Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1725

Hydraulic conductivity anisotropy of a drainage geocomposite exposed to root growth: experimental insights for numerical modelling

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ABSTRACT: Designing geotechnical structures requires a thorough understanding and quantification of interactions between adopted materials and environmental factors. In this context, numerical modelling could play a crucial role, serving as a powerful tool for addressing complex geotechnical problems. However, the efficacy of the employed models relies on a deep understanding of material behaviour, notably in the case of anisotropic materials, whether natural or artificial, whose hydraulic and mechanical properties can significantly influence the performance of earthen structures.

An example of such materials can be found in drainage geocomposites (GCDs), which are increasingly used to manage water infiltration in geotechnical applications, offering an alternative to traditional granular materials, such as sand and gravel. Their composite configuration, consisting of multiple geosynthetics – typically a geonet or a geomat between two geotextiles – results in inherent anisotropic behaviour. Regarding hydraulic characteristics, a GCD exhibits different water permeability normal to its plane compared to that measured "in-plane". Additionally, the functioning of GDCs can be affected by physical, chemical and biological processes. Among these, vegetation represents a biological factor often interacting with geosynthetics, especially when design methodologies promote their integration with vegetation throughout the service life of geotechnical structures.

This study investigates the extent to which GCD anisotropy, both related to manufacturing and induced by roots, influences the overall drainage capacity of the geosynthetic itself. The research is founded on a previous experimental investigation aimed at obtaining root-penetrated drainage geocomposite specimens by burying GCD specimens in boxes filled with a thin layer of soil and plants. After plant growth, the specimens affected by roots were exhumed and subjected to laboratory tests to determine their water permeability, both normal and parallel to their plane. The test results were compared with those from undisturbed drainage geocomposite specimens to evaluate root-induced changes in the hydraulic properties of the GCD.

KEYWORDS: Geosynthetics, hydraulic conductivity, anisotropy, roots, drainage.

1 INTRODUCTION

Geotechnical engineering increasingly relies on advanced materials and design strategies to address challenges related to soil stability, drainage, and environmental sustainability. Among the various materials and techniques adopted, geosynthetics are widely employed due to their versatility, ease of installation, and ability to replace substantial quantities of conventional materials (e.g., sand, gravel, and clay), exhibiting equal or superior performance (Cazzuffi et al., 2025; Chatrabhuj, 2024; Palmeira, 2021; Stucki, 2011).

Drainage geocomposites (GCDs) represent a class of geosynthetics designed to ensure fluid drainage, typically water and biogas, in a variety of geotechnical applications, including soil-retaining walls, drainage trenches, landfill capping, and subsurface drainage for road and railway construction. Their multilayer polymeric structure usually consists of a geonet as an in-plane drainage core, encased between two geotextiles for filtration and separation functions. This combination of different geosynthetics, along with the inherent texture of each component, results in an anisotropic response of the GCD to water flow, with values of water permeability varying between the normal and in-plane directions.

Incorporating this anisotropy in numerical modelling approaches provides more accurate analytical results for geotechnical problems. However, the extent to which this anisotropic behaviour is considered into numerical models varies significantly across the literature: while some studies treat the GCD as a boundary condition, such as a drainage interface or a seepage face (Ito, 2011), others advocate for a more detailed representation of the GCD as a material with its hydraulic properties, offering a more physically consistent representation of the GCD. For instance, Iryo and Rowe (2005) model each component of the GCD – geotextiles and geonet – as separate elements, assigning distinct values of saturated hydraulic conductivity to non-woven geotextiles for in-plane and cross-plane directions. Amato et al. (2024a) approximate the GCD to a homogeneous material with an equivalent saturated in-plane hydraulic conductivity to obtain the same drainage capacity as the real GCD.

The modelling challenge becomes even more pronounced when considering the long-term hydraulic performance of geosynthetics. Drainage geocomposites may experience a decline in hydraulic performance over time, mainly due to creep (Giroud, 2000), clogging (Gallagher, 1998), or bio-clogging, for example, caused by root intrusion. Vegetation represents a biological factor often interacting with geosynthetics, especially when design methodologies promote their integration with plant cover throughout the service life of geotechnical structures.

This study investigates the extent to which GCD matrix anisotropy – both inherent to the manufacturing process and induced by root growth – affects its overall drainage capacity. The research is based on an experimental campaign designed to obtain root-penetrated specimens of drainage geocomposites and geotextiles: the specimens were buried in boxes filled with a relatively thin layer of soil and selected vegetation, namely Vetiver (*Chrysopogon zizanioides*, (L.) Roberty). After a period of plant growth, the rooted specimens were exhumed and subjected to laboratory testing to evaluate their water permeability in both the in-plane and normal directions. The results were compared with those from undisturbed reference specimens to assess the hydraulic impact of root intrusion.

The in-plane water permeability can be expressed for a geosynthetic in terms of hydraulic flow rate, expressed in ((l/s)/m) or (m^2/s). This represents the drainage capacity of a geosynthetic in its plane, per unit width, under a defined normal stress and gradient, and determined through laboratory tests according to EN ISO 12958-1. Table 1 presents the hydraulic flow rates measured for two representative rooted specimens (H2V and H4V) at different normal pressures and for unit gradient (i=1.00), along with their variation relative to the average values obtained for the reference specimens. These findings are discussed in detail in Amato et al. (2024b).

Table 1. In-plane water flow capacity test results referred to two rooted specimens (H2V, H4V): hydraulic flow rate at different normal pressures and gradients (i), and variation of hydraulic flow rate for each rooted specimen, for average values obtained for reference specimens.

Specimen code	H2V		H4V	
Normal Pressure (kPa)	Hydraulic flow rate (m^2/s) at gradient i=1.0	Hydraulic flow rate variation (%)	Hydraulic flow rate (m^2/s) at gradient i=1.0	Hydraulic flow rate variation (%)
20	1.39E-03	-37.7	9.46E-04	-57.8
50	1.21E-03	-42.2	7.80E-04	-62.7
100	1.13E-03	-43.8	6.97E-04	-65.2
200	1.04E-03	-44.0	6.28E-04	-66.2

A comparison of the test results from rooted and virgin reference specimens showed that the rooted specimens exhibited a significantly reduced drainage capacity: H2V shows a flow rate reduction of 37.7% at 20 kPa and 44.0% at 200 kPa; H4V shows a stronger decline, from 57.8% to 66.2%.

In the present study, the focus shifts to the determination of the cross-plane hydraulic conductivity of geosynthetics. To this aim, a custom-built prototype inspired by the EN ISO 11058 standard was developed. Unlike the standard apparatus, which is designed to measure the permeability of geotextiles alone, this modified setup enables the assessment of hydraulic conductivity for both geotextiles and drainage geocomposites, whether rooted or unrooted. This experimental framework supports both numerical modelling approaches: the strategy of isolating the behaviour of the individual components of the GCD, and the homogeneous equivalent material representation, in order to achieve a more accurate numerical simulation of the hydraulic behaviour of geocomposites in vegetated geotechnical systems.

It should be noted that the experimental programme presented, at this stage, is limited to a first, partial set of specimens. Therefore, the outcomes discussed in the following must be interpreted as preliminary indications of the hydraulic response of rooted geosynthetics, providing a basis for the design of further, more comprehensive investigations.

2 METHODOLOGY

2.1 *Materials and equipment*

The drainage geocomposite selected for this study was manufactured by Tenax S.p.A. (Italy) and consists of two nonwoven polypropylene (PP) geotextiles laminated onto a PP drainage geonet core. The geotextiles serve as separation and filtration functions, having a porous structure with a characteristic opening size (O90) of 70 μm (EN ISO 12956). The drainage core is a geonet composed of three overlaid sets of PP strands, whose intersections form a three-dimensional matrix of quadrangular cells. The geotextile (GTX) used in isolation is identical to that employed in the GCD's manufacturing. To induce root interaction, the plant species selected was Vetiver, a perennial gramineous plant commonly used in soil bioengineering for slope stabilisation and erosion control due to its dense and penetrating root system.

The apparatus used to perform water permeability tests normal to the plane is a custom-built prototype (Figure 1) developed following the guidelines of the EN ISO 11058 standard, specifically for the falling head method. It consists of two transparent Plexiglas cylinders (inner diameter: 60 mm; outer diameter: 70 mm; height: 600 mm) arranged in vertical position and connected via standard Polyvinyl chloride (PVC) fittings. A central valve allows water to pass from the left to the right cylinder. The junctions between the tubes and the fittings are achieved using custom-designed flanges, manufactured through stereolithography 3D printing. One of the flanges—the one positioned on the right side—is specifically designed to accommodate either the geotextile or the geocomposite specimens. The specimen is supported by a 3D-printed grid, featuring a 9 mm mesh size and 1 mm strand thickness. The water level passing through the specimen can be visually tracked on a graduated scale placed on the right cylinder.

Figure 1. Test apparatus designed for the determination of water permeability normal to the plane of geotextiles GTX and drainage geocomposites GCD.

2.2 *Procedure*

The tests were performed on the vetiver-rooted specimens ("rooted") and on as-manufactured specimens ("reference") to compare the results and evaluate root-induced changes in the hydraulic performance of the geosynthetics. Circular specimens with a diameter of 70 mm were cut from different samples of geosynthetic, as follows:

- 5 specimens from reference geotextile sample (code: GTX-UN).
- 5 specimens from rooted geotextile sample (code: GTX-R).
- 5 specimens from reference geocomposite sample (code: GCD-UN).
- 5 specimens from rooted geocomposite sample (code: GCD-R).

The specimens are submerged in water to remove air bubbles and left to saturate for at least 12 hours. Once saturation is completed, the specimens are positioned in the test apparatus (Figure 2).

Figure 2. Positioning of the specimen in the test apparatus.

The left cylinder is filled with water until the water head is approximately 550 mm above the specimen. Upon opening the valve, digital video equipment is used to record the change in water level over time in the right-hand cylinder. From the video analysis, the time-dependent water level is extracted. Thus, the flow velocity at 20°C (v_{20}) is calculated by considering adjacent and overlapping time lapses equal to 1/10 of the total time required to carry out the test, and the corresponding water levels, using the following formula:

$$v_{20}=\frac{\Delta h}{\Delta t}\,Rt \qquad [\mathrm{mm/s}] \tag{1}$$

Where:

Δh is the difference between the upper water level and the lower water level at the time interval Δt.

Δt is the time interval between upper and lower water levels, in seconds.

Rt is the correction factor for a water temperature of 20 °C.

For each specimen, the relationship between flow velocity (v_{20}) and head loss (H) is analysed by plotting the corresponding curve and fitting a quadratic function that passes through the origin, as follows:

$$H = a\, v_{20} + b\, v_{20}^2 \ [\mathrm{mm}] \tag{2}$$

Hence, from the resulting values of a and b, the flow velocity corresponding to a head loss of 50 mm is determined, named velocity index v_{i50} (mm/s). Figure 3 illustrates the fitted quadratic regression curve between flow velocity, v_{20} – Head loss, H and the determination of the velocity index v_{i50} obtained for a specimen of reference GTX. The test is conducted on five specimens, and the mean value of the velocity index is adopted as the representative value.

3 EXPERIMENTAL RESULTS

Water permeability normal to the plane of GTX and GCD was assessed using a custom-built prototype, following EN ISO 11058 standard guidelines. Table 1 summarises the velocity index v_{i50}, calculated as the average value of the five specimens extracted from each sample of GTX and GCD, both in the reference and rooted conditions.

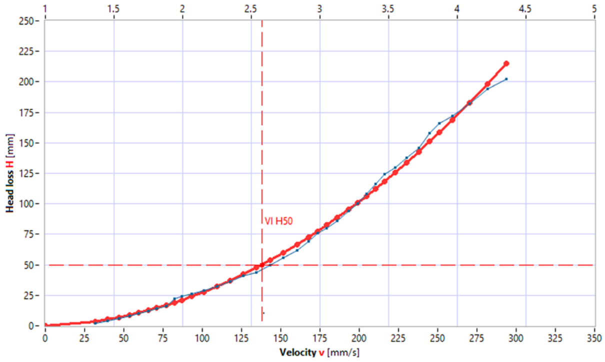

Figure 3. Fitted quadratic regression curve v_{20} – H and the indication of the velocity index v_{i50} obtained for a reference specimen of GTX.

The data presented in Table 2 demonstrate the influence of root intrusion on the hydraulic performance of both geotextile and drainage geocomposites.

For each sample, the average thickness was determined. Measurements were taken with a calliper, excluding the contribution to thickness from roots on the external surface of the geosynthetics, as their distribution is non-uniform. Thickness increase was therefore attributed solely to root intrusion within the geocomposite structure.

Table 2. Water permeability characteristic normal to the plane, determined as a velocity value at a head loss of 50 mm (velocity index v_{i50}) for GCD and GTX samples, undisturbed and rooted, and corresponding average thickness.

Sample	Thickness (mm)	Velocity index v_{i50} (mm/s)
GTX_UN	0.75	135.40
GTX_R	0.80	98.60
GCD_UN	5.85	64.10
GCD_R	6.45	41.50

The analysis of the results presented in Table 2 reveals differences in the hydraulic behaviour of GTX and GCD materials between reference specimens and those rooted. In both cases, a reduction in the velocity index v_{i50} is observed in rooted specimens: for GTX, the value decreases from 135.4 mm/s to 98.6 mm/s, corresponding to a reduction of approximately 27.2%; for GCD, the decrease is from 64.10 mm/s to 41.5 mm/s, which represents a reduction of about 35.3%.

These results suggest that the presence of roots within the material may partially obstruct flow paths and modify the porosity of the material. This, in turn, can contribute to the observed reduction in permeability and the measurable decrease in flow velocity.

4 CONCLUSION

The experimental campaign aimed to assess the hydraulic performance of drainage geocomposites, both in their as-manufactured condition and after root intrusion. Considering the inherent anisotropy of these materials, resulting from their texture and material heterogeneity, specific tests were conducted to characterise their hydraulic conductivity both in-plane and perpendicular to the plane.

Vetiver-rooted specimens showed reduced drainage capacity compared to virgin reference specimens, indicating root-induced obstruction of the drainage core. The results of a previous study showed that the decrease in drainage capacity is more pronounced in the case of the highest density of roots in the drainage core. In-plane water flow tests revealed a progressive decline in hydraulic flow rate with increasing normal pressure, with rooted specimens showing reductions of up to 44% or 66 % compared to virgin samples, depending on whether the drainage core of the GCD exhibited lower or higher root density, respectively.

In this new study, the focus is on determining the water permeability perpendicular to the plane of GCD and its components, i.e. the geotextiles. Cross-plane permeability, expressed through the velocity index v_{i50}, decreased by approximately 27.2% in GTX and 35.3% in GCD due to root intrusion, compared to their corresponding undisturbed reference samples.

The results confirm that root intrusion leads to a reduction in water flow in both directions – normal and in-plane. However, the nature of the reduction suggests a different hydraulic response depending on the flow direction. In particular, the more pronounced reduction observed in the in-plane flow rates may indicate that root systems interfere more significantly with the internal drainage pathways of the geocomposite core. These findings offer insights for numerical simulation of drainage processes in the presence of geocomposites affected by roots, especially when these latter are modelled as homogeneous but not isotropic layers.

Future work, based on an extended dataset, will be required to better define and quantify the variability of the hydraulic response normal to the plane observed in this preliminary study.

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