Design of Lightweight Fills for Road Embankments on Boston's Central Artery/Tunnel Project

Hany L. Riad
Bechtel/Parsons Brinckerhoff, Boston, Massachusetts

Anthony L. Ricci
Massachusetts Turnpike Authority, Boston, Massachusetts

Peter W. Osborn
U.S. Federal Highway Administration, Baltimore, Maryland

David A. D'Angelo
Bechtel/Parsons Brinckerhoff, Boston, Massachusetts

John S. Horvath
Manhattan College, Bronx, New York

Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

Design of Lightweight Fills for Road Embankments on Boston's Central Artery/Tunnel Project

Hany L. Riad, Ph.D., P.E.
Bechtel/Parsons Brinckerhoff
Boston, Massachusetts 02111, U.S.A.

Anthony L. Ricci, P.E.
Massachusetts Turnpike Authority
Boston, Massachusetts 02111, U.S.A.

Peter W. Osborn
U.S. Federal Highway Administration
Baltimore, Maryland 21201, U.S.A.

David A. D'Angelo
Bechtel/Parsons Brinckerhoff
Boston, Massachusetts 02111, U.S.A.

John S. Horvath, Ph.D., P.E.
Manhattan College
Bronx, New York 10471, U.S.A.

ABSTRACT

The use of lightweight-fill materials for highway construction increased significantly worldwide during the 1990s. Predominant with this trend was the increased use of cellular geosynthetics (geofoams and geocombs), especially block-molded expanded polystyrene (EPS) geofoam, on highway and bridge embankments. EPS geofoam is increasingly recognized as an important tool for reducing overall cost of highways through "accelerated construction". Thus, it was appropriate that lightweight-fill materials, mostly EPS, were the materials of choice on Boston's Central Artery/Tunnel (CA/T) Project, commonly known as the "Big Dig". EPS highway embankments have been constructed, as part of a cost-and schedule-initiative, replacing the original design concepts for eight transition highway structures on a recent CA/T construction contract.

The use of EPS-block geofoam on the CA/T included the first-time implementation of newly developed NCHRP research and AASHTO based design guidelines, material/product specifications as well as formulating innovative solutions to several technical challenges. These challenges centered on relatively tall and slender EPS fills placed over soft soils subjected to periodic flooding and seismic loading within a crowded urban environment. This paper presents a detailed outline of the design process together with the impacts of the buoyancy conditions and seismic loading on the design of EPS highway embankments. Also included is a discussion of other lightweight-fill materials such as geocombs (considered but not used) and expanded-shale aggregate (used in limited quantities).

INTRODUCTION

The C09C2 construction contract of Boston's CA/T Project consists primarily of constructing viaducts, bridges, transition structures, and boat and tunnel sections on I-93 within the I-90/I-93 South Bay Interchange area of the Project. This paper focuses on eight transition structures and ramps within the C09C2 contract that are located on I-93 and connect to I-90 and other roadways south of downtown Boston and South Station. The lengths of these transition structures range from 23 to 122 m (75 to 400 ft), with heights to 7 m (23 ft). Widths range from 8 to 24 m (25 to 75 ft).

Prior to implementing EPS-geofoam fills for these transition structures, the original design consisted of various types of structures such as precast-concrete bridges (PCB), elevated slabs-on-piles/drilled shafts (SOP), and fill over slab-on-piles/drilled shafts (FSOP). All original PCB and SOP designs included architectural precast concrete curtain walls supported on drilled shafts on both sides. All FSOP designs included the use of cast-in-place structural concrete walls to contain the fill placed over the foundation slab as well as serving for architectural purposes.

For each of these transition structures, the originally intended primary means of foundation support for all structural elements was drilled shafts. Each shaft was designed to bypass the upper strata of fill, organic silt, and clay, and would have been founded in the underlying glacial till and bedrock. The surface-fill stratum ranges in thickness from 1.5 to 11 m (5 to 35 ft). It is variable though primarily granular in its composition, placed in an uncontrolled fashion decades ago over the organic soils that formed the old Boston shore line. The organic stratum also ranges from 1.5 to 11 m (5 to 35 ft) thick. Below the organic stratum lies the famous 'Boston Blue Clay' which in this area is 24 to 37 m (80 to 120 ft) thick.

Clearly, the large number and aggregate length of drilled shafts to support the original, structure-based design concepts would have been substantial. This would be adverse to the Project from the standpoint of cost and schedule.

Consequently, the objective was aimed at reducing the number of drilled shafts or, perhaps, by eliminating their presence in some structures entirely.

The scope and focus of this paper is documenting the evolution of the final design for the transition structures of the C09C2 contract. By implementing EPS as lightweight fill, the final design included some distinct and novel elements that were dictated in part by the complexities of working in a crowded urban environment [Riad et al. 2003a, 2003b].

ORIGINAL DESIGN CONCEPTS

Schematic cross-sections of the three design concepts for the transition structures originally planned for use on the C09C2 contract are shown in Figs. 1 through 3.

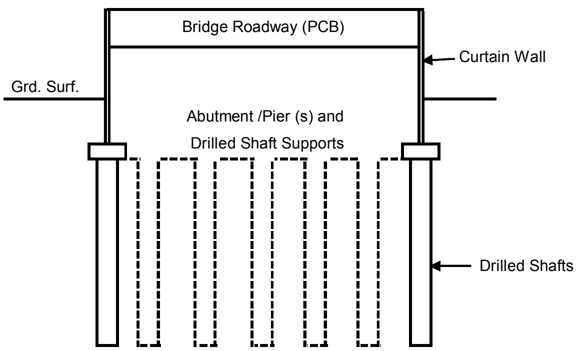

Fig. 1. Precast-Concrete Bridge (PCB) Design Concept.

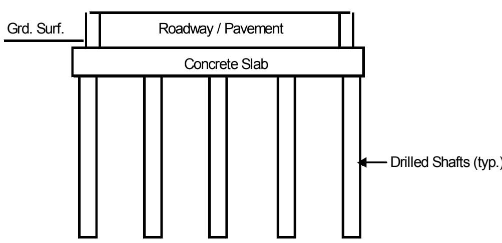

Fig. 2. Elevated Slab-on-Piles (SOP) Design Concept.

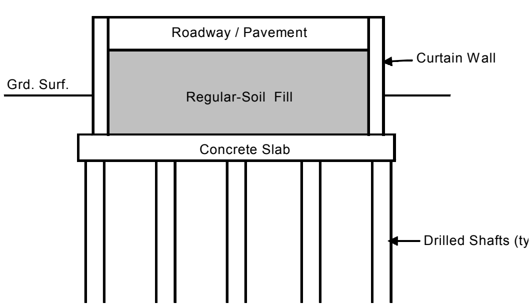

Fig. 3. Fill over Slab-on-Piles (FSOP) Design Concept.

INITIAL INVESTIGATIONS

Review of the original designs for the transition structures concluded that the primary purpose of the numerous drilled shafts was to bypass the upper compressible soil strata. This would, in turn, eliminate any settlement that would have occurred due to their primary consolidation if loaded beyond the current vertical effective overburden stresses.

One analytical exercise that was conducted was to estimate by calculation the magnitude of settlement should, for example, a particular structure or curtain wall be constructed to bear directly upon compressible soils. It was concluded that such settlements were unacceptable both in their magnitude and variation. The use of preloading was not considered to be a viable ground-improvement alternative due to schedule constraints. Thus it became clear that for the final design alternative, there had to be no net vertical effective stress increase on the existing soils. It should be noted, however, that removal or in-situ treatment of the fill and organic strata were also considered impractical. This is due to their substantial combined thickness (approximately 12 m (40 ft)) together with the limitations of schedule and site constraints. Ultimately, these factors led to the logical conclusion that directed final design towards using lightweight-fill materials.

Prior to the ca. 2000 Contract C09C2 design-modification initiative, the CA/T Project had used two lightweight-fill materials (both geofoams) since Project planning and design began in the late 1980s: the aforementioned EPS geofoam and lightweight-foam-concrete (LFC) geofoam. With EPS, prior project experience was limited to only one application as a temporary fill and construction ramp within a previously constructed boat section to allow passage of construction vehicles within the construction site of the C09A4 contract.

With LFC, prior Project experience was both more substantial and its function more permanent as the material was integrated into final designs. Overall, there was a better Project understanding of LFC as a material, its application and uses similar to many of the other construction materials used on the Project. However, the density/unit weight of LFC was still relatively high to provide an effective solution to the no-net-stress increase design criterion of the C09C2 contract. Altogether, the implementation of LFC as a lightweight-fill material, while substantially lighter than regular fill, would not translate into a viable alternative design for the C09C2 transition structures. The use of LFC could only be viable if substantial settlements could be tolerated or if vast amounts of the existing soils could be removed to offset the increased load from the roadway structure and the LFC itself. Calculated settlements, while smaller in magnitude compared to the use of regular fill, remained quite substantial. The estimated volumes of existing soil that would have had to have been removed were also too large. This proved to be cost prohibitive in addition to being impractical from an access and traffic standpoint given the proximity of the construction site to a congested metropolitan area. In short, cost savings using LFC would have been minimal or even non-existent.

Considering all of the above, the choice of lightweight-fill material for the C09C2 transition structures was narrowed down to EPS geofoam. The use of EPS offered a unique advantage compared to other lightweight materials, namely overall cost savings due to its uniquely low density/unit weight (typically in the range of 15 to 30 kg/m^3 (1 to 2 lb/ft^3) which is only 1 to 2% that of soil) which eliminated the need for any type of ground improvement (e.g. preloading, overexcavation and replacement). EPS geofoam also offered the benefits of adequate strength and stiffness properties comparable to those of soil.

In addition to above basic technical considerations, there were several important supporting factors that created a "comfort level" with using EPS geofoam as a permanent construction material at the time (ca. 2000) that the initial decision making process was taking place:

- EPS technology is supported and promoted by the U.S. Federal Highway Administration (FHWA) who consider it to be an important component of its successful Ground Improvement Workshop (Demonstration Project 116) that was ultimately converted to a National Highway Institute course
- Preliminary documented results were available from a multi-year research project into the use of EPS geofoam as lightweight fill for road construction [Stark et al. 2000]
- The availability of a comprehensive monograph on the subject [Horvath 1995], together with possibility of arranging comprehensive seminars on designing with EPS to be given locally to the appropriate Project personnel

CONTRACT C09C2 REDESIGN WITH EPS GEOFOAM

Overview

The redesign effort to implement the use of EPS geofoam as a lightweight-fill material was largely an iterative process aimed at reducing or possibly eliminating the drilled shafts. In addition to the cost and schedule advantages, elimination of drilled shafts also offered the advantage of reducing construction complexity and minimizing the level of changes to the existing contract documents. Note that the C09C2 contract, while not yet awarded, was soon to be issued for bid.

Original Structure Loads

The first step in developing design alternatives was to define the major dead load contributions from the three original design concepts shown in Figs. 1 to 3.

For the Precast Concrete Bridge (PCB) design concept, primary dead load contribution was from the following elements:

- Abutments and piers
- Superstructure girders, slabs and diaphragm
- Roadway "hardware" (pavement, barriers, utilities, etc.)
- Architectural curtain wall and supporting grade beam

For the Elevated Slab-on-Piles (SOP) design concept, the primary sources of dead load were:

- Elevated concrete slab
- Roadway hardware
- Architectural curtain wall and supporting grade beam

For the Fill over Slab-on-Piles (FSOP) design concept, the primary sources of dead load were:

- Concrete slab at grade
- Roadway hardware
- Wing, retaining and curtain-walls together with supporting grade beams
- Regular fill over the concrete slab

Initial Redesign Concept Alternatives

In general, all redesign alternatives were conceptually based on minimizing the aforementioned dead loads together with the transfer of all or part of these loads from being founded on drilled shafts to being supported directly on the existing soils. Any design alternative together with redefined supporting conditions could not result in any net increase in the vertical effective stresses on the existing soils. To achieve this goal, any increase in stress from the proposed structures (which was obviously unavoidable) had to be compensated by removing an equivalent mass of soil and replacing it with a lightweight-fill material.

The process of having to remove existing soil and replace it with EPS geofoam produced two major design issues. First, the deeper the excavation of existing soils, the deeper the bottom elevation of the EPS blocks would be, approaching and ultimately extending below the normal ground-water table. This condition resulted in increasingly larger buoyant forces on the embankment structure which in turn significantly reduced the factor of safety against uplift. The second issue was that the deeper the bottom elevation of EPS blocks, the greater the volume of soil that would have to be removed. This in turn meant diminished savings with respect to cost and schedule or possibly even an increase in cost or schedule.

Initially, it was desired to transform each of the three original structure types (PCB, SOP and FSOP) into a simple stand-alone embankment constructed primarily of EPS geofoam. However, it was obvious based on initial evaluation that the issues of buoyant forces and potentially excessive excavation would limit the number of candidate structures where the EPS-geofoam alternative could be implemented. This realization led to the preliminary concept of three basic design alternatives:

- Redesign Alternative 1: EPS-geofoam fill embankment supporting overall roadway structure and architectural curtains walls

- Redesign Alternative 2: EPS-geofoam fill embankment supporting overall roadway structure with architectural curtain walls supported independently on drilled shafts
- Redesign Alternative 3: Roadway structure and architectural curtain walls supported by a slab on drilled shafts with EPS geofoam acting only as a lightweight filler between the roadway structure and the concrete slab

Schematic cross-sections of these three alternatives are shown in Figs. 4 to 6.

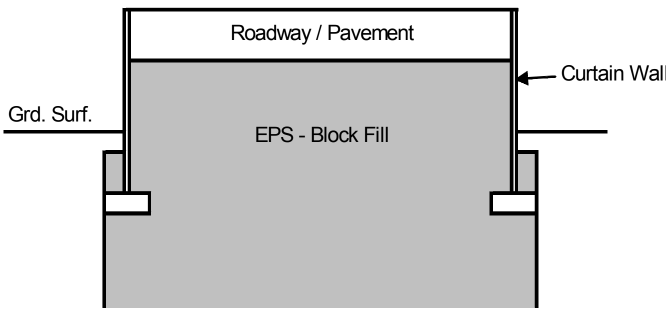

Fig. 4. Redesign Alternative 1.

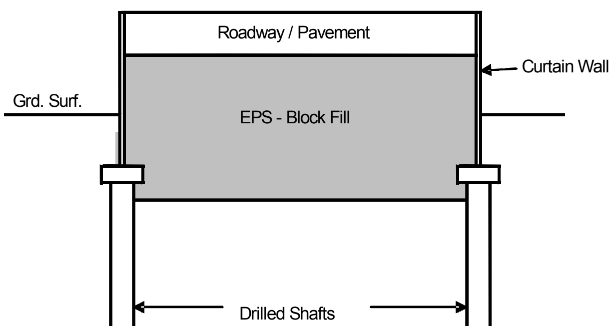

Fig. 5. Redesign Alternative 2.

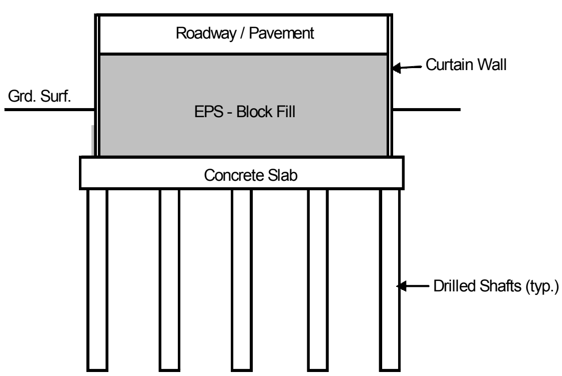

Fig. 6. Redesign Alternative 3.

Selection of Preliminary Redesign Alternatives

The order of preference among the three redesign alternatives was Alternative 1, followed by 2 then 3. The reason for this preference was based on the obvious decreasing simplicity among them. The decrease in simplicity translates into less and less saving with respect to cost and schedule.

The first iteration toward selecting the appropriate alternative for a given structure was to first presume that Alternative 1 would "work". Within that iteration, the necessary load balancing calculations are performed to determine the depth the assemblage of EPS blocks would have to extend into the existing ground with due consideration of limiting post-construction settlements at the structure site. At the required depth, the volume of soil to be removed in conjunction with the factor of safety against buoyancy/uplift was assessed for feasibility. If the volume of soil to be removed was sufficiently small and the factor of safety against buoyancy was sufficiently large then Alternative 1 was pursued toward final design. Otherwise, Alternative 2 was considered.

From the descriptions of the redesign alternatives, it can be seen for Alternative 2 that with the independent support of the architectural curtain wall on drilled shafts, less load is required to be transferred to the existing soils compared to Alternative 1. Thus compared to Alternative 1, Alternative 2 required less soil to be removed, less EPS fill to be placed, and a greater factor of safety against buoyancy resulted. The down side, of course, was that there was a smaller reduction in cost and less schedule savings.

As with the analysis of Alternative 1, the necessary load balancing calculations for Alternative 2 were performed to determine what depth the EPS blocks needed to extend to so settlements would become a non-issue. Likewise, the corresponding volume of soil to be removed in conjunction with the factor of safety against buoyancy/uplift was again assessed for feasibility. Once again, if the volume of soil to be removed was sufficiently small and the factor of safety against buoyancy sufficiently large, then Alternative 2 was pursued toward final design. Otherwise, Alternative 3 was considered.

Redesign Alternative 3, with all structure loads supported by drilled shafts, eliminated the concern of buoyancy and the need to excavate for load-balancing purposes yet produced the least savings. The savings associated with Alternative 3 were essentially a reduction in the number of drilled shafts that would be needed due to a replacement of regular fill within the structural "container" with the much lighter EPS.

Final Design

The above-described iterative process, which formed the basis of the preliminary redesign phase, was performed by Bechtel/Parsons Brinckerhoff (B/PB), Management Consultant to the CA/T owner, the Massachusetts Turnpike Authority (MTA). Engineering representatives of the MTA participated extensively in this process and input was also provided by Dr. John S. Horvath, P.E. who served as a Consultant to the B/PB and MTA.

This process resulted in a preliminary selection of a redesign alternative for each transition structure. Final design of each was then performed by the Project's Section Design Consultant (SDC) which, for the C09C2 contract, was the joint venture of Berger, Lochner, Stone and Webster (BLSW). Given the fact that the use of EPS geofoam as a permanent construction material was a new technology for the CA/T Project and considering the accelerated redesign schedule, both B/PB and the MTA in conjunction with their consultants had ongoing participation with significant input even during the final-design phase by BLSW. In particular, B/PB developed a unique, comprehensive, Project and contract specific package of design guidelines that consisted of:

- Project Design Criteria manual
- Detailed numerical design examples
- Directive Drawings showing typical EPS details
- Project Specifications addressing all applicable product, material, fabrication and construction requirements

It is of interest to note that this package of technical material was developed with significant input from the results of the U.S. National Cooperative Highway Research Program (NCHRP) research reported in Stark et al. (2000). As such, the C09C2 contract marked the first project use of this NCHRP research. As best as could be determined, the CA/T Project Deign Criteria also marked the first time implementation of AASHTO Standard Specifications for Highway Bridges (16^{th} edition) into the design of an EPS highway embankment structure. AASHTO gravity and lateral loads including seismic, together with proper group load combinations, were integrated with NCHRP research results into the final design.

Key Final-Design Issues

Buoyancy/Uplift. For boat-section structures, the Project had early on established a minimum Safety Factor (SF) against buoyancy/uplift of 1.05 for a 100-year flood event (much of the CA/T Project area is close to coastal areas). This criterion was considered for the planned EPS-geofoam embankments but was deemed too low. This decision was based on the fact that the magnitude of vertical stress imposed on the subgrade by an EPS-geofoam fill structure was substantially lower than that of a typical all-concrete boat structure. This order-of-magnitude difference in stress levels translated to a much greater sensitivity of the calculated SF for the EPS fills to small changes in problem parameters. For this reason, the SF against buoyancy for a typical EPS-geofoam structure was increased to 1.40 for the same 100-year flood event.

Buoyancy turned out to be the primary controlling factor in determining the most cost-effective redesign alternative (1, 2 or 3 as shown in Figs. 4 to 6) and corresponding SF against uplift. It soon became apparent that many of the transition structures under consideration for redesign would end up with Redesign Alternative 3 (Fig. 6) which minimized the expected savings. In an effort to change this undesirable outcome, two initiatives were undertaken. The first was to reduce the load imposed by the curtain walls. The second was to reduce the buoyancy force on the EPS blocks by using a second, porous lightweight-fill material as an intermediate layer between the top of the existing soils and bottom of the EPS.

Curtain Walls. Although an assemblage of EPS blocks with vertical sides is structurally self-stable (assuming proper block layout and other well-established design and construction details are followed), the permanently exposed sides of an EPS fill must be covered to prevent long-term surficial degradation and incidental damage of the EPS blocks as well as to provide an appropriate architectural finish.

The effort to reduce the curtain-wall loads first focused on using lightweight precast-concrete panels. This alternative, while viable, remained ineffective in achieving the desired level of overall improvement. Thus precast-concrete curtain wall panels, which have become very popular in recent years both in the U.S.A. and elsewhere for vertical-sided EPS fills, were subsequently abandoned altogether. Efforts were concentrated on significantly lighter alternatives that would eliminate the need for supporting deep foundations.

The primary alternative that was pursued involved using what is formally called "Exterior Insulation and Finishing System" (EIFS) but is perhaps more-commonly known by the colloquial terms "synthetic stucco". EIFS is a well-proven technology that has been used worldwide for decades for the exterior walls of both commercial and residential buildings of all types and sizes. However, as best as could be determined, EIFS had never been used as the permanent side panels for an EPS roadway fill on a transportation project. Such an application, however, was actually suggested at one of the earliest symposia on EPS geofoam in 1994 [Horvath 1995].

EIFS consists of a mesh-reinforced, two-part coating system applied over a substrate of rigid-cellular polystyrene (RCPS) foam; in this case EPS board (see Fig. 7). The final appearance of the EIFS coating can be varied widely for architectural purposes. In the case of the C09C2 EPS structures, EIFS was specified with an architectural finish to create an aesthetic appearance matching that of the precast-concrete curtain walls utilized on adjoining transition structures and ramps in the South Bay Interchange area of the Project.

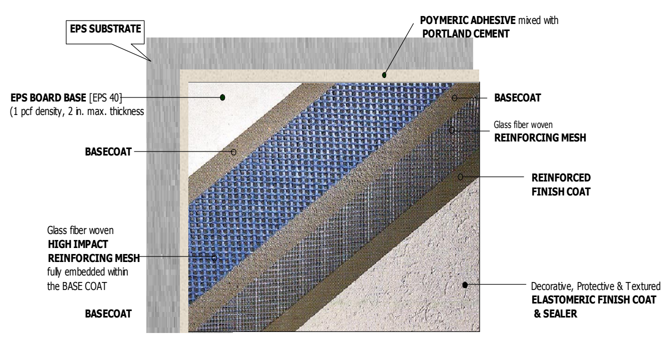

Fig. 7. Typical EIFS Cross-Section with an EPS Substrate.

In addition to eliminating the precast-concrete curtain walls and their deep foundations, the use of EIFS panels accomplished a number of objectives:

- The need for independent curtain-wall foundations could be eliminated. Thus Redesign Alternatives 1 and 2 (Figs. 4 and 5) could be combined into one design referred to as Redesign Alternative 1 (Modified)
- It simplified design, construction and maintenance through elimination of the pinned connections between the exterior panels and the load-distribution slab that is placed on top of the EPS blocks
- EIFS could be applied at any time after the EPS blocks are in place thereby providing a more-flexible schedule that would allow structures to open sooner to traffic
- EIFS with an EPS substrate is compatible with the EPS blocks used to create the fill from the standpoint of dead loads, stiffness, deformations and other mechanical and material properties. This would minimize the potential for differential movement between the two elements
- The significantly lighter EIFS panels would greatly reduce applied loads on the existing subgrade, thereby raising the bottom elevation of the EPS

Second Lightweight-Fill Material. The broad requirements for the second lightweight-fill material were as follows:

- Shall contribute to the overall goal of replacing in-situ soils with a lower-density material to achieve design goals
- It does not present the same buoyancy characteristics of EPS so that the desired SF against uplift could be achieved without excessive removal of existing soils

Three different materials/products were considered for this second lightweight-fill material.

The first material considered was geocomb blocks. Like geofoams, geocombs are a type or family of cellular geosynthetic materials and products but with the very important difference of having a distinctive, honeycomb-like open-cell structure. In fact, geocombs were developed in France in the 1980s to provide an alternative to EPS geofoam for precisely the type of buoyancy/uplift situation as was encountered on the C09C2 contract.

Although geocombs come in blocks comparable to EPS and have been used successfully in constructing road embankments since the 1980s [Perrier 1997, PIARC 1997], they were not reliably available in the U.S.A. at the time of the CA/T redesign process ca. 2000-2001. Therefore, while they were ideally suited for the C09C2 contract they were not given any further consideration.

The same was true of the second alternative considered which was "anti-buoyancy" EPS blocks. These are shape-molded EPS blocks that are 50 to 60% void inside. While not as effective as geocomb blocks (96% void) against buoyancy, they are significantly better than normal EPS blocks in this regard. However, these anti-buoyancy EPS blocks were only known to be available in Japan ca. 2000-2001 so the lack of a proven U.S. source for reliable availability eliminated them out from any serious consideration.

The third and final material considered was lightweight expanded clay/shale aggregate [PIARC 1997]. This material is significantly denser than EPS geofoam. However, given its inherent open texture and local availability it was chosen as the second lightweight-fill material.

Final Design

With the change to an EIFS side-covering system and the complementary use of EPS blocks and expanded-shale aggregate, most C09C2 transition structures that were candidates for redesign became viable for final design using Redesign Alternative 1 (Modified) as shown schematically in Fig. 8. A few structures remained with Redesign Alternative 3 (Fig. 6) due to their irregular geometry and associated redesign time.

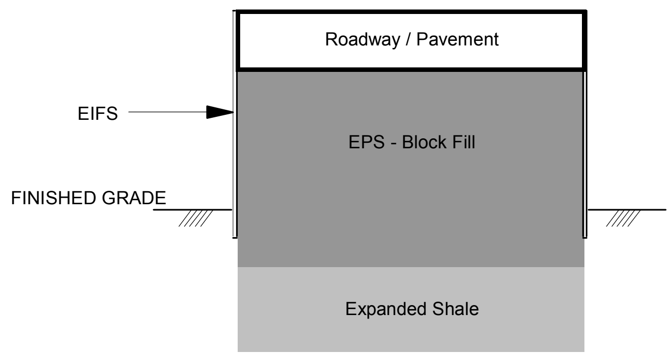

Fig. 8. Redesign Alternative 1(Modified).

FINAL DESIGN CONSIDERATIONS

Overview

As noted previously, the CA/T Project design team developed several contract-specific design documents using the basic concept shown in Fig. 8. During this development phase, several interesting and ultimately important technical issues were encountered. These were a result of the relatively slender transverse cross-section of the C09C2 EPS embankments.

Analysis and Design of EPS Structures

The C09C2 EPS embankments were designed using the Allowable Stress Design (ASD) method and service loads, for the following AASHTO defined gravity and lateral loads:

- Dead loads (DL)
- Live loads (LL)
- Buoyancy forces (B)
- Wind loads (W) and Wind on live load (WL)

- Centrifugal forces (CF) resulting from live loads
- Seismic loads (E)

The above loads were combined using the corresponding AASHTO group-load combinations to produce the design cases of loading to which the structure may be subjected.

As is typical, under gravity loading the uppermost layers of EPS blocks had the largest vertical stresses due to combined vehicle live loads and dead weight of the pavement system (see Fig. 9). As is now well known, this significantly impacts EPS design since there is a direct correlation between normal stresses applied to EPS and required EPS properties (including, but not limited to, density).

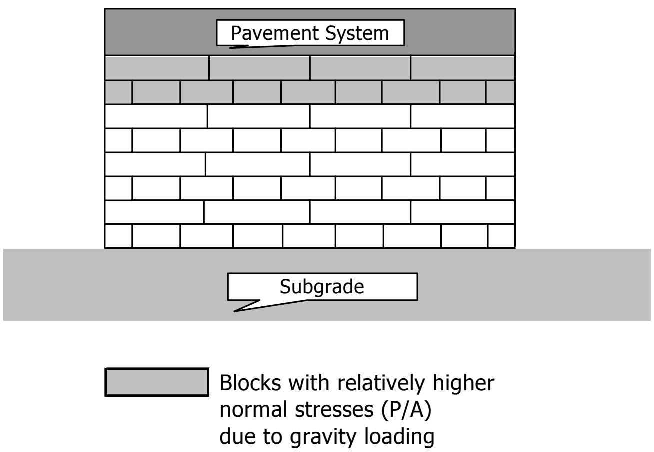

Fig. 9. Relative Compressive Normal Stresses in EPS Blocks due to Gravity Loads.

Seismic Analysis and Design

Overview. Seismic loads turned out to govern the design of all C09C2 EPS structures. Historically, two different behavioral modes are considered for the behavior of an EPS-geofoam highway embankment:

- Rigid-body sliding of a wedge of EPS blocks in the longitudinal direction of the embankment when confined behind some type of earth-retaining structure such as a bridge abutment. Conceptually, this is identical to the Mononobe-Okabe type of model used for soil.
- Flexible, horizontal sway of the entire embankment in either its longitudinal or transverse direction (the latter is usually more critical). This is modeled as a classical single-degree-of-freedom (SDOF) system and visualized as an elastic cantilever beam with a lumped mass at the top, representing the mass of the roadway system (see Fig. 10). Details can be found in Horvath [1995] and Stark et al. [2000, 2002].

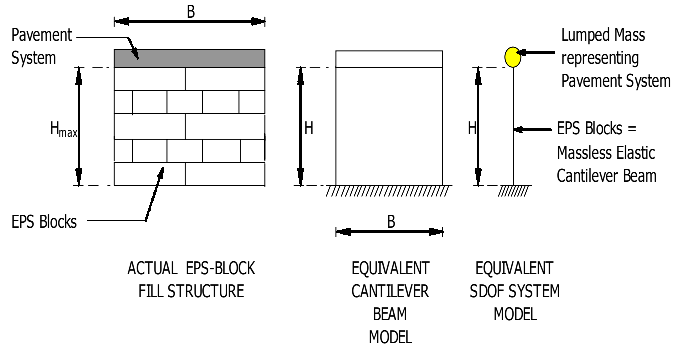

Fig. 10. Flexible Dynamic-Analysis Model for EPS.

Seismic Rocking. As the redesign process evolved, the CA/T design team recognized the potential for a mode of seismic behavior that is referred to hereinafter as "seismic rocking".

This is defined as rigid-body rotation of the entire embankment in its shorter (transverse) direction due to the moment created by the relatively concentrated, elevated mass of the pavement system. With reference to Fig. 10, this rotation would occur about an axis perpendicular to the figure.

While seismic rocking can occur with any EPS embankment, it appeared to be critical for the C09C2 EPS structures because of their height / width ratio given their relatively slender transverse cross-section. This behavior was confirmed by a coincidental review of literature [Nishi et al. 1998, Hotta et al. 1998] that was obtained at the time the C09C2 redesign work was beginning (early 2001). Seismic rocking had apparently been observed for the slender EPS structures reported in that literature but the mode itself was not recognized or identified as such.

The practical relevance and importance of seismic rocking is that the lowermost/outermost portions of the EPS blocks can be subjected to relatively large vertical normal stress increases due to the rocking motion. These stresses are due to what is referred to as the 'M-c-on-I' (Mc/I) effect. Note that these dynamic stresses must be added to the vertical normal stresses due to gravity loads.

The effect of seismic stresses on the distribution of normal stresses is shown in Fig. 11. Strong support for the conclusions shown in Fig. 11 came from a careful review of Nishi et al. [1998] and Hotta et al. [1998]. When the EPS blocks were removed at the end of their tests, crushing of the EPS was found in exactly those areas where the stresses as shown qualitatively in Fig. 11 were the largest in magnitude.

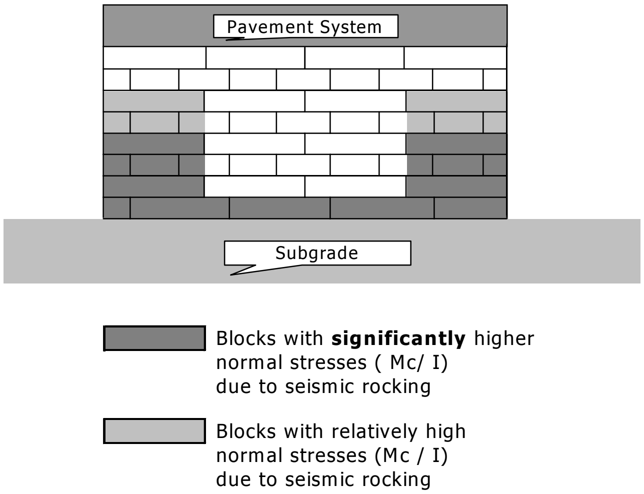

Fig. 11. Relative Compressive Normal Stresses in EPS Blocks due to Seismic Loads.

Choice of EPS Properties. Considering the combined effect of both gravity (Fig. 9) and seismic (Fig. 11) loading conditions, it was decided to use a single type or grade of EPS blocks for all C09C2 embankments in the interest of satisfying both technical need and construction simplicity. Specifically, blocks with a minimum density of 32 kg/m^3 (2.0 lb/ft^3) were specified.

External Stability. The overturning moment at the base of an embankment from the above-described Mc/I effect also affects the external stability of that embankment in various ways:

- Rigid-body overturning of the entire embankment
- Partial embankment liftoff or separation along horizontal EPS-block joints due to vertical tensile stresses, and
- Bearing-capacity failure due to the reduced effective area of the embankment bearing on the underlying subgrade.

Each of these constitutes a behavioral mode that required explicit consideration but did not, however, control the final design.

CONSTRUCTION

Construction of the C09C2 highway embankments using EPS geofoam started during Summer of 2002. The only significant deviation, to date, from what was anticipated during the redesign process outlined in this paper has been the unplanned use of shotcrete facing on some of the fills. This was the direct result of certain scheduling issues that could not have been foreseen or anticipated during the final-design phase.

CONCLUSION

EPS geofoam, lightweight expanded-shale aggregate, EIFS and shotcrete are, individually, well-established construction technologies. However, their synergistic use on the transition embankment structures of Boston's CA/T Project Contract C09C2 involved several innovative procedures and design details that will hopefully be useful on other projects.

ACKNOWLEDGEMENTS

The permission of the CA/T owner, the Massachusetts Turnpike Authority (MTA), allowing publication of this paper is gratefully acknowledged.

REFERENCES

Horvath, J. S. [1995]. "*Geofoam Geosynthetic*", Horvath Engr., P.C., Scarsdale, N.Y.

Hotta, H., T. Nishi, S. Kuroda, H. Hasegawa, J. Ri and H. Tsukamoto [1998]. "Shaking Tests for Full-Sized EPS Fills (Part 2: Simulation Analysis)", *Proc. of the 33rd Presentation Mtg. of the Japanese Geotech. Soc.*, 2463-2464 [in Japanese].

Nishi, G., H. Hotta, S. Kuroda, H. Hasegawa, G. Lee and H. Tsukamoto [1998]. "Shaking Tests for Full-Sized EPS Embankment (Part 1: Shaking Table Tests)", *Proc. of the 33rd Presentation Mtg. of the Japanese Geotech. Soc.*, 2461-2462 [in Japanese].

Perrier, H. [1997]. "Ultra Light Cellular Structure - French Approach", *Geotextiles and Geomembranes*, Elsevier Science Ltd., London, U.K., 15 (1-3), 59-76.

PIARC Technical Committee C12 on Earthworks, Drainage, Subgrade [1997]. "*Matériaux Légers pour Remblais/Lightweight Filling Materials*", PIARC - World Road Assoc., La Defense, France.

Riad, H. L., A. L. Ricci, P. W. Osborn, D. C. Wood and J. S. Horvath [2003a]. "Innovative Aspects of the Use of Expanded Polystyrene (EPS) on Boston's 'Big Dig'", preprint paper No. 03-2823, Trans. Res. Bd. 82nd Ann. Mtg., Wash., D.C.

Riad, H. L., A. L. Ricci, P. W. Osborn and J. S. Horvath [2003b]. "Expanded Polystyrene (EPS) Geofoam for Road Embankments and Other Lightweight Fills in Urban Environments", Soil and Rock America 2003, Cambridge, Mass.

Stark, T. D., D. Arellano, J. S. Horvath and D. Leshchinsky [2000]. "*Guidelines for Geofoam Applications in Embankment Projects*", Interim (Phase I) Rpt. - Natl. Coop. Hwy. Res. Prog. Proj. No. 24-11, submitted to the Trans. Res. Bd. by the Univ. of Ill. at Urbana-Champaign.

Stark, T. D., D. Arellano, J. S. Horvath and D. Leshchinsky [2002]. "*Guidelines for Geofoam Applications in Embankment Projects*", Final Rpt. - Natl. Coop. Hwy. Res. Prog. Proj. No. 24-11, submitted to the Trans. Res. Bd. by the Univ. of Ill. at Urbana-Champaign.