Bridge foundations supported by EPS geofoam embankments on soft soil

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ABSTRACT: EPS geofoam can be used to support highway bridge structures without the aid of deep foundations. The development of this technology is important to accelerate construction on soft compressible soil. EPS geofoam allows for the rapid construction of bridge foundations on such soils without the time and cost involved in installing traditional foundations. Because EPS geofoam is an extremely light weight fill, it can be used to avoid settlement impacts at bridge approaches.

In Norway, bridges have been directly supported by EPS geofoam. Norwegian Public Roads Administration has pioneered this application for a few bridges underlain by soft, clayey deposit where the bridge structure rest solely on EPS geofoam blocks.

Investigating bridge foundations supported by EPS geofoam embankments is a joint effort starting summer 2013 between the University of Utah, University of Memphis and Norwegian Public Roads Administration. This paper will include some tasks and conceptual design that address development of performance goals, design criteria, material testing, prototype analyses, numerical modeling and constructability of this innovative bridge support system.

Keywords: Geofoam, bridges, foundations, soft clay

1. INTRODUCTION

In 1972, the Norwegian Public Roads Administration (NPRA) adopted the use of Expanded Polystyrene (EPS) geofoam as a super light-weight fill material in road embankments. The first project involved the successful reconstruction of road embankment adjacent to a bridge founded on piles to firm ground. Prior to reconstruction, the pre-existing embankments, resting on a 3 m thick layer of peat above 10 m of soft marine clay, experienced a settlement rate of more than 200 mm per year. However, by replacing 1 m of ordinary embankment material with two layers of EPS blocks, each 0.5-m thick, the settlement was successfully halted. The EPS blocks deployed had a density of 20 kg/m3, which is nearly 100 times lighter than the replaced materials (Aabøe and Frydenlund, 2011).

Subsequently, EPS geofoam technology has been successfully used elsewhere in Europe, Japan and the United States as a super light-weight material which is placed around highway bridges supported on deep foundations.

The extremely lightweight nature of EPS allows for rapid embankment construction atop soft ground conditions without causing damaging settlement to the deep foundations, bridge structure and approach pavements. The EPS embankment technology is well-developed for such applications, but except for a few cases in Norway, it has not been used elsewhere for the direct support of bridge structures (i.e., placing the bridge foundation support directly on the EPS without the installation of deep foundations (e.g., piles, shafts, caissons or piers). However, in Norway, bridges have been directly supported by EPS geofoam without deep foundations. The NPRA has pioneered this application for a few bridges underlain by soft, clayey deposits where the bridge structure rest solely on EPS blocks. These sites are: (1) the Lokkeberg Bridge (2) the Gimsøyvegen bridge (3) the Hjelmungen bridge (4) three pedestrian bridges in the City of Fredrikstad, which consisted of EPS block supports clad with protective panels. The NPRA reports that an EPS bridge support system has provided considerable cost and time savings when compared with traditional bridge support systems (Aabøe and Frydenlund, 2011).

The overall goal of the research summarized herein is to develop a guideline for design of EPS bridge support systems that will include the requisite engineering evaluation(s) and recommended design methodologies to support the design and construction of EPS bridge support systems. The objectives of the proposed research are: (1) evaluate an EPS support system for single span structures and pedestrian overpasses supported on EPS using the knowledge and data gained from the Norwegian case studies, (2) evaluate the expected performance of this system(s) under static and dynamic loading using material testing and numerical modeling of prototypes and full-scale systems previously used and installed in Norway, and (3) develop recommendations for future research/testing/development required for implementation of this technology. This paper summarizes the tasks to be performed to accomplish these research objectives and will address development of performance goals, design criteria, material testing, prototype analyses, numerical modeling and constructability of this innovative bridge support system.

2. PERFORMANCE GOALS

The types of structures considered for the EPS bridge support system will consist of permanent or temporary construction consisting of 1 to 2-lane highway overpass structures and pedestrian bridges. In general, it is anticipated that the candidate bridges will be generally single-span structures with span lengths of 35 m or less. Steel construction is believed to be preferable over concrete and wood, but these latter materials will also be considered, if feasible.

Candidate sites for the EPS bridge support system with consist of soft or problematic soil sites (e.g., compressible and sensitive soils). However, we recommend that the candidate bridge sites not be located on modern flood plains, or at major river crossings having significant flooding potential and major earth quake prone areas.

For soft and compressible soil sites, limiting the amount of construction and post-construction settlement of the bridge support system is an important consideration and the total settlement of the EPS bridge support and foundation system should be determined on a project-by-project basis using project-specific loading and soil data. The settlement of the bridge system can occur from three primary mechanisms: (1) elastic compression of the EPS blocks from the applied structural and pavement loads which is recommended to remain in the allowable elastic range under the combination of dead, live and traffic loads and that the construction-related vertical strain of the blocks be limited to 1 percent during the construction of the bridge and pavement system., (2) creep strain of the blocks resulting from long-term dead loads which is recommended to be limited to about 2 percent vertical in 50 years, and (3) consolidation settlement of foundation soils.

In addition, the underlying foundation soils will undergo consolidation settlement resulting from the applied dead loads of the bridge structure, approach slab and roadway pavement materials. The subsequent consolidation settlement is generally associated with the long-term creep (i.e., secondary consolidation settlement) of the foundation soils. Farnsworth et al. (2008) have noted based on field measurements that bridge system approach systems will generally have acceptable performance, if the post-construction creep settlement of the foundation soils is limited to about 7.5 cm in a 10-year period post-construction period. Figure 1 shows this proposed, post-construction settlement performance goal projected to 50, 75 and 100 years by assuming a semi-log linear relationship for the creep settlement of the foundation soils.

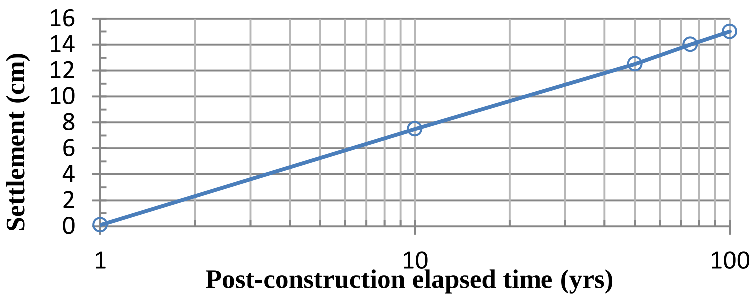


Figure 1. Proposed post-construction foundation settlement performance goal versus post-construction elapsed time.

In addition to the traffic loading, the EPS bridge support system must be designed to withstanding loadings from seismic events in earthquake prone regions of the world. Regarding seismic events, it is proposed that the bridge support system for permanent bridges be designed to withstand earthquake ground motion associated with a 1000-year return period event (i.e., 7.5 percent change of exceedance in 75 years), which is commonly used design basis event in the U.S. for highway bridge design.

3. DESIGN CRITERIA

In developing the EPS bridge support system, design guidance and material standards developed in Europe and the U.S. will be review and incorporated. These will consist of EN14933 found in the "EPS White Book" (EUMEPS, 2011), "Use of Expanded Polystyrene in Road Embankments" (NPRA, 1992), "Guideline and Recommended Standard for Geofoam Applications in Highway Embankment" (NCHRP 529, Stark et al., 2004a) and its companion document "Geofoam Applications in the Design and Construction of Highway Embankment" (NCHRP Web Document 65, Stark et al., 2004b).

For permanent bridge structures located in the United States, the American Association of State Highway and Transportation Officials has developed design criteria for highway bridges based on load and resistance factored design (LRFD) (AASHTO, 2013). The design of pedestrian bridges is completed according to LRFD Guide Specifications for Design of Pedestrian Bridges (AASHTO, 2009). Seismic design of permanent bridge structures is completed using the AASHTO Guide Specifications for LRFD Seismic Bridge Design (2014). In addition AASHTO HL93 truck load which consists of a "design truck plus design lane load" or "design tandem plus design lane load," whichever is the worst case can be used for traffic loading.

4. MATERIALS TESTING

Laboratory testing will used to define the stress-strain, creep (time-dependent or stress-strain-time behavior) and dynamic (cyclic) properties of EPS. Some of the testing has already been completed by various researchers (Stark et al., 2004b; Lingwall, 2011; Trandafir et al. 2011a, 2011b; Kafash, 2013), but additional material testing may be required to address some of the behaviors introduced in development of the conceptual design. For example, analysis and design methods for EPS geofoam as lightweight fill are based on explicit deformations of the geofoam mass (Stark et al. 2004a; 2004b). Therefore, the most important properties of block-molded EPS to test are those related to the overall mechanical (stress-strain-time) behavior of an entire EPS block in compression as this is what will be loaded in the final bridge structure. However, testing of full-size blocks is not feasible on a routine basis and, in practice, testing is performed on 50 mm cube-shaped specimens prepared from samples cut from blocks. Additionally, there are inherent property variations within the block that result from the molding process (Stark et al. 2004b; Kafash, 2013). Therefore, larger specimen sizes than the traditional 50 mm cube-sized specimen currently used in practice will be evaluated under static unconfined uniaxial compression loads to obtain the effect of specimen size on the stress-strain behavior of EPS blocks.

Both the stress-strain and stress-strain-time behavior of EPS is related to the density of an EPS block (Stark et al. 2004b). Traditional EPS densities that are currently readily available in the market and utilized for lightweight fill applications in stand-alone embankments over soft ground and for slope stabilization range from 18.4 to 45.7 kg/m3 based on the ASTM D6817 property requirements. Creep test data is available for these density ranges and are summarized by Stark et al. (2004b) and Arellano et al. (2001). However, ASTM has incorporated higher density EPS blocks with densities of 38.4 and 45.7 kg/m3 for which creep and cyclic test data is not readily available. Therefore, shear strength tests, creep and cyclic tests will be performed on specimens with 38.4 and 45.7 kg/m3. In addition, cyclic, creep and flexural tests will be performed for samples which have higher densities than 45.7 kg/m3. Reduced-scale test embankments may also be used to explore the stress distribution created in the EPS by various long-term and live loading conditions.

5. PROTOTYPE ANALYSES

The selection of EPS embankment geometries, block layout pattern and material quality to be used vary according to the bridge clearance, the subsoil condition and other project design specific criteria. From practical experiences gathered through monitoring programmes on EPS embankments as well as full scale laboratory tests, EPS blocks with 2H:1V slopes and vertical EPS fills have given satisfactory results and the same slope geometry will be used for further analysis. In addition, the study will use sub soil conditions which have compressible non-sensitive soil profiles, crust over compressible sensitive profile and granular over compressible soil profile.

Depending on the extent of the load that is coming from the bridge deck, several combination of EPS density can be used in the design. However, this study will consider three different EPS density and configurations: uniform density, increasing density near top of EPS system and intermediate load distribution slabs. EPS blocks will be placed in such a way that spaces between two EPS blocks in the same row will not exceed 3cm and a vertical staggering of blocks by avoiding a continuous vertical gap.

6. NUMERICAL MODELING

Numerical models which are able to capture the EPS behaviour during loading and unloading can fill the gap of data limitation and gives us a better insight over the stress-strain-time relationship. Different models exist for soils and rocks from sophisticated to simpler ones. Nevertheless, in built models specifically prepared to analyse the EPS behaviour is not available commercially. However, using similarities in stress-strain relationships between soil and EPS geofoam, therefore, one can calibrate EPS parameters using models usually used for soils/rocks. Simple hand calculations together with simplified techniques based on elastic theories and PLAXIS & FLAC, the performance of the EPS support system will be evaluated and potentially implemented in future design of such systems.

7. BRIDGES SUPPORTED ON EPS GEOFOAM EMBANKMENTS, CASES FROM NORWAY

7.1 Løkkeberg bridge

7.1.1 Introduction

Løkkeberg bridge is a 36.8m long, single span and acrow steel bridge across the E6 (on Rv. 121 road) to facilitate the traffic flowing temporarily in that area. The bridge was built and opened in 1989 and it had been expected to function between 3 to 5 years. However, it lasted until 2005/6 (for a total of 16 years) before it has been removed. Due to the soft clay deposit, which ranges from 6m to 16m in thickness below the abutment, and low bearing capacity, it was decided to use EPS embankment as an abutment to carry the weight of the bridge as an alternative to end bearing piles. It is the first bridge to be constructed on EPS embankments.

7.1.2 Dimension and material quality

Løkkeberg bridge is constructed as a single lane bridge which ranges 36.8m in length and is built 5.5m above the ground level. The bridge weighs 68t and it rested on a 7.4m x 7.5m footing slab which had a thickness of up to 1m below the girder and 0.5m elsewhere. In order to support the traffic and dead load coming from the bridge deck, a 5m and 4,5m high EPS fill embankment had been used on either ends of the bridge. Three types of EPS had been used for this project, EPS240 (40 Kg/m3) on the first top layer immediately below the bridge deck, EPS180 (30Kg/m3) until halfway through the embankment and the rest was filled with EPS100(20Kg/m3). A 10cm concrete slab was laid down on the middle layer of EPS embankment.

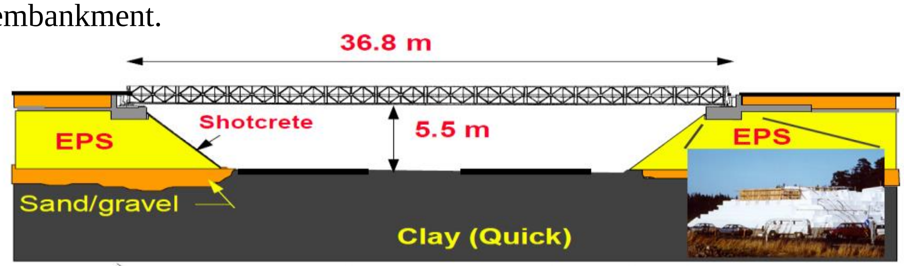


Figure 2. Temporary single-lane steel truss bridge structure supported on EPS block at Lokkeberg, Norway. (Note the absence of deep foundation system at this location.) (after Aabøe and Frydenlund, 2011).

7.1.3 Stress distribution

As one part of the monitoring program, stress distribution in the EPS embankment was measured using 10 hydraulic earth pressure cells (7 in the EPS and 3 in the sand layer beneath the EPS) 10 years after the construction ended. A consistent data was able to be obtained one year after installation of the cells. Figure 3 illustrates the measured data on EPS blocks after 10 years of operation.

7.1.4 Measured deformation

Total deformation measured 12 years after operation is nearly 6cm which accounts about 1,3% of the EPS thickness. Average creep measured for 10years on the bottom layer of EPS accounts for 6,5% of the thickness. On performance point of view, a satisfactory result was obtained.

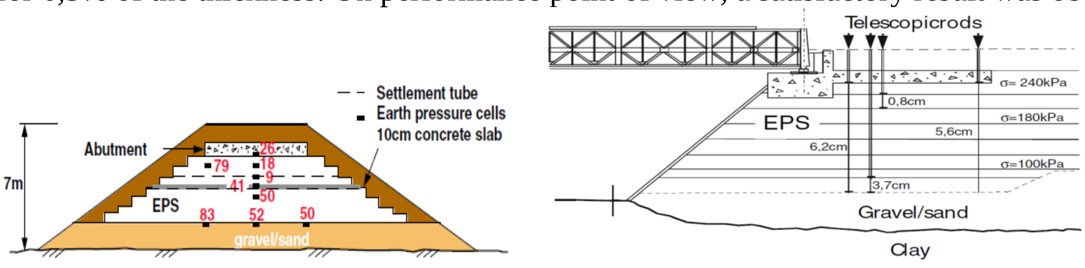


Figure 3. Observed stress distribution and deformation at Løkkeberg bridge after 10years in operation

7.2 Hjelmungen bridge

7.2.1 Introduction

This is an overpass bridge over the E6 road in which the bridge is founded directly on EPS embankment. It is located in a close proximity to Løkkeberg bridge. Hjelmungen bridge connects a local road over an E6 motorway in Østfold county.

The bridge was built in 1992 and it was originally founded on concrete piles together with a 5m high approach embankment which was filled partially with light weight leca-blocks(γ=8Kg/m3) and commonly used fill material(γ=20Kg/m3). The foundation soil is mainly composed of clay which is highly sensitive and weak with thickness ranging from 11-14m. High settlement, nearly 600mm, was registered in the approach embankment which leads to an immediate reparation of the bridge foundation. The high settlement is known to be caused by the heavy weight of the fill material and an overestimation of pre-consolidation stress for the underlying clay. The reparation started in 1995 and is finished in 1996. The abutment and the approach embankment fill was dug out and replaced by EPS geofoam blocks. The original concrete pile where the bridge was supported on, got trimmed off and made to be rested directly on EPS filled embankment.

7.2.2 Dimension and material quality

The bridge was 54m long with three spans (16m at either end of the bridge and 22m in between). The EPS filled embankment was composed of three different EPS blocks: EPS235 on the first top three layers, further below was EPS180 and EPS100 for the rest of the filling. A 10m long and 20cm thick friction plate was installed in the abutment to resist horizontal load and a concrete plate with thickness 10cm was used in the approach EPS embankment.

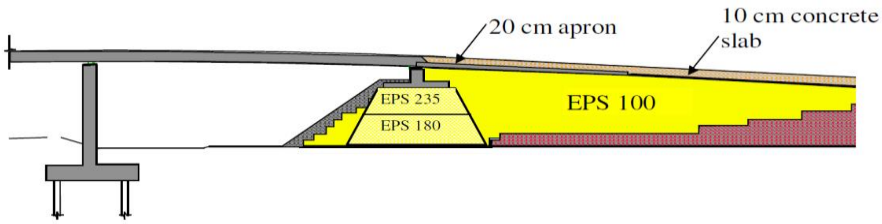


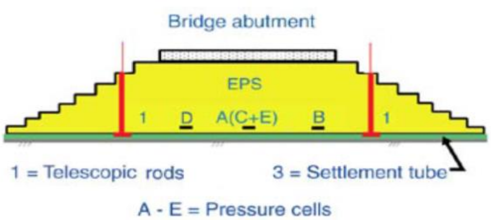
Figure 4. Principal sketch for re-foundation of Hjelmungen bridge

7.2.3 Stress distribution

Monitoring program was carried out to check the development of settlement after reconstruction of the abutment. Pressure cells and settlement tubes were installed for this purpose as shown in figure 5. Measured stresses, in figure 5, show that higher stresses are measured on the middle than to the either sides of the embankment. However, the excess pressure measured in the middle of the embankment taught to have come from while jacking up the bridge deck during reconstruction.

7.2.4 Measured deformation

Development of deformation was monitored using measurement gauges installed under the lower EPS layer, in the leveling sand. A total deformation of 3.5cm registered which constitutes about 0.7% the filling height.



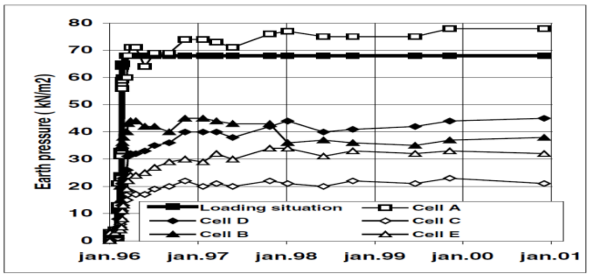


Figure 5. Location of pressure cells, measured total deformation and settlement tubes & observed stress distribution below EPS layer at Hjelmungen bridge

7.3 Gimsøyveien bridge

7.3.1 Introduction

This is a temporarily bridge which was constructed across a highway during the expansion of E6 road from two to four lane in Østfold county. EPS blocks which were used in the Løkkeberg bridge is re-used for this construction as well. Highly sensitive, soft clay is discovered during ground investigation. Settlement and local stability were expected to be a major problem. Therefore, EPS fill embankment was selected to carry the load from the bridge.

7.3.2 Dimension and material quality

The bridge was founded on top of 4,5m and 5m EPS filled embankments at either side of the road. From 8-9 EPS layers were used where the top three layers were EPS300. The EPS blocks were staggered to form a front slope and vertical to the sides. The blocks were laid down on top of a levelled gravel material and protected with sprayed concrete and geotextiles.

7.3.3 *Measured deformation*

During the bridges lifetime a total settlement of 5cm (<1%) is registered, which was less than the calculated value beforehand.

Figure 6. Gimsøyveien bridge during construction

7.4 Leie, Skovbøle and Høiendal bridges

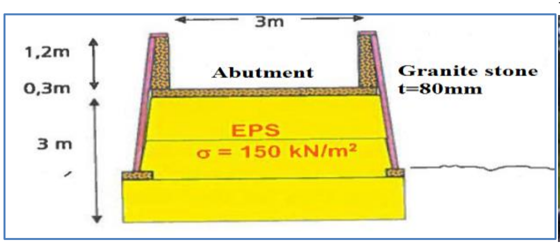
7.4.1 *Introduction*

In the mid-1990's four pedestrian and cycle bridges are constructed in Fredrikstad, Norway in connection with the expansion of Rv. 109 road from two lanes in to four. Out of the four bridges three of them are founded directly on EPS blocks.

The bridges are constructed across the main road, Rv.109, which follows the bottom of the valley. The area is characterised by thick sediments of clay which ranges up to 50m in depth. A part of the clay deposit is known to be very sensitive (quick clay) and susceptible for large settlements. Depending on the ground investigation results, it was decided to use EPS blocks to undergo the likely problem of bearing capacity and settlement if the foundation were to be shallow concrete foundation.

7.4.2 *Dimension and material quality*

EPS embankment is used as a direct foundation to the bridge deck and the total height of the EPS blocks in the embankment is 3m from which 1m of the EPS filling is under excavation, minimizing settlement on the subsoil. EPS150 is used in this case and the design compression load coming from the deck of the bridge is 36KPa. The abutment is finished with a 10:1 slopped wall, made of plastered granite stone, on either side of EPS blocks and extends 1.5m vertically over the top EPS layers, see figure 7.



Leie bridge (Photo: Simen Hermensen)

Figure 7. Principal abutment dimension for Leie, Skovbøle and Høiendal bridges;

7.4.3 *Measured deformation*

Monitoring programmed with regard to settlement and stress measurements are not performed in these bridges, however, successive site visits indicate that the bridges are on satisfactory performance condition.

8. CONCLUSIONS

Bridges which are supported directly on EPS geofoam have shown success according to engineering evaluation. Further studies regarding a conceptual and standard design of such bridge foundation are highly recommendable with the view of adopting similar experiences to a different candidate sites, in addition to getting lesser construction time and cost.

9. REFERENCES

Aabøe R. and Frydenlund, T. E., (2011). “40 Years of Experience with the Use of EPS Geofoam Blocks in Road Construction,” EPS 2011, Lillestrom, Norway.

AASHTO LRFD Guide Specifications for Design of Pedestrian Bridges, 2nd Edition, 2009.

AASHTO LRFD Bridge Design Specifications, Customary U.S. Units, 6th Edition, with 2013 Interim Revisions.

AASHTO Guide Specifications for LRFD Seismic Bridge Design, 2nd Edition, with 2012 and 2014 Interim Revisions.

Arellano, D., Stark, T.D., Horvath, J.S., Leshchinsky, D. (2011). "Guidelines for Geofoam Applications in Slope Stability Projects." NCHRP Project 24-11(02) Final Report, Transportation Research Board, Washington, D.C., 602 pp. Available at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP24-11(02)_FR.pdf .

Arellano, D., Aabøe, R., and Stark, T.D. (2001). “Comparison of Existing EPS-Block Geofoam Creep Models with Field Measurements,” Proceedings of EPS Geofoam 2001 3rd International Conference: December 10-12, 2001, Salt Lake City, Utah (CD-ROM), Geofoam Research Center, Syracuse University, Syracuse, NY.

ASTM D6817. “Standard Specification for Rigid Cellular Polystyrene Geofoam.” American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.

Bartlett, S. F., Negussey, D., Kimball, M., (2000). “Design and Use of Geofoam on the I-15 Reconstruction Project,” Transportation Research Board, January 9th to 13th, 2000.

Bartlett S. F., Farnsworth, C., Negussey, D., and Stuedlein, A. W., (2001). “Instrumentation and Long-Term Monitoring of Geofoam Embankments, I-15 Reconstruction Project, Salt Lake City, Utah,” EPS Geofoam 2001, 3rd International Conference, Dec. 10th to 12th, 2001, Salt Lake City, Utah, 23 p.

Bartlett, S. F., Negussey, D., Farnsworth, C. B., and Stuedlein, A., (2011). “Construction and Long-Term Performance of Transportation Infrastructure Constructed Using EPS Geofoam on Soft Soil Sites in Salt Lake Valley, Utah,” EPS 2011 Geofoam Blocks in Construction Applications, Oslo Norway.

Farnsworth C. F., Bartlett S. F., Negussey, D. and Stuedlein A. (2008). “Construction and Post-Construction Settlement Performance of Innovative Embankment Systems, I-15 Reconstruction Project, Salt Lake City, Utah,” Journal of Geotechnical and Geoenvironmental Engineering, ASCE (Vol. 134 pp. 289-301, March 2008).

EUMEPS (2011). “EPS White Book,” EUMEPS Background Information on Standardization of EPS, Version 31/03/11.

Frydenlund, T. E. and Aabøe R. (2001). “Long-Term Performance and Durability of EPS as a Lightweight Filling Material, EPS 2001, Salt Lake City, Utah.

Kafash, M.H. (2013). “Seismic Stability Analysis of Landslides Stabilized with Expanded Polystyrene (EPS)-Block Geofoam,” Ph.D. Dissertation, The University of Memphis.

Kafash, M.H., Arellano, D., D., Hosseini, S.M., Pezeshk, S., (2013). "Feasibility of MASW (Multi-Channel Analysis of Surface Waves) for Evaluating the Dynamic Properties of Geofoam," Proceedings of Geosynthetics 2013, Long Beach, CA. April 1-3, 2013.

Miki, G. (1996). “EPS Construction Method in Japan.” Proceedings of the International Symposium on EPS Construction Method, Tokyo, Japan.

NPRA (1992). “Use of Expanded Polystyrene in Road Embankments” Norwegian Public Roads Administration, Directorate of Public Roads, Norwegian Roads Research Laboratory (NRRL), Oslo, Norway, August 1992 in English.

Stark, T.D., Arellano, D., Horvath, J.S., and Leshchinsky, D. (2004a). “NCHRP Report 529: Guideline and Recommended Standard for Geofoam Applications in Highway Embankments,” Transportation Research Board, Washington, D.C., 71 pp. Available at http://trb.org/publications/nchrp/nchrp_rpt_529.pdf .

Stark, T.D., Arellano, D., Horvath, J.S., and Leshchinsky, D. (2004b). “NCHRP Web Document 65 (Project 24-11): Geofoam Applications in the Design and Construction of Highway Embankments,” Transportation Research Board, Washington, D.C., 792 pp. Available at http://trb.org/publications/nchrp/nchrp_w65.pdf .

Roald Aabøe, Tor Erik Frydenlund, Intern rapport nr. 2209 ‘’ EPS- den lette løsningen’’, Norwegian Public Road Administration (NPRA), Norway, 2001