E3S Web of Conferences **569**, 25003 (2024) https://doi.org/10.1051/e3sconf/202456925003
GeoAmericas 2024

Experimental evaluation of water infiltration through concrete-geocell liners

Carlos Acosta[1*], *Gustavo* Fierro[2], and *Jorge* Zornberg[1]

[1] Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, Austin, TX 78712, USA
[2] TDM Group, Alameda Marqués de la Bula 339, Lima, Perú.

Abstract. In this article we study the infiltration rate and flow characteristics of water through concrete-geocell liners by experimental and analytical means. Geocells filled with concrete have been used in the construction of many hydraulic works, such as shore protections (both marine and riverine), spillways, and canal liners; these liners have been reported to offer high performance, as they are able to withstand large flow velocities, hydrodynamic effects, and environmental stresses, while still being more cost-effective than other hard-armor systems such as reinforced concrete and articulating concrete blocks (ACBs). Despite their increasing use there is no report of their hydraulic conductivity in the literature, which this paper aims to fulfil. First, an analytical solution to the problem is achieved by parting from the incompressible Navier-Stokes equations and applying reasonable assumptions to arrive at a formula that relates flow rate to pressure gradient, fluid properties, and importantly, the hydraulic aperture (the idealized gap at the concrete-geocell interface); this gap is then estimated using the ACI-209 method for the prediction of concrete shrinkage, resulting in the proposed semi-analytical method. The formulation was then evaluated experimentally by conducting hydraulic tests on full scale geocell specimens filled with concrete under conditions that are deemed representative of real case applications. The results indicate that the proposed methodology has satisfactory predictive capabilities and provides flow rate estimates in accordance with measured data.

1 Introduction

Geocells filled with concrete have increasingly been used in the construction of hydraulic works; typical applications include using concrete-geocell slabs as canal liners in water conveyance systems and mine channels, river and marine protections, and spillways. It is thus important to know the hydraulic conductivity properties this liner, particularly the amount of water such a system allows to seep or infiltrate through it. In the case of irrigation canals or other fluid transportation systems this infiltration represents losses of precious resources. In the case of canals involved in mining operations these losses may trigger environmental concerns due to the possibility of liquid waste and mining byproducts ending

* Corresponding author: carlosacosta@utexas.edu

up seeping into the subsurface. Geocells, once expanded are filled with concrete to create the canal liner, Figure 1 depicts this process and highlights the wall characteristics, i.e., texture and perforations on the walls; it will be shown that this texture translates into considerably tortuous flow paths, it is also noticeably larger than the expected shrinkage of concrete under most conditions. The perforations allow for crosscell concrete flow that once hardened interconnects adjacent cells and because the perforations are arranged in a quincunx pattern, they effectively block water flow for a large segment of the interface.

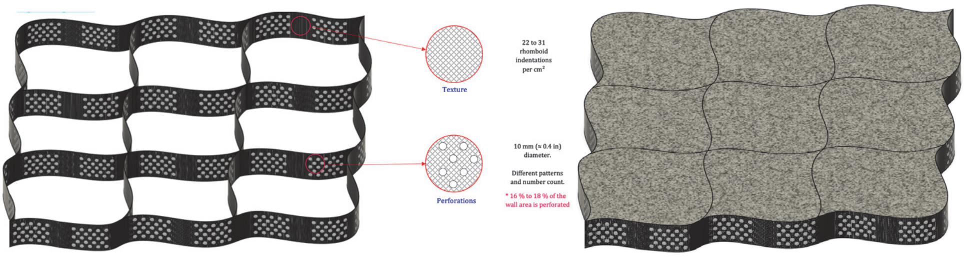

Fig. 1. Concrete geocell liner; Left: empty geocells, Center: Wall characteristics, Right: geocells filled with concrete

Concrete-geocell canals fall under the category of “hard-armored liners”, which also includes reinforced concrete liners (RCL) and Articulating Concrete Blocks (ACB); concrete-geocell liners offer significant benefits compared to both systems, as described in Section 1.1. It is estimated that hard-armored liners experience water losses in the range of 20 % to 50 % during conveyance, mostly due to evaporation, and secondarily to seepage across the liner and infiltration through joins and defects. Currently, no specific data on water loss or hydraulic conductivity exists exclusively for concrete-geocell canals; however, it is thought that the figures are similar to the aforementioned ones. Engineers have established ways to account for evaporation losses, which depend on environmental factors (i.e., temperature, wind velocity, humidity, time of the year, etc.) and it is not the objective of this paper, the goal here is to develop a way to estimate losses due to infiltration across the joints of the liner.

In the case of reinforced concrete canals these joints are purposely made during construction to relieve the stresses generated by volume changes in the liner; for concrete-geocell canals these joins occur naturally due to the gap created by concrete shrinkage at the interface with the geocell wall; because all geocells in the system share the same size and properties these joints are also uniform all along, and microscopic in width (see 3.1), giving the concrete-geocell liner a significant advantage over RCL. As for ACB liners these are by definition prefabricated pieces fit together and as such the seams between every piece will form an interface along which water can leak unimpeded compared to the other hard-armor systems.

1.1 Comparison of concrete-geocell liners and other systems

Geocells with concrete infill offer considerable advantages over competing systems such as pour-in-place reinforced concrete and articulating concrete blocks (ACB). Some of these advantages stem from technical aspects while others come from reduced labor, construction time and durability. Table 1 compiles some of the technical aspects, similarities, and differences between these systems. The main advantages of geocells with concrete infill are related to their semi-articulated nature, the ability to develop controlled shrinkage, the fact that it requires no steel reinforcement, and that it can offer equivalent levels of performance to reinforced concrete at reduced costs.

Table 1. Comparison of concrete-geocell slabs with reinforced concrete and ACBs

Aspect	Geocell with concrete infill	Reinforced concrete	Articulating Concrete Blocks
Formwork	None needed.	Extensive formwork needed.	Not necessary.
Reinforcement	None needed.	High cost, labor-intensive steel reinforcement.	Cable reinforcement needed
Environmental durability	Predicted life over 120 years, observations confirm durability	Corrosion is a significant concern.	Erosion and weathering are long-term concerns.
Construction joints	Not needed. Controlled cracking occurs along geocell-concrete interface.	Joints needed, impermeabilization work required as well, and periodic inspection.	Blocks individually disjointed.
Tolerance to distresses	Semi-articulated system with concrete connecting cells across wall perforations. The system can conform to ground geometry and tolerate a degree relative displacement.	Solid slabs of concrete, susceptible to distress or damage due to relative displacements.	Articulated system able to tolerate a significant displacement, however long-term performance affected.
Concrete pouring volume and control	The uniform, well-defined geometry of geocells allows for pouring volumes of concrete with less waste and consistent slab thickness.	More control measures needed to ensure uniform pouring along the alignment.	Not a concern on site. Pre-cast blocks arrive pre-made.
Concrete slump	High slump concrete, easy to pour, can potentially save costs of concrete mixes.	Lower slump concrete needed, workability more a concern, and large slab pouring requires slump control on steep sides.	Not a concern. Pieces are pre-made offsite.
Specialty equipment	There is no need to use special or heavy-weight equipment. Geocell rolls arrive to the site in compact state and can be extended by hand.	Large quantities of wood and steel needed, equipment to transport, lift and handle them.	Large, heavy individual pieces need to be transported to site and then lifted to place in location.
Uplift capacity	Observed and measured data suggest the system is able to tolerate high uplift forces.	High uplift capacity, but field observations suggest progressive uplift effects on construction joints	Individual blocks are easier to displace. Considerably less uplift capacity compared to either of previous systems.

Figure 2 shows a graphical comparison of these systems in the context of hard-armor canal lining. Attention is drawn to the joint requirements of the reinforced concrete canal, and the need for heavy equipment to lift a connected set of articulating concrete blocks. The effect of uplift on reinforced concrete canal linings (RCL) has been observed to be destructive (Fahmi et al., 2015) manifesting mainly along construction joints with erosion of the bedding material soon following, leading to failure of the system. In the case of ACB systems high velocity flow can easily displace blocks as well.

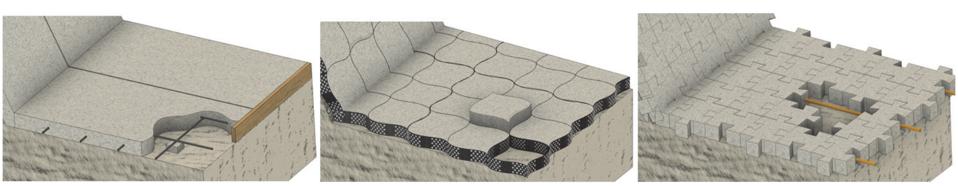

Fig. 2. Types of hard-armor canal lining systems, in clockwise order from top-left to bottom: Reinforced concrete liner, concrete-geocell liner, articulating concrete blocks.

1.2 The nature of flow conditions and permeability of the system

Permeability, the ability of a fluid to flow through a medium, is typically measured under saturated conditions and reported in terms of the coefficient of hydraulic conductivity, K, in m/s. The permeability of ordinary Portland cement is a function of several variables, among them water/cement ratio, age, curing conditions, aggregate size, workmanship, porosity, and most importantly pore interconnectivity. Even with the aforementioned list of variables, it is typical to assume concrete to have a coefficient of hydraulic conductivity equal to 1×10^{-12} m/s for practical purposes. Moreover, geocells are made of highly impervious polymers, usually HDPE and/or PP; according to Koerner (2005) the permeability coefficient of geocells is around 1×10^{-15} m/s, in fact, they are so impermeable that this property cannot sensibly be measured with water, therefore Vapor Transmission Test is used instead. It is thus clear that both of these materials individually are exceedingly impervious and can be considered impermeable for practical purposes when compared to the permeability of the subgrade they rest upon. Rather than with the individual materials we are concerned with the conductivity of the concrete-geocell system. In concrete-geocell liners a microscopic separation occurs at the interface between the concrete and geocell due to the natural shrinkage of concrete; it is this tiny gap that is responsible for the infiltration of water through the liner. Figure 3 depicts this hypothesis on a cross section of a trapezoidal concrete-geocell canal. Take for instance the interface labelled '3', because geocells have texture and perforations that allow for concrete to creep into, the final interface is extraordinarily tortuous and contains features that prevent water from simply seeping through; this interface is clearly a complex one, and rather a three-dimensional one than the 2D depicted here. One first approach to the problem is to consider the idealized case where this interface is formed by a smooth geocell wall with concrete on both sides and their corresponding shrinkage separation as shown in the right. Smooth geocells were once a prominent commercial product, today most manufacturers produce geocells with some type of textured pattern and perforations in their wall such that flowing conditions are far from "smooth".

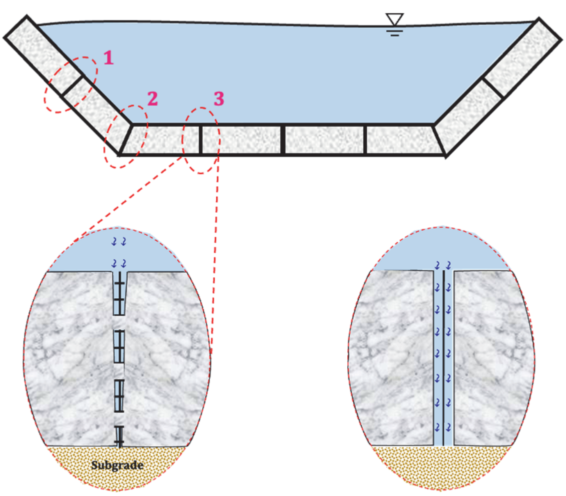

Fig. 3. Hypothesis of flow through the concrete-geocell system –Left: textured-perforated geocell wall, Right: smooth geocell wall.

A solution to the problem of flow through a smooth interface can be found analytically (Eq. 1) by a simplification of the Navier-Stokes equations, often called "cubic law" since it indicates that flow rate is proportional to the cube of the gap separating the interface.

$$Q_s = \frac{s^3 \gamma_w L}{12\mu} \frac{(\Delta h)}{H} \tag{1}$$

Here Q_s is the volumetric flow rate, the subindex "s" indicated that it assumes the interface is smooth; the variable s is the hydraulic aperture (idealized gap of the interface), γ_w is the unit weight of water; L is the length of the interface in consideration, Δh is the head difference driving the flow, μ is the dynamic viscosity of water; and H is the height of the geocell.

The presence of texture and perforations on the geocell wall (Fig. 4) will inherently make any experimental measurement to deviate from estimates made using Eq. 1. Further modifications to the cubic law have been proposed to account for rugosity and other characteristics of the interface, however, in its simplest form it has been found to be good enough for some cases. A correction factor can also be introduce to account for such variation.

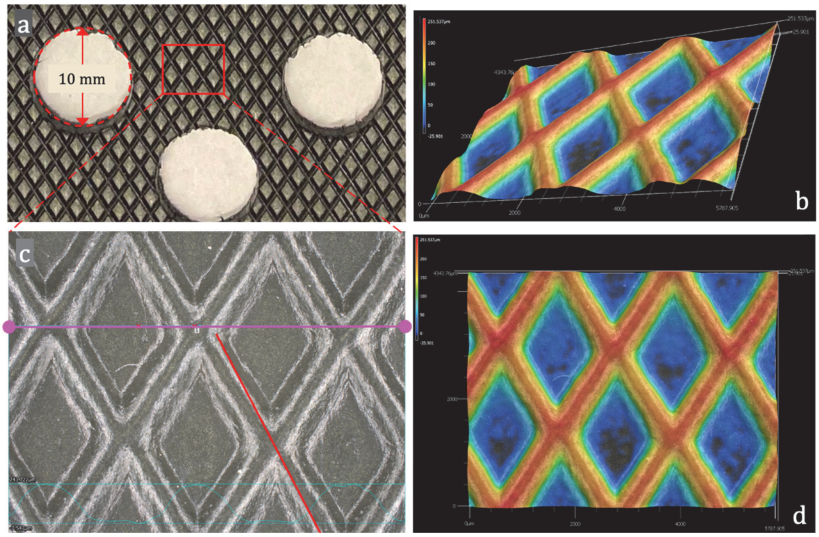

Fig. 4. Characteristics of the geocell wall: a) texture and perforations, b) 3D view of texture height, c) close-up of texture, d) 2D view of texture.

2 MATERIALS AND METHODS

The geocells used in this research program are made of high-density polyethylene (HDPE) and are sourced from a commercial manufacturer; the specimen size selected is 580 mm in weld spacing and 75 mm tall. The concrete infill used in the experiments is general-purpose Portland cement concrete, with an average slump of 90 mm (≈ 3.5 in) and mass density of 2300 kg/m³ (≈ 144 lb/ft³).

For the construction of the specimens a single geocell was placed inside a large-diameter polycarbonate tube, the inside was then filled with concrete and allowed to cure for 28 days, finally a zero-shrinkage casting was poured in the outside of the geocell and allowed to fill the space within the tube. Increasing levels of water heads are exerted on the sample, and the resulting infiltration is measured with a sensor. The amount of water that passes through the interface is adopted as the flow rate per unit length of concrete-geocell interface. A schematic of a specimen is shown in Fig. 5.

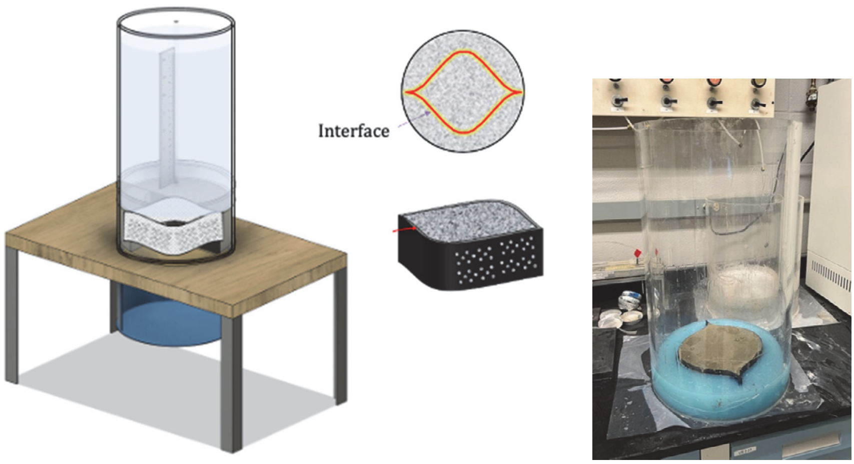

Fig. 5. Depiction of the unit-cell infiltration device and an assembled specimen

3 RESULTS AND ANALYSIS

An infiltration rate can be estimated for the geocell size and concrete characteristics of our specimens by means of Eq. 1. The variables are:

- s ≈ 0.00004 m, adopted as the average most likely shrinkage of concrete at the interface according to the American Concrete Institute shrinkage prediction methodology, ACI-209.
- γ_w = 9807 N/m³, the standard unit weight of water.
- L = 1.16 m which is the perimeter of the geocell or twice the weld spacing.
- Δh is the head difference, varied from 0.03 m (1.2 in) to 0.37 m (14.5 in).
- μ = 0.00089 N·s/m² at 25 °C (often μ = 0.001 N·s/m² at 20 °C is used for simplicity).
- H = 0.075 m, the height of the geocell and thickness of the liner.

The infiltration tests were performed at different hydraulic heads, the results are presented in Fig. 6 alongside estimated ones, both normalized per unit length of interface.

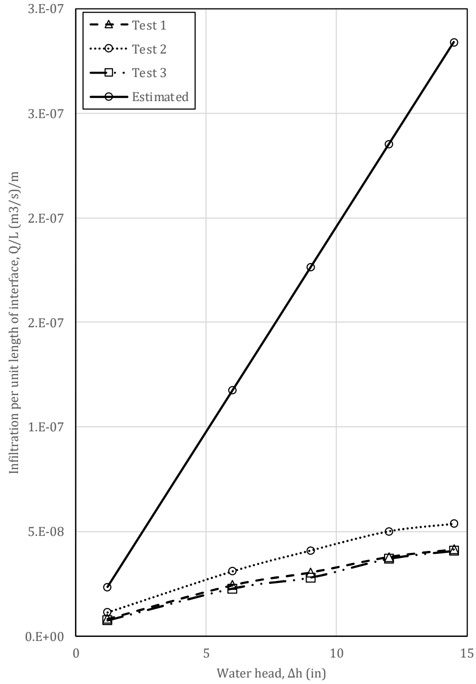

Fig. 6. Infiltration test results

The results indicate that the flow rate grows linearly as the pressure gradient increases, as suggested by the cubic law formula (Eq. 1), this proportional relation is maintained by hydraulic gradients varying from 0.3 to 4.0. The measured flow rate is quite smaller than the estimated one, which is expected since the real interface is a more tortuous path for water compared to the idealized smooth interface. The presence of perforations also allows for concrete to flow across cells and harden thus providing more resistance to the flow. The effect of the textured and perforated interface can be estimated by comparing the measured flow rate and the estimated flow rate for a corresponding smooth interface. If such an approach is used, the hydraulic aperture (gap or interface thickness) can be backcalculated. In this case it is assessed that the actual hydraulic aperture is about 0.5 to 0.6 of the estimated one.

4 CONCLUSIONS

In this paper we studied the characteristics of flow through concrete-geocell liners and the magnitude at which infiltration takes place. Concrete-geocell liners are compared against traditional alternatives such as reinforced concrete and articulating concrete blocks, and the advantages and disadvantages of each system are listed. The nature of flow conditions and importance of the interface is highlighted, this interface is microscopic, and the presence of wall texture and perforations make it considerably unlike a smooth interface. An analytical solution for smooth interfaces is presented. Such a solution can be adjusted with the introduction of a correction factor. The magnitude of the infiltration rate was measured experimentally on individual specimens of real-scale size and general-purpose concrete as used in practice. A back calculation of the hydraulic aperture using measured flow rate data indicates that it is about 0.5 to 0.6 smaller than initially estimated.