. Geotextile ($\mu = 400$ g/m^2).
9. Concrete slabs (0.14 m thick, 4.5 x 5.0 m^2 size).

To this respect, the first case reported for a geotextile as protection of geomembrane was Lago Nero dam in Italy, where a GCM was applied (see Fig. 19 and paragraph 3.2.2): in some zones particularly deteriorated of the concrete upstream face, it was decided to add an additional geotextile layer as an extra protection between the GCM and the dam.

The first case reported for the application of an additional geonet performing the same function was Publino dam in Italy, 42 m high, constructed in 1951 and rehabilitated in 1989 (Zuccoli et al., 1989): for this work, a HDPE geonet was used as protection of the GCM, formed by a PVC geomembrane (t_{GM} = 2.5 mm) and a PET geotextile (μ = 500 g/m²).

Roller compacted concrete (RCC) dams

In RCC dams only nonwoven needle-punched geotextiles have been used to perform mechanical protection of the geomembrane, to which they are usually thermocoupled in factory. The mechanical characteristics of geotextiles adopted to perform this function are not so high as for rehabilitation of concrete dams, mainly because the application is made over a new structure and not over a deteriorated upstream face. For example, at Riou dam in France, the selected PET nonwoven geotextiles exhibited tensile strength ranging between 10.5 and 13.0 kN/m (Scuero, 1990).

3.2.4 Filtration

Embankment dams

The first application of a geotextile filter in an embankment dam was in 1970 at Valcros dam in France, 17 m high (Fig. 23): according to Giroud and Gross (1993), PET nonwoven geotextile filters were used both around the downstream gravel drain (μ = 300 g/m²) and also under the rip-rap protecting the upper portion of the upstream slope (μ = 400 g/m²). The performance of the dam and the extensive investigations on geotextile samples taken from the dam by several independent teams have clearly demonstrated the viability of geotextile filters in dams (Delmas et al., 1993).

After this pioneering application, geotextiles have been worldwide used as filters in various locations within the embankment dams, both for new construction and rehabilitation purposes (Bertacchi and Cazzuffi, 1985).

The main use has been a replacement or a supplement for granular filters: geotextiles do not act in the same way as granular filters, as the stability of interfaces between different soils under hydraulic flow involves complex mechanisms (Gourc and Faure, 1990).

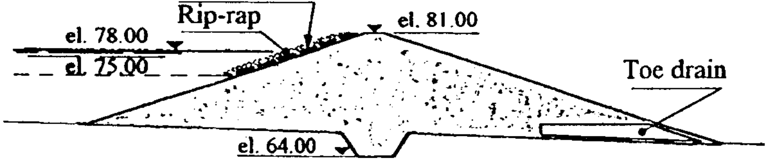

Fig. 23 Valcros earth dam in France, 17 m high (tentative reconstruction of the cross-section).

Many of the uses of geotextiles as filters have been in non-critical locations within the dams, often where examination and repair is relatively easy (ICOLD, 1986): most applications have been in fact realized below the entire upstream slope protection (like rip-rap).

More attention has to be devoted to applications in critical locations, like filters in zoned embankment dams: for this critical location, the present practice is more oriented to use geotextiles in association with granular filters, than to completely substitute earth materials. The first remarkable example of such tendency is represented by Hans Strijdom dam in South Africa, 57 m high, constructed from 1975 to 1980 (Fig. 24): for this zoned rockfill dam, problems were encountered in obtaining filter sand in sufficient quantities. Therefore, it was decided to use a PET nonwoven geotextile filter (μ = 340 g/m²) between the core material and the sand filter, thus reducing to 1 m the thickness of the sand filter itself, both on the upstream and the downstream sides of the core zone (Hollingworth and Druyts, 1982).

In any case, geotextile filters in embankment dams have to be carefully selected: several design criteria have already been proposed (see, for example, the review of design criteria by Bertacchi and Cazzuffi, 1985 and by

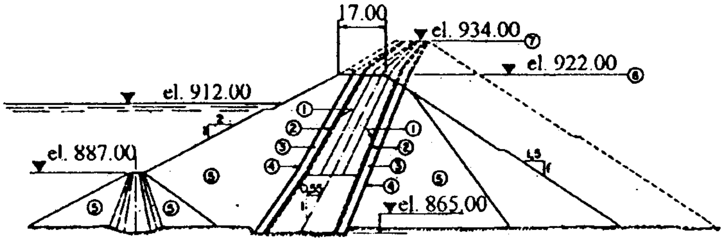

Fig. 24 Hans Strijdom zoned rockfill dam in South Africa, 57 m high at the time of the reference, to be raised up to 69 m (modified after Hollingworth and Druyts, 1982).

1. PET geotextile filter (μ = 340 g/m²).
2. Sand filter.
3. Gravel filter.
4. Selected rockfill transition.
5. Rockfill.
6. Attained crest level.
7. Final foreseen crest level.

ICOLD, 1986), but a lot of work has to be done in this field, particularly for critical locations within the dam and large hydraulic heads. Surely, more substantial coordinated efforts by manufacturers, designers and installers are needed: manufacturers should develop and propose special products for such important application (even if the market is not "booming" in this area), while dam designers have to be less conservative in relation to geotextile filters. In fact, according to Lawson (1982), it is important to remember that, unless some risks are accepted in the use of these relatively "new" materials, there can be no important progress in dam engineering technology.

3.2.5 Reinforcement

Embankment dams

For new constructions, the first dam in which geosynthetics have been used with reinforcement function was Maraval dam in France, 8 m high, constructed in 1976 (Fig. 25). The dam has a sloping upstream face lined with a bituminous geomembrane ($t_{GM} = 4.8$ mm) and a vertical downstream face obtained by constructing a multilayered geotextile-soil mass, reinforced with a high-strength PET woven geotextile ($\mu = 750$ g/m² and $T = 210$ kN/m). Due to the vertical downstream face, the spillway is short and therefore not particularly expensive, which is beneficial for such small dams, where spillways usually represent a large fraction of the total construction cost. It is also interesting to note that the dam was overtopped three times during construction with virtually no damage (Kern, 1977).

Perhaps also due to the negative impact on the landscape (the geotextile remains exposed on the vertical downstream face), the geosynthetic-reinforced soil mass technique has not developed remarkably for construction of small dams. This consideration does not exclude further developments of this type of dam application in the future, particularly taking into consideration the recent constant effort to conceive geosynthetic-reinforced structures exhibiting also facing systems more consistent with the landscape. In fact, the use of metallic reinforcements, with more aesthetically attractive facing systems, was already reported for about ten dams around the world with a low or moderate height (maximum 22.5 m), as illustrated by ICOLD (1993a).

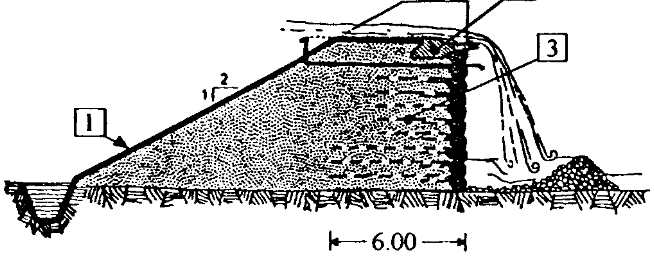

Fig. 25 Maraval earth dam in France, 8 m high (modified after Kern, 1977).
1. Bituminous geomembrane ($t_{GM} = 4.8$ mm).
2. Concrete spillway.
3. Earth mass reinforced with PET geotextiles ($\mu = 350$ g/m²).

Some examples of uses of geosynthetics with reinforcement function have to be reported for dam heightening, both for rehabilitation and new construction purposes.

This technique has been used, for example, at Davis Creek dam in the United States (Engemoen and Hensley, 1989): the dam, constructed in 1990, is 33 m high; its upper part presents a steep geogrid-reinforced downstream slope. Two types of geogrids were adopted (Fig. 26): six layers (each 5 m long) of one type of HDPE geogrid were used to provide adequate deep-seated stability, while 19 layers (each 2 m long) of a lighter HDPE geogrid type, were placed to give adequate near-surface stability. Of course, particular attention was dedicated to establishing vegetation on the downstream

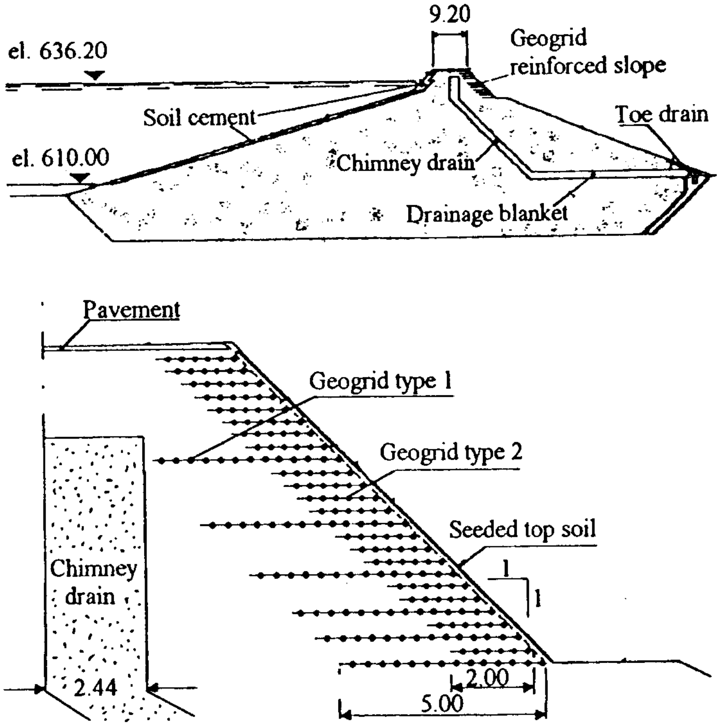

Fig. 26 Davis Creek earth dam in United States, 33 m high (modified after Engemoen and Hensley, 1989).

slope (1V:1H): to this goal, hydro-seed was covered by natural fibres (coconut) and then irrigated for longtime.

The geosynthetic-reinforced techniques for dam heightening will surely have an important development in the coming years. In fact, even for rehabilitation purposes, reinforced structures constructed on the narrow crest of existing embankment dams represent an ideal way to heighten the dam itself, in order to increase the storage capacity or, eventually, the freeboard, taking also into consideration the environmental aspects related to the soil/vegetative cover.

Always in the field of embankment dams, a number of applications of geosynthetics used to reinforce bituminous concrete or cement concrete cover layers have to be mentioned. In particular, some cases of light geogrids as reinforcement of gunite layers placed as external protection of geomembranes liners were reported. For example, at Pappadai secondary dams in Italy (height ranging from 6.5 to 8.5 m), constructed in 1992, the protection of the GCM liner (including a PVC geomembrane and a PET geotextile) was obtained by a PP nonwoven geotextile over which a layer of gunite, 60 mm thick, reinforced with a PP bioriented geogrid ($\mu = 70$ g/m^2), was sprayed (Sarti, 1994). Finally, especially in seismic regions, it is good practice to adopt geosynthetics also in order to reinforce bituminous concrete layers incorporated in embankment dams revetments: usually PET woven geotextiles ($\mu = 250$ g/m^2 and $T = 50$ kN/m) able to resist thermal shock due to the contact with bitumen at about 160°C, have been selected (Cazzuffi, 1988).

3.2.6 Surficial erosion control

Embankment dams

Geosynthetics have been used to control surficial erosion in a number of embankment dams, both for new construction and rehabilitation purposes.

Two main groups of applications could be mentioned, according to the origin of the erosion to be dealt with:

- erosion caused by atmospheric agents (mostly rainwater);
- erosion caused by overtopping of the dam.

In the first group, the applications have concerned mostly the entire downstream facing and the upper portion of the upstream facing; in fact, the portion of the upstream facing directly in contact with the stored water has been generally protected using the typical techniques adopted for river bank revetments, as rip-rap, in which geotextiles are performing a filter function (see paragraph 3.2.4) or, in alternative, other solutions (see ICOLD 1993b), as soil-cement blankets, concrete slabs, bituminous concrete layers and so on, in which geosynthetics could be incorporated with a separation or even a reinforcement function (see the last part of paragraph 3.2.5).

The products commonly used to control surficial erosion due to atmospheric agents are mainly geomats and geocells, but also biotextiles, biomats and biocells are adopted, particularly when biodegradation is desirable in case of temporary role during the vegetation growth. This solution is not only typical of earth dam facings, but today has became common practice to solve problems induced by erosion due to rainfall and consequent runoff, also on natural slopes, embankment slopes, man made cut-slopes and so on.

The group of surficial erosion control applications really peculiar for dams is related to protection against overtopping. This type of application is surely one of the possible future remarkable expansion areas concerning the use of geosynthetics and bioproducts in dams: the protection against overtopping represents in fact a crucial aspect of dam engineering. Many failures of embankment dams have been induced in the past by overtopping, mainly because the downstream face was not protected. Documented case histories have shown that phenomena induced by overtopping have been influenced by several factors, as valley morphology, dam type and size, physical and mechanical characteristics of the construction soils, hydraulic regime of the reservoir and so on. In particular, the soil grain sizes have an important influence on the failure mechanism induced by overtopping, as illustrated in Fig. 27 (after Croce, 1989).

All the observed failure mechanisms due to overtopping (both on site real cases and on physical model studies) have been originated in the downstream face and have then progressed towards the dam body. On the basis of this consideration, it is of course evident the need to protect the downstream face: different experiences could be mentioned on this subject, using different techniques, but only few incorporating geosynthetics.

Particularly interesting is the Australian experience, where about 40 rockfill dams since 1964 have been protected and reinforced on their downstream side using metallic grids and gabions: up to now reinforced rockfill has been used mostly in the construction phase. Such a technology allows for substantial saving in diversion works: therefore, it has mainly temporary character and it

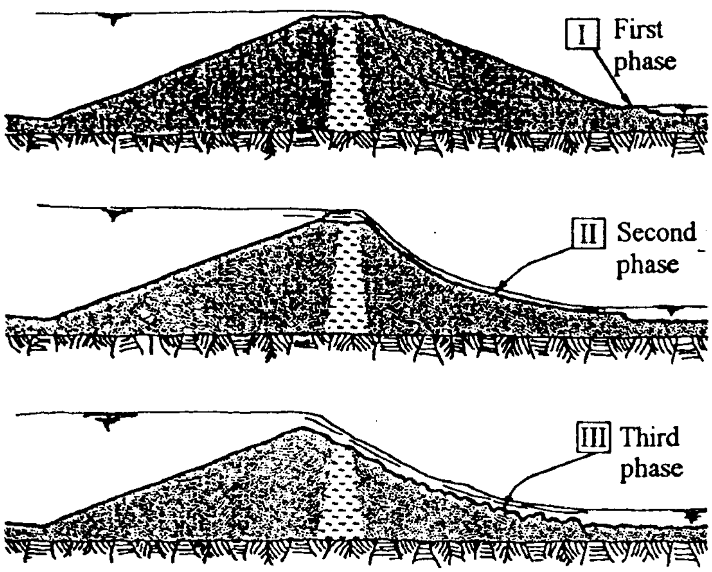

Fig. 27 Typical failure mechanism induced by overtopping, according to phisical models of embankment dams constructed with coarse grained materials without protection on the downstream face (after Croce, 1989).

I. Piping caused by filtration flow.
II. Saturation of the downstream side.
III. Failure induced by mass transport of coarse grained material within the stream.

does not involve any corrosion consideration (ICOLD, 1993a). Different protection and reinforcing systems have been developed and used: some of them are patented and the commercial ownership of these patents has to be complied with for any application.

Among the different examples, the case of Moochalabra dam in Australia (Fig. 28), 12 m high, constructed in 1971, could be mentioned. In fact, in this dam metallic grids and meshes were adopted to reinforce the downstream side and also to protect the downstream face for a longer term than the construction period (Johnson, 1974): the dam was already overtopped several times, without any substantial damage. Only some pieces of timber were found on the downstream face after each overflow. In any case, the Moochalabra dam was supposed to be enlarged ten years after completion of the first stage, and also to be provided with a separate spillway.

Some applications of geosynthetics and bioproducts have already been reported to solve the problem of overtopping protection, both for new construction and rehabilitation purposes. For example, Lake-in-the-Sky earth dam in United States, 10 m high, constructed in 1964, was rehabilitated in 1991 by placing a turf biomat (reinforced with a geosynthetic) over the entire downstream facing, in order to control the erosion phenomena in case of short-term overtopping: the reinforced biomat represented a technical solution significantly less expensive than conventional concrete spillway (Giroud and Bonaparte, 1993).

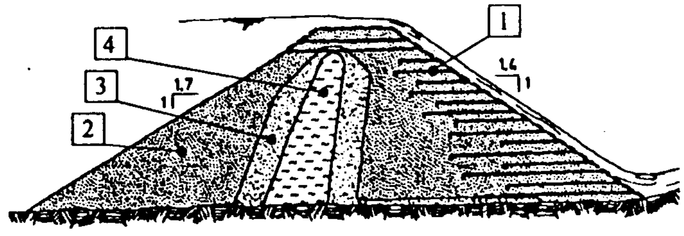

Fig. 28 Moochalabra zoned rockfill dam in Australia, 15 m high (modified after Johnson, 1973).

1. Steel mesh reinforcement and protection.
2. Rockfill.
3. Granular filter.
4. Clay core.

In the case of the construction of Maraval dam in France (see paragraph 3.2.5 and Fig. 25) the PET woven geotextiles (μ = 750 g/m^2) were adopted also to improve the resistance to overtopping, but mainly to perform a reinforcement function.

In the case of rehabilitation of three small dams in United States (Bass Lake dam, 12 m high, constructed in 1990; Trout Lake dam, 8.5 m high, constructed in 1951; and Price Lake dam , 9 m high, constructed in 1958), articulate concrete blocks linked by cables and resting on a geotextile have been used in 1991 in order to protect the crest and the downstream slope against overtopping (Wooten et al., 1990). In those cases, woven geotextiles were adopted mainly to perform a filter function; it is interesting to note that the geotextile opening size was selected not only to satisfy filter criteria, but also to allow penetration by grass roots: in fact, the articulate blocks were covered by grassed topsoil layer. This soil/vegetative cover has given the overtopping protection a natural appearance and also provided additional anchorage for the articulate concrete blocks (Fig. 29).

It seems evident that the geosynthetic applications in the field of overtopping protection are still at an experimental stage: surely, considering their flexibility even in presence of important settlements of the downstream face and also their durability already exhibited in other relevant applications, a bright future

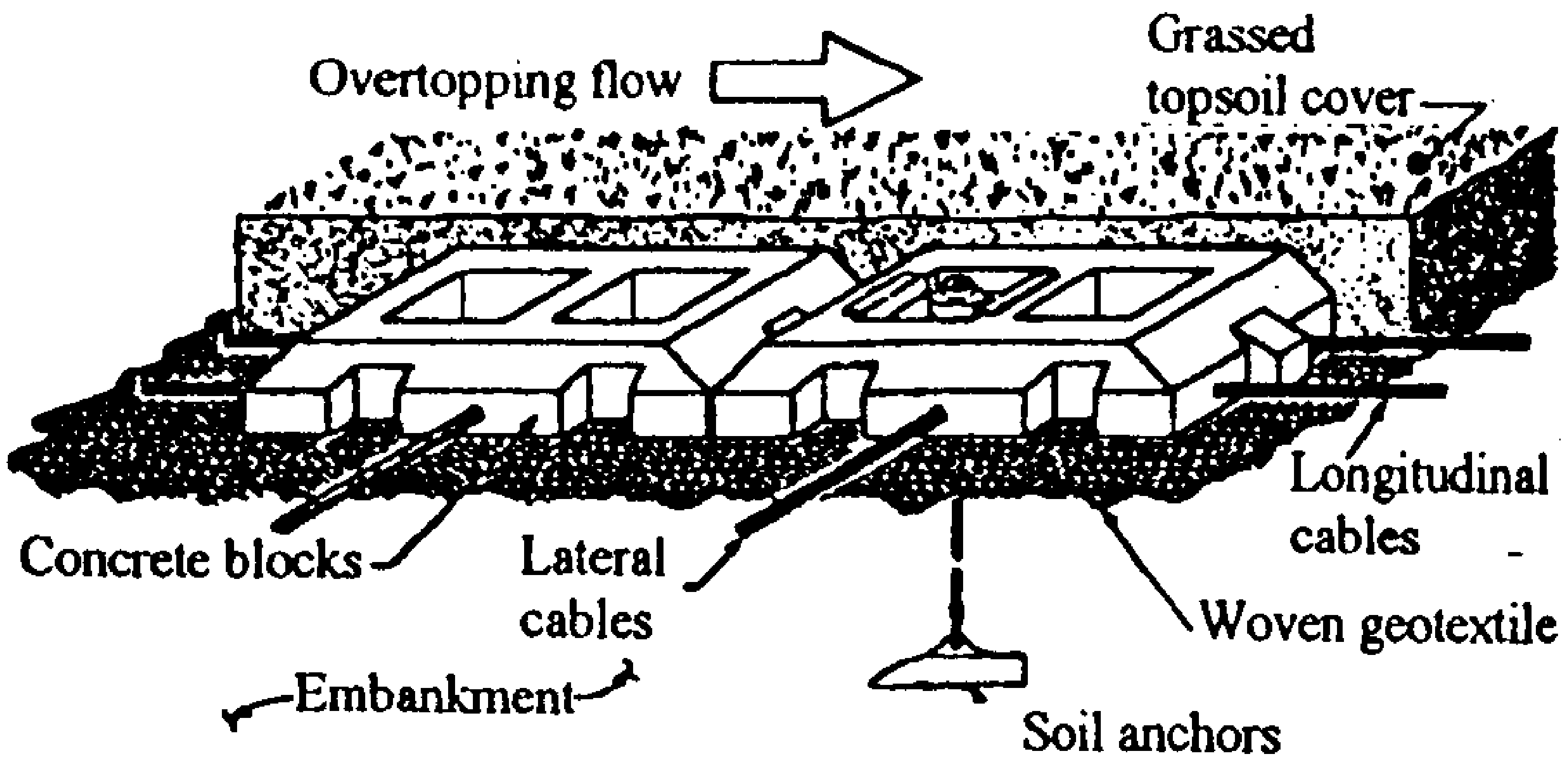

Fig. 29 Detail of the articulate concrete blocks, with a geotextile filter and a grassed topsoil cover, for the downstream face protection against overtopping of Blue Ridge Parkways dams in United States, 8.5 m to 12.0 m high (modified after Wooten et al., 1990).

could be envisaged for the use of geosynthetics in this specific area, but only provided that specific design procedures should be developed, with the aid of both physical and mathematical models, validated by means of full scale experiments.

In definitive, from a safety point of view, geosynthetics, eventually associated with a combination of bioproducts, earth materials and vegetation, could represent a stable solution to resist overtopping phenomena in embankment dams. From an environmental point of view, the same combination of materials, could represent the "natural" alternative (much more attractive also from the aesthetical aspect) to traditional protection systems on the downstream slope, like rigid concrete slabs.

Finally, a concluding remark concerns the applications of geosynthetics for performing the surficial erosion control function in embankment dams: not always the use of geosynthetics in this field is giving a positive impact of the entire structure on the landscape and, more generally, on the environment.

For example, the use of geotextiles according to the fabric-forming technique should be generally adopted only for emergency applications. This technique consists of pouring a highly fluid sand-cement mortar between two geotextile layers kept parallel by separators yarns, thus generating a mattress-like slab (Fig. 30-a). Also geotextile tubes filled with sand or clay granules (Fig. 30-b) do not represent an environmentally acceptable solution for erosion control systems.

Nevertheless, both types of revetments have been sometimes used to control erosion on the upstream face of small embankment dams: being vegetation growth practically impossible through these structures, the impact of these solutions on the landscape is surely negative. Therefore, for both solutions (mattresses and tubes) some further efforts by the geosynthetics manufacturers, designers and installers are needed to solve the problem related to the environmental impact on the landscape.

3.3 Environmental impacts for geosynthetics in dams

As described in the previous paragraph 2.2, geosynthetics have been used in concrete and masonry dams mainly for rehabilitation works and in RCC dams for new constructions, while for embankment dams they have been employed for both purposes.

For embankment dams and also, in some way, for RCC dams, the use of geosynthetics is always associated to a reduction of the natural earth materials to be exploited and placed: therefore, this result represents surely one of the most important positive environmental impact related to applications of geosynthetics on such structures.

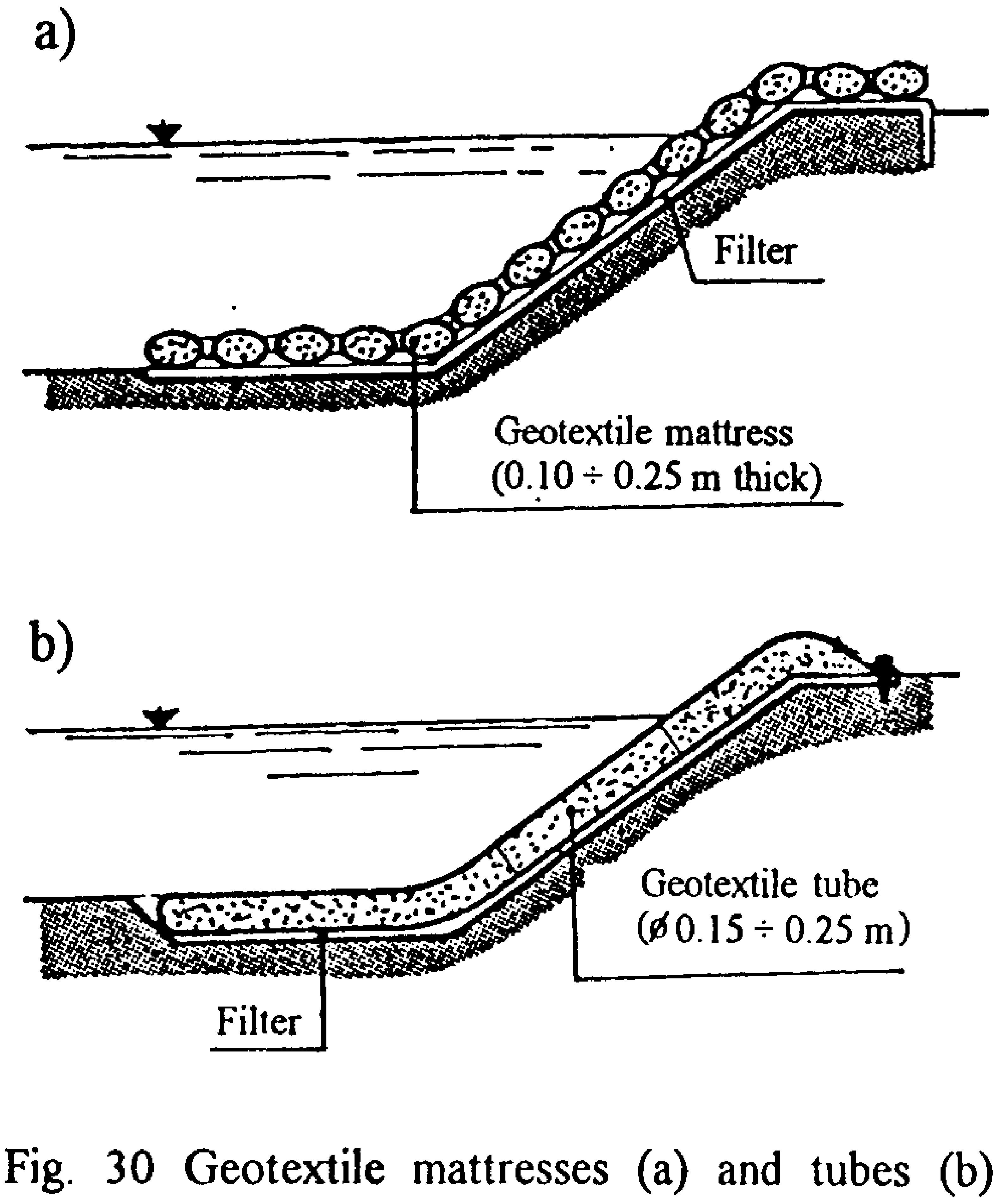

Fig. 30 Geotextile mattresses (a) and tubes (b) for erosion-control systems in small embankment dams (modified after Bigalli et al., 1986): drawings are not to scale.

Moreover, for all types of dams, geosynthetics, if properly designed and correctly installed, surely contribute to increase safety: this is particularly evident for rehabilitation works. The safety improvement necessarily means a reduction of the hazards, and this result corresponds to another important positive environmental impact due to the use of geosynthetics on dam structures.

Other positive impacts are typical of the different dam structures and also of the specific performed functions. For example, geomembranes or eventually geocomposite membrane liners, adopted for rehabilitation of concrete and masonry dams upstream facings, could be easily transported by using helicopters, even to the remote locations typical of such applications (mountain areas, arid regions and so on). On the contrary, conventional techniques usually request the transport of higher quantities of different materials (like cement, selected aggregates and so on), therefore involving the need to build or, at least, to renovate adequate access roads. The environmental implications of the different solutions are self-explaining.

4. CONCLUSIONS

Through the analysis of case histories, the wide diffusion of geosynthetics (and bioproducts) and their multifarious applications in large man-made structures with containment function, such as landfills and dams, has been emphasized.

As a first general comment, the types of products used in landfills and dams are, for the most part, the same, while the raw materials are sometimes different, according also to the chemical nature of the stored fluid (for example, PVC geomembranes are generally selected for dam applications and HDPE geomembranes for landfills); moreover, the functions performed by the different products are very similar. On the contrary, the approach to the applications is quite different, for a series of reasons.

Before all, actions on dams derive essentially from water, and the involved materials (soils, rocks, concrete, masonry) are practically stable, at least at reduced temporal scale. Actions on landfills derive from different fluids (water, leachate, gas) and the involved materials (mainly wastes) change remarkably their characteristics within a time span of less than one human generation.

Secondly, dam engineering has a very old, well assessed tradition; of course, progress still occur, but design and technological innovations are hardly accepted, or accepted with suspect. Landfill engineering has a very short history; innovative solutions are often accepted even beyond any reasonable doubt, and progress can have drastic effects on landfill design and construction.

Most dams are very old (up to several decades) and rehabilitation works are an important part of the total. All landfills are relatively new, and rehabilitation problems are still rare.

At last, the global costs are quite different, being the cost of a new dam from one to two orders higher than the cost of a landfill. The consequence of this is reflected by the quality of investigations, design and construction works.

Despite of such differences, landfills and dams also present some important similarities, all related to their important impact on the environment.

In both cases, bad performances or even unforeseen failures could have tremendous consequences on the environment and also on the population, in terms of pollution or flood hazards and related risks (respectively, for landfills and for dams). To reduce hazard and risk deriving from such man-made structures is a compelling duty for all people involved in their design, construction, maintenance and management.

Reducing the hazard means to realize safer structures; to this aim, the application of geosynthetics is acknowledged as an important contribution, both in landfills and in dams.

The last decades have seen impressive progress in geosynthetics technologies and applications and substantial development of testing and design methods, as demonstrated also by the many international conferences, symposia and technical publications dedicated to such topics. The recent evolution of the state of the art shows a growing interest of researchers and users towards the problems of durability (to be intended in its widest sense, including durability of the raw materials, durability of the manufactured products, and long-term performance of the structures in which the products are incorporated); this interest goes in the direction of realizing more durable and consequently safer structures.

It can be observed that the present trend of durability investigations leads to approach the problems of interplaying between geosynthetics and environment on the side of "the impact of the environment on geosynthetics".

This lecture was intended to give a contribution in order to put the geosynthetic community in front of the problem also on the opposite side, that is "the impact of geosynthetics on the environment".

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APPENDIX

Terminology of products

The proposed terminology for products has been compiled taking also into account the recent discussion on that matter appeared on IGS News (Rigo, 1992; Gevers et al., 1992; Rimoldi et al., 1993; Koerner, 1993). The following definitions are here proposed (see also Table 1 for abbreviations):

GT) Geotextile (generic): a permeable synthetic textile product in the form of manufactured sheet, which may be woven, nonwoven or knitted, used in geotechnical, environmental, hydraulic and transportation engineering applications.

GTW) Woven geotextile: a geotextile produced by interlacing, usually at right angles, two or more sets of fibres, filaments, tapes or other elements.

GTN) Nonwoven geotextile: a geotextile produced by bonding (by means of friction and/or cohesion and/or adhesion) of directionally or randomly oriented fibres.

GTK) Knitted geotextile: a geotextile produced by interlooping one or more fibres, yarns, filaments or other elements.

GG) Geogrid (generic): a synthetic structure, in the form of manufactured sheet, consisting of a regular network of integrally connected elements, which may be linked by extrusion, bonding or interlacing, whose openings are larger than the constituents, used in geotechnical, environmental, hydraulic and transportation engineering applications.

GGE) Extruded geogrid: a geogrid produced by stretching uniaxially or biaxially an extruded integral structure.

GGB) Bonded geogrid: a geogrid produced by bonding, usually at right angles, two or more sets of strands or other elements.

GGW) Woven geogrid: a geogrid produced by interlacing, usually at right angles, two or more sets of fibres, yarns, filaments of other elements.

GN) Geonet: a synthetic structure, in the form of manufactured sheet, consisting of a regular network of integrally connected overlapping ribs, whose openings are usually larger than the constituents, used in geotechnical, environmental, hydraulic and transportation engineering applications.

GS) Geospacer: a synthetic molded structure, consisting of a cuspidated or corrugated plates (eventually perforated), used in geotechnical, environmental, hydraulic and transportation engineering applications.

GA) Geomat: a structure, in the form of manufactured sheet, consisting of a non-regular network of synthetic fibres, yarns, filaments, tapes or other elements (which may be thermally or mechanically connected), whose openings are usually larger than the constituents, used in geotechnical, environmental, hydraulic and transportation engineering applications.

GL) Geocell: a cellular structure, consisting of a regular open network of synthetic strips, linked by extrusion or adhesion or other methods, used in geotechnical, environmental, hydraulic and transportation engineering applications.

GM) Geomembrane (generic): a very low permeability membrane, in the form of manufactured sheet, which may be plastomeric, elastomeric, or bituminous, used in geotechnical, environmental, hydraulic and transportation engineering applications.

GMP) Plastomeric geomembrane: a geomembrane produced by plastic industries by extrusion or calendering of a plastomeric compound, with or without a fabric reinforcement, or by spreading a polymer on a sheet removed at the end of the manufacturing process.

GME) Elastomeric geomembrane: a geomembrane produced by rubber industries by a process of calendering of an elastomeric compound.

GMB) Bituminous geomembrane: a geomembrane produced in factory or on site by impregnating with bitumen (eventually modified with elastomers) both sides of a fabric (woven or nonwoven).

GC) Geocomposite: generic name adopted to define an assembled structure of geosynthetic products, in the form of manufactured sheet or strip, used in geotechnical, environmental, hydraulic and transportation engineering applications, for performing a specific function.

GCD) Geocomposite drain: an assembled structure of geosynthetic products, in the form of manufactured sheet or strip, used in geotechnical, environmental, hydraulic and transportation engineering applications, for performing drainage function.

GCR) Geocomposite reinforcement: an assembled structure of geosynthetic products, in the form of manufactured sheet, used in geotechnical, environmental, hydraulic and transportation engineering applications, for performing reinforcement function.

GCL) Geocomposite clay liner: an assembled structure of geosynthetic products and low permeability earth materials (clay, bentonite and so on), in the form of manufactured sheet, used in geotechnical, environmental, hydraulic and transportation engineering applications, for performing barrier function.

GCM) Geocomposite membrane liner: an assembled structure of geosynthetic products, in the form of manufactured sheet, consisting at least of one geomembrane among the components, used in geotechnical, environmental, hydraulic and transportation engineering applications, for performing barrier function.

BT) Biotextile: a permeable textile material, made by biodegradable natural fibres, in the form of manufactured sheet, usually woven, used in geotechnical, environmental, hydraulic and transportation engineering applications.

BA) Biomat: a structure, in the form of manufactured sheet, consisting of a non-regular network of biodegradable natural fibres, yarns, filaments or other elements (generally mechanically connected), whose openings are usually larger than constituents, used in geotechnical, environmental, hydraulic and transportation engineering applications.

BL) Biocell: a cellular structure, consisting of a regular open network of biodegradable natural strips, connected by various methods, used in geotechnical, environmental, hydraulic and transportation engineering applications.

BC) Biocomposite: generic name adopted to define an assembled structure of biodegradable natural products, in the form of manufactured sheet or strip, used in geotechnical, environmental, hydraulic and transportation engineering applications, for performing a specific function.

BCD) Biocomposite drain: an assembled structure of biodegradable natural products, in the form of manufactured sheet or strip, used in geotechnical, environmental, hydraulic and transportation engineering applications, for performing drainage function.