Manhattan College

Center for Geotechnology

Innovative Aspects of the Use of Expanded Polystyrene (EPS) on Boston's 'Big Dig'

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The Manhattan College School of Engineering *Center for Geotechnology* and Its Mission

The **Manhattan College School of Engineering** ***Center for Geotechnology*** **(CGT)** is a unique organization that strives to be more than the typical academic research center or institute. It was founded in 2001 at the personal initiative of Prof. John S. Horvath, Ph.D., P.E. of the Civil Engineering Department who serves as its first Director. The CGT was the result of Prof. Horvath's evolutionary realization after almost 30 years of geotechnical engineering practice that the explosive growth in geotechnical and geoenvironmental engineering technology has made it difficult for the engineering practitioner to keep abreast of new technical developments. The traditional academic approach of simply publishing research results in narrowly disseminated technical reports and papers (a philosophy of "if you print it, they will learn") has proven to be an increasingly ineffective way of reaching practitioners and moving the state of art to the state of practice. There is an ever-growing gulf between these two states of knowledge in geotechnical engineering. The critical need for a total rethinking of how life-long continuing education is achieved not only for engineering practitioners but academicians themselves is evidenced by the appearance of "teach-the-teacher" training courses in drilled shaft foundations and geosynthetics beginning in the late 1980s. If even academicians cannot keep up with new developments by reading journal papers and conference proceedings, how can practitioners be expected to? The stagnation of geotechnology also affects current engineering students and perpetuates the cycle. The desirability of involving the practitioner in the process of formulating research programs so that they may have a more direct and immediate benefit to practice is also something that is now recognized more and more.

The CGT seeks to address the current need for effective, meaningful continuing education by recognizing that the cycle of growth for any technology has three interdependent components, what can be called the "trilogy of technology". Like a three-legged stool, each of these components must be of equal length and strength if a given technology is to succeed. Thus the CGT has adopted a holistic strategy of supporting geotechnology growth by recognizing the need to concurrently address:

- Technology advancement through research and development that involves not only the engineering practitioner but also other end users of geotechnology such as construction contractors and material manufacturers to the greatest extent practicable.

- Technology transfer (T^2) through education of engineers, contractors and manufacturers in a multi-faceted, proactive way.

- Technology documentation through standards development so that all end users (practitioners, contractors and manufacturers) of a given technology work to a common set of guidelines.

This trilogy-of-technology growth cycle is the cornerstone of all activities of the CGT. It is important to note that the interaction of these three components is never completed but assumes a constant cycle that leads to continuous growth of a technology. This concept is embodied in the CGT logo of three interconnected arrows that is displayed on all CGT documents.

Another issue that the CGT seeks to address is the increasing specialization and compartmentalization within civil engineering. This is a problem that affects numerous professions and can only be expected to worsen as technology grows and a professional must concentrate their education and practice ever more. Despite the inevitability of specialization, there are steps that can be taken to soften its effects by sensitizing and informing professionals of the work of those in allied professions. Toward this end, the CGT seeks to involve other areas of related professional activity such as structural engineering, environmental engineering and science, and geology in both its research and, especially, technology transfer activities.

The CGT receives no direct financial support on a regular basis from Manhattan College. Thus the success and growth of the CGT is totally a function of outside funding from individuals and organizations whose philanthropic philosophies are consistent with the stated goal of the CGT to treat technology growth in a more holistic fashion than is typically done in academia and considers the entire process from research to standards with end-user input at all stages. In addition, as part of its mission to promote technology transfer through education to the greatest extent practicable the CGT is willing to partner with industry and other academic institutions not only in research but also technology transfer and standards activities on any topic relevant to geotechnical or geoenvironmental engineering. The new Manhattan College School of Engineering William J. Scala Academy Room, which is located on the main floor of the Leo Engineering Building and available for CGT activities, offers modern facilities for hosting technology transfer activities. One benefit of Manhattan College's location on the northern edge of New York City adjacent to both Interstate I-87 and mass transit is that it is quite accessible (including free, off-street parking adjacent to Leo Engineering Building) from both within and outside the City. When appropriate, the CGT will bring its technology transfer activities off campus to meet the needs of a particular activity.

Regardless of financial support, the ultimate success and growth of the CGT will depend on its being responsive to the needs of the engineering practitioner. Towards this end, the CGT welcomes input from practitioners on an ongoing, continual basis. Suggestions for future research and technology transfer activities based on perceived needs in practice are always welcome. There is no topic that is too modest or simple for consideration. In fact, much of the research conducted by Prof. Horvath since he came to Manhattan College in 1987 has been based on ideas, large and small, that he developed as a result of his years in engineering practice. Additional information about the CGT as well as access to published documents and other resources can be found on the Internet at **www.engineering.manhattan.edu/civil/CGT.html**.

Preface

This report contains the complete manuscript of a technical paper that was originally presented on January 16, 2003 at Session No. 823 (titled "Geosynthetic Case Studies") of the 82nd Annual Meeting of the Transportation Research Board (TRB) in Washington, D.C., U.S.A. Unfortunately, the TRB decided beforehand to make this paper manuscript available only as preprint No. 03-2823 on the CD that was provided to meeting attendees as part of their registration package. Because this paper will not be published in another, more-formal TRB venue such as the *Transportation Research Record* series that could be obtained or accessed by a larger, more-general audience, I decided to make the paper manuscript available through the Manhattan College Center for Geotechnology (CGT) research report series. I felt that this was especially important given the fact that the work documented in the original paper involved a major, publicly-funded project. In preparing this CGT report, the contents of the TRB paper manuscript have not been altered in any way from what appeared on the TRB meeting CD. Only the formatting and layout of the text has been changed editorially to be consistent with that of other CGT reports.

I acknowledge and thank my four co-authors of the original paper for their collective contributions and efforts in preparing the paper. I particularly thank Dr. Hany L. Riad, P.E. for his lead role not only in the design effort that is discussed in this paper but also for coordinating submission of the original manuscript to TRB as well as making the presentation at the TRB meeting.

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ABSTRACT

The Central Artery/Tunnel (CA/T) Project, also referred to as the 'Big Dig', in Boston, Massachusetts, U.S.A., has utilized many innovative technologies in the rebuilding of interstate highways I-90 and I-93 through the heart of that city. This paper addresses the use of expanded polystyrene (EPS) as both a geofoam lightweight fill and substrate for exterior insulation finishing system (EIFS) on the Big Dig. While both EPS geofoam and EIFS are well established and proven technologies, there are several innovative aspects of their use on the Big Dig. The purpose of this paper is to summarize these innovations. Topics covered include: use of new design guidelines and model specifications from NCHRP-funded research into the use of EPS-block geofoam as lightweight fill for road embankments; full implementation of AASHTO codes in the design of the EPS fills; design of the relatively slender, vertical-sided EPS fills used on the Big Dig for rigid-body rocking under seismic load; the use of EIFS side panels on the EPS fills to eliminate costly and heavy reinforced concrete panels; and design of an EPS fill that has both permanent and temporary components.

PROJECT DESCRIPTION

Overview

This paper involves the Central Artery/Tunnel (CA/T) Project in Boston, Massachusetts, U.S.A. This massive public-works project, which is referred to as the 'Big Dig', has as its focus the total reconstruction of Interstate highway I-93 as it passes through the heart of the City of Boston and the extension of Interstate I-90 from its terminus at I-93 just south of downtown Boston to Logan International Airport in east Boston. An overview of the CA/T Project can be found at (*1*).

The technical challenges facing the construction of this project are many and varied. Among the numerous constraints involved are working under very tight schedules in a densely developed urban environment that includes elevated roadways, roadways and rail lines at grade, and underground tunnels and subways; maintaining traffic on the existing I-90 and I-93 until the new roads and connecting ramps are completed; soft ground conditions throughout most of the Project area which includes filled-in portions of Boston Harbor; and project-wide seismic design requirements. The end result of these factors has been the extensive use of numerous innovative, state-of-art structural and geotechnical engineering technologies on the CA/T Project.

CA/T CONTRACT C09C2

To manage and facilitate both design and construction of such a large project, work has been divided into 118 separate construction contracts (*2*). The overall subject of this paper is a contract formally designated as C09C2 and titled "I-93/I-90 Interchange, Ramps and Surface Restoration at Albany St." (*3*) but colloquially called simply '9C2'. This contract encompasses viaducts, bridges, transition structures, 'boat' (depressed highway) and tunnel sections on the I-93 mainline and connecting to I-90 in the west as well as roadways at grade for the South Bay interchange.

The focus of this paper is eight transition structures and ramps within the 9C2 Contract that are located on the I-93 Northbound and Southbound mainlines and also connecting to existing I-90 and other surface roadways and boat sections south of downtown Boston and South Station. These structures are precast concrete girder bridges with curtain walls on both sides, elevated slabs and/or regular fill on boats, all supported on pile foundations and drilled shafts. A schedule initiative to accelerate construction on 9C2 proposed replacement of the eight transition structures and ramps with roadway embankments constructed primarily of expanded polystyrene (EPS) blocks used as a geofoam lightweight-fill material. The heights of these eight EPS-geofoam ramps vary with a maximum height of the finished roadway pavement above existing grade of approximately 8 metres (25 feet). The use of EPS as a geofoam lightweight fill resolved the primary technical challenge of constructing a finished roadway that is elevated above existing grade in an area that is underlain by extremely soft, compressible soils. The basic geotechnical design criterion for 9C2 is that the new construction must exert zero net pressure increase on the existing soils.

SCOPE OF PAPER

Given the overall difficult conditions under which the CA/T Project in general is being constructed, it is no surprise that the design for the 9C2 Contract required use of various design concepts and details that pushed the edge of the geotechnology envelope. This paper focuses on some of the innovative aspects of the design that was eventually used for the EPS-geofoam ramps on this contract.

DESIGN ISSUES

Overview of Geotechnical and Structural Design

To better understand the design philosophy behind the use of lightweight fills in general and EPS-geofoam in particular, it is useful to review the basic concept that underlies all geotechnical and structural design. The traditional Allowable Stress Design (ASD) method, based on the Working Stress concept, applied to any structural element, foundation, or earthwork requires satisfying the following basic relationship:

Actual Stresses Allowable Stresses **(1a)**

Actual stresses are a function of the applied service loads (demand) required of the structure and allowable stresses are a result of dividing the limiting stress (supply), usually the material yield or rupture stress as appropriate, by a number greater than one that is called the 'safety factor' (SF). SF represents the excess 'supply' in the system expressed as:

SF = (Limiting Stress / Allowable Stress) **(1b)**

Using the increasingly common Load and Resistance Factor Design (LRFD) method, based on the Limit State concept, the same principle is satisfied with 'safety' built into the load and resistance factors. Typically, a different factor, each greater than one, is applied to each type of load (dead, live, etc.) and another factor, normally less than one, is applied to the strength or resistance supplied by the material. The basic LRFD relationship is expressed as:

Factored Loads Reduced Resistance **(1c)**

It is important to note that in these equations resistance must include both strength and stiffness considerations as geotechnical 'failure' in particular can result from either excessive deformation (the Serviceability Limit State, SLS) or collapse (the Ultimate Limit State, ULS).

Historically, civil engineers have been educated to satisfy equations 1a and 1c by increasing the resistance side, i.e. increasing the strength and/or stiffness of the structure components as necessary to accept the loads dictated by nature. While this is certainly a technically valid approach that continues to work well in practice, it is important to recognize that an equally viable approach to satisfying these equations is to reduce the loads wherever and whenever possible. Load reduction is typically attractive in situations where the mass of the structure contributes predominantly to the applied loads, e.g. under gravity or seismic loading conditions. This is often the case with geotechnical structures such as earthworks. By reducing the mass of the structure, there is a one-for-one reduction in loads caused by both gravity and seismic inertia. Mass reduction is typically accomplished by using 'lightweight' (more correctly, 'low-density') materials.

Note that there are always an infinite number of intermediate solutions involving combinations of resistance increase and load reduction. On any project, the optimum design alternative is the one that satisfies equations 1a or 1c at the lowest cost. Note also that cost estimates should always include a consideration of not only capital construction costs but also the cost of structure operation and maintenance for the design life of the structure. While this is true for any engineered construction, experience indicates that it is especially important to do when lightweight materials are involved if their true cost benefits are to be predetermined ahead of time for the decision-making process. Very often lightweight materials significantly reduce long-term operation and maintenance costs attributed to mitigation of settlement damage.

Another cost-related concept that is rapidly achieving recognition for its practical importance is 'accelerated construction' (4). Simply stated, it is now appreciated that there is tangible overall cost benefit to using construction technologies that accelerate road and bridge construction. It is of interest to note that the use of EPS geofoam as lightweight fill is recognized as an underutilized accelerated-construction geotechnology in the U.S.A. at the present time (4).

The use of lightweight materials, especially in geotechnical engineering where structure mass tends to generate most of the loads and thus dominate design, has seen tremendous growth worldwide throughout the 1990s. Examples of this international attention are recent development of a manual with design and specification guidelines for a wide variety of lightweight materials (*5*) and inclusion of lightweight materials in a U.S. Federal Highway Administration (FHWA) technical publication and companion short-course developed as part of FHWA Demonstration Project 116 on ground improvement methods (*6*). The latter FHWA technology transfer initiative has recently (2002) been turned over to the National Highway Institute (NHI) for future administration.

Ramps of 9C2 Contract

Design Requirements

Figure 1 shows a cross-section through a typical ramp of the 9C2 Contract. Principal issues to be considered in the design of all ramps on this contract are:

- No net stress increase is allowed on the existing subgrade.

- The ramps have a variety of vertical profiles and horizontal curve alignments. Maximum height above existing grade varies with some ramps up to 8 metres (25 feet) high. While this is not particularly noteworthy, the average overall ramp width is typically only of the order of 8 metres (25 feet). Thus many of the EPS fills are relatively slender compared to most. As discussed subsequently, this resulted in some critical design outcomes.

- Because of right-of-way constraints, the width of the overall ramp structure must be more or less constant over its entire height. This means that if a fill is used it must have vertical sides. Because of the CA/T Project architectural requirements, these vertical sides must have a certain aesthetic appearance to achieve uniformity with adjacent structures, which limits the choice of facing materials.

- In some cases, a 'temporary' ramp occupies the same general alignment as a permanent ramp. Important features of these temporary ramps is that they are intended for public use so must have an appropriate paved surface and necessary safety barriers. In addition, temporary ramps may remain in service for more than one year. Therefore the presence, construction sequencing and demolition of the temporary ramps must be considered in the analysis, design and details of the permanent ramps with which they interact.

- All CA/T Project structures must be designed for seismic loading in conformance with the Seismic Design requirements of the Standard Specification of Highway Bridges published by the American Association of State Highway and Transportation Officials (AASHTO). The basic bedrock acceleration at the Project site must first be determined. The ramps of the 9C2 Contract have been designed to satisfy an AASHTO defined Seismic Performance Category (SPC) 'B' with a corresponding gravitational acceleration coefficient of 0.17. This means a design bedrock acceleration of $0.17g$, where g is the gravitational acceleration coefficient.

The bedrock acceleration is amplified, as necessary, based on overlying soil conditions to produce a surface acceleration. As the 9C2 Contract site is generally underlain by soft fine-grain soil with a depth to bedrock in excess of 30 metres (100 feet), amplification of the bedrock motion within the soil overlying bedrock must be considered. The soil conditions at the project site correspond to AASHTO defined Soil Type III with an amplification factor of 1.5. The response of the EPS fills to this motion is discussed subsequently.

- Because the 9C2 Contract area is located close to Fort Point Channel, which is part of Boston Harbor, the potential for flooding to a defined elevation must also be considered.

Design Alternatives

The design process for the 9C2 transition structures and ramps went through many changes. Preliminary concepts called for precast, prestressed concrete girder bridges; cast-in-place reinforced concrete elevated slabs; and soil fill within boat sections, each supported on deep foundations extending to the underlying bedrock. However, a cost and schedule initiative in 2000 subsequently led to a reconsideration of these initial design choices. Due to schedule constraints, traffic, the required early opening of certain ramps, and construction-staging issues, in-situ ground improvement of the existing site soils followed by the use of soil fills was not considered viable for the 9C2 Contract. It should be noted, however, that various types of in-situ ground improvement have been used extensively on the CA/T Project, including areas close to the 9C2 Contract area (*7*,*8*).

The alternative chosen for final design for most (eight) of the transitions structures and ramps on the 9C2 Contract was to construct embankments using a lightweight fill material consisting of blocks of a polymeric (plastic) foam called expanded polystyrene (EPS). This is now referred to generically as 'EPS-block geofoam' or, more simply, 'EPS geofoam'. Geofoams are a family of geosynthetics that encompass many different types of plastic, glass and cementitious foams that are used in a wide variety of functional applications in addition to lightweight fill (*9,10*). EPS is by far the most commonly used geofoam material worldwide and the predominant geofoam material for lightweight-fill applications.

The use of EPS geofoam offered superior advantages in weight, performance characteristics and schedule over other design alternatives, including other lightweight fill materials, namely:

- Despite an extraordinarily low density of about 1% of the density of soil, EPS has compressive strength and stiffness properties comparable to soil and is thus capable of supporting the appropriate AASHTO roadway design loads.

- The significant reduction in material density compared to a traditional soil embankment resulted in reduced stresses due to gravity loads on the underlying soil subgrade as well as a significant reduction in seismic inertia loads on the embankment itself. Accordingly, the EPS fills on the 9C2 Contract did not require any collateral ground improvement such as preloading and artificial drainage, which translated into cost and schedule savings.

- With an effective, in-place Poisson's ratio close to zero as demonstrated by observation of full-scale structures, lateral pressures on abutments and other vertical walls adjacent to an EPS fill are reduced to almost zero.

- The use of the EPS-geofoam alternative offered substantial cost savings and schedule advantages over the various types of concrete bridges and the deep foundations that would have been required to support them.

- The EPS-geofoam alternative offered additional schedule savings due to its ease of handling; inherent free-standing, self-supporting ability which resulted-in stability during erection; and construction under all weather conditions.

INNOVATIVE ASPECTS OF THE C09C2 CONTRACT RAMP DESIGN

Introduction

Although the 9C2 Contract represented the first use of EPS geofoam in permanent construction on the CA/T Project, it is important to note that the use of geofoams in general, and EPS geofoam in particular, in road earthworks is not new. Geofoam use as pavement insulation was patented in the U.S.A. in 1966 (*11*) and for lightweight fills in 1971 (*12*). The oldest documented project involving the use of EPS geofoam as lightweight fill for a road dates back to 1972, in Norway (*9*). Problems with EPS-geofoam fills have been few and most are attributed to various construction errors (*13*). Most recently, EPS geofoam was used in the extensive reconstruction of Interstate highway I-15 in Salt Lake City, Utah, U.S.A. The general application on I-15 looked essentially the same as that shown in Figure 1. However, on I-15, traffic and geometry requirements resulted in EPS-geofoam structures that were relatively much wider than the 9C2 ramp fills to accommodate several lanes of traffic on multi-lane, mainline roads. This detail had important consequences as will be discussed subsequently. Because the use of EPS geofoam as lightweight fill can be considered a reasonably mature technology, basic aspects of behavior, design, etc. will not be addressed in this paper. Those seeking background information can find this in a number of sources (*5*,*6*,*9*,*14*).

It is also important to note that EPS was invented circa 1950 so any original material patents have long since expired. Therefore, basic block-molded EPS is a commodity material that can be manufactured by dozens of independent companies in the U.S.A. alone. However, end users are cautioned that there is a growing trend for EPS manufacturers (called 'block molders') to tradename their particular EPS block product for marketing identification purposes in what is essentially a commodity market.

Despite the fact that the use of EPS geofoam as lightweight fill for roads can now be considered both routine and generic, the application of this geotechnology to the 9C2 Contract still allowed for the use of a surprising number of innovations. These are the focus of this paper and are detailed in the sections below. It is of interest to note none of these innovations is limited in application to the 9C2 Contract or the conditions encountered on the CA/T Project. Therefore, it is anticipated that each of these innovations will find potential application on projects worldwide.

Reference Documents Used in Design

Despite the longstanding, increasingly-common use of EPS geofoam as lightweight fill for road construction and the documentation of design procedures and material requirements in the published literature for some time now (*9*), use and application of this technology, at least in the U.S.A., is still surprisingly inconsistent. This is due primarily to the lack of detailed-but-concise generic guidelines for design, construction and material/product specifications.

Filling this void is the primary goal of the recently-concluded (*14*) National Cooperative Highway Research Program (NCHRP) Project 24-11 for Fiscal Year 1998 titled "Guidelines for Geofoam Applications in Embankment Projects" (*15*). As part of the important technology-transfer component of this practice-oriented research project, in 2000 the CA/T Project was provided access to the Phase I (interim) report (*16*) for use in the design process for the 9C2 Contract which occurred throughout 2001. Two parts of this report were utilized in particular:

- Appendix B, titled "Provisional Design Guideline (AASHTO Format)". This document contains a detailed design procedure based on material presented originally in (*9*) and updated based on subsequently published work from around the world (*17*).

- Appendix C, titled "Provisional Standard (AASHTO Format)". This document is arguably the most revolutionary and useful part of (*16*) as it was the first known material, product and construction standard for EPS lightweight fills to be developed in the U.S.A. from scratch. As a result, this allowed the NCHRP Project 24-11 research team the opportunity to present, in an AASHTO format that is familiar to those involved in highway and bridge design, a comprehensive standard that considered all of the EPS material properties such as elastic limit stress and initial tangent Young's modulus that are now recognized as essential for designing with EPS in small-strain applications such as lightweight fills. In addition, an entirely new nomenclature for EPS geofoam was introduced that is both intuitive and useful in design. The basic nomenclature is 'EPSxx' where 'xx' is the lower-bound elastic limit stress in kilopascals. This immediately identifies the maximum long-term compressive stress that would normally be applied to the EPS. By multiplying 'xx' by 100, this gives a lower-bound estimate of the initial tangent Young's modulus of the EPS, which allows material strains to be calculated. A summary of the most important parts of Appendix C that deal with EPS material issues is currently available at (*18*).

It is of interest to note that the basic contents of these two appendices are applicable to all types of cellular geosynthetics (geofoams and geocombs). This broader application is discussed in (*19*).

Based on the material presented in (*16*) as well as requirements outlined in the Standard Specification of Highway Bridges published by AASHTO that is applicable to the analysis and design of bridge structures, the CA/T Project design team developed separate documents with Project-specific design criteria and detailed numerical examples. Both of these documents considered technical issues that were unique to the analysis and design of the relatively slender fills to be implemented on the 9C2 Contract.

Based on the material presented in (*16*), the CA/T Project design team developed contract specifications that were tailored to the requirements of the 9C2 Contract. This is believed to be the first use of what will hopefully be adopted as the first AASHTO standard for EPS geofoam as lightweight fill in road and highway construction.

Seismic Loading

Traditional Behavioral Mechanisms

Most of the current state-of-knowledge regarding the behavior of EPS-geofoam fills under seismic loading is the result of research conducted since the late 1980s under the auspices of the EPS Development Organization (EDO) in Japan. This ongoing research consists of a broad spectrum of reduced-scale and full-scale shake-table tests, numerical analyses, and the observation of actual fills.

Based on initial, early research as summarized in (*9*), two different behavioral mechanisms are traditionally considered possible for an EPS fill used beneath a roadway and were thus considered for the eight EPS fills on the 9C2 Contract:

- Rigid-body sliding of a wedge of EPS blocks when confined behind some type of earth retaining structure such as a bridge abutment. In this model, the horizontal seismic acceleration of the EPS blocks and overlying pavement is taken to be the same as the underlying ground. This is conceptually identical to the classical Mononobe-Okabe analysis perform for rigid retaining walls with soil backfill. However, in this case the EPS fill is assumed to be essentially massless compared to the mass contributed by the approximately one metre (3 feet) of pavement section that is typically placed on top of the EPS in roadway applications.

- Flexible horizontal sway of an assemblage of EPS blocks as an equivalent elastic cantilever beam fixed at its base, which is taken to be the bottom of the EPS fill/top of the underlying subgrade. This type of model is judged appropriate for oscillation of a free-standing EPS fill in a direction transverse to the alignment of the road, e.g. in a horizontal direction in the plane of Figure 1. The EPS fill is again assumed to be essentially massless compared to the mass contributed by the approximately one metre (3 feet) of pavement section that is typically placed on top of the EPS in roadway applications. The behavior of the combined EPS fill-pavement system is modeled as a classical single-degree-of-freedom (SDOF) system where the lumped mass represents the mass of the pavement system and the spring and dashpot (damper) reflects the material characteristics of the assemblage of EPS blocks. Details can be found in (*9,14,16*). In general, this type of analysis results in seismic accelerations at the top of the fill that are somewhat greater than those of the underlying ground surface (which may themselves be amplified above bedrock accelerations as noted previously). This represents the seismic amplification that is typical of flexible structures, including free-standing earthworks, whose fundamental period (natural frequency) is within the range of predominant earthquake periods/frequencies using typical response spectra. Such was the case for the eight EPS fills on the 9C2 Contract.

Newly Recognized Behavioral Mechanisms

Of particular interest and relevance to the 9C2 Contract design was the most recent series of shake-table tests that were performed under the auspices of the EDO in Japan in the late 1990s. These were the first tests conducted at 'full scale', with EPS fill heights of 3.3 metres (11 feet), 6.4 metres (21 feet) and 8.5 metres (28 feet). The cross-sectional dimensions of the test fills were 3 metres (10 feet) by 5 metres (16 feet) so the taller fills represented relatively slender fills very similar to those in 9C2 Contract. Published summaries of these tests (*20,21*) indicated that a previously unrecognized third mechanism of EPS-fill behavior under seismic load is possible. It will be referred to herein as 'seismic rocking'.

Seismic rocking can be visualized and modeled as a rigid-body oscillation, i.e. back-and-forth rotation, of the entire EPS fill and overlying pavement system. With reference to Figure 1, this oscillation or rocking would occur in the plane of the figure about an axis perpendicular to the plane of the figure. This rotational axis would go through a point where the vertical centerline of the overall fill intersected the horizontal interface between the bottom of the EPS blocks and underlying ground surface.

The noteworthy consequences of seismic rocking is that the two exterior edges along the bottom of an EPS fill such as shown in Figure 1 are subjected to significant variations in vertical normal stresses relative to the constant gravity-induced stresses due to what is called the 'M-c-on-I effect'. This term derives from the familiar equation for combined normal stresses, , due to flexure and axial loads within a prismatic member subjected to both bending moment, *M*, and axial force, *P*:

$$\sigma = \frac{P}{A} \pm \frac{Mc}{I} \tag{2}$$

where *A*, *c* and *I* are the cross-sectional area, distance from neutral axis to extreme fiber, and moment of inertia, respectively, of the member cross-section. EPS fills are typically designed only for the axial stress component due to P/A where P represents the vertical gravity forces due to dead and live loads acting on the fill. The flexural-stress (Mc/I) component from seismic rocking alternately adds compressive stress on one side of the 'beam' (base of the EPS fill in this case) and tensile stress on the other side of the fill. The additive compressive stresses can physically yield and crush the EPS (this was actually noted in the EDO shake-table tests) while the tensile stresses may exceed the compressive stresses due to gravity which could lead to block separation or liftoff from the subgrade. In the extreme, the entire EPS fill could suffer rigid-body overturning.

The CA/T Project design team recognized the potential for this newly identified mode of seismic rocking in the transverse direction for the 9C2 Contract EPS ramps and transition structures. Because of the relatively slender nature of most of these fills, analyses using Equation 2 indicated that this mode was actually the controlling factor in the design of many of the 9C2 Contract EPS-geofoam fills under the combination of dead and earthquake loading in conformance with AASHTO group loading. Specifically, the additive compressive stresses along the outer edges of the bottom of the fills resulted in the use of higher-density EPS blocks which have an increased elastic-stress range compared to lower-density blocks that would ordinarily be considered acceptable. The use of this higher grade of EPS is intended to prevent permanent, irreversible crushing of the EPS under seismic rocking. The validity of this calculated, theoretical outcome was demonstrated by the above-described shake-table tests. As discussed in (*20,21*), the lowest level of EPS blocks in the test fills, which had not been designed for seismic rocking, were clearly crushed at the end of the tests.

It is believed that this is the first time, at least in U.S. practice, that seismic rocking has been considered for an EPS fill. The fact that it was found to govern the design in this case suggests that it is a behavior mode that should be considered for all EPS embankments where seismic loading is an appropriate design consideration. The outcome of an analysis for seismic rocking is likely to be very sensitive to the width of the fill at its base as the moment of inertia in Equation 2 is a function of the fill width cubed.

Side Covering

The use of EPS fills with vertical sides, also called 'geofoam walls' (*9*), as shown in Figure 1 has been increasing rapidly in recent years. Vertical-side EPS fills have become increasingly attractive in practice for a variety of reasons:

- The right-of-way width required for the fill is minimized. This, in turn, has technical, cost, environmental and public-relation benefits that vary in their relative importance from project to project.

- The volume of EPS required for construction is minimized, which reduces material and construction costs and allows schedule savings due to shorter construction time.

- There are, however, consequences to the use of vertical-side fills that must also be considered so that the total costs can be properly evaluated. These include:

- Although an assemblage of EPS blocks with vertical sides is completely self-stable, the exposed sides of a permanent EPS fill must be covered to prevent long-term surficial degradation and incidental damage of the EPS as well as to provide an appropriate architectural finish.

- The use of a reinforced concrete slab, sometimes referred to as 'load distribution slab' (LDS), across the top of the EPS blocks is highly desirable if not mandatory for most vertical-side EPS fills (it is not so for EPS-geofoam fills in general). The LDS is often used as a structural connection point for the required side-cover system. The LDS also provides anchorage for various 'road hardware' such as safety barriers, signage and lighting.

Experience indicates that both the side covering and LDS represent relatively significant cost components of the overall construction cost of an EPS-geofoam fill. This offsets the benefits of using vertical-side fills.

On the 9C2 Contract, roadway alignment and right-of-way restrictions were overwhelming factors in dictating the use of vertical-side fills to allow fitting them into a very crowded area. Therefore, the challenge was to optimize the design of both the side covering and LDS to minimize costs. As a result, novel solutions were considered along with the traditional.

There are a number of alternatives for side-facing systems for EPS fills. An up-to-date summary can be found at (*22*). Some of the more-common alternatives used to date are:

- various types of metal panels (some similar to what was used on the very earliest Reinforced Earth mechanically stabilized earth walls),
- wood timbers,
- segmental retaining wall (SRW) blocks,
- shotcrete,
- partial-height precast concrete panels as used for mechanically stabilized earth walls,
- partial-height precast concrete panels supported by steel H piles in a soldier-pile-and-lagging arrangement, and
- full-height cast-in-place concrete walls or precast concrete panels supported on their own foundation (shallow or deep as necessary).

It is important to keep in mind that that the side facing system is essentially an architectural element performing an aesthetic function and is not required to support the EPS blocks structurally in any way. However, most of the above alternatives are relatively massive for the intended purpose. Consequently, in most cases they cannot be supported by the EPS blocks and require their own foundation. Under poor soil conditions, such facing systems may require the use of deep foundations. In many ways, using a massive facing system supported on deep foundations is counterproductive technically and financially to the use of a lightweight fill material in the first place.

Full-height precast concrete panels have proven to be particularly popular, but costly, alternative in U.S. practice in recent years and were the design alternative considered initially for use on the EPS-geofoam fills on the 9C2 Contract. Moreover, uniformity with other precast concrete curtain walls utilized on adjoining transition structures and ramps in the South Bay area of the CA/T Project also favored their use. However, because of the extremely poor soil conditions at the site of the eight 9C2 EPS-geofoam fills, a relatively expensive deep-foundation system would have been required to support these heavy walls. In addition, analyses indicated that under seismic loading these walls would have transmitted a relatively significant horizontal inertia force (approximately 25% of their mass) to the assemblage of EPS blocks comprising the fill. Therefore, the CA/T Project design team actively investigated alternatives to the precast concrete panel wall facing.

Ultimately, an alternative was chosen that, as best as can be determined, has never been used previously for an EPS fill on a highway project although it was actually suggested at one of the earliest symposia on EPS geofoam in 1994 (*9*). This alternative involved the use of what is called 'exterior insulation finishing system' (EIFS) which is a well-proven technology that has been used worldwide for decades with buildings. EIFS consists of a mesh-reinforced, two-part covering that is applied over a plastic-foam substrate, most often a relatively thin (of the order of 50 millimetres (2 inches) thick) panel of EPS. The final appearance of the EIFS coating can vary widely for architectural purposes but is most often finished to create a stucco-like appearance. As a result, EIFS is often referred to colloquially as 'synthetic stucco'. The overall attraction of an EIFS system is that, if properly applied and maintained, it is very durable in the long-term in a wide variety of climates. The specific attraction for the 9C2 Contract EPS fills was that the EIFS panels are relatively light which meant that they could be attached to and supported by the exposed EPS blocks. The end result was a durable, architecturally attractive side panel system that was very cost effective and helped reduce the overall construction schedule through the elimination of foundation elements to support the facing.

Figure 2 illustrates a typical cross-section through a 9C2 Contract EPS-geofoam fill using the EIFS side panels. The CA/T Project design team developed a project-specific specification for the EIFS panels based on extensive research into existing EIFS standards from the American National Standards Institute (ANSI) as well as model specifications provided by several EIFS manufacturers in the U.S.A.

It is worth noting that EIFS technology has significant potential geotechnical engineering applications beyond EPS-geofoam lightweight fills. It could be used as part of facing systems for mechanically stabilized earth walls (MSEWs) as well as soil-nailed walls. In these applications not only would EIFS provide a durable, lightweight, architecturally attractive facing but also thermal insulation to prevent seasonal freezing of the retained soil and drainage system where necessary. In addition, it is possible to incorporate a geosynthetic sheet drain into the EPS substrate on which the EIFS finish is applied. The resulting geocomposite would then also provide insulated drainage of the retained soil.

Interface between Temporary and Permanent Fills

As noted previously, it is necessary to maintain traffic flow and patterns throughout the 9C2 Contract structures and with adjacent structures from other interfacing CA/T contracts. This requires a complex scheme of construction sequencing that includes the use of temporary ramps. In one case designated structure KK, the Temporary Ramp KK occupies more or less the same footprint area and alignment as the permanent Ramp KK. This led to the unique challenge of building two intertwined EPS fills so that one of them can be removed eventually with minimal disruption to the other. Because Temporary Ramp KK is expected to be in service for more than one year, a facing system was required to provide protection the sides of the temporary fill.

Figure 3 shows a typical cross-section through both Temporary Ramp KK and Ramp KK within the area where they overlap (each has different horizontal and vertical curves so the degree of overlap changes continuously along the road alignment). Key design details that were used are:

- The EPS block layout was designed so that blocks within the temporary fill would not interlock geometrically with those within the permanent fill. Normally, great care is taken in EPS block layout to maximize physical interlock so that an EPS fill behaves as homogenous mass under all types of loading. The reason for this significant deviation from practice on Temporary Ramp KK and Ramp KK was to facilitate eventual removal of the temporary blocks without compromising the integrity of the permanent ones. To avoid a vertical 'cold joint' where the temporary and permanent fills meet, barbed connector plates were used along this vertical surface to enhance the inherent frictional inter-block resistance. Although such plates are typically used along horizontal joints between layers of EPS blocks, there is no reason to prohibit their use along vertical surfaces and joints as well.

- The exterior vertical sides of the temporary fill will be covered with shotcrete. Architectural finish was deemed unimportant for temporary construction and shotcrete has proven to be the least expensive facing material that has been used with EPS-geofoam fills.

CONCLUDING COMMENTS

The C09C2 Contract is a multi-year contract that was awarded in early 2002 and started actual construction in the latter half of 2002. The first EPS fill constructed was the complex Ramp KK/Temporary Ramp KK structure. Because of the numerous novel design elements involving EPS in this contract, it is expected that some modifications may be required during construction. In addition, it is expected that construction may reveal areas where design details and/or specifications could be improved on. We expect to share what was learned during construction of the EPS fills of the 9C2 Contract with the civil engineering community via future publications.

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The Joint Venture of Berger, Lochner, Stone and Webster (BLSW) is acknowledged for performing the actual final design of the 9C2 Contract using the design criteria and specifications developed by the MTA, B/PB and Dr. John S. Horvath, P.E. acting as a consultant to the MTA and B/PB. All figures included in this paper have been provided as part of the final design documents developed by BLSW.

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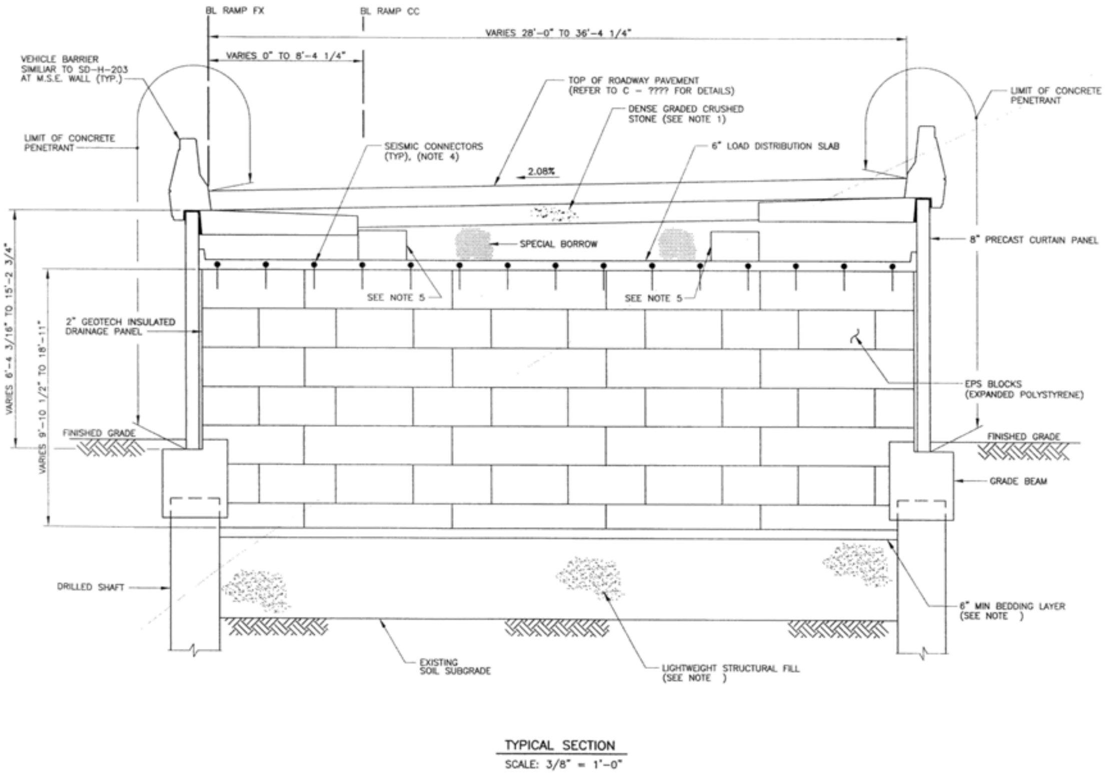

Figure 1. Typical ramp cross-section using precast concrete side panels

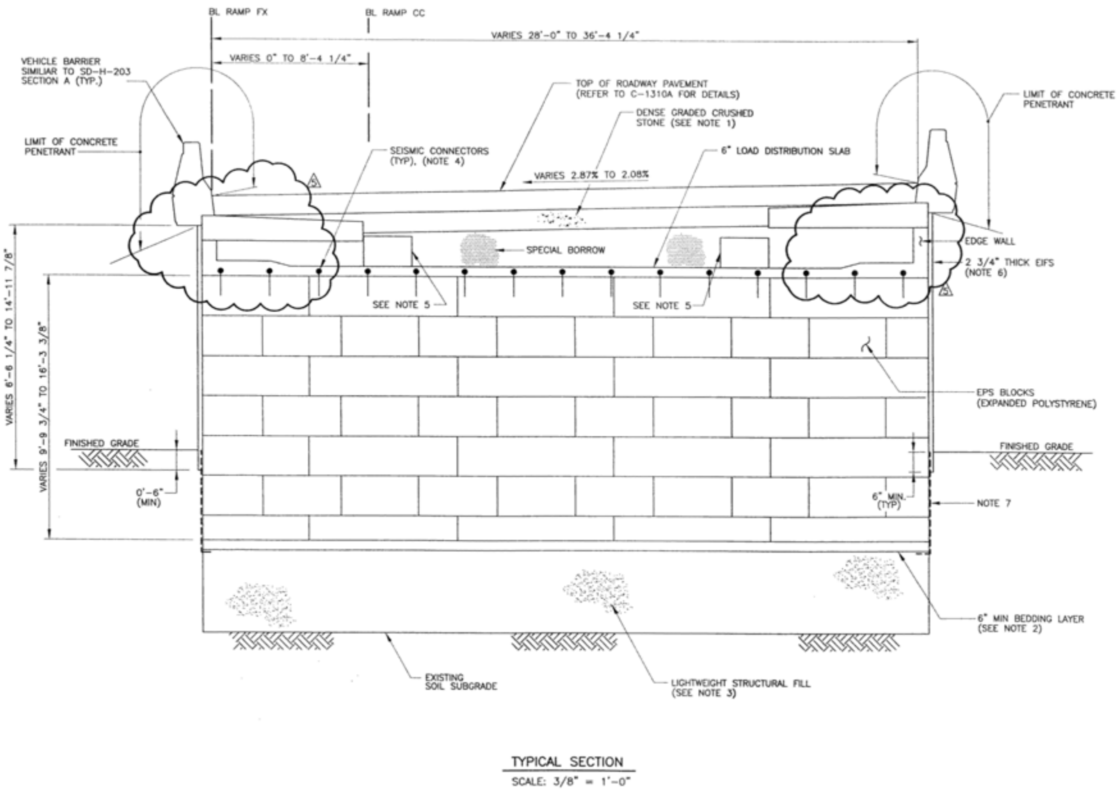

Figure 2. Typical ramp cross-section using EIFS side panels

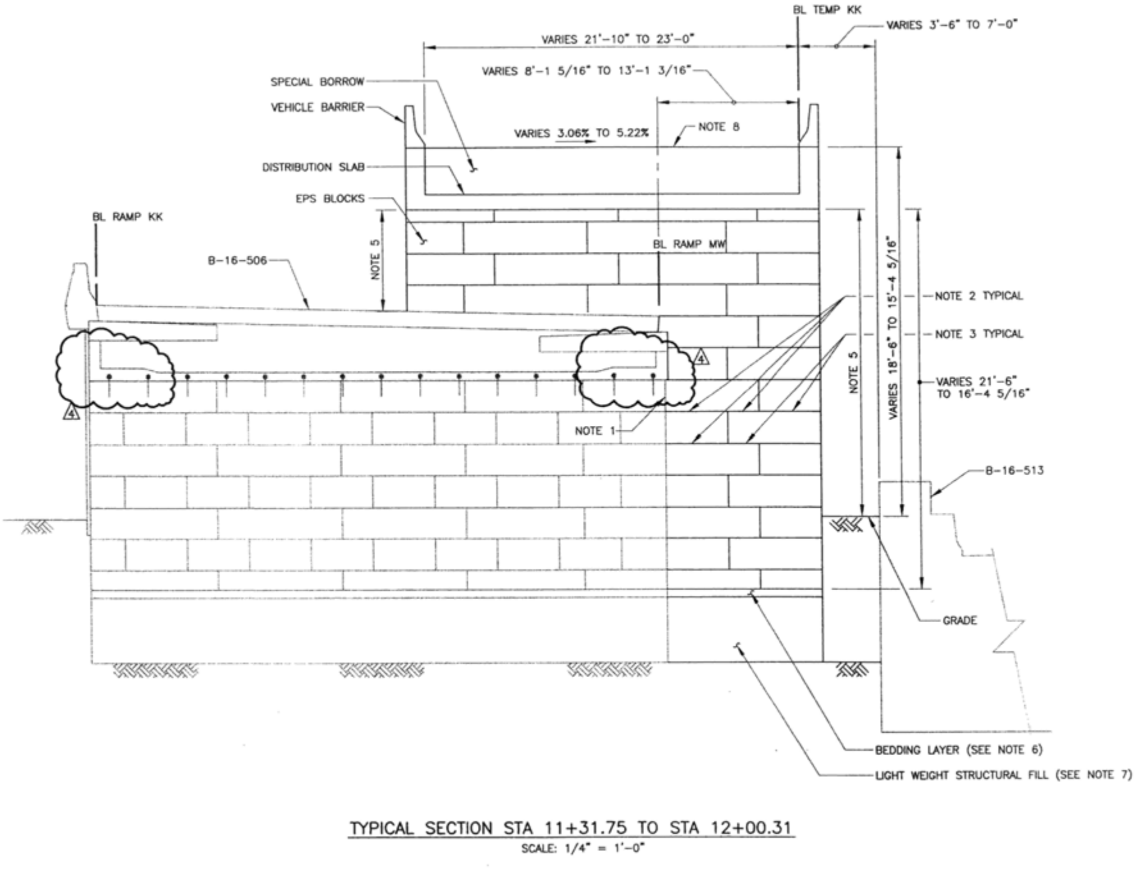

Figure 3. Cross-section showing both Temporary Ramp KK and Ramp KK