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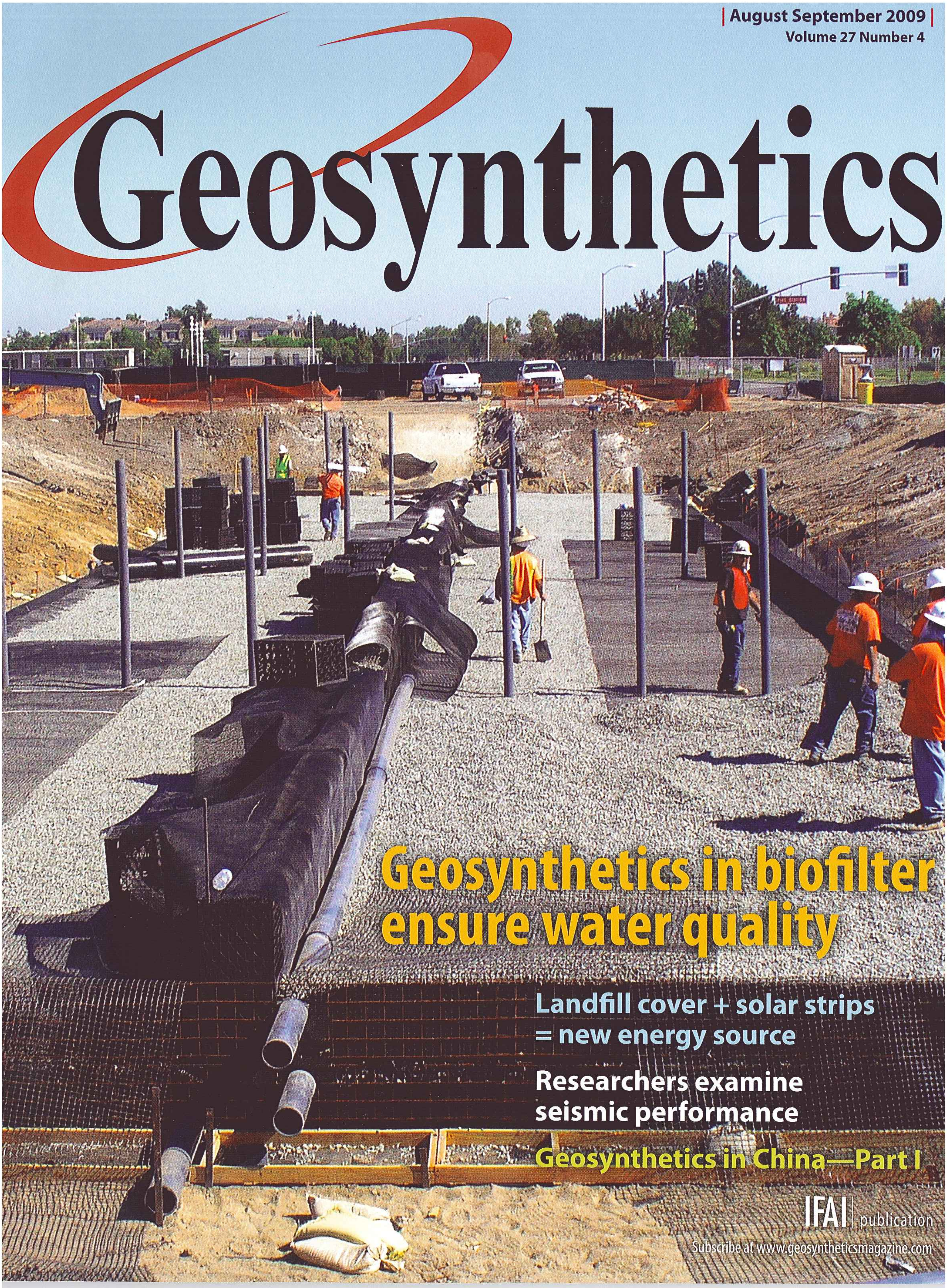

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Research and innovation: Seismic performance of various geocell earth-retention systems

Geosynthetics | August 2009

By Dov Leshchinsky

Editor's note: *Feature articles in Geosynthetics magazine focus on projects and how geosynthetic materials are used in a variety of applications. Very rarely is the focus solely on a specific product, company, or individual. Professor Leshchinsky and I note that this article—particularly the Introduction and Conclusions—departs from this policy in an effort to offer a guideline, an example, of how product development for the geosynthetics industry can be done effectively. We hope these lessons can further advance the geosynthetics industry into the 21st century with much success —**RB***

Introduction

Innovation has always required thinking out of the box. The development of various applications-oriented geosynthetic products demonstrates this hypothesis. For example, consider geomembranes, geogrids, and geotextiles, and think of landfills, MSE walls, and filters. While geotechnical structures become more cost-effective and have better performance, researchers are rewarded for positively impacting the profession.

An established player in the geocells arena, PRS-Mediterranean, envisioned a modification of its standard product to enable new, critical applications. The idea was to develop a new polymeric alloy that combines the desired properties of polyethylene and polyester, thus enabling an effective use of geocells as reinforcement for earth retention, load support in pavements and railroads, and more. While exploring the production of such an alloy (called Neoloy®), PRS commissioned research to develop design methodologies. Such research should also imply the desired properties of the new product.

This article provides an overview of the research where the use of geocells as an earth-retention structure was explored. The geocell used in the tests was standard, commonly used HDPE and, as such, was not appropriate for long-term reinforcement applications; that is, it was not stiff enough. However, it was adequate for investigation of short-term performance, thus implying the desired long-term properties of a polymer to be used as well as producing the basis for design, especially under severe seismic loading.

The research team included Professor Hoe Ling of Columbia University, Dr. Mohri of the National Research Institute of Rural Engineering in Tsukuba City, Japan, and the author. Detailed results were reported by Leshchinsky, et al. (2009) and Ling, et al. (2009).

Ideally, the design of any structure subjected to earthquakes should be based on tolerable recoverable and/or permanent displacements. This approach is difficult to implement for reasons such as a lack of acceptable criteria for tolerable displacements, highly random future seismic record, inaccurate identification of in situ soil constitutive behavior, and numerical difficulties in predicting displacements within the matrix soil-geosynthetic. The state-of-the-art in seismic slope stability analysis is not yet sufficiently developed to entirely replace the current design practice.

Design of slopes is typically based on limit equilibrium (LE) stability analysis. Pseudostatic slope stability analysis assumes an equivalent seismic coefficient, typically in the horizontal direction, which results in additional force components in the limit equilibrium equations, all proportional to gravity. Specifying the seismic coefficient as peak ground acceleration (PGA) is likely overly conservative as it considers the maximum seismic forces permanent rather than momentary.

The objective of this study was to quantify a reasonable reduction factor (RF) on the PGA for geocell retention structures. Reduced factors can then be integrated with well-established LE analysis to conduct seismic and static design.

Shake table testing program

This shake table is located at the Japan National Research Institute of Agricultural Engineering, Tsukuba City, and it can excite gross maximum payload of 500kN to vertical and/or horizontal acceleration of 1g; maximum accelerations for lighter payloads can be larger than 1g. The metal testing box containing the geocell retention systems was 2m wide, 6m long, and 3m tall. To minimize reflection of waves from the side and rear of the metal box, expanded polystyrene (EPS) boards, 5cm thick, were placed against the testing box walls. To reduce friction with the sidewalls, greased plastic sheeting was placed against the EPS.

In all tests, an amplified time record of the 1995 Kobe earthquake was applied to the shake table. The Kobe record used had horizontal PGA of 0.59g and a vertical PGA of 0.34g. The peak horizontal and vertical accelerations did not occur simultaneously. Table 1 shows the applied peak accelerations in four different tests. There were either two or three loading stages.

Table 1: Applied Peak Acceleration in Four Tests

Recorded Peak Ground Acceleration (PGA) in the Field	Test Number	Applied Peak Acceleration at Base of Shake Table					
		Horizontal			Vertical		
		Loading Stage:			Loading Stage:		
		1	2	3	1	2	3
Horizontal: 0.59g Vertical: 0.34g	1	0.46g	0.92g	N/A	0.21g	0.42g	N/A
	2	0.48g	0.94g	N/A	0.20g	0.39g	N/A
	3	0.47g	0.95g	1.22g	0.20g	0.37g	0.48g
	4	0.41g	0.87g	1.21g	0.18g	0.34g	0.50g

In the first loading stage, the Kobe record was attenuated in an attempt to verify whether excessive movements occurred. An hour later the second loading stage was applied, amplifying the Kobe record. In Tests 3 and 4, a third excitation was applied, this time reaching the capacity of the shake table. The third stage nearly doubled the Kobe recorded acceleration. Stage 2 was aimed at developing an active wedge; it was hoped that the third stage would bring about collapse.

In Tests 1-3, the retention system was 2.8m high; in Test 4 it was 2.7m. All retention systems were constructed over a 0.2m-thick foundation soil. The geocells, resembling a honeycomb structure, were 0.2m high with internal aperture of approximately 0.21m by 0.21m. The average face inclination of the systems was 2(v):1(h). The top geocell layer was 2.52m long, much longer than all layers below. This top layer was infilled with compacted gravel. It was assumed that long top layer made of geocell would inhibit crack or even slip surface formation immediately below this layer. Indeed, tests indicated that while numerous small and shallow tension cracks initiated at the crest, none was observed immediately below the long top geocell layer in any of the tests, thus supporting the initial assumption.

Figure 1 (a–d) shows the geocell layout in each of the four tests.

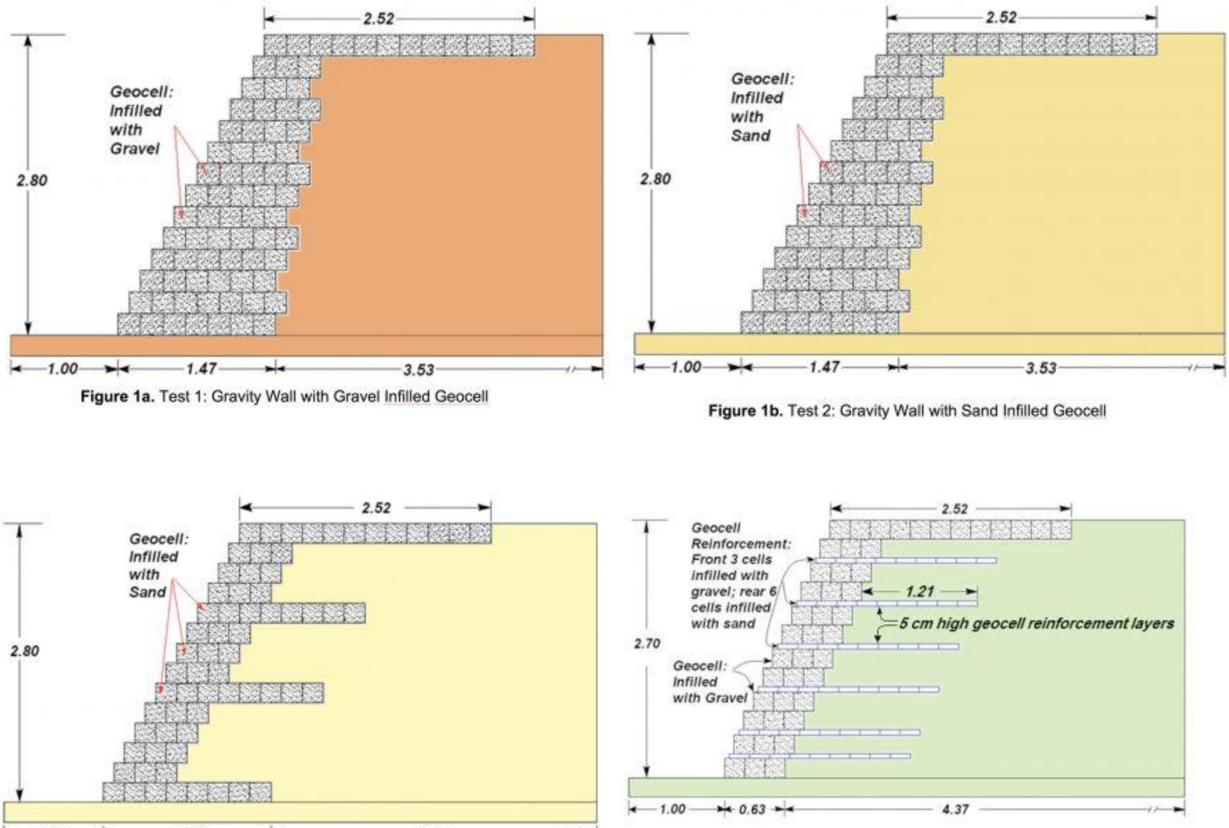

Figure 1a. Test 1: Gravity Wall with Gravel Infilled Geocell

Figure 1b. Test 2: Gravity Wall with Sand Infilled Geocell

Figure 1c. Test 3: Geocell Reinforcement Infilled with Sand

Figure 1d. Test 4: 5 cm High Geocell Reinforcement Infilled with Sand

Figure 1. Configuration of Tested Systems

Tests 1-2 represented flexible gravity walls and Tests 3-4 utilized geocell as reinforcement and facing. In terms of economics, the systems in Tests 3 and 4 are about the same. In Test 4 the layout of geocell resembled that of traditional geogrid reinforcement while still acting as 3-D element. Generally, the polyethylene geocell used in the tests cannot be used as reinforcement for sizeable structures since it has low long-term tensile strength. As tested, only sufficient short-term properties were needed to resist the seismic loading. However, the lessons should indicate the needed product improvements in developing Neoweb®, which is made of Neoloy®, as well as produce a simple design methodology.

The backfill soil behind the facing and in the 0.2m-thick foundation was fine uniform sand (Median Grain Size = 0.27mm; 0.35% passing sieve #200; Uniformity Coefficient = 2). The backfill was compacted to 90% of Standard Proctor at a moisture content of 16% yielding a dry unit weight of 13.5 kN/m3 or moist unit weight of 15.6 kN/m^3. Compaction was done by a handheld vibratory compactor. Drained triaxial tests yielded peak strength of =38 degrees. Unit weight of the compacted gravel was 19.9 kN/m^3.

Thin white seams of sand were placed every about 0.4m within the backfill material. Upon completion of each test, the backfill was carefully excavated to observe dislocations of these seams so that traces of slip surfaces could be identified. In addition, each test was comprehensively instrumented including pressure transducers, laser displacement gages, accelerometers, and strain gages (Ling et al, 2009).

Figure 2

Results and interpretation

Accelerometers embedded within the backfill soil and facing, at several elevations, indicate that magnification of base acceleration was negligibly small. This may not be surprising with flexible retention systems as they deform during shaking, dissipating energy and acting as shock absorbers.

Figure 2.

Table 2 shows the measured maximum displacements in each one of the tests. Note that displacements were not uniform and, therefore, the term maximum represents a rather narrow zone where it occurs. Also note that for Tests 1 and 2, the maximum applied acceleration was significantly lower than that for Tests 3 and 4 (see Table 1). Overall, considering the severity of the applied seismic excitation, the recorded values do not imply a catastrophic failure (e.g., see Figure 2 for typical post-shaking appearance).

Generally, the displacements reflect a well-developed active wedge where the shear strength of the soil is mobilized. Sufficient strength and stiffness of a geocell will enable acceptable structural long-term performance with even smaller displacements.

Table 2. Measured Maximum Displacements

Test Number	Maximum Horizontal Permanent Displacement of Face [mm]	Maximum Settlement of Crest [mm]
1	31	27
2	47	40
3	150	150
4	95	85

Post-test exhumation of the retention systems while measuring dislocations of the white sand seams helped in establishing the location of the active wedge surface (e.g., see Figure 3, a–c).

This enables complete limit equilibrium (LE) stability analysis where the soil strength is fully mobilized rendering an active wedge, meaning the factor of safety on soil strength, Fs, equals unity.

To find an equivalent seismic coefficient for design, it is convenient to define seismic reduction factor, RFs=a/PGA, where a is the equivalent pseudostatic seismic coefficient. RFs for each test was determined using the recorded PGA that caused an active wedge to develop without rendering excessively large displacement combined with an adequate LE analysis.

The pseudostatic acceleration in the LE analysis was adjusted to render Fs of unity; i.e., to reflect the existence of an active wedge. The locations of the predicted and observed active wedges were compared and used to assess the predictive value of the analysis. It is noted that in LE design, one would input a(=RFs PGA) to obtain adequate seismic stability where the factor of safety, Fs, under pseudostatic conditions is typically about 1.1. In fact, if one had to design the tested retention systems, use of RF and Fs>1.1 would have produced smaller displacements than those reported in Table 2.

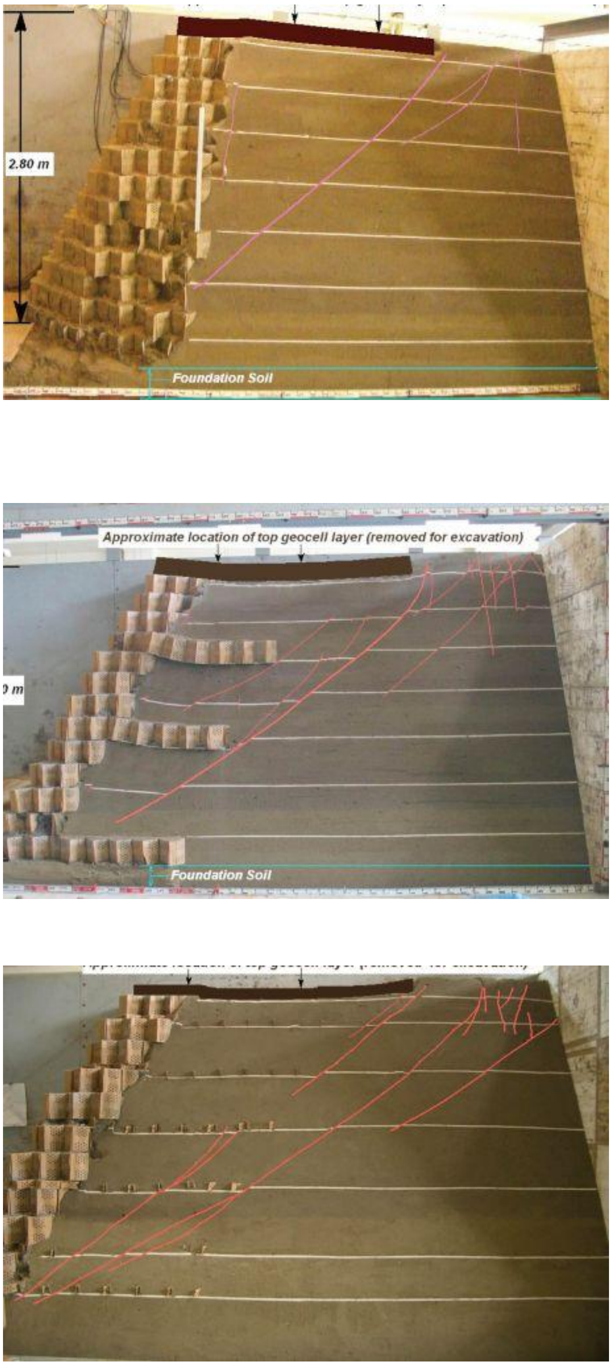

Figure 3a, 3b, 3c

LE stability analysis was performed using program ReSSA (www.geoprograms.com; also see Leshchinsky and Han, 2004). Rotational (Bishop) and translational (Spencer) analyses were conducted to determine the RFs. The safety map feature (Baker and Leshchinsky, 2001) facilitated the process. (For example, see Figure 4.)

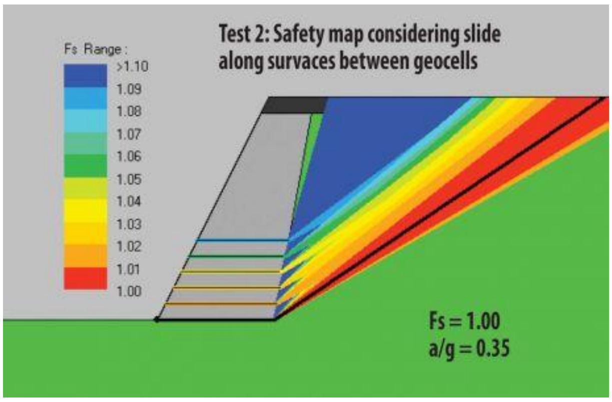

Figure 4.

While the observed slip surface emerged between the second and third geocell facing layer, the numerically predicted surface (at a/PGA=0.35) emerged along the interface between the geocell and the foundation soil. However, the safety map shows that practically this is an insignificant difference, as the safety factors for any predicted slip surface emerging at the lower geocell layers is within about 1–2%. Such an observation affords confidence in the predictions, especially when comparing Figures 3a and 4; i.e., the observed and predicted traces of slip surfaces, respectively. Figures 5a and 5b show the predicted active wedges and their respective RFs values; they can be compared with the observed wedges shown in Figures 3b and 3c, respectively.

Apropos Figures 3c and 5b: As can be seen, contrary to a common legend, these figures demonstrate that slip surfaces can develop through the reinforcement. Such "internal" global instability can occur when the reinforcement is too soft or weak. Clearly, while the HDPE geocell used was adequate to test a design-oriented analysis, it lacks long-term strength to serve as reinforcement. However, it enables one to establish the desired properties in geocells so it can serve as soil reinforcement.

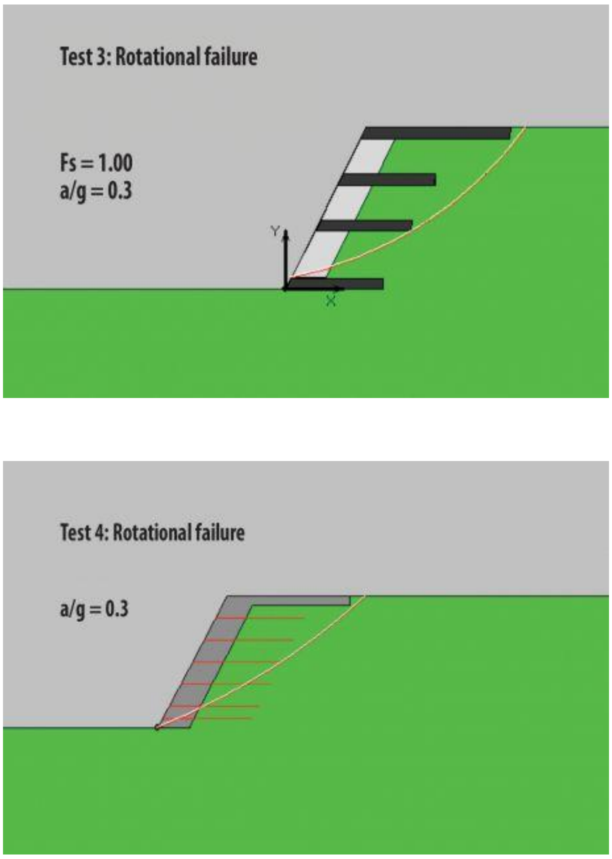

Figure 5a, 5b

Table 3 summarizes the reduction factors that are implied by the testing program when a pseudostatic LE is used.

Table 3

Test Number	Seismic Reduction Factor RFs=a/PGA
1	0.38
2	0.37
3	0.25
4	0.25

As can be seen, for geocell gravity systems, RFs of about 0.4 are adequate. For geocell-reinforced soil systems, RFs of 0.3 are adequate.

Conclusions

Current practice of designing reinforced or unreinforced slopes and walls is to identify the local PGA and use a fraction of it in a pseudostatic analysis. This fraction is the reduction factor for pseudostatic analysis.

The Kobe earthquake was used as a reference for an excitation to identify this coefficient. It is likely that if another excitation was used, the reduction factor would be different. However, the Kobe earthquake was significant in terms of damage to slopes and walls, thus qualifying it to serve as a good reference for calibrating this reduction factor and the associated seismic coefficient.

Tests results are compared with a pseudostatic limit equilibrium analysis. The predicted failure mechanisms are similar to those observed in the tested geocell retention systems. The seismic coefficients required to produce failure in the analysis were much smaller than the actual peak value obtained in the tests. For the geocell gravity wall, the seismic reduction factor, RFs, needed to render failure is about 0.4. For geocell reinforced retention systems RFs is about 0.3.

The FHWA (2001) guidelines for reinforced steep slopes allow for RFs of 0.5. Hence, compared with this work, the FHWA recommendation is slightly conservative. The IITK (2005) recommendation for unreinforced slopes of one-third of the Peak Ground Acceleration is amazingly close to the measured results.

Tests 1 and 2 show that gravity walls made of geocell can perform well under seismic loading. Such gravity systems may be economical for walls up to 3-4m high. Tests 3 and 4 show that a reinforced system, made entirely of geocell and soil, can be effective and likely economical.

The tests reported herein are relevant to short-term performance when considering the utilized HDPE geocell. However, without improvement, HDPE geomembranes are not suitable for long-term applications. Problems of durability related to leaching of additives, oxidation, and to UV exposed facing should be addressed. Large thermal contraction and expansion of outer cells due to daily and seasonal temperature changes combined with high intrinsic thermal coefficient of the geocell material could lead to progressive failure initiating at the outer cells. Stress cracking of exposed facing could occur in low temperature. Low stiffness and strength may lead to significant creep having poor long-term dimensional stability.

Considering the objectives of this research, PRS-Mediterranean received guidelines for developing the new polymeric alloy, Neoloy®, and thus improve its Neoweb® system, facilitating its use in retention systems. It also obtained design tools enabling utilization of the Neoweb® in demanding applications considering long-term performance.

Dov Leshchinsky, Ph.D., is a professor of civil and environmental engineering at the University of Delaware and is a regular contributor to Geosynthetics magazine. His last article, "The case of the percolating water," appeared in the April/May 2008 issue.

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