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Design using geosynthetics —

Part 4: **Drainage**

Design pour géosynthétiques —

Partie 4: Drainage

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 221, *Geosynthetics*.

A list of all parts in the ISO 18228 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The ISO 18228 series provides guidance for designs using geosynthetics for soils and below ground structures in contact with natural soils, fills and asphalt. The series contains 10 parts which cover designs using geosynthetics, including guidance for characterization of the materials to be used and other factors affecting the design and performance of the systems which are particular to each part, with ISO/TR 18228-1 providing general guidance relevant to the subsequent parts of the series.

The series is generally written in a limit state format and guidelines are provided in terms of partial material factors and load factors for various applications and design lives, where appropriate.

This document includes information relating to the drainage function. Details of design methodology adopted in a number of regions are provided.

Parts of this document have been adapted from *Comité français des géosynthétiques*, 2014[10].

Design using geosynthetics —

Part 4: Drainage

1 Scope

This document outlines the criteria for evaluating the available and the required flow rate of geosynthetics in various situations, provides a summary of the available laboratory testing, and lists the safety factors and reduction factors that can be applied to the parameters when designing using geosynthetics for drainage systems.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10318-1, *Geosynthetics — Part 1: Terms and definitions*

3 Terms, definitions and symbols

For the purposes of this document, the terms and definitions given in ISO 10318-1 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1 Symbols and abbreviations

O_{90}	characteristic opening size of a geosynthetic (µm)
k_n	coefficient of permeability normal to the plane(m/s)
q_n	flux(l/m^2·s)
v-index	velocity index(mm/s)
ψ	permittivity(s^{-1})
ϑ	transmissivity (m^3/s/m or l/s/m)
GCD	acronym used for draining geocomposites
dQ/dt	volumetric flow rate of water through the soil (m^3/s or l/s)
A	bulk cross-sectional area through which the flow occurs (m^2)
h	hydraulic head (m)

l	distance travelled by the bulk water flow (m)
dh/dl	hydraulic gradient (dimensionless)
K	hydraulic conductivity or permeability of the soil (m/s)
q	equal to (dQ/dt), volumetric flow rate (m^3/s or l/s)
i	equal to (dh/dl), hydraulic gradient (dimensionless)
q_p	in-plane flow capacity, equal to the volumetric flow rate of water and/or other liquids per unit width of specimen, at defined gradients in the plane of a product (l/s·m).
k_p	coefficient of permeability in the plane, equal to the ratio between in-plane flow capacity q_p and the product of thickness d and hydraulic gradient i (m/s)
q_r	rainfall per unit horizontal area ($m^3/s/m^2$)
P	rainfall flow rate (m^3/s)
A_h	horizontal area (m^2)
q_s	rainfall per unit sloping area ($m^3/s/m^2$)
β	slope angle (deg or °)
q_D	rainfall per unit area entering the drainage system ($m^3/s/m^2$)
f	coefficient of infiltration (dimensionless)
Q_R	input flow rate due to rainfall (m^3/s/m or l/s/m)
L	length of the slope (m)
L_h	horizontal length of the slope (m)
h_r	height of rainfall (mm)
t	duration of the rainfall (h)
j	rainfall intensity (mm/h)
a	parameter of the pluviometric curve (mm h^{-n})
n	exponent of the pluviometric curve (-)
$F_{S,Q}$	Factor of Safety on input flow rate (dimensionless)
Q_S	input flow rate due to additional surficial flow (m^3/s/m or l/s/m)
Q_D	design input flow rate in the geocomposite (m^3/s/m or l/s/m)
Q_F	total rainfall flow on the catchment zone (m^3/s or l/s)
A_c	horizontal area of the catchment zone (m^2)
B_g	running width of the geocomposite drain (m)
h_{max}	maximum thickness of liquid in the granular liquid collection layer

Q	Specific flow rate = discharge per unit width in the geocomposite, under a specified hydraulic gradient ($m^3/s/m$ or l/s/m)
B	width of geocomposite specimen in the flow rate test (m)
q_m	measured flow rate for a geocomposite specimen of width B (l/s or m^3/s)
p	applied pressure (kPa)
γ	saturated unit weight of the soil or material placed on the geocomposite (kN/m^3)
H	thickness of the soil or the material placed on the geocomposite (m)
w_s	distributed surcharge on the ground surface (kPa)
H_l	depth of the lowest point of the geocomposite below the ground surface (m)
K_a	coefficient of active pressure of the soil (dimensionless)
φ	friction angle of the soil (deg or °)
t, t_{GCD}	geocomposite thickness (m)
L_{sp}	distance between geotextile support points (m)
Q_{i1}	specific flow rate for the i_1 gradient (l/s/m or m^2/s)
Q_{i0}	specific flow rate for the i_0 gradient (l/s/m or m^2/s)
i_1	hydraulic gradient on the diagram, immediately higher than the actual hydraulic gradient (dimensionless)
i_0	actual hydraulic gradient (dimensionless)
Q_v	discharge or volumetric flow rate (m^3/s)
A_g	cross-sectional area of the geocomposite (m^2)
χ	parameter depending on the roughness of the flow surface ($m^{1/2}$ / s)
R	hydraulic radius of the flow conduit (m)
C	parameter as a function of geometry and roughness of the flow surface
σ_n	pressure applied in lab tests (kPa)
i_1, i_2	hydraulic gradients applied in lab tests (dimensionless)
i_o	actual hydraulic gradient (dimensionless)
$Q(\sigma_n , i)$	flow rate evaluated for the values σ_n, i (l/s/m or m^2/s)
$Q_{i0}(\sigma_n , i_0)$	flow rate evaluated for the values σ_n, i_0 (l/s/m or m^2/s)
Q_{20}, Q_T	specific flow rates at 20 °C and T °C
μ_{20}, μ_T	viscosity of water at 20 °C and T °C
T	actual temperature of water (°C)
C_T	correction factor for temperature and viscosity (dimensionless)

Q_a available long term flow rate for the geocomposite (l/s/m or m^2/s)

Q_L short term flow rate obtained from laboratory tests with the appropriate boundary conditions (l/s/m or m^2/s)

$R_{F,in}$ Reduction Factor for the intrusion of filter geotextiles into the draining core due to tensile creep of the geotextile, occurring after the short term flow rate test (dimensionless)

$R_{F,cr-Q}$ Reduction Factor for the compressive creep of the geocomposite (dimensionless)

$R_{F,cc}$ Reduction Factor for chemical clogging of the draining core (dimensionless)

$R_{F,bc}$ Reduction Factor for biological clogging of the draining core (dimensionless)

$R_{F,L}$ Reduction Factor for overall uncertainties on laboratory data and field conditions (dimensionless)

q_h flow rate of liquid supply ($m^3/s/m^2$)

j factor of the Giroud theory (dimensionless)

$t_{prescribed}$ prescribed thickness of the granular layer (m)

$F_{S,E}$ Factor of Safety on equivalency (dimensionless)

E equivalency coefficient (dimensionless)

Q_{GCD} minimum short term input flow rate for the geocomposite in order to be considered equivalent to the granular layer having thickness larger than h_{max} ($m^3/s/m$ or l/s/m)

Q_{Darcy} flow rate in the granular soil layer according to Darcy's law ($m^3/s/m$)

K_{lt} long term permeability of the granular soil layer evaluated in situ at the end of its design life (m/s)

q_h^* equivalent flow rate of liquid supply in the granular soil layer at equilibrium ($m^3/s/m^2$)

j^* factor of the Giroud theory related to Q_{Darcy} (dimensionless)

E^* equivalency coefficient for the thickness $t_{prescribed}$ (dimensionless)

Q_{GCD}^* short term input flow rate for the geocomposite in order to be considered equivalent to the granular layer having thickness $t_{prescribed}$ ($m^3/s/m$)

Q_{GL} flow rate afforded by the granular drainage layer ($m^3/s/m$ or l/s/m)

U Darcy's velocity (m/s)

z vertical distance in the soil (m)

k intrinsic permeability of the soil, which depends only on properties of the solid matrix (m^2)

ρ density of the fluid ($N\ s^2/m^4$ or kg/m^3)

μ dynamic viscosity of the fluid ($N / m^2\ s$)

C Hazen's empirical coefficient for intrinsic permeability (dimensionless)

C^* Hazen's empirical coefficient for permeability ($m^{-1}\ s^{-1}$)

C_U	coefficient of uniformity of the soil = D_{60} / D_{10} (dimensionless)
D_{10}, D_{60}	diameter of soil particles for 10 % and 60 % cumulative passing (m)
g	acceleration due to gravity = 9,81 m/s^2
γ_w	unit weight of water for the given temperature (kN/m^3)
n	soil porosity = void volume / total volume (dimensionless)
$R_{F,in(R/R)\ short\ term}$	Reduction Factor for the intrusion of filter geotextiles into the draining core for Rigid / Rigid boundaries at short term (dimensionless)
$R_{F,in(R/S)\ short\ term}$	Reduction Factor for the intrusion of filter geotextiles into the draining core for Soft / Soft boundaries at short term (dimensionless)
$R_{F,in(S/S)\ short\ term}$	Reduction Factor for the intrusion of filter geotextiles into the draining core for Rigid / Soft boundaries at short term (dimensionless)
$R_{F,in(R/R)\ long\ term}$	Reduction Factor for the intrusion of filter geotextiles into the draining core for Rigid / Rigid boundaries at long term (dimensionless)
$R_{F,in(R/S)\ long\ term}$	Reduction Factor for the intrusion of filter geotextiles into the draining core for Soft / Soft boundaries at long term (dimensionless)
$R_{F,in(S/S)\ long\ term}$	Reduction Factor for the intrusion of filter geotextiles into the draining core for Rigid / Soft boundaries at long term (dimensionless)
$Q_{L\ (R/R)\ short\ term}$	Specific flow rate for Rigid / Rigid boundaries at short term (m^3/s/m or l/s/m)
$Q_{L\ (R/S)\ short\ term}$	Specific flow rate for Rigid / Soft boundaries at short term (m^3/s/m or l/s/m)
$Q_{L\ (S/S)\ short\ term}$	Specific flow rate for Soft / Soft boundaries at short term (m^3/s/m or l/s/m)
$Q_{L\ (R/R)\ long\ term}$	Specific flow rate for Rigid / Rigid boundaries at long term (m^3/s/m or l/s/m)
$Q_{L\ (R/S)\ long\ term}$	Specific flow rate for Rigid / Soft boundaries at long term (m^3/s/m or l/s/m)
$Q_{L\ (S/S)\ long\ term}$	Specific flow rate for Soft / Soft boundaries at long term (m^3/s/m or l/s/m)
$R_{F,cr,th}$	Reduction Factor for thickness (dimensionless)
t_{virgin}	thickness of the geocomposite core before load application (m);
t_{cr}	thickness measured at long term (1 year, 10 years, ... 100 years) in compressive creep tests (m)
$q(\sigma_n, i, \text{long term})$	long term available flow rate for applied pressure σ_n and hydraulic gradient i (m^3/s/m or l/s/m);
$q(\sigma_n, i)$	short term available flow rate for applied pressure σ_n and hydraulic gradient i (m^3/s/m or l/s/m);
$x(\sigma_n, 0)$	short term thickness of geocomposite for applied pressure σ_n (m);
$x(\sigma_n, t)$	long term thickness of geocomposite for applied pressure σ_n (m);
F	Reduction Factor for thickness (dimensionless)
α	Reduction Factor for the long term effect of compressive creep and geotextile intrusion (dimensionless)

$Q_{long\ term}$ long term flow rate (m^3/s/m or l/s/m)

4 Concepts

Some types of geosynthetics, particularly geocomposites, can be used as planar drainage medium in subsurface drainage systems.

The design of planar drainage geosynthetics requires hydraulic and geotechnical concepts for defining the design input flow rates, and a detailed method for defining the allowable long-term flow of geosynthetics, based on laboratory testing.

Drainage geosynthetics typically consist of a continuous drainage core (geonet, geomat, geospacer) capable of transporting a fluid along its own plane, and geotextiles and/or geomembranes, coupled to the drainage core, which prevent the drainage core itself from being clogged by the surrounding soil. The components of a draining geocomposite with continuous draining core are filtering geotextiles (on one or both sides), draining core and geomembrane, as shown in Figure 1.

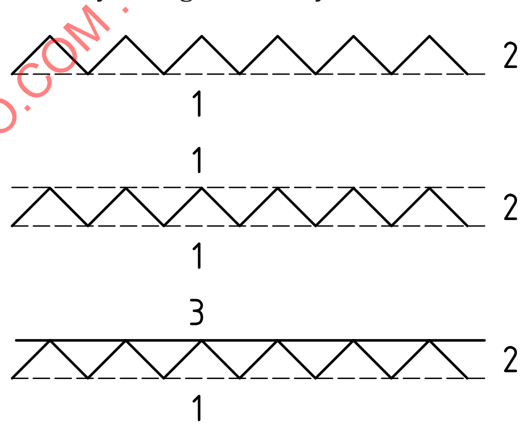
Some geocomposites available on the market include discrete draining elements, such as small diameter pipes, instead of a continuous draining core (Figure 2). In this type of geocomposite, the geotextiles act as a filter and also contribute to carrying the water flow. In general, the water flow capacity provided by geotextiles is very small compared to that provided by the discrete draining elements.

Drainage geosynthetics are widely used in controlled landfills, roads, railways, airports, tunnels and buildings. Drainage systems with geosynthetics are used within a performance envelope between the extreme cases of drainage along a sub-horizontal plane and along a vertical plane; between a hydraulic gradient close to 0 and a hydraulic gradient of 1.

In addition to the hydraulic gradient, the draining capacity of a geocomposite depends on the pressure applied and the materials in contact with the two faces.

The design of a drainage system with geosynthetics is based on the evaluation of the drainage capacity available under actual operating conditions and on the flow rate required by the project.

The drainage capacity can be assessed on the basis of appropriate laboratory tests, while the required flow rate is evaluated on the basis of hydrological and hydraulic considerations.



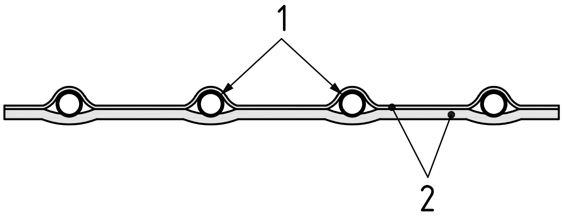
Key

1 geotextile

2 draining core

3 geomembrane

Figure 1 — Components of a draining geocomposite with continuous draining core: 1) Draining core + geotextile; 2) Geotextile + draining core + geotextile; 3) Geotextile + draining core + geomembrane

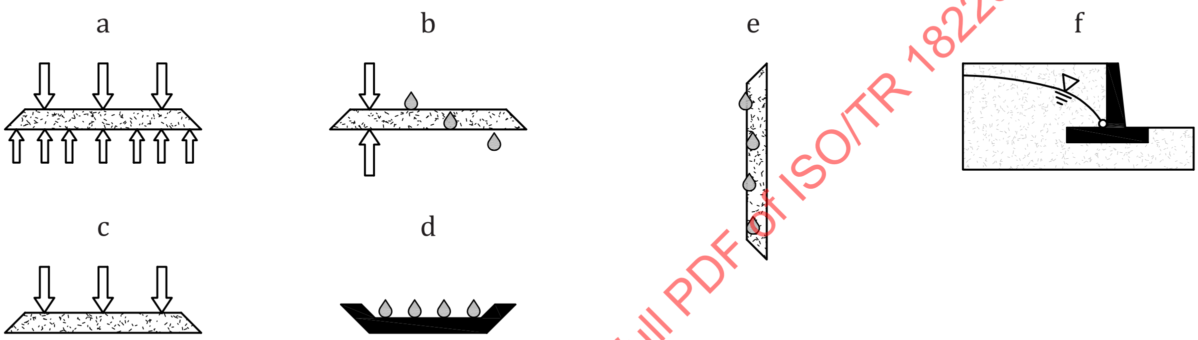


Key

1 discrete draining elements

2 geotextile

Figure 2 — Draining geocomposite with discrete draining elements



Key

a separation function

b filtration function

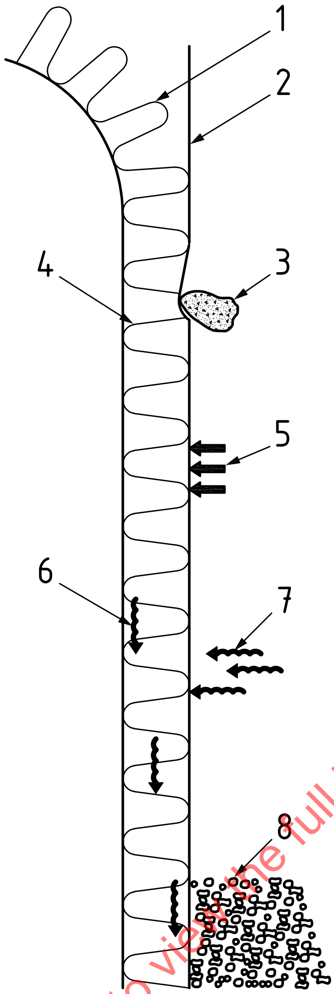
c protection function

d barrier function

e drainage function

f drainage systems applications

Figure 3 — Functions and Applications of drainage geocomposites (Source: ISO 10318-2)



Key

1 plastic core

2 geotextile

3 protects waterproofing from damage

4 distributes pressure

5 retains its drainage capacity even under high earth pressure

6 transports water to the collector drain

7 removes excess water from the soil

8 prevents the collector drain from silting up with fine soil particles

Figure 4 — Principles of the functions afforded by drainage geocomposites

5 Applications

Drainage geocomposites are made from a plastic drainage core that is thermally or otherwise bonded to a geotextile on one or both sides or to a waterproofing layer on one side.

They are capable of providing one or more main functions within the application as a drainage system, shown in Figure 3. The principles of the functions offered by drainage geocomposites are illustrated in Figure 4.

The main applications of planar drainage geocomposites are the following:

— Drainage of concrete walls

— Drainage of reinforced soil structures

— Drainage in road, railway and airport applications

— Horizontal drainage and capillary break layer in embankments made up of fine and cohesive fill

— Drainage trenches

— Leachate collection and gas ventilation in landfill applications (also used as a protection layer against geomembrane puncturing)

— Drainage of rainfall water infiltration in landfill applications

— Drainage in natural and artificial tunnel applications

— Drainage layer in roofing and deck pavement applications

— Drainage of sport fields

6 Materials

6.1 Components of draining geocomposites

The most commonly used drainage geosynthetics are the geocomposites which are produced by laminating one or two geotextiles, with a filter function, onto a drainage element.

— The filtering component can have the following characteristics under operating conditions: adequate permeability to gases and liquids in the direction perpendicular to the filter plane

— retention capacity of the soil particles

The draining component may have the following characteristics under operating conditions:

— adequate permeability to gases and liquids in the direction planar to the drainage structure

— adequate compressive strength and creep resistance for the loads to be applied

6.2 Filter Component of draining geocomposites

The filters are typically made up of nonwoven geotextiles, yet in certain specific applications some types of woven fabrics are occasionally used. The most commonly used nonwoven geotextiles are:

— staple fibres nonwoven, mechanically needled;

— continuous fibres nonwoven, thermally bonded or mechanically needled.

The physico-mechanical properties of nonwoven geotextiles are qualitatively as follows:

— Staple or continuous filament fibres needle-punched (only) nonwoven:

  — Relatively high thickness

  — High compressibility

  — Highly deformable over time

  — Potential clogging both on the surface and internally and limited blinding

— Staple fibres needle-punched and thermocalandered non-woven:

  — Moderate thickness

  — Moderate compressibility

  - Moderate deformability over time
  - Potential clogging both on the surface and internally and blinding risk on the heat-bonded surface and limited blinding on the other face
- Continuous fibres heat-bonded nonwoven:
  - Lowest thickness
  - Very low compressibility
  - Slightly deformable over time
  - Blinding risks

6.3 Drainage cores

The drainage cores are characterized by a three-dimensional structure with a high void ratio, and they differ according to the mode of manufacture and the type of polymer.

The main types of drainage cores can be grouped into the following categories:

- **Geomats**: made from a set of filaments which are tangled and welded at the contact points; the profile of the core can be different (cuspated, channelled, etc.) according to the required thickness and resistance to compression. These profiles are usually made of polyamide (PA) or polypropylene (PP).
- **Geonets**: made by the extrusion of two or three sets of parallel strands. Geonets are typically made of high-density polyethylene (HDPE).
- **Geospacers**: cuspated foils produced from extruded laminates, which are profiled during production into wave-shaped or truncated cuspate cone profiles, on one or both faces. They are typically made of polypropylene (PP) or high-density polyethylene (HDPE).

It is important for all forms and grades of geosynthetic drains that their strength and long-term creep and drainage performance is demonstrated to be appropriate for the loadings and design life envisaged.

Since geosynthetic drains may exhibit high resistance to compression in the short term but may be prone to sudden collapse if the loads are maintained for a long time, it is also important to check if the draining core behaves as compressible or collapsible for the project conditions of applied load, slope and design life.

6.4 Definitions and acronyms for the various products

ISO 10318-1 provides definitions and acronyms for many of the various products presently available on the market. In the present document the acronym GCD is used for draining geocomposites.

7 Properties relevant to design

Geosynthetics testing standards relevant to design for drainage are listed under further reading at the end of this document.

8 Darcy's law

The unidirectional movement of water through the soil is represented by Darcy's law.

Information on the movement of water in the ground is provided in Annex A.

9 Subsurface drainage structures

The uncontrolled movement of groundwater can be deleterious to geotechnical structures by:

— reducing or eliminating cohesion in soils;

— originating pore water pressures that reduce effective stresses, thereby lowering shear strength;

— producing horizontally inclined forces which increase the moments acting on them;

— lubricating failure planes;

— supplying water which leads to liquefaction during earthquakes; or

— promoting the uncontrolled movement of soil particles (piping).

The design engineer would normally be aware of all these risks and either account for this presence of water within their calculations (resulting in a conservative and expensive solution) or provide a technique to control it.

Subsurface drainage is the technique to control the flow of groundwater, through interception and/or deviation.

An effective subsurface drainage system will:

— reduce pore water pressures and thus increase effective stresses, thereby increasing shear strength;

— reduce horizontal forces, and thus reduce overturning moments and the possibility of failure;

— prevent the lubrication of failure planes;

— prevent the uncontrolled movement of soil particles (piping).

An essential feature of the successful use of subsurface drainage is that the groundwater can be removed in a controlled manner (i.e. without causing undue disturbance to surrounding areas). This is particularly important where its removal causes movements or subsidence in surrounding areas. In order for a subsurface drainage system to be effective, due consideration would normally be given to the positioning of the drain and to the materials selected.

All of the three following criteria apply

a) The drainage system may intercept the zone of seepage which can be the cause of the problem. The proper placement and configuration of the subsurface drainage system are important.

b) The seepage water can enter the subsurface drainage system with minimal resistance whilst at the same time cause minimal disturbance (piping) at the drain/soil interface. To facilitate this, filters are positioned around the outside perimeter of the subsurface drains.

c) The subsurface drainage system can remove the required amount of groundwater from the soil in the required time interval. The dimensions of the drains, the selection of appropriate drainage media, and the configuration of the drainage system all contribute to its ability to perform satisfactorily.

10 Geosynthetic properties

When considering drainage projects, the hydraulic properties of the geosynthetics are the most important.

ISO 10318-1 defines the hydraulic properties of geosynthetics listed in Table 1.

Table 1 — Relevant hydraulic properties of geosynthetics defined in ISO 10318-1

Characteristic opening size O_{90}
Permeability
Coefficient of permeability normal to the plane k_n
Flux q_n
Velocity index (v-index)
Permittivity ψ
In-plane flow capacity q_p
Transmissivity θ
Coefficient of permeability in the plane k_p

11 Geotextile filter performance and filter criteria

For designing the geotextile filters of drainage geocomposites see ISO/TR 18228-3.

12 Geocomposite drainage systems design

12.1 General

The design of a geocomposite drainage system may be carried out as follows:

a) Identify/set all the design conditions, including (but not limited to):

— Type of project (landfill bottom or capping, vertical wall, etc.)

— Types of soil involved (stones, gravel, clay, etc.) and their grading curves

— Environment (aggressive for landfill bottom, medium for landfill capping, ordinary for walls or roof gardens, etc.)

— Chemical and physical properties of the materials in contact with the geocomposite (pH, chemical and biological content, hardness, stiffness, etc.) and of the liquid to be drained (pH, chemical and biological content, density, viscosity, turbidity, etc.)

b) Set the boundary conditions, that is the type of materials in contact with the two faces of the geocomposite;

c) Calculate the maximum applied pressure, the hydraulic gradient and the design input flow rate for the geocomposite;

d) Select one or more geocomposites and, for each of them, calculate the available flow rate for the design conditions of materials in contact with the two faces, maximum applied pressure, and hydraulic gradient;

e) Compare the available flow rate with the design input flow rate and consider only the geocomposites for which the former is larger than the latter;

f) Make the final selection of the geocomposite;

g) Provide design specifications and details, in particular the method for fixing the geocomposites on the supporting surface and the connections/overlaps between geocomposite rolls and between the geocomposites and other elements of the drainage system (manholes, perforated pipes, etc.).

12.2 Calculation of input flow rate

12.2.1 General

The calculation of the input flow rate is project specific, therefore it is possible to provide indications only for the most common and simple cases.

12.2.2 Rainfall on sloping surface

The input flow from rainfall onto a sloping surface is of interest in many common situations: landfill bottom and side slopes (before capping), landfill capping, roads, railways, airports, roof gardens and deck pavements.

In all these cases there is a common calculation scheme applicable, as shown in Figure 5.

With reference to this scheme, the rainfall per unit area is given by Formula (1):

$$q_r = P / A_h \tag{1}$$

where

P is the rainfall flow rate (m^3/s);

A_h is the horizontal area (m^2);

q_r is the rainfall per unit horizontal area ($m^3/s/m^2$).

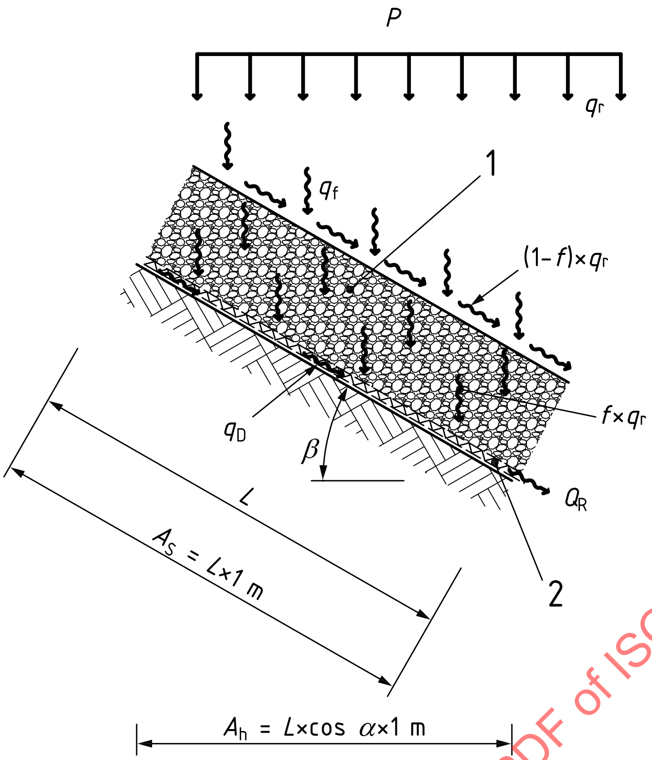
Since the actual surface is sloping, the effective rainfall per unit sloping area is given in Formula (2):

$$q_s = q_r \cdot \cos \beta \tag{2}$$

where

q_s is the rainfall per unit sloping area ($m^3/s/m^2$);

β is the slope angle (deg).



Key

1 soil or waste or no cover material

2 geocomposite

Figure 5 — Scheme for the calculation of the input flow rate in case of rainfall on sloping surface

Not all the rainfall reaches the drainage system, since a part of it becomes runoff; therefore, the input rainfall is given by Formula (3):

$$q_D = f \cdot q_s = f \cdot q_r \cdot \cos\beta \qquad (3)$$

where

f is the coefficient of infiltration;

q_D is the rainfall per unit sloping area entering the drainage system ($m^3/s/m^2$).

The input rainfall collects along the slope to produce the flow rate Formula (4):

$$Q_R = q_D \cdot L = f \cdot q_r \cdot L_h \qquad (4)$$

where

L is the length of the slope (m);

L_h is the horizontal length of the slope (m);

Q_R is the input flow rate per unit width of slope due to rainfall ($m^3/s/m$).

The rainfall per unit area q_r can be calculated knowing the rainfall intensity j. According to the principles of hydrology it is possible to compute j by the formula of the pluviometric curve relative to the specific hydrologic region, which is usually written in the form given in Formula (5):

$$h_r = a \cdot t^n \quad (5)$$

Therefore Formula (6) gives:

$$j = h_r / t = a \cdot t^{n-1} \quad (6)$$

where

h_r is the height of rainfall (mm);

t is the duration of the rainfall (h);

j is the rainfall intensity (mm/h);

a is the parameter of the pluviometric curve (mm/h^n);

n is the exponent of the pluviometric curve (dimensionless).

Finally, to pass from j(mm/h) to q_r(m^3/s/m^2 = m/s), Formula (7) applies:

$$q_r = j \cdot 2{,}777 \cdot 10^7 \quad (7)$$

Hence the input flow rate due to rainfall is given in Formula (8):

$$Q_R = 2{,}777 \cdot 10^7 \cdot a \cdot t^{n-1} \cdot L \cdot f \cdot \cos\beta \quad (8)$$

or Formula (9):

$$Q_R = 2{,}777 \cdot 10^7 \cdot j \cdot L \cdot f \cdot \cos\beta \quad (9)$$

It is evident that the rainfall intensity depends on the rainfall duration being considered and hence such parameters may be carefully selected based on the type of application and/or on hydrologic considerations.

Only the most intense rainfalls, occurring during storm events, are meaningful for the geocomposite drainage system design, while the long duration rain events with low intensity do not produce high water flows. Additionally, very intense yet very short rainfall events might not produce the highest input flow rates for the geocomposite, since the soil absorbs the rain and delays the filtration flow to a great extent.

Therefore, a general rule is to consider rainfall durations of 0,5 h to 1 h.

When the hydrologic parameters of the pluviometric curve are not available, Formula (9) is used and the rainfall intensity j for the duration of 1 h may be estimated or provided by local authorities/agencies.

There are many situations where an additional input flow in the geocomposite needs to be considered, for example, if there is an upstream slope that produces runoff, a pipe discharging water on the ground surface just upstream of the geocomposite or if there is a higher roof that discharges the water on the roof garden below.

In all these cases the additional surficial flow rate per unit width of slope, Q_S, may be evaluated and added to the rainfall generated flow rate Q_R.

Finally, the design input flow rate can be calculated as given in Formula (10):

$$Q_D = F_{S,Q} \cdot (Q_R + Q_S) \quad (10)$$

where

$F_{S,Q}$ *is* the Factor of Safety on input flow rate;

Q_R is the input flow rate due to rainfall (m^3/s/m or l/s/m);

Q_S is the input flow rate due to additional surficial flow (m^3/s/m or l/s/m);

Q_D is the design input flow rate in the geocomposite (m^3/s/m or l/s/m).

12.2.3 Filtration from soil or rock

The condition of input flow produced by water filtration from soil or rock is common to several situations of practical interest: vertical walls, reinforced slopes, drainage trenches, tunnels.

Only with tunnels is there no simple method for calculating the input flow. Instead, it needs to be evaluated on the basis of project specific geological and geotechnical analyses.

In the other cases the common feature is that the geocomposite is placed vertically or in a near-vertical position within the soil.

Therefore, in most cases the input flow is originated by the rainfall on the ground surface, which subsequently infiltrates the ground and reaches the drainage geocomposite following more or less curved filtration patterns.

The correct method for calculating the input flow in the geocomposite would be to use the well-known methods of filtration hydraulics: draw the flow net of the filtration water towards the draining geocomposite and then integrate the incoming flow over the whole length of the geocomposite. Such calculation can be carried out using commercially available software.

However, a simpler method is to define the catchment area for the geocomposite, based on the surface slopes of the ground surface, and to assume that the total flow that infiltrates the ground and reaches, sooner or later, the geocomposite is given by the total rainfall on the catchment area multiplied by the infiltration coefficient *f*. If such a coefficient is properly selected, this simple method results in a conservative rate.

Including the hypothesis that the filtration flow reaches the geocomposite in a uniform way along its entire width, the flow rate in the geocomposite due to rainfall on the catchment zone is given in Formula (11):

$$Q_F = 2{,}777 \cdot 10^7 \cdot a \cdot t^{n-1} \cdot (A_c / B_g) \cdot f \quad (11)$$

or Formula (12):

$$Q_F = 2{,}777 \cdot 10^7 \cdot j \cdot (A_c / B_g) \cdot f \quad (12)$$

In this case there is still the possibility of an additional input flow in the geocomposite, produced for example by an upstream slope that produces runoff or by a pipe discharging water on the ground surface inside the catchment zone. In these situations, the additional surficial flow rate per unit running width of wall, Q_S, may be evaluated and added to the filtration generated flow rate Q_F.

Hence the input flow rate in the geocomposite is given in Formula (13):

$$Q_D = F_{S,Q} \cdot (Q_F + Q_S) \quad (13)$$

where

Q_F is the total rainfall flow on the catchment zone (m³/s or l/s)

A_c is the horizontal area of the catchment zone (m^2)

B_g is the running width of the geocomposite drain (m)

Q_S is the input flow rate due to additional surficial flow (m^3/s/m or l/s/m)

$F_{S,Q}$ *is* the Factor of Safety on input flow rate (dimensionless)

Q_D is the input flow rate in the geocomposite (m^3/s/m or l/s/m)

In general, it can be assumed that $F_{S,Q}$ = 1,30 but engineering judgement may be applied to define the appropriate value for the specific project conditions.

12.3 Calculation of available flow rate

12.3.1 Hydraulic gradient

The flow velocity inside a geocomposite is proportional to the hydraulic gradient *i* which is defined as given in Formula (14):

$$i = \delta h / L \qquad (14)$$

where

δh is the hydraulic head loss along the distance L for the fluid flow in the geosynthetic (m);

L is the distance between two points along the average direction of flow in the geosynthetic (m).

Since the design of the drainage system ensures that the available flow rate of the geocomposite is always larger than the design input flow rate, pressure flow will never occur, and the flow will always occur at atmospheric pressure.

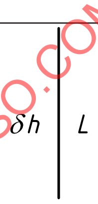
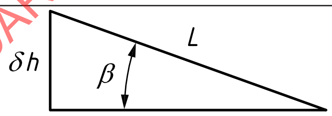
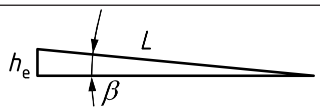
	Vertical flow: $\delta h = L$, hence i = 1,00
	Flow on slope: $\delta h = L \sin \beta$, hence $i = \sin \beta$ e.g. if β = 30°:i = 0,50
	Flow on flat slope: $\delta h = L \sin \beta$, but $\sin \beta \sim \tan \beta = \delta h / L$ e.g. if h_e / L = 2 %: i = 0,02

Figure 6 — Types of fluid flow for defining the hydraulic gradient

With reference to Figure 6, in such conditions only three cases can occur for the hydraulic gradient:

— Vertical fluid flow: if the liquid flows vertically in the geocomposite at atmospheric pressure, the head loss over a vertical distance L is equal to that distance itself. Hence for vertical flow $\delta h = L$ and therefore Formula (15) applies:

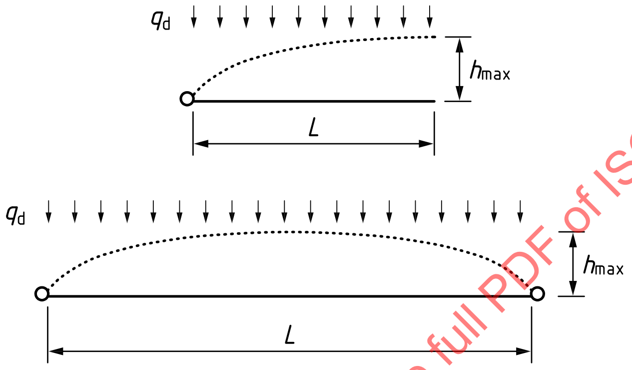
$$i = 1{,}00 \quad (15)$$

— Flow along a slope: when the geocomposite is placed on a slope inclined at an angle α to the horizontal, the distance L travelled by the fluid represents the hypotenuse of a right triangle while the head loss δh represents the vertical cathetus. Therefore, for flow along a slope Formula (16) applies:

$$i = \sin\beta \quad (16)$$

— Flow along a flat slope: when the geocomposite is placed on an almost horizontal slope, it is possible to approximate the hypotenuse of the right triangle with its horizontal cathetus; effectively, tan α can substitute sin α and therefore for flow along a flat, sub-horizontal slope Formula (17) applies:

$$i \sim \tan\beta = \delta h / L \quad (17)$$



Key

q_d uniform rainfall per unit area

h_{max} maximum height of the free surface water level

L length of water flow

NOTE Adapted from *Comité Français des géosynthétiques*, 2014[10].

Figure 7 — Evaluation of the hydraulic gradient for a perfectly horizontal geocomposite with water outlet at one end or at both ends

If the geocomposite is perfectly horizontal, then $\beta = 0$ and $L = L_h$. If one or both ends of the geocomposite are at atmospheric pressure (Figure 7), the hydraulic head at the other end or at mid length of the geocomposite still produces a hydraulic gradient, whose average value is given in Formula (18) and Formula (19):

— For water outlet at one end only: $i_0 = h_{max} / L$ (18)

— For water outlet at both ends: $i_0 = h_{max} / (L/2)$ (19)

where

h_{max} is the maximum height of the free surface water level (m)

L or $L/2$ is the length of water flow (m)

12.3.2 Discharge capacity

The discharge capacity of a geocomposite can be given in terms of:

— Transmissivity = discharge per unit width of the geocomposite and per unit of hydraulic gradient as given in Formula (20):

$$\vartheta = (q_m / B) / i \tag{20}$$

— Specific flow rate = discharge per unit width in the geocomposite, under a specified hydraulic gradient as given in Formula (21):

$$Q = q_m / B \tag{21}$$

where

θ is the transmissivity of the geocomposite (l/s/m or m^3/s/m);

B is the width of geocomposite specimen in the flow rate test (m);

q_m is the measured flow rate for a geocomposite specimen of width B (l/s or m^3/s);

Q is the specific flow rate per unit width of the geocomposite (l/s/m or m^3/s/m).

NOTE θ decreases if i increases, hence it is often misleading: as example, $\theta = 10^{-3}$ m^2/s with i = 0,10 in reality means a flow rate of 10^{-4} m^2/s; the same value $\theta = 10^{-3}$ m^2/s with i = 0,01 in reality means a flow rate of 10^{-5} m^2/s;. to avoid this potential confusion, internationally only the specific flow rate Q is used.

12.3.3 Pressure applied to the geocomposite

The evaluation of the pressure applied to the geocomposite is of fundamental importance in the design process.

The applied pressure depends on the position of the geocomposite and the characteristics of materials placed against it.

The situations of practical interest can be divided into two classes:

a) Geocomposite placed on flat or sloping surface (Figure 8), such as for roof gardens or landfill capping. In this case the applied pressure p (kPa) is produced by the overburden weight of the soil or material placed on the geocomposite plus the distributed surcharge on the ground surface (such as in the case of drainage of a road embankment) as given in Formula (22):

$$p = \gamma \cdot H + w_s \tag{22}$$

where

γ is the saturated unit weight of the soil or material placed on the geocomposite (kN/m^3);

H is the thickness of the soil or the material placed on the geocomposite (m);

w_s is the distributed surcharge on the ground surface (kPa).

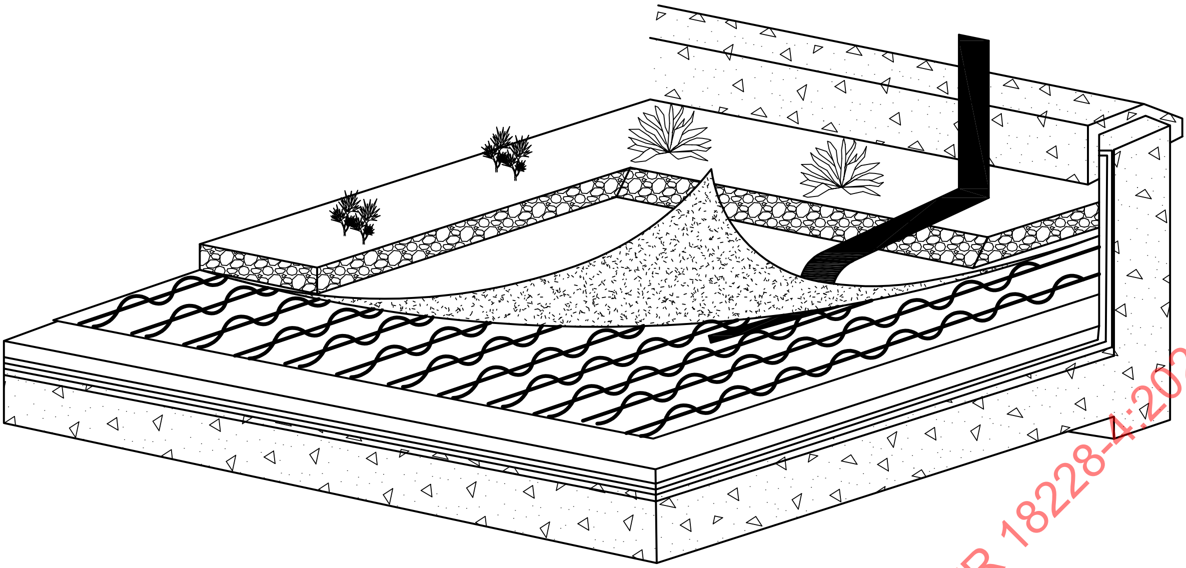


Figure 8 — Example of a geocomposite placed on a flat or sloping surface

b) Geocomposite placed vertically (Figure 9), such as for walls or drainage trenches. In this case the applied pressure p (kPa)is produced by the active thrust of the soil against the geocomposite. Therefore, the applied pressure p has a triangular distribution over the height of the geocomposite and the maximum pressure occurs at the lowest point of the geocomposite (usually coincident with the base of the wall or the bottom of the trench) as given in Formula (23):

$$p = (\gamma \cdot H_1 + w_s) \cdot K_a = (\gamma \cdot H_1 + w_s) \cdot \tan^2 (45° + \phi / 2) \quad (23)$$

where

γ is the saturated unit weight of the soil (kN/m^3);

H_1 is the depth of the lowest point of the geocomposite below the ground surface (m);

q is the distributed surcharge on the ground surface (kPa);

K_a is the coefficient of active pressure of the soil (dimensionless);

φ is the friction angle of the soil (deg or °).

In other situations, like in tunnels, the applied pressure may be evaluated for the specific case.

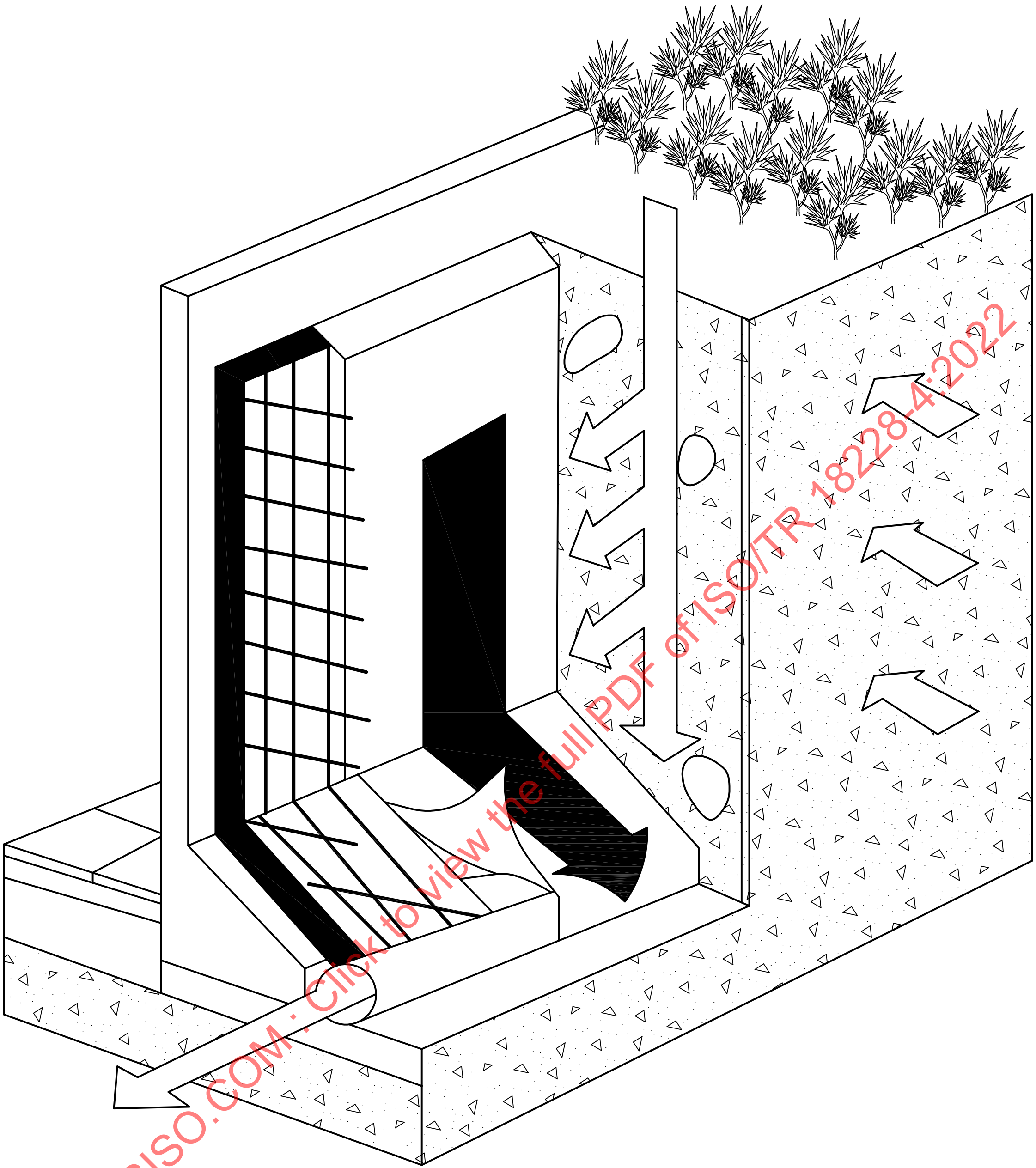


Figure 9 — Example of a geocomposite placed vertically

12.3.4 Materials in contact with the faces of the drainage geocomposite

The available flow rate of a geocomposite will greatly depend on the types of material in contact with its two faces.

As Figure 10 shows, it is evident that a very rigid material (concrete walls, HDPE geomembrane in landfills, etc.) will compress and will deform the geocomposite very evenly, imparting a homogeneous decrease in its thickness but without pushing the geotextile into the channels of the draining core. Hence rigid materials produce negligible geotextile intrusion into the core. Conversely, a soft material (like a soil) in contact with the geocomposite will deform the geotextile, forcing the geotextile to intrude into the draining core, with a resulting reduction in the cross-sectional area of the draining core and commensurate decrease of the draining capacity. Therefore, with reference to Figure 10, the available flow rate of a geocomposite with a given structure will be a function of:

— thickness of the geocomposite (t);

— distance (L_{sp}) between the support points of the geotextile filter;

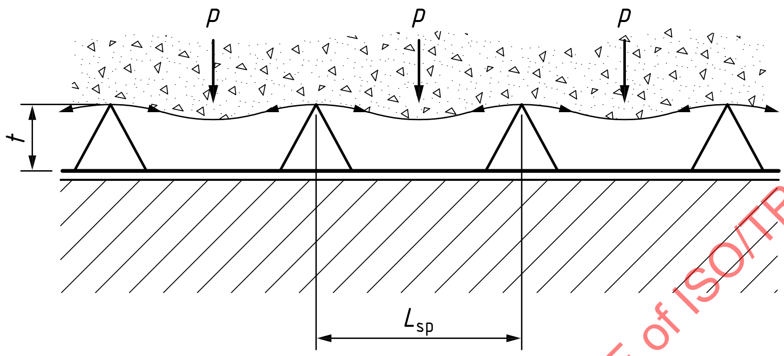
— pressure (p) on the filter;

— strength, modulus and tensile creep of the geotextile filter;

— deformability of the material in contact with the geocomposite; and

— roughness of the geotextile filter.

The impact of these factors is very relevant, and the test results are highly influenced by the interface condition, whether rigid - rigid, rigid -soft or soft-soft contacts.



Key

t geocomposite thickness

L_{sp} distance between geotextile support points

p applied pressure

Figure 10 — Decrease of draining cross-sectional area in a geocomposite in contact with a soft material (like soil or waste)

12.3.5 Compressive behaviour of geocomposites

Depending on the type of drainage core, all geocomposites will be typically subjected to short term compression and compressive creep under the applied loads and pressures. In general, an increase of load will lead to a reduction, gradual or sudden, in the thickness of the core.

It is possible to identify two types of behaviour of the draining cores under sustained compressive loads (Figure 11):

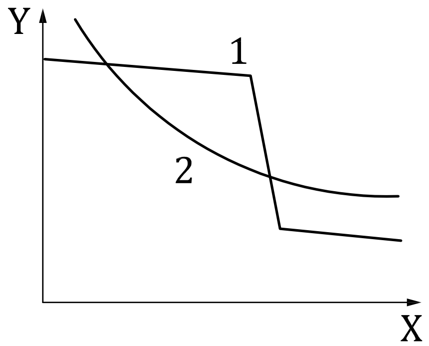
— Compressible cores, without any defined point of collapse; and

— Collapsible cores, with a well-defined point of collapse.

The drainage capacity of geocomposites is directly proportional to the thickness of the core and therefore the reference value of the flow rate may be determined only when the applied loads and the geocomposite have reached equilibrium and there will be no further reduction of thickness and drainage capacity.

Compressible drains achieve this equilibrium in a few hours, while for the collapsible ones, equilibrium is more difficult to determine.

For collapsible drains it is incorrect to extrapolate long term behaviour on the basis of data obtained with short term compression tests. Given that after the collapse, the drain assumes an indefinite form, the measure of its drainage capacity will be meaningful only at lower pressures than the critical load. The moment of collapse not only depends on the critical pressure, but also on the duration of loading (Figure 12); a shorter time to collapse corresponds to higher sustained loads.



Key

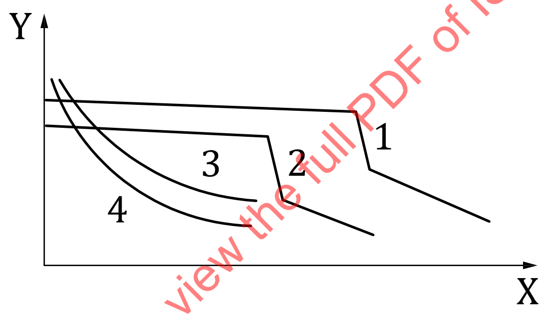
X pressure

Y thickness

1 collapsible cores

2 compressible cores

Figure 11 — Effects of pressure on the thickness of the draining cores of geocomposites



Key

X time

Y thickness

1 collapsible core under pressure of 50 kPa

2 collapsible core under pressure of 100 kPa

3 compressible core under pressure of 50 kPa

4 compressible core under pressure of 100 kPa

Figure 12 — Effects of pressure and load duration on the thickness of draining cores

Therefore, for collapsible cores, there is the need for a full compressive creep testing programme, in order to define the time to collapse for each value of the applied pressure. The limit pressure may be determined as the pressure at which the time to collapse is equal or larger to the design lifetime of the geocomposite.

Some types of drainage core show higher tendency to behave as collapsible drain, anyway the compressible or collapsible behaviour depends both on the property of the core and the boundary conditions. Therefore, it is important to evaluate, at design stage, if for the project conditions a geocomposite drain will be expected to behave as compressible or collapsible.

The levels of pressure to which drainage geocomposites may be subjected vary greatly from one application to another. This can be from 10 kPa under a layer of topsoil in a roof garden up to 500 kPa as a leachate collection layer at the bottom of a landfill or at the base of a very high embankment (around 25 m). Higher loads are possible but are very uncommon.

It is impossible that one geocomposite is applicable for this wide range of pressures and so each geocomposite grade is selected to suit the specific conditions of use.

Considering this, the conditions of use can be divided into three main classes:

— Applications where high flow rates are required with low applied pressures (e.g. roof gardens, landfill capping);

— Applications where relatively low flow rates are required with high applied pressures (e.g. leachate collection at landfill bottom, base drainage under tall embankments);

— In special cases there maybe applications where high flow rates are required with high applied pressures (e.g. specific conditions in tunnel or mine drainage).

Nevertheless, the final selection of a drainage geocomposite can be made only after performing calculations according to the present design method.

Usually more than one product fulfils the design requirements; hence the final decision may consider also selling price, availability, transportation costs, and other criteria.

12.3.6 Factors influencing the available flow rate

The available flow rate for a specific geocomposite depends on the following factors:

— Type and characteristics of the draining core;

— Type and characteristics of the filter geotextiles, and process of bonding to the draining core;

— Characteristics of the materials in contact with the two faces of the geocomposite;

— Applied pressure;

— Load duration (usually equal to the design life); and

— Hydraulic gradient for the flow inside the geocomposite core.

For the materials in contact with the two faces of the geocomposite, as stated above, a “soft” material will produce a more pronounced intrusion of the geotextiles into the draining core, while a “rigid” material will produce practically no intrusion of the geotextiles into the draining core.

Considering that the geocomposite has two faces, there are only three possible combinations:

— Rigid–Rigid contacts (R/R);

— Rigid–Soft contacts (R/S);

— Soft–Soft contacts (S/S).

Each application of geocomposites exhibits typical boundary conditions and therefore for each application, the flow rate may be measured with the appropriate contacts.

Typical contacts for various applications are listed in Table 2.

Although a preliminary guideline, each project may be properly evaluated.

Table 2 — Typical contacts for various applications

Rigid–Rigid contacts	Rigid–Soft contacts	Soft–Soft contacts
— GCD for leakage detection in landfills, between two geomembranes — GCD between shotcrete and structural arch in tunnels	— GCD behind retaining walls — GCD in a capping package or for leachate collection in landfills, in contact with geomembrane at the bottom and soil/gravel on top — GCD for roof gardens or vegetated terraces	— GCD inside a draining trench — GCD under a road or railway embankment — GCD in parking areas — GCD behind a reinforced slope

12.3.7 Laboratory tests for water flow capacity of geocomposites

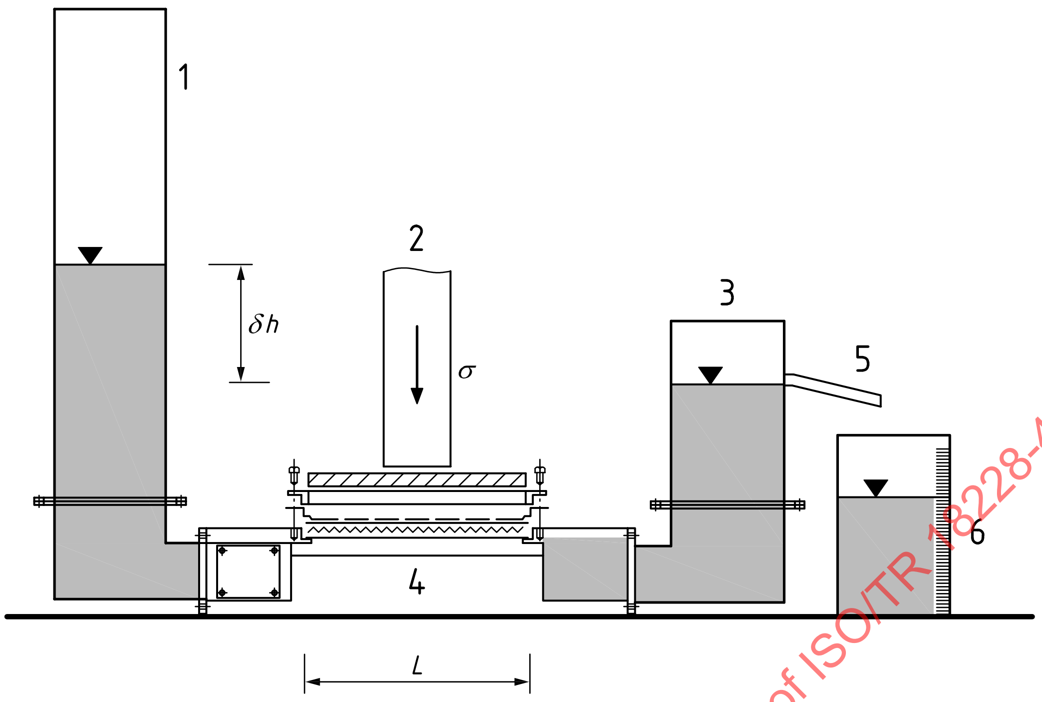
Since the intrusion of the geotextile into the draining core occurs in a different way for each geocomposite and for each type of contact, it is fundamental that the water flow capacity is measured with an apparatus which can reproduce all the possible conditions of use:

— Materials in contact with the two faces;

— Applied pressure;

— Hydraulic gradient.

The water flow capacity in the plane of draining geocomposites can be measured according to the ISO 12958-1 test standard for index tests and according to ISO 12958-2 test standard for performance tests. The scheme of the testing apparatus is shown in Figure 13 and with such apparatus it is possible to reproduce all the above-mentioned conditions of use.



Key

1 upstream chamber
2 uniform pressure application system
3 downstream chamber
4 specimen
5 weir
6 volume or flow measuring unit
δh hydraulic head drop
σ uniform applied pressure
L specimen length between water inlet and outlet

Figure 13 — Schematic of the apparatus for measuring the water flow capacity in the plane of drainage geocomposites, according to ISO 12958-1 and ISO 12958-2.

About the evaluation of short term and long-term water flow capacity of draining geocomposites, attention is drawn to the following points:

1) The soft contact of ISO 12958-1 is suitable for getting standard test conditions, but for a specific project it is advisable to perform the flow rate test using the specific materials in contact with the geocomposite (soil, waste, etc.), according to ISO 12958-2.

2) Even with Rigid–Rigid contacts the full draining geosynthetics may be tested, without removing the geotextile (if present).

3) Even if the client or contractor purchases the draining core and the filter geotextile separately, the test may always be performed on the full geocomposite, either assembled at site or bonded at the factory.

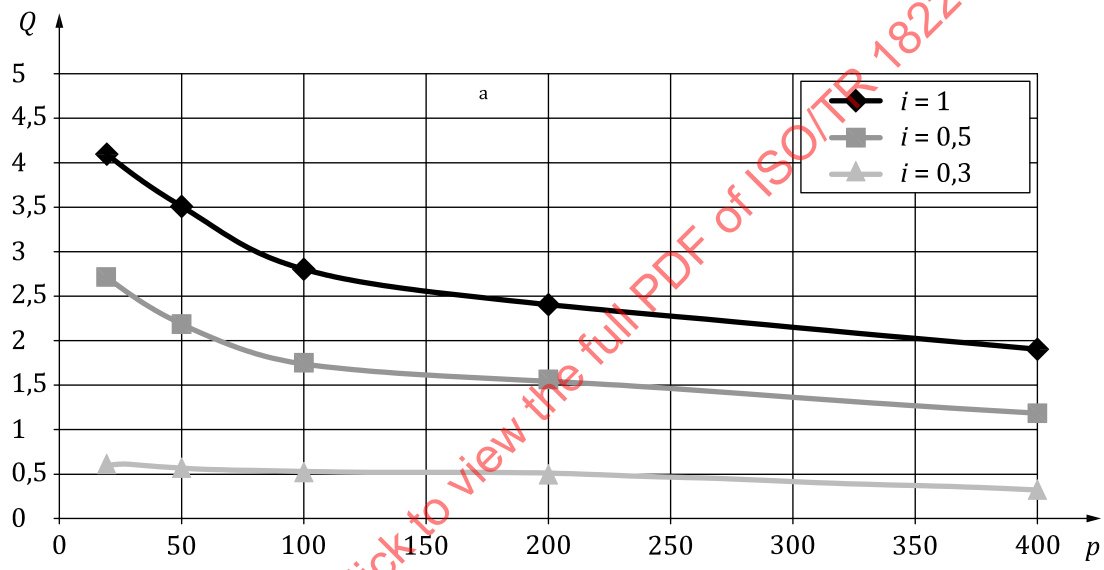
4) In case of anisotropic geocomposites, depending on the flow direction in the actual conditions of use/installation on site, the water flow capacity either in the machine direction or in the cross-machine direction may be considered[10].

5) In case of geocomposites with discrete draining elements (Figure 2) some soil arching can occur, depending on the geometry of the product, the applied pressure, the type of soil. It is the

responsibility of the supplier to provide data and criteria for evaluating the behaviour of specific products under long term compressive loads.

6) In case of geocomposites with discrete draining elements (Figure 2), all the previous and following considerations fully apply to all components of the geocomposite (e.g. geotextiles and discrete draining elements), hence compressive creep, geotextile intrusion, chemical and biological clogging may be addressed for determining the long-term available flow rate. Moreover, care needs to be taken in the evaluation of the available flow rate for these products: the contribution of the geotextiles and the spacing of the discrete draining elements may be properly considered. Indications and formulas for determining the in-plane water flow of these products are provided in ISO 12958-1 and ISO 12958-2.

7) The general procedure described for evaluating the available flow rate is assumed to be applicable to all planar draining geosynthetics. It is the responsibility of the supplier to provide data and criteria for evaluating the available flow rate for specific products.



Key

p applied pressure *p* (kPa)

Q specific flow rate *Q* (l/s/m)

a contacts R - R (or R – S, or S - S)

i hydraulic gradient *i* (dimensionless)

Figure 14 — Typical diagram showing the results of the water flow capacity tests for a drainage geocomposite

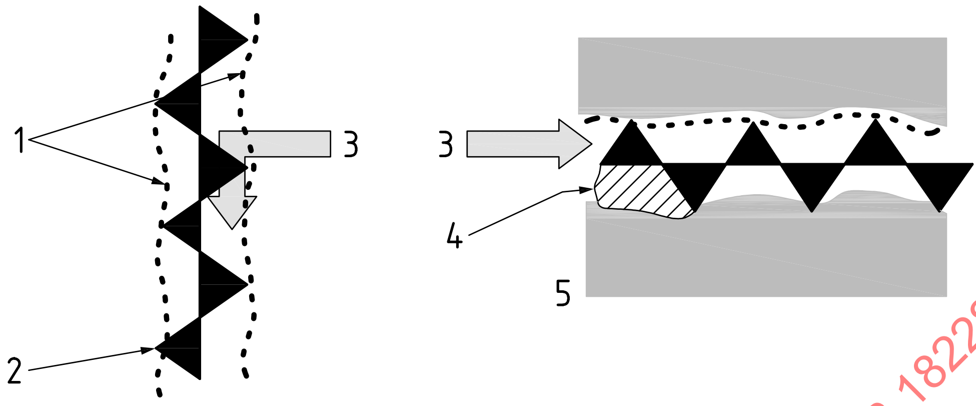
Testing results are usually summarized in diagrams giving the specific flow rate *Q* (m^3/s/m or l/s/m) vs the applied compressive stress (in terms of uniform applied pressure) *p* (kPa). A typical diagram is shown in Figure 14.

12.3.8 Specific situations

When the geocomposite includes an impermeable drainage core (e.g. a cuspated sheet) and the flow to drain penetrates only from one face of the geosynthetic (see Figure 15), the flow capacity test may be performed on a specimen purposely prepared in order to prevent the input flow along one of the two faces of the impermeable core (as example by placing a rubber or mastic strip at the inlet of the specimen, as shown in Figure 15).

If the flow collected by the geosynthetic is transported on both sides of the impermeable core to the outlet (see Figure 16), the flow capacity tests may be carried out using contacts as appropriate to the proposed usage[10].

When the geocomposite with an impermeable core is not planarly continuous, but it is used in the form of discrete narrow strips, the input flow in the geocomposite strips can also occur laterally (Figure 17) and be transported on both sides of the impermeable core. In this case the flow capacity tests may be carried out using contacts as appropriate to the proposed usage[10].



Key

1 geotextile

2 impermeable draining core

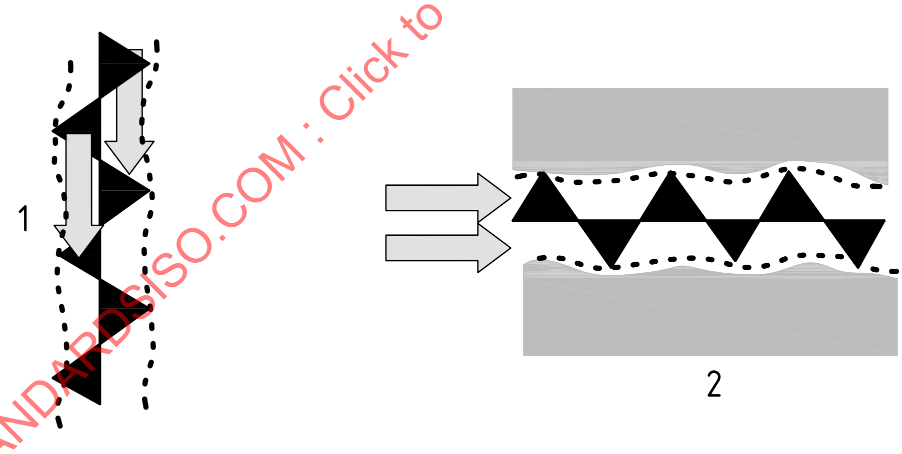
3 input flow

4 rubber or mastic

5 contacts as appropriate to the proposed usage with input flow prevented on one side of the core

NOTE Adapted from *Comité Français des géosynthétiques*, 2014[10].

Figure 15 — Test conditions for the measurement of the discharge capacity in the case where water penetrates only from one side of the geosynthetic



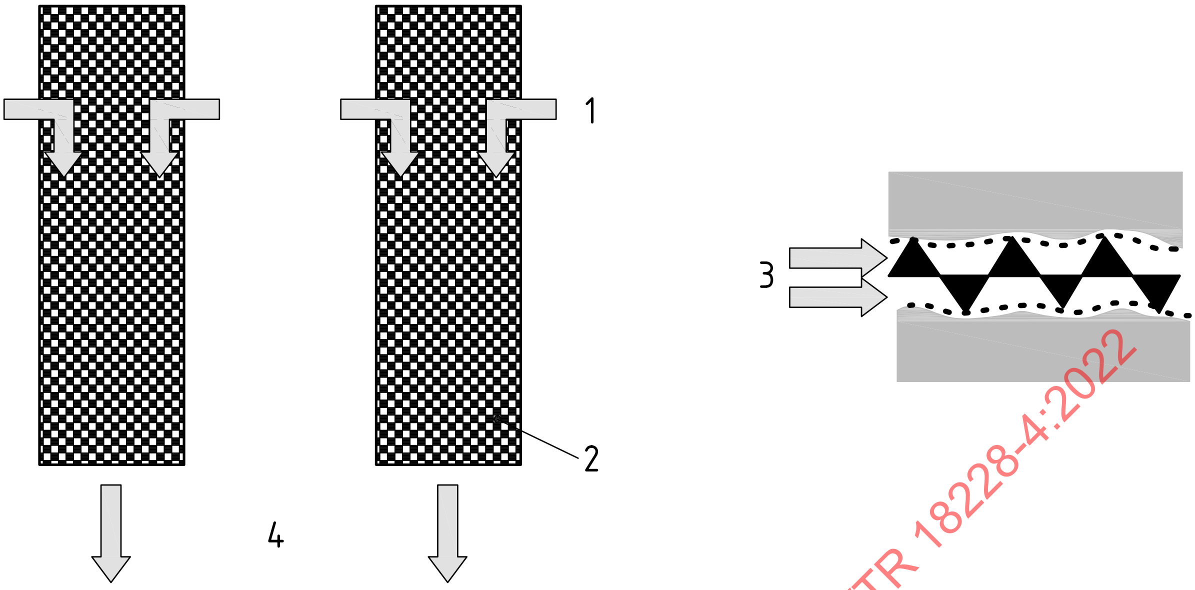
Key

1 flow on both sides of the draining core

2 contacts as appropriate to the proposed usage on the geocomposite with 2 geotextile filters

NOTE Adapted from *Comité Français des géosynthétiques*, 2014[11].

Figure 16 — Test conditions for measurement of flow capacity in the case where water is transported from both sides of the impermeable core



Key

1 input flow

2 geocomposite strip with impermeable draining core

3 contacts as appropriate to the proposed usage on the geocomposite with 2 geotextile filters

4 plan view

NOTE Adapted from *Comité Français des géosynthétiques*, 2014[10].

Figure 17 — Test conditions for measuring the flow capacity in case water can also enter laterally and can be carried on both sides of the impermeable core

12.3.9 Flow rate versus hydraulic gradient

If the flow rate is to be evaluated for a gradient i_0 different from the closest higher value i_1 used for testing (as example, one of the i values shown in Figure 14), it is possible to evaluate the specific flow rate for the actual hydraulic gradient i_0 by Formula (24) (Cancelli and Rimoldi,1989):

$$Q_{i_0} = Q_{i_1} \cdot \sqrt{\frac{i_0}{i_1}} \quad (24)$$

where

Q_{i_1} is the specific flowrate for the i_1 gradient from the diagram in Fig.14 (l/s/m or m^2/s);

Q_{i_0} is the specific flowrate for the actual i_0 gradient (l/s/m or m^2/s);

i_1 is the hydraulic gradient on the diagram in Fig.14, immediately higher than the actual hydraulic gradient (dimensionless);

i_0 is the actual hydraulic gradient (dimensionless).

The above formula can be easily obtained by considering that the flow in the geocomposite is not a laminar filtration flow but a free surface turbulent or transitional flow, under the hypothesis that the water in the geocomposite is always at atmospheric pressure and it never goes under pressures higher than the atmospheric one.

The free surface flow in fully turbulent flow conditions inside the geocomposite follows the Chezy formula (Chow, 1959) given in Formula (25):

$$Q_v = A_g \cdot \chi \sqrt{R \cdot i} \qquad (25)$$

where

Q_v is the discharge or volumetric flow rate (m^3/s)

A_g is the cross-sectional area of the geocomposite (m^2);

χ is the parameter depending on the roughness of the flow surface ($m^{1/2}/s$);

R is the hydraulic radius of the flow conduit (m).

The Chezy Formula (25) reflects the experimental observations that in free surface and fully turbulent flow conditions the flow rate is proportional to $i^{0,50}$; in other words, for a geocomposite the Chezy formula can be expressed as given in Formula (26):

$$Q = C \cdot i^n \qquad (26)$$

where

Q is the specific flowrate (l/s/m or m^2/s);

C is the parameter as a function of geometry and roughness of the flow surface (l/s/m or m^2/s);

n is 0,50 in free surface and fully turbulent flow conditions.

Hence the flow rate in the same geocomposite at two different hydraulic gradients will be:

$$Q_{i1} = C \cdot {i_1}^{0,50} \qquad (27)$$

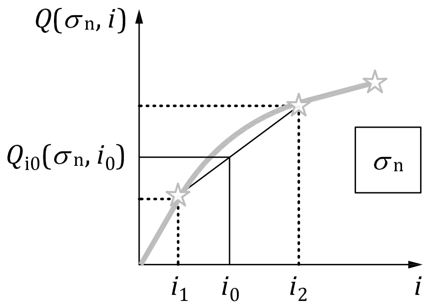
$$Q_{i0} = C \cdot {i_0}^{0,50} \qquad (28)$$

Therefore, the ratio of the two flow rates (Formulas 27 and 28) results in Formula (24).

It is possible to get Q_{i0} with another approximate method[10]. If the results of flow rate tests are plotted as the flow rate Q vs the gradient i, then Q_{i0} can be obtained by linear interpolation between the test values for the gradients i_1 and i_2 immediately above and below i_0, as shown in Figure 18.

The disadvantage of this method is that it is valid only if the actual applied pressure σ_{no} is equal to the pressure σ_n applied in lab tests.

If the actual applied pressure σ_{no} is not equal to the pressure σ_n applied in lab tests, one further interpolation is required between the value Q_{i0} obtained for the applied pressure σ_{n1} and σ_{n2} applied in lab tests, immediately below and above the actual applied pressure σ_{no}.



Key

σ_n	the pressure applied in lab tests
i	the hydraulic gradient
i_1, i_2	the hydraulic gradients applied in lab tests
i_o	the actual hydraulic gradient
$Q(\sigma_n , i)$	the flow rate evaluated for the values $\sigma_{n, i}$
$Q_{i0}(\sigma_n , i_0)$	the flow rate evaluated for the values σ_n, i_0

NOTE Adapted from *Comité Français des géosynthétiques*, 2014[10].

Figure 18 — Procedure to get Q_{i0} from Q vs i plot of laboratory flow rate test

12.3.10 Flow rate versus viscosity

Moreover, standard tests are performed using water at 20 °C.

It is possible to calculate the specific flow rate for another temperature or liquid viscosity with Formula (29).

$$Q_T = Q_{20} \cdot \left(\frac{\mu_{20}}{\mu_T}\right) = Q_{20} \cdot C_T \tag{29}$$

where

Q_{20}, Q_T	are the specific flow rate at 20 °C and T °C;
μ_{20}, μ_T	are the viscosity of water at 20 °C and T °C;
$C_T = (\mu_{20} / \mu_T)$	is the correction factor for temperature and viscosity.

According to the formulas reported in ISO 12958-1 and ISO 12958-2, C_T (dimensionless) can be determined with Formula (30):

$$C_T = \left(\frac{\mu_{20}}{\mu_T}\right) = \frac{1+0{,}0337T+0{,}00022T^2}{1{,}762} \tag{30}$$

where

μ_T is the dynamic viscosity at T °C, in centiPoises (cP) = milliPascal·seconds (mPa·s), given by Formula (32):

$$\mu_T = \frac{1{,}78}{1+0{,}0337T+0{,}00022T^2} \tag{32}$$

where

T is the water temperature, in °C.

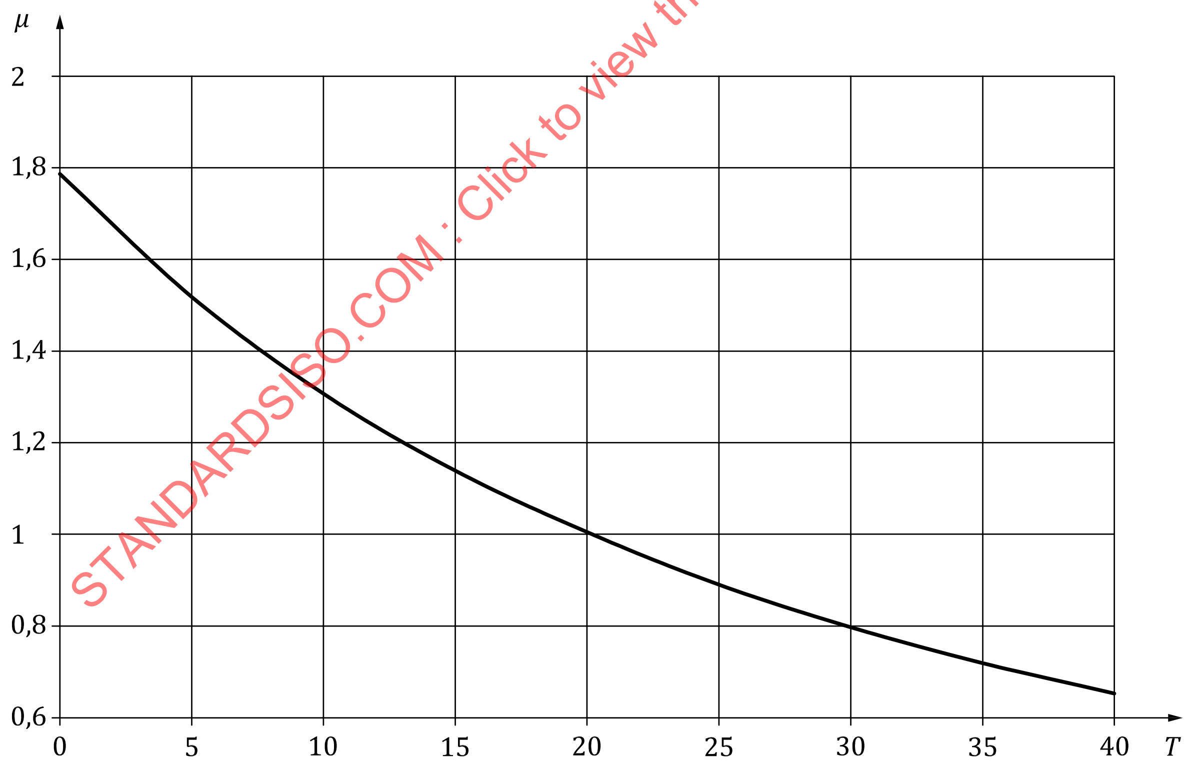
The values of the dynamic viscosity of water *μ* (in centiPoise = mPa·s) vs temperature *T* (°C) are listed in Table 3 and shown in the graph in Figure 19. The values of the dynamic viscosity of several liquids are listed in Table 4.

From Tables 3 and 4 it is evident that the temperature of the liquid to be drained heavily affects the available flow rate of the geocomposites, therefore the design temperature should be carefully evaluated. The most common situations are the following:

— Drainage of water from the surrounding soil or rock: the water temperature can be assumed to be approximately equal to the average yearly temperature of the specific place (as a rough indication: *T* = 10 °C to 15 °C in northern countries; *T* = 20 °C in countries with a moderate climate; *T* = 25 °C to 30 °C in equatorial countries with a hot climate);

Table 3 — Values of the dynamic viscosity of water vs temperature

T (°C)	*μ* (cP = mPa·s)
0	1,7870
5	1,5190
10	1,3070
15	1,1390
20	1,0050
25	0,890 4
30	0,797 5
35	0,719 4
40	0,652 9



Key

T temperature *T* (°C)

μ dynamic viscosity *μ* (cP = mPa·s)

Figure 19 — Dynamic viscosity of water vs temperature

Table 4 — Values of the dynamic viscosity of several fluids

Liquid	Dynamic viscosity (in cP = mPa·s)	Reference temperature
Acetic acid at 15 °C	1,310	15 °C
Acetic acid at 100 °C	0,430	100 °C
Ethyl alcohol at 20 °C	1,200	20 °C
Methyl alcohol at 20 °C	0,597	20 °C
Sulfuric acid at 20 °C	25,400	20 °C
Water at 0 °C	1,787	0 °C
Water at 4 °C	1,567	4 °C
Water at 8 °C	1,386	8 °C
Water at 20 °C	1,001	20 °C
Water at 40 °C	0,653	40 °C
Air at 18 °C	0,018	18 °C
Air at 40 °C	0,019	40 °C

— Drainage of leachate in landfills: the temperature in landfills during fermentation of waste can reach 40 °C to 50 °C; in any case the viscosity of leachate can be very different to that of clean water, hence it is advisable to evaluate the viscosity of the specific leachate.

12.3.11 General procedure for evaluating the available flow rate of the geocomposites

For all applications, the general procedure for evaluating the available flow rate of the geocomposites includes applying a set of Reduction Factors (Cancelli and Rimoldi, 1989; Koerner, 2012) which take into account all the phenomena that may decrease the flow rate over the entire design life compared to the short term flow rate measured in the tests according to ISO 12958-1 or ISO 12958-2 standards[2,3] as given in Formula (32):

$$Q_a = \frac{Q_L}{R_{F,in} \cdot R_{F,cr,Q} \cdot R_{F,cc} \cdot R_{F,bc} \cdot R_{F,L}} \tag{32}$$

where

Q_a is the available long-term flow rate for the geocomposite (l/s/m or m^2/s);

Q_L is the short-term flow rate obtained from laboratory tests with the appropriate boundary conditions l/s/m or m^2/s);

$R_{F,in}$ is the Reduction Factor for the intrusion of filter geotextiles into the draining core due to tensile creep of the geotextile, occurring after the short-term test (dimensionless);

$R_{F,cr,Q}$ is the Reduction Factor for the compressive creep of the geocomposite (dimensionless);

$R_{F,cc}$ is the Reduction Factor for chemical clogging of the draining core (dimensionless);

$R_{F,bc}$ is the Reduction Factor for biological clogging of the draining core (dimensionless);

$R_{F,L}$ is the Reduction Factor for overall uncertainties on laboratory data and field conditions (dimensionless).

The Reduction Factors may be set considering the specific conditions of each project, taking into consideration the experience and/or research on similar conditions of use. Project specific tests may also be used to define the proper R_F for each project condition.

Table 5 lists the indicative range of values of the different RF for drainage geocomposites.

Reduction Factors are product specific for any design condition, hence it is advisable to require specific data from suppliers and/or to perform project specific tests. Further indications are provided in Annex B.

Table 5 — Indicative range of values for the different RFs

Term	Description	Indicative range
$R_{F,in}$	Reduction Factor for intrusion of the filter geotextiles into the draining core	1,0 to 2,0
$R_{F,cr,Q}$	Reduction Factor for flow rate due to compressive creep of the core	1,0 to 6,0
$R_{F,cc}$	Reduction Factor for pore/volume reduction due to chemical clogging	1,0 to 1,5
$R_{F,bc}$	Reduction Factor for pore/volume reduction due to biological clogging (not including applications in landfills)	1,0 to 1,3
$R_{F,L}$	Reduction Factor for overall uncertainties on laboratory data and field conditions	1,0 to 1,5
Π R_F	**Product of all Reduction Factors for the site-specific conditions**	**1,0 to 35,1**

12.4 Selection of the geocomposite

Once the design input flow Q_D has been calculated, the available input flow Q_a may be calculated for one or more geocomposites.

The final Factor of Safety $F_{F,G}$ afforded by the design with each geocomposite is given in Formula (33):

$$F_{S,G} = Q_a / Q_D \qquad (33)$$

The final selection of the geocomposite may be done among the geocomposites for which Formula (34):

$$F_{S,G} \geq 1{,}00 \qquad (34)$$

12.5 Equivalence with a granular drainage layer

12.5.1 General

There are often situations where the original design specifications require a granular drainage layer, e.g. a thick layer of sand/gravel soil.

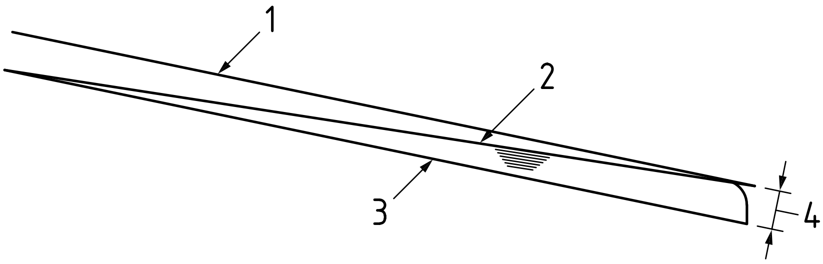
In such cases, the use of a draining geocomposite in place of the traditional drainage layer is possible only if it can be demonstrated that the geocomposite is "equivalent" to the sand/gravel layer in terms of hydraulic performance.

12.5.2 Equivalence for water flow on slopes

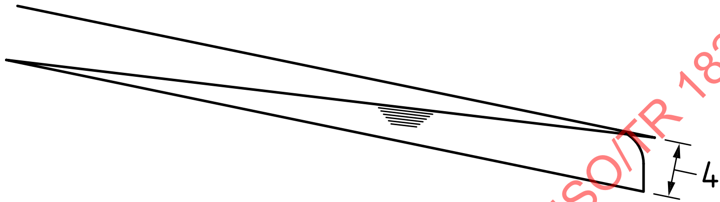
The problem of the hydraulic transmissivity equivalency between geosynthetics and granular soil layers on slopes has been analysed by Giroud et al (2000). Such analyses led to the conclusion that the unconfined liquid flow in a thin geocomposite and in the thick granular soil layer are different, as shown in Figure 20:

— In the thin geocomposite, the hydraulic gradient is constant, and the unconfined flow free surface is practically parallel to the slope.

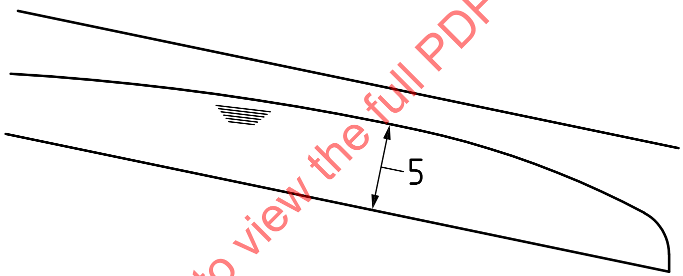
In the thick granular soil layer, the free water surface is steeper at the front, meaning that the hydraulic gradient is not constant but is increasing towards the outlet and therefore the actual water flow in the granular soil layer is higher than the value calculated with constant hydraulic gradient.



Case of a geosynthetic liquid collection layer at full capacity with unconfined flow



Case of a thicker geosynthetic liquid collection layer, also at full capacity with unconfined flow



Case of a granular soil layer with the maximum liquid thickness lower than the prescribed thickness of the granular soil layer

Key

1 upper boundary of liquid collection layer

2 liquid surface

3 lower boundary of liquid collection layer

4 geocomposite thickness t_{GCD}

5 maximum thickness h_{max} of liquid in the granular soil layer

NOTE The geosynthetic liquid collection layers are thin (e.g. thinner than approximately 20 mm). In contrast, the granular liquid collection layer is thick (thickness is typically 300 mm).

Figure 20 — Schematic representation of the shape of the liquid surface in liquid collection layers (Based on Giroud et al, 2000).

In other words, the flow in a thick granular soil layer used for drainage on a slope, is unconfined in most cases. In this condition, Darcy's law in Formula (A.2), which applies to confined filtration flow (that is when the piezometric line of the flow is always above the top surface of the granular soil layer), cannot be used directly since it provides a lower flow rate than that which occurs with the actual unconfined flow. The correct flow rate for unconfined flow can be obtained only by applying a correction factor to the flow rate calculated with Darcy's law.

The conclusion is that, considering a constant value of hydraulic gradient, the flow rate in the geocomposite is equivalent to the flow rate in the thick granular soil layer only if the equivalency coefficient defined by Giroud et al (2000) is applied.

It is important to consider that, when comparing the drainage capacity of geosynthetic drains with those of granular drainage materials, the comparison may be made on the same base: since the flow rate of geocomposites is evaluated at the end of their design life, even the permeability of the drainage aggregate may be evaluated in situ at the end of its design life, not as a laboratory value on fresh, clean material placed under ideal conditions.

As shown by Giroud et al (2000), based on preceding work by Giroud et al. (1992) and Giroud and Houlihan (1995), in unconfined flow conditions, the maximum thickness of liquid in a granular soil layer, h_{max} (m), is given by Formula (35):

$$h_{max} = j\frac{\sqrt{\tan^2\beta + 4q_h / K_{lt}} - \tan\beta}{2\cos\beta}L_h \tag{35}$$

where

β is the slope angle (deg or °);

q_h is the flow rate of liquid supply ($m^3/s/m^2$)

K_{lt} is the long-term permeability of the granular soil layer evaluated in situ at the end of its design life (m/s)

L_h is the horizontal length of the soil layer (m);

j is the factor of the Giroud theory (dimensionless).

When the liquid supply is due only to rainfall, q_h is equal to q_D from Formula (3).

The factor j has the expression given in Formula (36):

$$j = 1 - 0{,}12 exp\left\{-\left[log\left(\frac{8(q_h / K_{lt})}{5\tan^2\beta}\right)^{5/8}\right]^2\right\} \tag{36}$$

Therefore, the flow in the granular soil layer will be unconfined only if the layer thickness is larger than h_{max} from Formula (35); hence it may be:

$$t_{prescribed} \geq h_{max} \tag{37}$$

where

$t_{prescribed}$ is the prescribed thickness of the granular soil layer (m).

Formulas (35) and (36) are important because they define the minimum thickness required for the granular layer in order to be able to carry the full input flow rate q_h in conditions of free surface flow.

Once the correct minimum thickness of the granular soil layer has been set, satisfying Formula (37), it is then possible to calculate the equivalency coefficient for a geocomposite drainage layer, in order to afford the same flow rate as the granular soil layer considering an unconfined flow under the constant hydraulic gradient given by Formula (38):

$$E = \frac{1}{j}\left[1+\left(\left(\frac{h_{max}}{j \cdot L_h}\right)\cdot\left(\frac{\cos\beta}{\tan\beta}\right)\right)\right] \quad (38)$$

Assuming that the flow in the granular soil layer is unconfined, the equivalency concept translates into the minimum specific flow rate for the geocomposite in order to be able to carry the same flow rate of the granular soil layer as given in Formula (39):

$$Q_{GCD} = E \cdot q_h \cdot L_h Q_{GCD} \quad (39)$$

where

Q_{GCD} *is* the minimum short-term input flow rate for the geocomposite in order to be considered equivalent to the granular soil layer having thickness larger than h_{max} (m^3/s/m or l/s/m).

In this case the Factor of Safety $F_{S,G}$ is not normally applied.

The selection of one or more geocomposites equivalent to the granular drainage layer having thickness t_{max} can be performed with the following procedure:

— Calculate the available long-term flow rate Q_a for one or more geocomposites with Formula (32).

— For each geocomposite calculate the final Factor of Safety on equivalency $F_{S,E}$ as given in Formula (40):

$$F_{S,E} = Q_a / Q_{GCD} \quad (40)$$

— All the geocomposites for which Formula (41) applies:

$$F_{S,E} \geq 1{,}00 \quad (41)$$

may be considered equivalent to the granular soil layer having thickness $t_{prescribed} \geq t_{max}$.

Alternatively, when $t_{prescribed}$ has been previously set, there are two possible situations:

1) $t_{prescribed} \geq h_{max}$: in this case the flow in the granular soil layer is unconfined, and the same conditions as above apply; therefore, Q_{GCD} can be calculated as shown above;

2) $t_{prescribed} < h_{max}$: in this case the flow in the granular soil layer is confined; if the flow rate of liquid supply remains constant, the piezometric level in the granular soil layer will grow and the hydraulic gradient at outflow will grow as well, until an equilibrium is reached, such that the increased hydraulic gradient at outflow is enough to discharge all the incoming water supply; the equilibrium hydraulic gradient at outflow is unknown; therefore the evaluation of Q_{GCD} is necessarily approximate.

   In such case the calculation of Q_{GCD} can be performed using the following procedure, which provides an approximate solution:

   — Calculate the flow rate in the granular soil layer according to Darcy's law (hence assuming confined flow) Q_{Darcy} (m^3/s/m) as given in Formula (42):

   $$Q_{Darcy} = K_{lt} \cdot t_{prescribed} \cdot i \quad (42)$$

   — Calculate the equivalent flow rate of liquid supply in the granular soil layer at equilibrium q_h^* ($m^3/s/m^2$) as given in Formula (43):

   $$q_h{}^* = Q_{Darcy} / L_h \quad (43)$$

   — Calculate the factor j^* (dimensionless) related to Q_{Darcy} using Formula (44):

$$j^* = 1 - 0{,}12 exp \left\{ - \left[log \left(\frac{8 (q_h * / K_{lt})}{5 \tan^2 \beta} \right)^{5/8} \right]^2 \right\} \quad (44)$$

— Calculate the factor E^* (dimensionless) for the thickness $t_{prescribed}$ as given in Formula (45):

$$E^* = \frac{1}{j^*} \cdot \left[1 + \left(\frac{t_{prescribed}}{j^* \cdot L_h} \right) \cdot \left(\frac{\cos \beta}{\tan \beta} \right) \right] \quad (45)$$

— calculate the minimum short-term input flow rate for the geocomposite Q_{GCD}^* ($m^3/s/m$) in order to be considered equivalent to the granular layer having thickness $t_{prescribed}$ as given in Formula (46):

$$Q_{GCD}^* = q_h^* \cdot L_h \cdot E^* \quad (46)$$

— Calculate the available long-term flow rate Q_a for one or more geocomposites with Formula (32).

— For each geocomposite calculate the final Factor of Safety on equivalency FS_E as given in Formula (47):

$$F_{S,E} = Q_a / Q_{GCD}^* \quad (47)$$

— All the geocomposites for which $F_{S,E} \geq 1{,}0$ may be considered equivalent to the granular soil layer having thickness $t_{prescribed} < t_{max}$.

The French Committee on Geotextiles[10] suggests a different method. With reference to the symbols shown in Figure 21, the flow rate Q_{GL} afforded by the granular drainage layer as given in Formula (48):

$$Q_{GL} = q_h \cdot L \cdot \cos \beta = \frac{K \cdot (L \cdot \sin \beta + h_{max})^2}{L} \quad (48)$$

with the condition: $h_{max} < t$

where

t is the granular soil layer thickness (m)

q_h is the flow rate of liquid supply ($m^3/s/m^2$)

h_{max} is the maximum thickness of liquid in the granular layer (m)

L is the length of water flow (m)

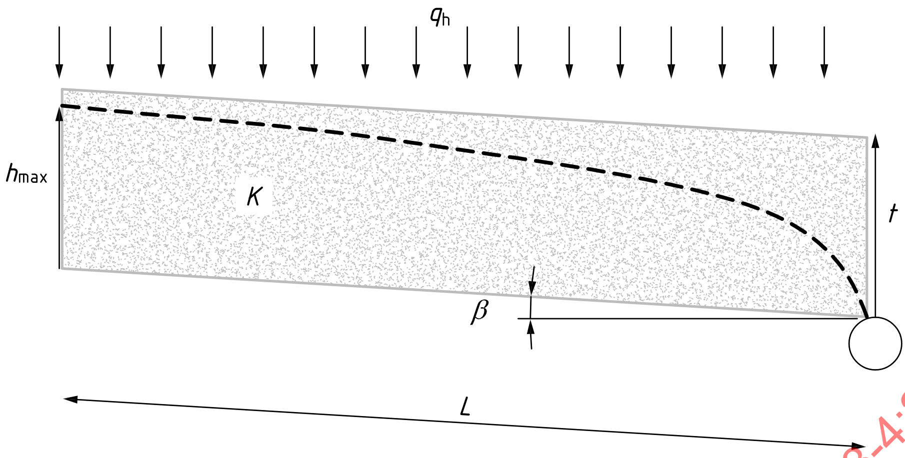
β is the slope angle (deg or °)

K is the soil permeability (m/s)

The condition for considering a geocomposite equivalent to the granular soil layer becomes Formula (49):

$$Q_a \geq Q_{GL} \quad (49)$$

where Q_a is obtained from Formula (32).



Key

t granular soil layer thickness (m)

q_h flow rate of liquid supply ($m^3/s/m^2$)

h_{max} maximum thickness of liquid in the granular layer (m)

L length of water flow

β slope angle (deg or °)

K soil permeability (m/s)

NOTE Adapted from *Comité Français des géosynthétiques*, 2014[10].

Figure 21 — Scheme for evaluating the flow rate afforded by a granular drainage layer

12.5.3 Equivalence for vertical water flow

In the case of vertical or sub-vertical water flow, the problem of the hydraulic transmissivity equivalency between geosynthetics and granular liquid collection layers is greatly simplified because Darcy's law is valid since the piezometric head loss corresponds to the length of the travel of water in the drainage medium.

In the case of vertical or sub-vertical flow (with drainage layer slope in the range 80 deg ≤ β ≤ 90 deg), the calculation procedure is as follows:

— Calculate the hydraulic gradient according to Formula (50):

$$i = \sin \beta \tag{50}$$

— Calculate the flow rate in the granular soil layer for vertical flow, equal to the design input flow Q_D in the geocomposite ($m^3/s/m$) according to Formula (51):

$$Q_D = K_{lt} \cdot t_{prescribed} \cdot i \tag{51}$$

where

K_{lt} is the permeability of the mineral layer evaluated in situ at the end of its design life (m/s);

$t_{prescribed}$ is the prescribed thickness of the granular soil layer (m).

— Calculate the available long-term flow rate Q_a for one or more geocomposites with Formula (32).

— For each geocomposite calculate the final Factor of Safety on equivalency $F_{S,E}$ with Formula (40).

— All the geocomposites for which Formula (40) is verified may be considered equivalent to the granular soil layer having thickness $t_{prescribed}$.

Annex A
(informative)

The movement of water in the ground

A.1 Darcy's law

The unidirectional movement of water through the soil is represented by Darcy's law in differential form (Whitaker, 1986):

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = K \cdot A \cdot \frac{\mathrm{d}h}{\mathrm{d}l} \tag{A.1}$$

where

$\mathrm{d}Q/\mathrm{d}t$	is the volumetric flow rate of water through the soil
A	is the bulk cross-sectional area through which the flow occurs
h	is the hydraulic head
l	is the distance travelled by the bulk water flow
$\mathrm{d}h/\mathrm{d}l$	is the hydraulic gradient
K	is the hydraulic conductivity or permeability of the soil

In Formula (A.1), the hydraulic gradient is the driving force producing seepage flow: it is the ratio between the difference in hydraulic head between two points and the distance the water travels between those two points.

In most cases, it is common practice to present Darcy's law in a simplified form given in Formula (A.2):

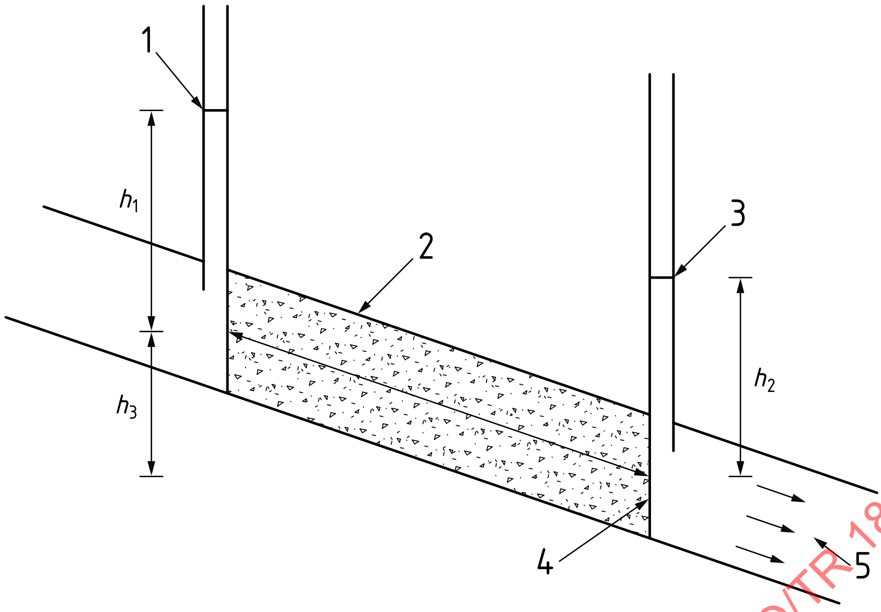
$$q = K \cdot A \cdot i \tag{A.2}$$

where

q	is ($\mathrm{d}Q/\mathrm{d}t$) in Formula (A.1), the volumetric flow rate
i	is ($\mathrm{d}h/\mathrm{d}l$) in Formula (A.1), the hydraulic gradient

The unit of q is volume per unit time (e.g. m^3/s or l/s), i is dimensionless, while the unit of K is distance per unit time (m/s).

A practical example of the use of Darcy's law is shown in Figure A.1.



Key

1 water head in upstream piezometer
2 soil sample with permeability *K*
3 water head in downstream piezometer
4 cross sectional area *A*
5 outflow *q*

Figure A.1 — Practical application of Darcy's law

A.2 Hydraulic conductivity and permeability

The hydraulic conductivity of a soil is a measure of the soil's ability to transmit water when submitted to a hydraulic gradient. Hydraulic conductivity is defined by Darcy's law, which, for one-dimensional vertical flow, can be written as given in Formula (A.3):

$$U = -K \frac{dh}{dz} \quad \text{(A.3)}$$

where

U is Darcy's velocity, or the average velocity of the soil fluid through a geometric cross-sectional area within the soil (m/s)

h is the hydraulic head (m)

z is the vertical distance in the soil (m)

K is the coefficient of proportionality, or the hydraulic conductivity (m/s)

With reference to Fig.A.1, the hydraulic gradient is given in Formula (A.4):

$$i = [(h_1 + h_3) - h_2] / L \quad (A.4)$$

The discharge is given in Formula (A.5):

$$q = K \cdot A \cdot i \quad (A.5)$$

The coefficient of proportionality, *K,* in Formula (A.3) is called the hydraulic conductivity. The term “permeability” is also used as a synonym for hydraulic conductivity. On the basis of Formula (A.3), the hydraulic conductivity is defined as the ratio of Darcy's velocity to the applied hydraulic gradient. The dimension of *K* is the same as that for velocity, that is, length per unit of time ($l\ T^{-1}$).

Hydraulic conductivity is one of the hydraulic properties of the soil; the other involves the fluid retention characteristics of the soil. These properties determine the behaviour of the fluid within the soil system under specified conditions. More accurately, the hydraulic conductivity determines the ability of the fluid to flow through the soil matrix system under a specified hydraulic gradient whilst the fluid retention characteristics determine the ability of the system to retain the fluid under a specified pressure condition.

The hydraulic conductivity depends on the soil grain size, the structure of the soil matrix, the type of fluid, and the relative amount of fluid (saturation) present in the soil matrix. The important properties relevant to the solid matrix of the soil include pore size distribution, pore shape, tortuosity, specific surface (ratio of total surface area of soil granules to the volume occupied by soil granules), and porosity (ratio of void volume to total volume). In relation to the fluid, the important properties include fluid density and fluid viscosity.

For a subsurface system saturated with the soil fluid, the hydraulic conductivity *K* can be expressed given in Formula (A.6) (Bear, 1972):

$$K = \frac{k \cdot \rho \cdot g}{\mu} \quad (A.6)$$

where

- k is the intrinsic permeability of the soil, which depends only on properties of the solid matrix (m^2)
- ρ is the density of the fluid ($N\ s^2\ /m^4$)
- μ is the dynamic viscosity of the fluid ($N\ /\ m^2\ s$)
- g is the gravity acceleration (m/s^2)

Thus, the hydraulic conductivity, *K*, is expressed in terms of length per unit of time (L/T^{-1}), while the intrinsic permeability, *k*, is expressed in L^2.

For clean water at 20 °C the relationship between *K* (m/s) and *k* (m^2) is given in Formula (A.7):

$$K = k \cdot \left(10^7\ m^{-1} s^{-1}\right) \quad (A.7)$$

By using formulas (A.3) and (A.6), Darcy's law can be rewritten explicitly in terms of its coefficient of proportionality (hydraulic conductivity *K*):

$$K = \frac{k \cdot \rho \cdot g}{\mu} = \frac{|U|}{|\mathrm{d}h / \mathrm{d}z|} \quad (A.8)$$

Formula (A.8) can be used, which allows to determine the value of the hydraulic conductivity *K* once *U* and *dh/dz* are experimentally determined*;* then, *w*hen the fluid properties of density and viscosity are known, intrinsic permeability, *k*, can be evaluated using the same Formula (A.8).

The intrinsic permeability in fluid mechanics and earth sciences (symbolized as k) is a measure of the ability of a porous material (rock or unconsolidated material) to allow fluids to pass through it.

The hydraulic conductivity or coefficient of permeability, symbolically represented as K, is a property of soil or rock that describes the ease with which a fluid (usually water) can move through pore spaces or fractures. It depends on the intrinsic permeability of the material and its degree of saturation, and on the density and viscosity of the fluid. Saturated hydraulic conductivity, K_{sat}, describes water movement through saturated media.

Hence the following:

— The intrinsic permeability k is a measure of how well a porous media transmits a fluid. It has nothing to do with the fluid itself. It is measured in $(\text{length})^2$.

— The hydraulic conductivity K is a measure of how easily water moves through the porous media. It depends on the permeability of the matrix, but also is a function of the fluid. It is measured in (length)/(time).

A.3 Evaluation of soil permeability

The values of saturated hydraulic conductivity in soils vary within a wide range of several orders of magnitude, depending on the soil material, e.g. the hydraulic conductivity of a sand (or the average bulk speed of water in sand) is between 0,5 and 5 meters per day. Table A.1 lists the range of expected values of K for various unconsolidated and consolidated soil materials. Table A.2 presents the expected representative values of K for soil materials of different textures. A more detailed list of expected representative values of K based on the grain size distribution, degree of sorting, and silt content of several soil materials is presented in Tables A.3 and A.4.

Due to the spatial variability normally found in the geological formation of soils, saturated hydraulic conductivity values also show variations throughout the space domain within a subsurface geological formation. Such a geological formation is said to be 'heterogeneous'. If the properties of the geologic formation are invariable in space, the formation is 'homogeneous'. A geological formation is said to be 'isotropic' if at any point in the medium, the values of the saturated hydraulic conductivity (K) are independent of the direction of measurement. Due to the usually stratified nature of unconsolidated sedimentary soil materials, soils are usually anisotropic.

Within an anisotropic geological formation, the vertical component of the saturated hydraulic conductivity is usually smaller (one to two orders of magnitude) than the horizontal component. Permeability is typically determined in the laboratory by the application of Darcy's law under steady state conditions or, more generally, by application of various solutions to the diffusion formula for unsteady flow conditions, or through estimation using empirically derived formulas. Only for some simple models of porous media, permeability can be calculated (e.g. random close packing of identical spheres).

Soil permeability is influenced by the following soil characteristics:

— Soil gradation: soil permeability relates to soil texture and structure since the size of the soil pores is of great importance with regard to the rate of infiltration (movement of water into the soil) and to the rate of percolation (movement of water through the soil). Pore size and the number of pores closely relate to soil texture and structure, and also influence soil permeability: usually, the finer the soil texture, the lower the permeability. Figure A.2 shows typical hydraulic conductivity values (in m/day) for soils of various grading. It is evident that the quantity of fines (particles less than 0,15 mm diameter) drastically affects the permeability of soils.

— Soil density: any increase in soil density will lead to a reduction in soil permeability. Figure A.3 shows typical curves of permeability versus consolidation pressures for several soil types. It is evident that increased consolidation, that is higher soil density, produces a decrease in the soil permeability. An increase in consolidation pressure has a higher effect on the permeability of finer grained soils than on coarser soils.

Figure A.4 and Table A.5 provide typical values of saturated hydraulic conductivity (K) for different types of soil. Values are for typical fresh groundwater conditions, using standard values of viscosity and specific gravity for water at 20 °C and 1 atm.

Table A.1 — Range of saturated hydraulic conductivity of various soil materials

Soil type	Saturated hydraulic conductivity, K (m/yr)
Unconsolidated deposits	
Gravel	1×10^{4} to 1×10^{7}
Clean sand	1×10^{2} to 1×10^{5}
Silty sand	1×10^{1} to 1×10^{4}
Silt, loess	1×10^{-2} to 1×10^{2}
Glacial till	1×10^{-5} to 1×10^{1}
Unweathered marine clay	1×10^{-5} to 1×10^{-2}
Rocks	
Shale	1×10^{-6} to 1×10^{-2}
Unfractured metamorphic and igneous rocks	1×10^{-7} to 1×10^{-3}
Sandstone	1×10^{-3} to 1×10^{1}
Limestone and dolomite	1×10^{-2} to 1×10^{1}
Fractured metamorphic and igneous rocks	1×10^{-1} to 1×10^{3}
Permeable basalt	1×10^{1} to 1×10^{5}
Karst limestone	1×10^{1} to 1×10^{5}

[SOURCE: Based on Freeze and Cherry, 1979]

Table A.2 — Representative values of saturated hydraulic conductivity of different soil textures

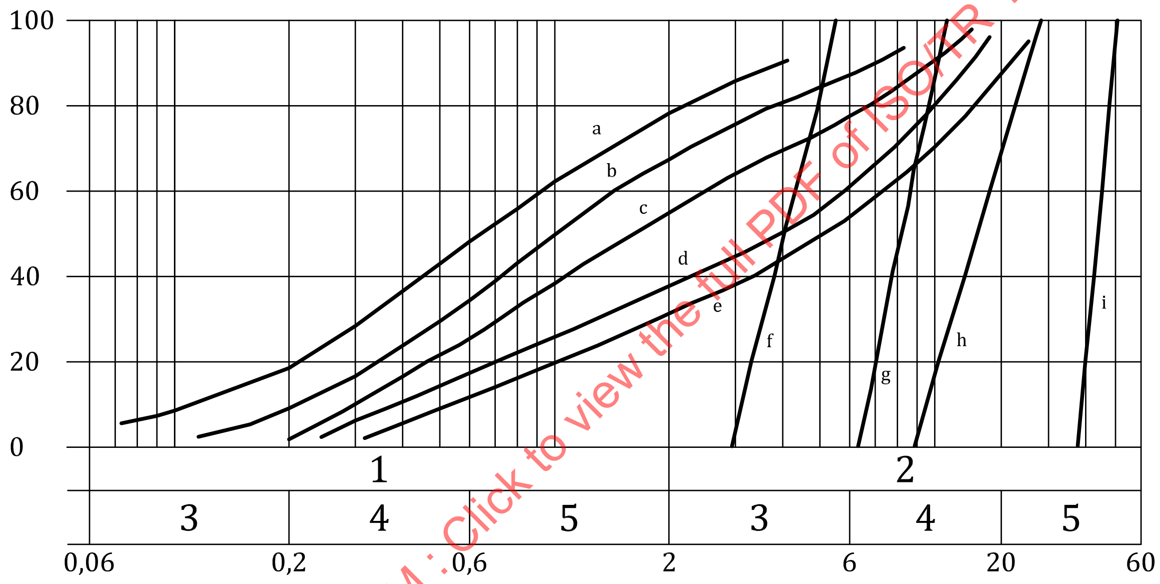
Texture	Saturated hydraulic conductivity, K (m/yr)
Sand	$5{,}5 \times 10^{3}$
Loamy sand	$4{,}93 \times 10^{3}$
Sandy loam	$1{,}09 \times 10^{3}$
Silty loam	$2{,}27 \times 10^{2}$
Loam	$2{,}19 \times 10^{2}$
Sandy clay loam	$1{,}99 \times 10^{2}$
Silty clay loam	$5{,}36 \times 10^{1}$
Clay loam	$7{,}73 \times 10^{1}$
Sandy clay	$6{,}84 \times 10^{1}$
Silty clay	$3{,}21 \times 10^{1}$
Clay	$4{,}05 \times 10^{1}$

[SOURCE: Based on Clapp and Hornberger, 1978]

Table A.3 — Estimated saturated hydraulic conductivities for fine-grained materials

Grain-size class	Saturated hydraulic conductivity, *K* (10^3 m/yr)
Clay	< 0,000 1
Silt, clayey	0,1 – 0,4
Silt, slightly sandy	0,5
Silt, moderately sandy	0,8 – 0,9
Silt, very sandy	1,0 – 1,2
Sandy silt	1,2
Silty sand	1,4

[SOURCE: Based on EPA, 1986]



Key

a 0,5 m/day
b 5 m/day
c 10 m/day
d 20 m/day
e 30 m/day
f 2 000 m/day
g 5 000 m/day
h 1 000 0 m/day
i 3 000 0 m/day
1 sand
2 gravel
3 fine
4 medium
5 coarse

Figure A.2 — Typical hydraulic permeability values (in m/day) for soils of various grading

Table A.4 — Estimated saturated hydraulic conductivities for sands and gravels according to degree of sorting and silt content

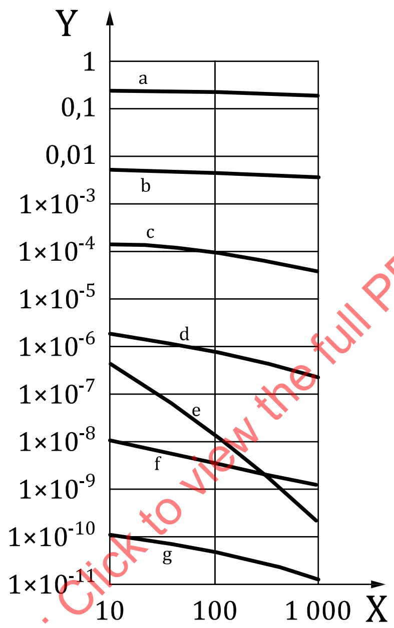
Grain-Size Class or Range	Saturated Hydraulic Conductivity, *K* (10^3 m/yr)					
	Degree of Sorting			Silt Content		
	Poor	Moderate	Well	Slight	Moderate	High
Very fine sand	1	2	3	3	2	1
Very fine to fine sand	3	3	-	3	2	1
Very fine to medium sand	4	5	-	4	3	2
Very fine to coarse sand	5	-	-	4	3	3
Very fine to very coarse sand	7	-	-	6	4	3
Very fine sand to fine gravel	8	-	-	7	6	4
Very fine sand to medium gravel	11	-	-	9	7	5
Very fine sand to coarse gravel	14	-	-	12	10	7
Fine sand	3	4	6	4	3	2
Fine to medium sand	6	7	-	5	4	3
Fine to coarse sand	6	8	-	6	5	4
Fine to very coarse sand	8	-	-	7	5	4
Fine sand to fine gravel	10	-	-	8	7	5
Fine sand to medium gravel	13	-	-	10	8	6
Fine sand to coarse gravel	16	-	-	12	10	8
Medium sand	7	9	10	7	6	4
Medium to coarse sand	8	10	-	8	6	5
Medium to very coarse sand	9	12	-	8	7	5
Medium sand to fine gravel	11	-	-	9	8	6
Medium sand to medium gravel	15	-	-	13	9	7
Medium sand to coarse gravel	18	-	-	15	12	9
Coarse sand	9	12	15	10	8	6
Coarse to very coarse sand	10	15	-	10	8	6
Coarse sand to fine gravel	13	16	-	12	10	8
Coarse sand to medium gravel	16	-	-	13	10	8
Coarse sand to coarse gravel	20	-	-	15	11	10
Very coarse sand	12	16	21	13	10	8
Very coarse to fine gravel	15	24	-	13	12	10
Very coarse to medium gravel	19	25	-	16	14	11
Very coarse sand to coarse gravel	23	-	-	18	15	12
Fine gravel	18	24	30	25	16	12
Fine to medium gravel	22	37	-	22	19	15
Fine to coarse gravel	27	37	-	26	21	16
Medium gravel	27	26	45	27	22	18
Medium to coarse gravel	33	52	-	33	27	21
Coarse gravel	37	52	67	37	32	26

[SOURCE: Based on EPA, 1986]

Table A.5 — Typical values of the saturated hydraulic conductivity (*K*) of different types of soil

K (m/s)	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}
Relative permeability	Pervious				Semi-pervious				Impervious				
Aquifer	Good					Poor				None			
Unconsolidated sand and gravel	Well sorted gravel		Well sorted sand or sand and gravel			Very fine sand, silt, loess, loam							
Unconsolidated clay and organic					Peat		Layered clay			Fat/unweathered clay, bentonite			
Consolidated rocks	Highly fractured rocks				Oil reservoir rocks			Fresh sandstone		Fresh limestone, dolomite		Fresh granite	

[SOURCE: Based on Bear, 1972]



Key

X consolidation pressure (kPa)
Y permeability (m/s)
a clean gravel
b coarse sand
c fine sand
d silt
e organic clay
f silty clay
g clay

Figure A.3 — Typical curves of permeability versus consolidation pressures for several soil types