

## Geocells, a 25-year perspective Part 2: channel erosion control and retaining walls

Part 1 of this series (August 2004) reviewed the early history of geocells and their applications to roadway type systems. Part 2 examines the use of geocells in channel erosion control and retaining wall applications. While these applications were not envisioned in the early Army development of roadway improvement systems, they now represent a major market for geocells. As in Part 1 of this series, each application is reviewed to examine the important physical parameters of the geocell that should be calculated and then specified by the designer. Since geocells are produced under license to the Corps of Engineers, most physical properties are shared by all commercial geocells. These shared properties must be ensured by the manufacturer's quality control program and confirmed by the engineer prior to acceptance of the product. The various commercial geocells do differ in whether the geocell walls are textured or

contain penetrations. The designer must understand the relative merits of these product-specific variations.

### Slope erosion control

Geocells offer an economical means of providing either a vegetated (green) or hardened surface on slopes too steep for conventional slope erosion control techniques. Steep here refers to slopes that are generally steeper than 2H:1V (26.6°). Both techniques rely on our ability to "nail" the geocell honeycomb structure to the slope using a combination of earth anchors and tendons. The honeycomb structure of the geocell provides a blanket of small cells that can adequately contain either topsoil for vegetative systems or stone or concrete for hardened systems. In such slope applications, the geocell must have perforations in the side wall to allow water to drain from the cells. These same perforations aid the

geocell in restraining the soil or stone placed within the cell. In such applications where the subgrade is erodable, a light nonwoven geotextile is placed beneath the geocell.

### Vegetated erosion control system

Photo 1 shows an example of a vegetated (green) geocell erosion control system installed on a steep slope. Once filled with a suitable soil, each cell in the honeycomb functions as an individual "pot" to contain the soil and young vegetation and as part of the honeycomb system that initially protrudes and reduces the velocity of water draining down the surface of the slope. The height of cell required is a function of both the slope angle and the vegetative root depth potential of the underlying subgrade. The effective depth of vegetation is approximately 0.75 of the standard geocell heights over the typical range of potential slopes. If the subgrade will not support vegetation, then the cell height must be selected based on anticipated rooting requirements. However, if roots will penetrate into the subgrade, then the height of the cell can be reduced. This latter condition is preferred, since the roots will provide significant long term anchorage of the geocell reinforced vegetative surface veneer to the slope.

Rainwater that percolates into the geocell layer must either drain vertically into the subgrade soils or parallel to the slope through the geocell system. A typical subgrade requiring geocell protection is poorly drained. For this reason, perforations are provided in the geocell wall to allow water to drain parallel to the slope. The perforations must provide adequate drainage while not significantly impacting the stiffness of the honeycomb system.

So how does the "green" geocell system work? As with turf reinforcement mats (TRMs), the geocell system must provide reinforcement to the root network of the vegetation. The roots are quickly attracted to the moisture stored in the underlying nonwoven geotextile and are soon entwined within the fabric. Additionally, roots can intertwine through perforations in the geocells walls if present. The root network is thus relied on to bind the topsoil/geocell



**Photo 1.** Vegetated geocells on steep slopes. Note how both sides of this highway ramp utilize a "green" approach.

cell/nonwoven into a composite erosion control layer. The weight of these composite and earth anchors are used to hold the system in place. Interestingly, this reliance on root intrusion also means that the penetrations in the geocell walls cannot be relied on for drainage of pore water parallel to the slope. However, unlike lateral drainage layers in landfills, we have physically nailed the geocell system to the subgrade so slippage can be prevented. It seems irrelevant whether the cell walls are textured or smooth. Like TRMs, the geocell structure only provides reinforcement to the root network of successful vegetation.

#### Aggregate erosion control system

As an alternative to vegetation, the geocell honeycomb can be filled with gravel. Here the geocell contains the smaller aggregate in cells to produce rip-rap like performance. The height of the cell is influenced by two factors:

- The maximum stone diameter must be approximately one-third the minimum dimension of the cell.
- The stone must fill at least one half of the cell vertically.

The latter condition is shown on **Figure 1** and can be expressed as follows:

$$\tan(\beta - \phi) = \frac{H}{2D}$$

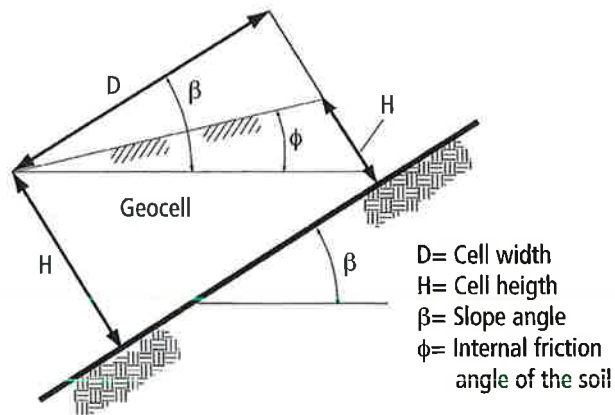
where  $\beta$  is the slope angle,  $\phi$  is the internal friction angle of the stone,  $H$  is the height of the cell and  $D$  is the effective width of the cell. Thus, for an geocell having  $D = 21.3 \text{ cm}$  (8.4 in.) placed on a  $40^\circ$  slope and filled with a stone having a friction angle of  $28^\circ$ , the minimum cell height is equal to

$$\begin{aligned} H &= 2D \tan(\beta - \phi) = \\ &= 2 \cdot 21.3 \cdot \tan(12^\circ) = \\ &= 9.1 \text{ cm} = 3.57 \text{ in.} \approx 4 \text{ in.} \end{aligned}$$

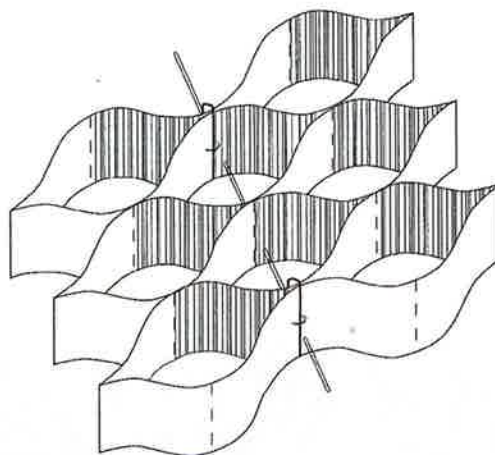
The maximum size of stone used to fill these cells should be  $9.1 \text{ cm}/3 \approx 3 \text{ cm}$  (1.2 in.). If larger stones are required, then a larger geocell must be used.

#### Anchorage of geocell honeycomb

To be effective, the geocell system allows a veneer of soil or stone to be placed on a steeper slope than they could be placed with-



**Figure 1.** When using stone, the material must fill at least one-half of the cell vertically.



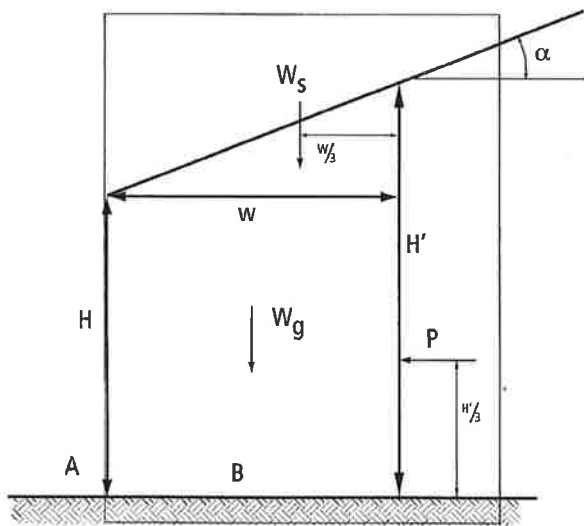
**Figure 2.** Tendons are strung through cell perforations to engage the anchors and lay directly down the slope.



**Photo 2.** Cellular system anchored by tendons prior to fill.



**Photo 3.** Concrete fill in geocells performs similar to concrete channels.



**Figure 3.** Forces to be considered in the design of a gravity wall..

out the geocell system. Supplemental anchorage must be provided to the geocell system to provide the additional restraint. The amount of supplemental restraint required is a function of the slope angle ( $\beta$ ), the internal friction angle of the stone or soil fill ( $\phi$ ), the unit weight ( $\gamma$ ) of the soil or stone, and the height of the geocells ( $H$ ). The minimum required anchorage force per square foot of geocell for a factor of safety of 1.5 is calculated as follows:

$$f_{\text{anchorage}} = (H \cdot \gamma)(1.5 \sin\beta - \cos\beta \tan\phi')$$

Here  $\phi'$  is the friction angle between the stone and the slope. This friction angle can be assumed to be the lower of the internal friction angles of the stone fill or the sub-

grade. The total anchorage force required,  $F_{\text{anchorage}}$ , is then equal to the  $f_{\text{anchorage}}$  times the total slope length,  $L$ . If  $F_{\text{anchorage}}$  is negative, then no supplemental anchorage is required.

Supplemental anchorage is provided using two distinct means:

- Stakes or anchors driven into the subgrade literally nail the geocell honeycomb to the slope.
- Tendons are anchored in an anchor trench behind the crest of the slope and at points in the geocell honeycomb down the slope. This suspends the geocell honeycomb from the top of the slope.

Site conditions dictate which combination of anchorage methods will be used. Typically, an anchor trench is provided at the

top of each slope to ensure that surface water does not run beneath the geocell system.

When subgrade conditions permit, the geocell honeycomb system can be anchored using #4 or larger steel reinforcing bars placed immediately below the welded connections and driven at least 3 times the cell height into the subgrade. These bars are commonly bent into a "J" hook form so that the geocell side wall is securely anchored. Also, it minimizes rotation of the pin under load. A minimum of 3 rows of anchors per panel ( $\approx 1$  per meter) is normally used to just deploy the geocell honeycomb. Each row will have anchors spaced one every meter. This provides a minimum of 1 per square meter (or 1 per 10.76 ft.<sup>2</sup>).

The greatest uncertainty with this means of anchorage is estimating the lateral force capacity of a single stake. Typically the lateral force obtained from one of the anchors is less than 27 kg (60 lb.). For the minimum anchor spacing, the maximum force provided is therefore 27 kg/m<sup>2</sup> (5.6 psf). Greater sliding resistance can be achieved by increasing the number of anchors to the limit of one anchor per cell. Typical anchor densities do not exceed one anchor every other cell in both directions. Field tests should be performed to evaluate the site-specific lateral force potential of specified drive stakes.

When the use of anchors does not provide sufficient supplemental restraining force, then tendons are anchored at the top of the slope and routed through the geocell penetrations to provide additional sliding resistance. On steep slopes, three to five tendons are commonly used per panel (2.44 m or 8 ft.). At the top of the slope, the tendons can be anchored by burying the end of the geocell honeycomb or by using a separate deadman anchor. Deadman anchors can be formed by concrete grade beams, earth anchors, rock anchors, etc.

Polymeric tendons are available in strengths ranging from 300 kg (700 lb.) to 900 kg (2000 lb.). The tendons are strung through the perforations in the deployed geocells such that they engage the anchors and lay directly down the slope. Figure 2 shows a single tendon placed in such a manner. Note that the tendon is wrapped around each anchor encountered so that the tensile strength of the tendon can be transferred to geocell without the potential for localized failure of the cell wall.

For design of the anchorage system the assistance of the geogrid manufacture is essential. I know of no simple design procedure and suspect that "design" is very empirical based on prior applications.

## Channel erosion control applications

Channel linings must satisfy the slope requirements previously discussed and additional forces generated by saturation and flowing water. All channel design methods use Manning's formula to determine the flow capacity and velocity or maximum shear stress exerted on the channel lining. The average velocity of water flowing in a channel,  $v$ , is given as follows:

$$v = \frac{R^{2/3}s^{1/2}}{n} \quad (\text{meters, seconds})$$

or

$$v = \frac{1.486R^{2/3}s^{1/2}}{n} \quad (\text{feet, seconds})$$

where  $R$  is the hydraulic radius of the channel defined as the flow area,  $A$ , divided by the wetted perimeter,  $P$ . And  $n$  is the roughness coefficient for the specific liner system, while  $s$  is the bed slope. This equation is used to determine the flow depth and velocity for a given total flow  $Q (= vA)$ . Different design requirements exist for vegetated, stone-filled, and concrete-filled geocell systems; therefore, these are discussed individually.

Having spent considerable time working with TRMs, I was curious as to similarities in the design of geocell erosion control mats. Both products are used when short-term current velocities exceed 5 to 6 feet per second (fps). This is generally agreed to be the velocity limit of natural vegetation linings. **Photos 1 and 3** show two distinct applications of geocells in erosion control. **Photo 1** is a "green" application where the geocells are filled with topsoil and serve in the short-term (.5 hour) to limit initial erosion and in the long-term to improve the root anchorage of the vegetation. **Photo 3** shows the geocells filled with concrete for a very "hard" armoring system. The "green" geocell system can handle short-term velocities of 20 fps when the vegetation is fully established. This is comparable to TRM limits so I would expect long-term (24-hour) al-

Manning's Coefficient, n	Vegetative growth vs. flow
0.002–0.010	Dense growth of turf grass where the average depth of flow is at least twice the height of the vegetation
0.010–0.025	Turf grass growing where the average flow is from one to two times the height of the grass.
0.025–0.050	Turf grass growing where the average flow is about equal to the height of the grass.
0.050–0.100	Turf grass growing where the average flow is less than half the height of the grass.

**Table 1.** Manning's coefficient for grass lined channels (*Guide for selecting...*).

lowable peak velocities to be approximately 14 fps like TRMs. The concrete-filled "hard" geocell system will handle flow velocities greater than this and approaches the performance of concrete-lined channels.

### Vegetated geocell channel lining

As previously discussed, the geocell honeycomb provides a stable layer of soil for the vegetation to germinate in and reinforces the root network as it develops. The topsoil filled geocells are commonly 3 in. high and placed on a 3 to 4 ounce per square yard (osy) nonwoven geotextile. Stakes placed approximately one per square meter are used to anchor the geocells to the subgrade. The topsoil is loosely placed in the cell and lightly tamped until completely filling the cell. Initial erosion leaves a series of small pools formed by the individual geocells that help limit overland flow while the vegetation is developing. Additional protection during this initial stage can be obtained by use of conventional temporary erosion control matting. On slopes steeper than 2H:1V, a 4 in. high cell is recommended, and a greater density of anchors may be required.

Two factors required for design are dependent on the type of vegetation and its

health: Manning's roughness coefficient,  $n$ , and the allowable velocity of flow acting on the vegetation,  $v$ . Manning's coefficient for a vegetated surface in a uniform channel with minor meandering can be estimated from **Table 1**. The height of grass must be estimated based on regional experience and operational practice. The allowable flow velocity acting on the developed vegetation ranges from 6 m/sec (20 ft./sec) for short duration flows (less than 1 hour) to 4 m/sec (14 ft./sec) for long duration flows (24 hrs+).

### Stone-filled geocell channel lining

When site conditions do not support vegetation, a hardened system using aggregate fill can be used with the aggregate fill. A 6 to 10 osy nonwoven geotextile is initially placed over the subgrade. A review of manufacturer's design information indicates that the geocell system conservatively allows a 60% increase in the average velocity sustainable against the aggregate and provides for the use of aggregate on steeper slopes (*Guide for selecting...*). This early testing used geocells with smooth, non-perforated sidewalls and is very conservative when used with perforated geocells. Neglecting the geocell system, the average allowable flow veloc-

*Editor's note: A follow-up article in the January issue will include pullout data for smooth, textured, textured/perforated, and smooth/perforated cell walls. Additional reader questions and requests for more information are welcomed. Write to gfr@ifai.com.*

ity of an aggregate lined channel is calculated as follows:

$$D_{50} = 0.0136 V^3/d^{0.5}K^{1.5}$$

Where  $D_{50}$  is the size of stone with 50% finer than,  $V$  is the allowable average flow velocity (in./sec),  $d$  is the depth of the channel (ft.), and  $K$  is a slope factor calculated by the following:

$$K = [1 - (\sin\theta^2/0.396)]^{0.5}$$

Here  $\theta$  is the side slope angle in degrees. The allowable average flow velocity for a channel having a depth of 6 ft. (1.83 m) and 14° side slopes is calculated as follows:

$$K = [1 - (\sin 14^\circ/0.396)]^{0.5} = 0.92$$

$$D_{50} = 3.94 \text{ in.} = 0.0136V^3/6^{0.5}0.92^{1.5} \\ \Rightarrow V = 7.12 \text{ ft./sec (2.17 m/sec)}$$

Thus, without the geocell system, the channel can be designed to handle long-term flows of 2.17 m/sec. Based on the flume testing at the Canadian National Water Research Institute (Engel and Flato 1987), the design allowable velocity can be increased 60% with the geocell system. Thus, the allowable average flow velocity in the example above can be increased to 11.4 ft./sec (3.47 m/sec).

The actual average flow velocity in the design channel is calculated using Manning's equation. The roughness coefficient,  $n$ , required in Manning's equation can be calculated as

$$n = 0.0395 (D_{50})^{1/6}$$

Here  $D_{50}$  is in feet. This process allows the designer to quickly evaluate alternative aggregate fills and channel sections to find the most economical design. Typically, the aggregate is well-graded and has a maximum particle size less than half the equivalent cell diameter. Interestingly, the allowable flow velocity increases as the geocell becomes visible due to aggregate initial surface scour. This adds to the conservatism of the above calculations. Manufacturer's literature indicates that scouring can be further reduced by infilling the upper 1 in. of stone with grout. While this is intuitively obvious, no specific design guidance is provided for this option. Also note that the concrete infill decreases Manning's

coefficient to as low as 0.22, which may result in increase flow velocities and diminish the apparent advantage of the concrete infill.

#### Concrete-filled geocell channel lining

For average flow velocities that exceed the limits of the green or aggregate geocell systems, the geocell honeycomb can be filled with concrete. Here the geocell system serves in the short-term as the concrete formwork and in the long-term as the anchorage mechanism for the individual concrete blocks formed by the geocell structure. In both applications, the geocell honeycomb must be anchored to the subgrade to resist movement due to slope stability or current generated forces. Slightly larger geocells are used in this application with a 4 in. cell height and 71.3 in.<sup>2</sup> area being common. The cell height is selected based on uplift forces that the system may experience in service.

Based on testing in England (CIRIA 1987) in the late '80s, the concrete-filled geocell systems can tolerate maximum flow velocities of 26 ft./sec (8 m/sec) if the mass of the system exceeds 28 lb./ft.<sup>2</sup> (135 kg/m<sup>2</sup>). For typical concrete, this would require a geocell only 3 in. tall. Design velocities in excess of the above would require thicker geocell systems. The English research involved smooth, non-perforated geocells and a number of other block systems. Suggested Manning's coefficients for the concrete filled geocell systems range from 0.12 for smooth troweled surface to 0.20 for a raked surface.

The geocell honeycomb structure must be able to retain the concrete under service loads. Newer geocell systems provide side walls that are perforated and/or textured to potentially more effectively bond to the cell side wall. This bond was evaluated for this paper by Rob Swan of SGI Testing Services. Textured, smooth, and perforated 4-in. high geocell system were cast with lifting hooks embedded in the blocks. Individual blocks were pulled from the honeycomb with the pullout force recorded. Data on the peak force required to extract a single block for the various cells will be published in January.

Geocell systems are particularly helpful when space available for the channel is limited. In these applications, steep side slopes are commonly required, and the geocell honeycomb structure allows vegetation and aggregate to be placed on steeper slopes. For concrete linings, the use of the geocell honeycomb pro-

vides for increased ability of the cast blocks to conform to changes in the subgrade.

## Retaining wall applications

Layers of the geocell honeycomb system can be stacked to form wall or dike structures. The geocell panels can be used by themselves to form gravity structures or as a facing system in conjunction with geosynthetic reinforcement to form mechanical stabilized earth (MSE) structures. While manufacturers indicate that geocell gravity structures can be built to a height of 20 ft. (6 m), I would recommend checking comparative costs when the height reaches half of that. I suspect that the MSE walls quickly become more economical as height increases. The face of walls constructed with geocell panels can be vegetated by filling the exposed cells with topsoil or hardened by filling these same cells with concrete.

This paper reviews only the considerations for integrating the geocell panels into conventional gravity or MSE retaining wall design procedures. The reader is directed to excellent summaries of the complete wall design process by Koerner (1996) and Holtz et al. (1997). As components in a gravity wall, the stacked geocell honeycomb panels must resist the active lateral earth pressures that develop behind the wall. Figure 3 shows the forces to be considered in the design of a gravity wall. The designer must evaluate the following:

- **Overtuning stability.** Taking moments about the toe of the wall, the factor of safety is defined as the ratio of moments resisting overturning divided by the moments driving overturning. The factor of safety is increased widening the gravity wall.
- **Sliding stability.** The shear strength at the bottom of the gravity wall must be greater than the horizontal force acting on the back of the wall. I have never seen this failure mode govern a design—but we still check it.
- **Bearing capacity.** The vertical pressure acting beneath the toe of the wall must not be greater than the subgrade can support. The neat trick here is to use a geocell layer to increase the bearing capacity as discussed in Part 1 of this series.

A minimum factor of safety of 1.5 is the goal for all modes. Typically, the overturning stability is the controlling factor. In my opinion, gravity walls constructed using geocell layers become uneconomical when the wall height is greater than 10 ft. (3 m). Above this height,

the designer should compare the cost of an MSE wall using the geocell panels as facing. For gravity wall applications, I would recommend using only granular fill in the geocell panels to promote drainage from behind the wall.

When used as facing in a MSE wall, the geocell panel is typically 4 cells deep. The geotextile or geogrid reinforcement used to form the MSE wall is simply sandwiched between the geocell layers to develop a frictional connection with the facing. My experience with MSE walls has shown that face bulging does not occur if the MSE layers of reinforcement are vertically spaced less than 18 in. apart. This could be achieved using three 6 in. high geocell layers or two 8 in. geocell layers. Since the face panels can be made in custom colors, e.g. green or brick tan, it might also be possible to have 9-in.-high face panels fabricated. This would be ideal since each geocell panel would be in direct contact with a layer of MSE reinforcement. Beyond a base layer or two of perforated cells for drainage, there would appear to be no benefit in using perforated or texture geocells for this application.

## Summary

Geocell systems provide a simple means of increasing the flow capacity of channels or reducing erosion on slopes. Construction of the systems requires no proprietary tools or equipment. The commercial geocell components are very light and compact such that shipping costs of the components to the site is minimal. To ensure the best performance of the geocell systems, a granular fill should be used unless a "green" alternative is desired. Geocell gravity channel walls can be combined with geocell channel floors to produce very compact channels having maximum erosion control protection without the need for concrete form work.

The use of geocell panels in MSE walls allows the designer an alternative to the armored appearance of masonry facing. The vegetative facing possible through the use of geocell facing softens the appearance of walls and may be more appropriate in many applications. While geocells remain the least understood of the geosynthetics, their

unique properties warrant a better understanding by all civil designers. **GFR**

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