GFR Engineering Solutions for Roads, Soil, Water and Waste

Volume 21, Number 8

Lessons learned from failure: EPS geofoam

By John S. Horvath, P.H.D., P.E.

Exactly 12 years ago I had the privilege of authoring the first *GFR* feature article on expanded polystyrene (EPS) geofoam. At that time, EPS geofoam was already well known and in routine use in western Europe and Japan but was still largely unknown in North America.

A lot has changed since then, and EPS is now the geofoam material of choice worldwide in many functional applications, so much so that some think the terms geofoam and EPS are synonymous (they are not, in the same way geomembrane does not mean a particular polymer). This growth has benefited from lessons learned from failures, not unlike what has occurred for traditional planar geosynthetics.

Despite the fact that "learning from failure" is a well-proven cornerstone of civil engineering, my feeling is we don't always learn all there is to learn from a failure. *GFR* has kindly given me the opportunity to comment on this.

Types of failures

The word "failure" scares some people. I know there are those who wish we wouldn't use that term at all, especially in writing. However, it is a useful word and could be even more useful for our collective learning process if we more precisely identified what it is we are talking about.

If we think of failure as meaning something didn't work out as planned in a given application of some technology, it is clear to me that there are at least two distinct types of failure:

- an avoidable failure that occurred not because we didn't know how to prevent it but because there was some shortcoming in the design, specification and/or construction process.
- an unavoidable failure that occurred due to some behavioral mechanism that was beyond the current state of knowledge and any reasonable extrapolation of that knowledge.

Knowing which category a given failure falls into is important, as it guides us as to where we should focus and deploy our resources in order to reduce the potential occurrence of future failures. I will give some examples using EPS geofoam and its very common functional application as lightweight fill for roads.

Avoidable failures in design and specification

My anecdotal experience is that most of the failures involving the use of EPS geofoam to date, at least in the United States, have been in this category. Simply stated, these largely avoidable failures occurred because EPS of the appropriate density and/or quality was not used on a given project. Although EPS density in and of itself does not guarantee a certain level of load-bearing performance (critically important when designing a lightweight fill), density

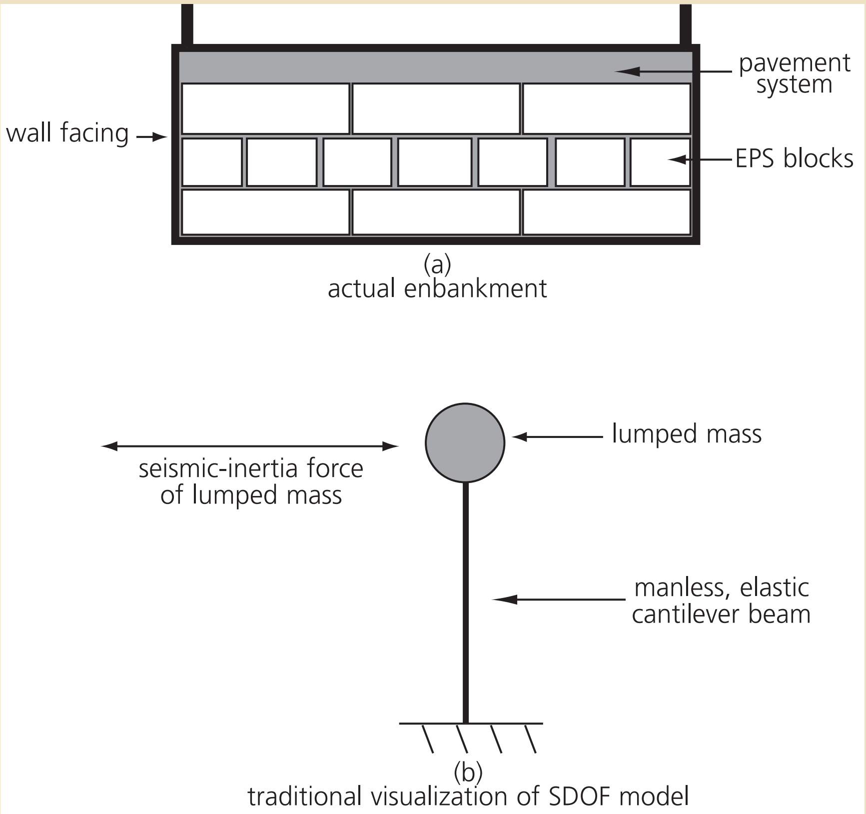

Figure 1. Seismic analysis model for an EPS geofoam embankment.

can be a very useful index property when used in conjunction with other, more-fundamental parameters such as Young's modulus.

Failures in this category can usually be traced to two distinct causes:

- The designer did not rationally select EPS density and/or quality for a lightweight fill. This is the result of the designer simply ot knowing how to properly design with EPS geofoam.
- The EPS molder (manufacturer) did not supply EPS of the correct density and/or quality to the project site. This can be the result of either an inappropriate project specification by the designer, allowing unacceptable material to be legitimately supplied, or insufficient manufacturing quality assurance (MQA) procedures by the inspection organization during construction to prevent inappropriate material from being placed in the earthwork.

In both cases, the true, underlying cause of the failure is a systemic failure to educate users of the technology of how to properly design and specify that technology. This type of failure is not unique to EPS geofoam. It has been observed for geotechnologies in general, typically when they first develop and evolve. However, this type of failure can be particularly acute and persistent for a generic, commodity material like EPS as there is no one manufacturer (in the U.S.) with a vested, proprietary interest in seeing that its material is used properly. Industry groups or organizations can be effective in such situations by proactively stepping in, taking the lead, and working with other interested parties such as government agencies, academia and professional societies to fill the information void. Unfortunately, with few exceptions this has not been the case for EPS geofoam, at least in the U.S.

The good news is that within the last few years there has finally been significant and notable progress in overcoming the knowledge deficiencies for both design and specification of EPS-geofoam lightweight fills. U.S. National Cooperative Highway Research Program (NCHRP) Project No. 24-11 for fiscal year 1998 was conceived and funded to provide information specific to the use of block-molded EPS geofoam as a lightweight fill for road embankments (Stark et al. 2000, 2002). The first project to use some of the outcomes of NCHRP 24-11 was Contract C09C2 of the well-known Boston "Big Dig." Several noteworthy advances to EPS-geofoam technology were ultimately made on this project (Horvath 2003), one of which is discussed subsequently, as it was based on lessons learned from failure.

It is useful to note that the results of NCHRP 24-11 are usable for a wider variety of applications in addition to roads. Even better news is that the Transportation Research Board (TRB) has recently (August 2004) formally and publicly made available the final report from NCHRP 24-11 as NCHRP Web Document #65. This document can be downloaded digitally in PDF format and at no cost from TRB's Web site (www.trb.org).

Unavoidable failures due to unexpected behavioral mechanisms

These might be called "true" failures and typically occur early in the use of a technology as well as when engineers try to push the edge of a technology's envelope. Despite best engineering efforts to anticipate performance when venturing into the technological unknown, sometimes a behavioral mechanism occurs that was simply unexpected. Fortunately, such failures have been relatively uncommon for EPS geofoam, yet each has produced valuable lessons for practice (Horvath 1999). To illustrate this point, a recent example will be discussed where a failure due to unexpected behavior occurred that had a dramatic impact on practice. Fortunately, the failure was

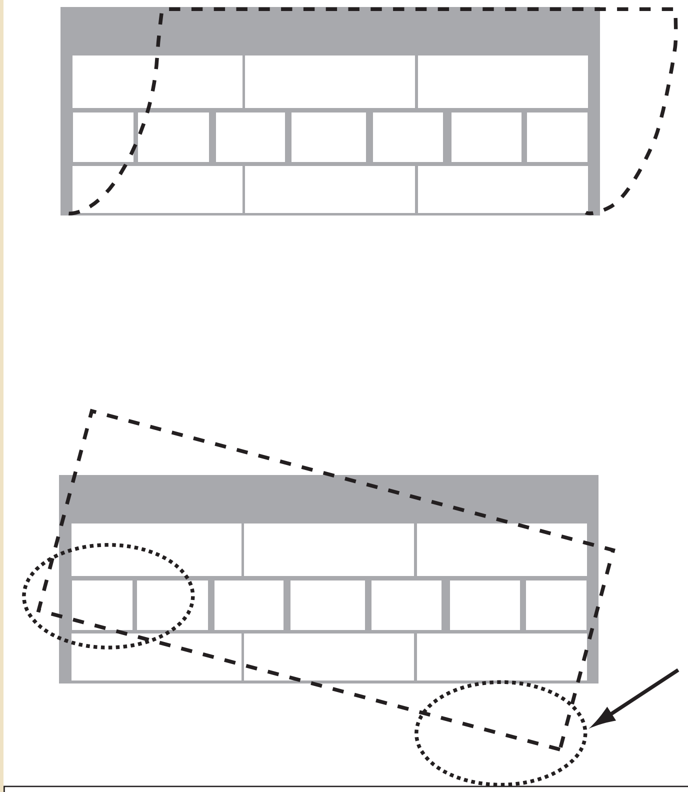

Figure 2. Seismic displacement and deformation modes.

observed under controlled testing conditions so its consequences did not have serious effects.

The previously noted Contract C09C2 on the Boston Big Dig is one of the final segments of this project and involves the extensive use of EPS geofoam for several embankments in the I-90/I-93 interchange area in South Boston. These embankments are somewhat atypical in cross-sectional geometry for EPS geofoam fills in the sense that they are relatively slender with a width-to-height ratio of the order of one in many cases.

For seismic analysis and design, EPS-geofoam fills are typically modeled as a single-degree-of-freedom (SDOF) system as shown in **Figure 1** because of their top-heavy nature (Horvath 1995, Nomaguchi 1996). For the historically more common case of an embankment wider than it is high, the primary mode of displacement and deformation as a result of the horizontal seismic-inertia force on the lumped mass (**Figure 1a**) is flexible in nature and in the form of lateral sway of the entire embankment as shown in **Figure 2a**. Traditional seismic analysis and design methodologies for EPS geofoam fills are based on this assumption (Horvath 1995, 2004).

However, during preliminary design of the Contract C09C2 embankments in early 2001 the project design team hypothesized an additional displacement/deformation mode in the form of rigid-body rotation of the entire embankment. This mode, which is shown in **Figure 2b** and was ultimately given the name seismic rocking, involves rigid-body rotation of the embankment in the plane of the figure about an axis perpendicular to the figure.

By happenstance, during the same time frame as the Contract C09C2, design activities were ongoing. Information was obtained by the project design team concerning shake-table tests performed in Japan in the late 1990s on full-scale models of EPS geofoam embankments (Nishi et al. 1998, Hotta et al. 1998). Some of these tests involved models with slenderness ratios similar to those being designed for the Contract C09C2 embankments. A careful review of both videotapes of the tests and English language translations of these references indicated some of the models experienced unexpected failure in the form of crushing of the EPS at the bottom, outer portions of the model. Fortunately, due to the controlled, experimental nature of these shake-table tests, there was no serious consequence of these failures.

Although these references did not elaborate on or explain the cause of these failures, it was quite apparent to the Contract C09C2 design team that the observed results were due to the previously unknown behavioral mode of seismic rocking. What happens during seismic rocking is that the lowermost/outermost portions of an assemblage of EPS blocks (see the highlighted areas in **Figure 2b**) are subjected to relatively large cyclic changes in vertical normal stresses due to the rocking motion. These stress changes are due to what is referred to as the *M-c-on-I (Mc/I)* effect. The moment referred to in this case is that caused by the seismic-inertia force shown in **Figure 1b**. This moment acts within the plane shown in this figure about an axis perpendicular to this figure and is obviously largest at the very bottom of the embankment. Note that these dynamic stress changes must be added vectorially to the usual vertical stresses within an embankment due to gravity loads. Under seismic rocking, unless the EPS has been designed to withstand the combined gravity + seismic compressive stresses, it will be pounded beyond its yield range into a stress-strain region of large plastic strains that are largely unrecoverable. Each cycle of seismic load only adds to the accumulated non-recoverable strain.

While seismic rocking can, theoretically, occur with any EPS geofoam embankment, subsequent calculations indicated that it controlled the design for all Contract C09C2 embankments (Riad and Horvath 2004). This was very sobering, as had the mode of seismic rocking not been hypothesized, verified and implemented into the final design, all of these embankments would have been underdesigned for seismic loads—even though the prevailing state of practice that considered the lateral-sway mode (**Figure 2a**) only would have been followed. The design experience on Contract C09C2 of course also raises the question of how many previously constructed EPS geofoam embankments worldwide may be seismically deficient due to the earlier lack of knowledge about seismic rocking.

Lessons learned about lessons learned from failure

Numerous authors have made the point over the years that we should learn from failure. To the extent that certain technical lessons are learned and used to permanently change design and construction practice this is certainly a valid point. However, it can be argued that equally important to the specific technical lessons learned from a failure, we should also consider the broader reasons behind a failure, i.e., we should not only learn from failures but about failures as well.

As noted previously, there can be at least two very different reasons why failures occur in the first place. One is related to systemic failure in educating end users as to how to properly use a technology and the other is due to the fundamental difficulty in anticipating all behavioral aspects of a new or evolving technology that is being pushed to new limits. The former reason, which is largely avoidable, suggests that allocating resources to educate end users should be a high priority. The latter reason, which history indicates may be impossible to prevent completely, can at least be minimized and controlled by allocating sufficient resources to adequately and thoroughly test and observe designs or loading conditions that go beyond the bounds of prior experience and use.

In conclusion, the process of learning from failure is very much like a coin and, as with any coin, has two distinct sides. Unfortunately, my experience has been that the education side of the coin is often perceived as being too mundane and thus tends to get less attention, even though in the coin-flip of failure it's the side that seems to come up more often.

GFR

References

Horvath, J. S. 1995. Geofoam geosynthetic, Horvath Engineering, P.C., Scarsdale, N.Y.

Horvath, J. S. 1999. "Lessons learned from failures involving geofoam in roads and embankments." *Research Report CE/GE-99-1*, Manhattan College, Civil Engineering Department, Bronx, N.Y.

Horvath, J. S. 2003. "Innovative aspects of the use of expanded polystyrene (EPS) on Boston's 'Big Dig'." *Research Report CGT-2003-1*, Manhattan College, School of Engineering, Center for Geotechnology, Bronx, N.Y.

Horvath, J. S. 2004. "Geomaterials research project—a technical note re-calculating the fundamental period of an EPS-block-geofoam embankment." *Research Report CGT-2004-1*, Manhattan College, School of Engineering, Center for Geotechnology, Bronx, N.Y.

Hotta, H., Nishi, T., Kuroda, S., Hasegawa, H., Ri, J. and Tsukamoto, H. 1998. "Shaking tests for full-sized EPS fills (part 2: simulation analysis)." *Proceedings of the 33rd Presentation Meeting of the Japanese Geotechnical Society*, pp. 2463–2464 [in Japanese].

Nishi, G., Hotta, H., Kuroda, S., Hasegawa, H., Lee, G. and Tsukamoto, H. 1998. "Shaking tests for full-sized EPS embankment (part 1: shaking table tests)." *Proceedings of the 33rd Presentation Meeting of the Japanese Geotechnical Society*, pp. 2461–2462 [in Japanese].

Nomaguchi, A. 1996. "Studies on earthquake resisting performance of EPS embankment." *Proceedings of the International Symposium on EPS Construction Method* (EPS Tokyo 1996), EPS Development Organization, Japan, pp. 382–393.

Riad, H. L. and Horvath, J. S. 2004. "Analysis and design of EPS-geofoam embankments for seismic loading." *Geotechnical Engineer for Transportation Projects*, M. K. Yegian and E. Kavazanjian (eds.), ASCE, pp. 2028–2037.

Stark, T. D., Arellano, D., Horvath, J. S. and Leshchinsky, D. 2000. *Guidelines for geofoam applications in embankment projects, Interim Report—National Cooperative Highway Research Program Project 24–11*.

Stark, T. D., Arellano, D., Horvath, J. S. and Leshchinsky, D. 2002. *Guidelines for geofoam applications in embankment projects, Final Report—National Cooperative Highay Research Program Project 24–11*.

John S. Horvath, Ph.D., P.E. is a professor of Civil Engineering at Manhattan College in New York City and the Founding Director of the Manhattan College Center for Geotechnology (CGT). Additional information about cellular geosynthetics (geofoams and geocombs) can be found at the CGT Web site (www.engineering.manhattan.edu/civil/CGT.html).