Research Report
KTC-07-14/SPR228-01-1F

KENTUCKY TRANSPORTATION CENTER

REDUCTION OF STRESSES ON BURIED RIGID HIGHWAY STRUCTURES USING THE IMPERFECT DITCH METHOD AND EXPANDED POLYSTERENE (GEOFOAM)

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REDUCTION OF STRESSES ON BURIED RIGID HIGHWAY STRUCTURES USING THE IMPERFECT DITCH METHOD AND EXPANDED POLYSTERENE (GEOFOAM)

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In cooperation with the
Kentucky Transportation Cabinet
The Commonwealth of Kentucky
and
Federal Highway Administration

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16. Abstract

The study of earth pressure distribution on buried structures has a great practical importance in constructing highway embankments above pipes and culverts. Based on Spangler's research, the supporting strength of a conduit depends primarily on three factors: 1. The inherent strength of the conduit; 2. The distribution of the vertical load and bottom reaction; and 3. The magnitude and distribution of lateral earth pressures that act against the sides of the structure. Rigid culverts are frequently used in Kentucky for routing streams beneath highway embankments because of rolling and mountainous terrain, numerous streams, shallow depths to bedrock, which creates unyielding foundations, and the necessity of using high fills which create large vertical stresses acting on culverts. As a means of exploring ways of reducing large vertical earth pressures acting on a buried structure, ultra-lightweight geofoam was placed in a trench above a reinforced rigid box culvert at Russell County, KY. This study provides strong evidences from both numerical model analysis and in-situ test data to indicate that geofoam is an ideal elasto-plastic material to reduce vertical load on top of rigid culvert resting on a rigid foundation. The load on the top of culvert can be reduced to 20 percent of traditional design load after two (2) feet thick of geofoam is placed on top of a culvert. Results from numerical model are more conservative when compared to actual test data. As much as 57 percent of settlement from geofoam has been recorded. Stresses on the top of culvert where geofoam was placed have reached a relatively stable level which is expected at the yield point of the geofoam. This technology can be used in applications which require controlled pressure on rigid underground structure. Whether geofoam is used or not used, the model analysis and test data show that the earth pressure acting on the sidewall does not change significantly. Although the pressure acting on the sidewall is slightly higher when geofoam is used on top of culvert only, the value is still below the design value used by the Kentucky Transportation Cabinet. Use of geofoam placed in an imperfect trench significantly reduces the vertical stresses acting on the top of the culvert.

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EXECUTIVE SUMMARY

Construction of highway embankments above highway pipes and culverts has a great practical significance because of stresses imposed by the fill on the buried structure. Relative stiffness of the culvert and fill controls the magnitude and distribution of earth pressures on the buried structure. The vertical earth pressure on a flexible culvert, or a culvert with a yielding foundation, is less than the weight of the soil about the culvert due to positive arching. However, the vertical earth pressure on a rigid culvert with a non-yielding foundation is greater than the weight of the soil above the structure because of a negative arching effect. Based on Spangler's research, the supporting strength of a conduit depends primarily on three factors: first, the inherent strength of the conduit; second, the distribution of the vertical load and the bottom reaction; and third, the magnitude and distribution of lateral earth pressures which may act against the sides of the structure. To reduce large vertical earth pressures on buried structures, the imperfect ditch method of construction was introduced by Marston (Handy and Spangler, 1973). This method has considerable merit from the standpoint of minimizing the load on a culvert under an embankment. This method involves installing a compressible layer above the culvert within the backfill. Expanded polystyrene (EPS, or Geofoam) can be used as the compressible material to promote positive arching (Vaslestad et al., 1993). Geofoam has low stiffness and exhibits the desirable elasto-plastic behavior.

To investigate different pressures on the culvert due to EPS (Geofoam), three different sections have been selected from the same culvert. On the first section, 2 feet of geofoam is placed above the culvert. The width of geofoam is the same as the top of the culvert. On the second section, geofoam is placed above the culvert directly at 2 feet thickness and the width is 1.5 times the culvert width. The third section will be a conventional one, which is used as a reference section for the other two sections with geofoam. These three sections have been instrumented to measure stresses on the top and sides. Three "sister" reinforcing steel bars containing strain gages have been placed in the culvert during construction to measure strains on top slab at three sections mentioned before. Twelve earth pressure cells have been placed on the top and one side of the structure. Two inverted settlement plates were installed on sections with geofoam to measure geofoam deformation.

This study provides strong evidence from both numerical model analysis and in-situ test data to indicate that geofoam is an ideal elasto-plastic material to reduce vertical load on top of rigid culvert resting on a rigid foundation. In the numerical model analysis, "calibrated" model helps to get more reasonable and closer results to in-situ data. Data from three efficient sections with and without geofoam, and with different sizes of geofoams, provide firsthand information to support numerical model analysis. Results from both numerical analysis and in-situ data show that geofoam has a great effect in reducing the vertical soil pressures above a culvert. The load on the top of culvert can be reduced to 20 percent of traditional design load after two (2) feet thick geofoam is placed on top of a culvert. The results from numerical model are more conservative compared to actual test data. Recorded geofoam settlements show how positive arching effect created by large geofoam deformation which is much bigger than deformation from adjacent normal soil filling. As much as 57 percent of settlement from geofoam has been recorded. Stresses on the top of culvert where geofoam was placed have reached a relatively stable level which is expected at the yield point of the geofoam. This technology can be used in applications that require controlled pressure on a rigid underground structure. Whether geofoam is used or not used, the model analysis and test data show that the earth pressure acting on the sidewall does not change significantly. Although the pressure acting on the sidewall is higher when geofoam is used on top of culvert only, the value is still below the design value used by the Kentucky Transportation Cabinet.

The linear-elastic model was used to simulate the geofoam stress-strain behavior in this numerical analysis. As pointed out earlier, the geofoam exhibits desirable elasto-plastic behavior during compression. The geofoam creates larger deformation, which makes bigger positive arching effect, under elasto-plastic model when stress on geofoam is beyond elastic range. This positive arching effect will reduce pressure on the top of culvert even more. In-situ test data have provided strong support for this analysis.

Geofoam deformations, which to date are occurring at a very low rate, are still being observed from the monitoring of two inverted settlement platforms. Continuation of long-term measurements of deformations is scheduled. Will and when will these deformations stop? What effect will the deformations have on the pressures surround the culvert? Long-term monitoring will answer these questions. One of the key elements of this research will be to determine if the arching effect on stresses continues over a long period of time.

INTRODUCTION

Construction of highway embankments above highway pipes and culverts has a great practical significance because of stresses imposed by the fill on the buried structure. Relative stiffness of the culvert and fill controls the magnitude and distribution of earth pressures on the buried structure. The vertical earth pressure on a flexible culvert, or a culvert with a yielding foundation, is less than the weight of the soil about the culvert due to positive arching. However, the vertical earth pressure on a rigid culvert with a non-yielding foundation is greater than the weight of the soil above the structure because of negative arching. Experiments by Marston (Spangler, 1958) showed that loads on rigid embankment culverts were some 90 to 95 percent greater than the weight of the soil directly above the structure. In model tests performed by Hoeg (1968), the crown pressure was about 1.5 times the applied surcharge. Penman et al. (1975) measured the earth pressure on a rigid reinforced concrete earth pressure below 174 feet of rock fill and found that the vertical earth pressure on the culvert crown was about 2 times the overburden stress due to the fill above the top of the culvert.

Based on Spangler's research, the supporting strength of a conduit depends primarily on three factors: first, the inherent strength of the conduit; second, the distribution of the vertical load and the bottom reaction; and third, the magnitude and distribution of lateral earth pressures which may act against the sides of the structure. The last two of those factors are greatly influenced by the character of the bedding on which the culvert is founded and by the backfilling against the sides. Considering the high fills above them and the high earth pressure they may experience, rigid culverts are usually used underneath highway embankments. To reduce large vertical earth pressures on buried structures, the imperfect ditch method of construction was introduced by Marston (Handy and Spangler, 1973). This method has considerable merit from the standpoint of minimizing the load on a culvert under an embankment.

Figure 1 shows a sketch of the traditional installation of the imperfect ditch concrete culvert and illustrates how relative settlements between soil prisms directly above and adjacent to a concrete culvert affect the earth pressure on the culvert. These relative settlements generate shearing stresses that are added to or subtracted from the dead weight of the central prism and affecting the resultant load on the culvert, as shown in Figure 1. When the relative settlement of the soil prism directly above the structure is less than that of the adjacent soil prisms, as usually found in embankment installations, the earth load on the culvert is increased by the amount of the downward shearing forces exerted on the central soil prism, which is referred to as negative arching (Selig 1972; Vaslestad et al. 1993). Likewise, when the relative settlement of the soil prism directly above the structure is greater than that of the adjacent soil prisms, as depicted in trench installations, the layers of soil in the central prism are subjected to a reverse arch shape deformation and consequently the earth load on the culvert is reduced by the upward shearing forces, as shown in Figure 1, exerted on the central soil prism, which is referred to as positive arching. The imperfect trench installation method is designed to gain the benefits of a trench installation in an embankment condition. The word "trench" is in fact a misnomer as there is no trench in the in situ soil. It is a remnant of a terminology used by Marston (1922). When the

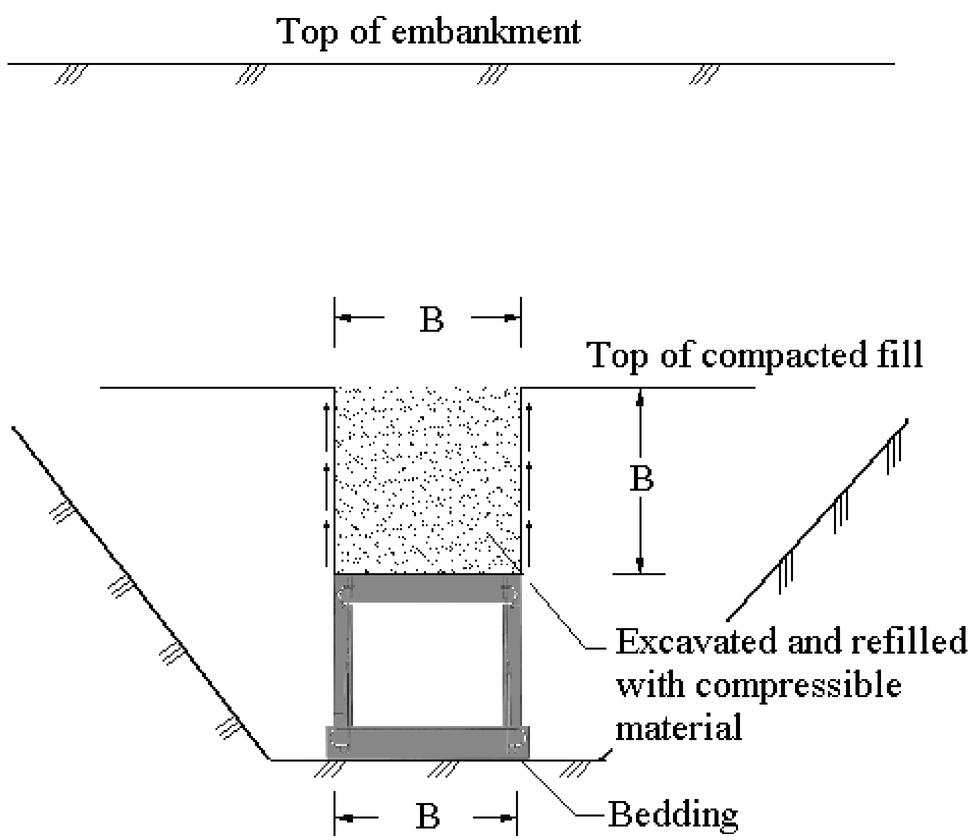

Figure 1. Imperfect ditch culvert traditional installation

soft zone induces greater relative settlement within the central soil prisms than that of the adjacent soil prisms, the upward shearing forces similar to those in the trench installations are developed.

This method involves installing a compressible layer above the culvert within the backfill. In field construction, the culvert is first installed as a positive projecting conduit and then surrounded by thoroughly compacted backfill. Next, a trench is dug in the compacted soil directly above the culvert. The trench is backfilled with compressible material, or organic fill, creating a soft zone. When the embankment is constructed, the soft zone compresses more than its surrounding fill, and thus positive arching is induced above the culvert. Traditionally, organic material such as baled straw, leaves, old tires (used in France), or compressible soil, have been used. Very little quantifiable data is available about the stress-strain properties of the soft organic materials. Also, the long-term stability and performance of the organic material was also questioned.

Expanded polystyrene (EPS, or Geofoam) can be used as the compressible material to promote positive arching (Vaslestad et al., 1993). geofoam has low stiffness and exhibits the desirable elasto-plastic behavior. An unconfined compressive strength test was conducted on geofoam by University of Kentucky Transportation Research Center and the result shows its stress-strain behavior is very similar to the one of an ideal elasto-plastic material (Figure 2). The maximum compressive strength of geofoam obtained from the test is about 3.0 ksf. Young's modulus in the linear range is 133 ksf.

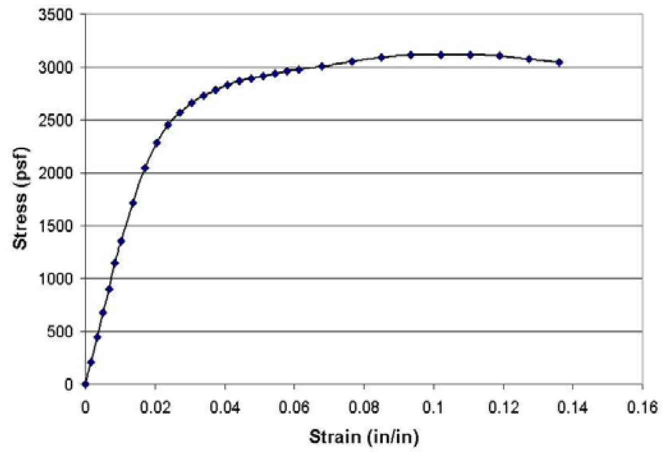

Figure 2. Typical Stress-Strain curve for geofoam

Despite the potential for considerable reductions in earth pressure, imperfect trench installations have not been widely exploited. There are reservation regarding long-term behavior as well as a lack of reliable information on the mechanical properties of lightweight materials and the optimum geometry for the soft zone. However, full-scale tests, conducted by the Norwegian Road Research Laboratory (Vaslestad et al. 1993) on limited imperfect trench installations, showed that there was no increase in earth pressure after a three year period. The use of non-bio-degradable lightweight materials such as geofoam, as opposed to baled straw or hay of bygone years, should alleviate past concerns over long term settlement above a buried structure. Nevertheless, the effects of time in imperfect trench installations are still an issue that needs to be resolved as the loss of load reduction over time was not studied in this report yet.

OBJECTIVES

The primary objective of this study is to examine the use of expanded polystyrene (EPS, or geofoam) and the imperfect ditch method for reducing the vertical stresses on rigid deeply buried highway structures, such as culverts. Accurate determination of the soil pressure associated with various stiffness of geofoam should be useful to the designers in designing concrete culverts with proper strengths for the given burial depth and backfill materials available. In this report, theoretical analysis and in-situ test data provide firm confident results for rigid deeply buried concrete culverts.

NUMERICAL ANALYSIS

The purpose of this analysis is to investigate the pressure changes when geofoam is used on the top of the culvert using the two-dimensional finite difference program FLAC (Version 4.0, Itasca 2003). A set of computer runs identified the optimal situation as a function of the geofoam size and position (Sun et al. 2005, 2006). Numerical model was calibrated by existing design and numerical analyses were conducted to investigate the effects of using different combinations of elastic modulus, Poisson's ratio, cohesion, and angle of internal friction of the backfill.

Program FLAC: Theoretical Background and General Feature

The program FLAC (Itasca Consulting Group, Inc.) is a two-dimensional explicit difference program best suited to simulate the behavior of materials that may undergo plastic flow and large deformations when these materials' yield limits are reached. It is a powerful tool for solving a wide range of complex problems in continuum mechanics, due to its formulation based on dynamic equations of motion that use an explicit Lagrangian calculation scheme and mixed discretization zoning technique. FLAC's ability to model plastic collapse and flow of highly nonlinear materials such as soil and rock very accurately makes it a useful tool for numerical analysis in geotechnical and mining engineering. In addition to the basic ability to represent the mechanical response of various materials, including the ability model groundwater flow and pore pressure dissipation, there are optional modules for dynamic analysis, thermal analysis and modeling of creep material behavior.

FLAC formulation is based on the dynamic equations of motion using an explicit time-marching method to solve the algebraic equations that correspond to a given set of governing differential equations, and initial and boundary conditions. The calculation scheme follows two-step calculation cycles. The first step of each cycle uses the equations of motion (equilibrium equation) to derive new velocities and displacements from stresses and forces. At the second step, the stress-strain relation (constitutive equation) is applied, and the velocities calculated during the first step are used to derive new strain rates, and new stresses from strain rates. One cycle occupies one calculation time step, which is small enough to ensure that the information cannot pass physically from one element to another in the chosen interval. Major advantages of FLAC formulation are: numerical scheme is stable when the physical system is unstable; plastic collapse and flow are modeled very accurately; large two-dimensional models can be analyzed without excessive memory requirements (matrices are not formed, iterations are not necessary to compute stresses from strain); objects of any shape and different properties can be modeled; the material can yield and flow, and in large-strain mode, the grid deforms and moves with the represented material. However, FLAC solution requires many steps because of the typically small time steps.

In current study, the program FLAC (Version 4.0) was chosen to analyze the behavior of culvert under geofoam and soil interaction because of its many advantages compared to other commercial programs, and particularly because of its ability to model accurately unstable states of geofoam-soil-culvert system.

Site Description and Analyzing Methodology

A culvert, selected for theoretical analyses and eventually instrumentation, is located on the Jamestown Bypass (US 127) in Russell County, Kentucky (Figure 3). Rock cores taken from this location revealed fossiliferous limestone with many shale laminations which the culvert will be constructed on. The culvert is a cast-in-place box culvert. The inner width of the structure is 9 feet and the wall thickness is 1 foot. The inner height is 8 feet and the ceiling thickness is 2 feet and 1 inch. The bottom thickness of the slab is 2 feet and 2 inches. It is continuously placed on an unyielding foundation, has a total length of 370 feet, and crosses a valley beneath an embankment of compacted backfill up to 54 feet above the culvert.

Figure 3. Culvert used to study

To investigate different pressures on the culvert due to EPS (Geofoam), three different sections were selected from the same culvert. On the first section, 2 feet of geofoam was placed above the culvert. The width of geofoam is the same as the top of the culvert (11 feet) as shown in Figure 4. On the second section, geofoam was placed above the culvert directly at 2 feet thickness and a width of 16 feet, which is 1.5 times the culvert width as shown in Figure 5. The length of both sections is 20 feet. The geofoam sections are located where the fill is highest, 54 feet. The third section will be a conventional one, which is used as a reference section for the other two sections with geofoam. These three sections were instrumented to measure stresses on

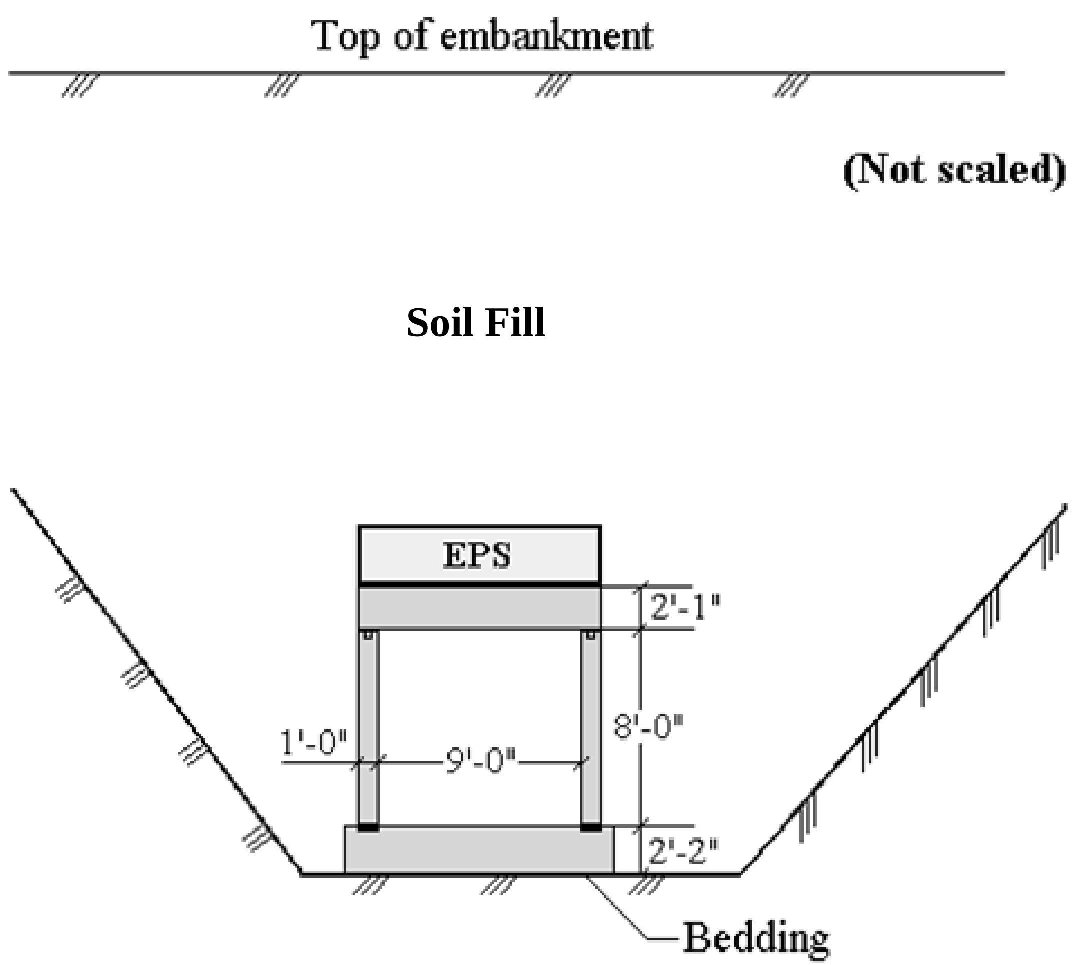

Figure 4. Same width geofoam on culvert

the top and sides. Strain of the top slab was also measured. Three "sister" reinforcing steel bars containing strain gages were placed in the culvert during construction. Twelve earth pressure cells were placed on the top and one side of the structure.

Numerical Model and Properties of Materials

Solving a problem using FLAC involves thousands of iterations. To speed up the iteration calculation, half space was considered for this symmetrical problem (Figure 6). The culvert is treated as a beam element with hinges on upper and bottom corners. Interface elements are used between culvert and soils or geofoam.

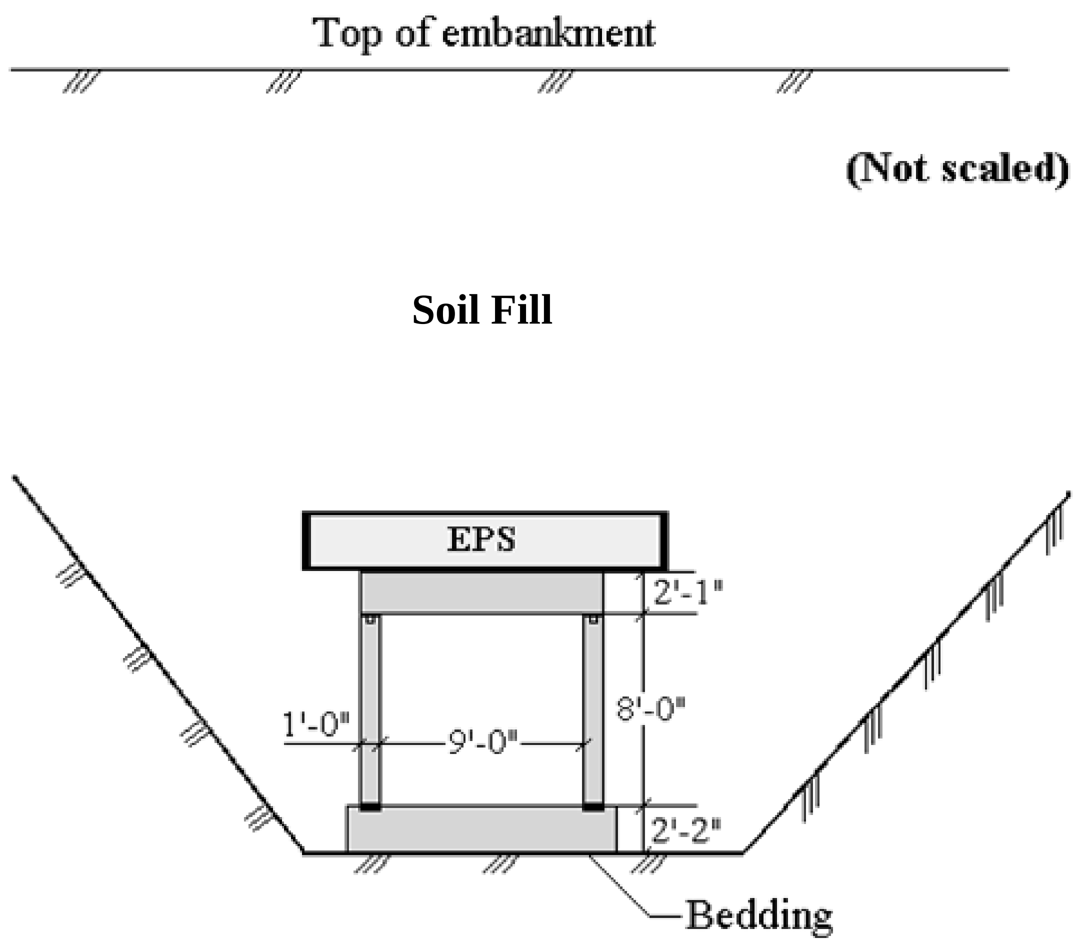

Figure 5. 1.5 times culvert width geofoam

The properties of materials (except for geofoam and soil data collected from job site) used in the analyses were based on data shown in the report by the Commonwealth of Kentucky Transportation Cabinet, Department of Highways, Division of Bridge Design. They represent typical values used in design practice.

The backfill soil was modeled as a cohesionless material using FLAC plastic constitutive model that corresponds to a Mohr-Coulomb failure criterion.

Bedrock and concrete were modeled as linear-elastic materials. Considering model availability in FLAC, geofoam is also modeled as a linear-elastic material. In this imperfect ditch approach, this model will create more conservative results. The specific material properties used in the FLAC software are listed in Table 1.

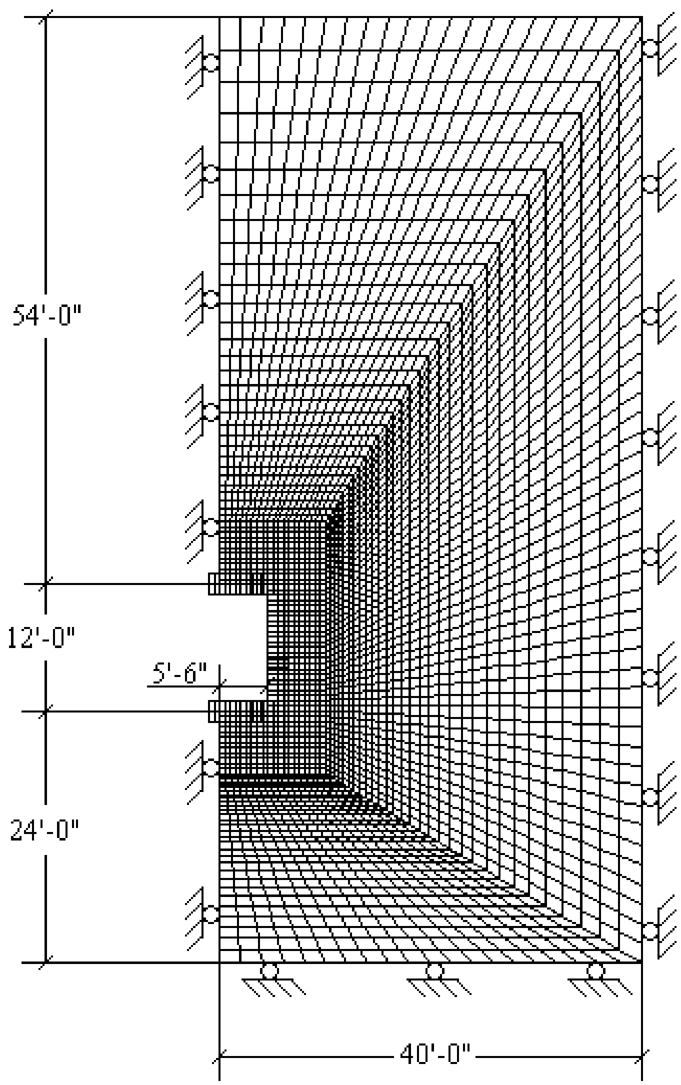

Figure 6. Model mesh

Calibration of the Numerical Model

Roughly described properties used in the job site backfill material yield some uncertain factors for numerical analysis. Varied sizes of geofoam makes the analyses more complicated. Based on original design conditions, the numerical model was calibrated by adjusting interface parameters between culvert and backfill, and trying different combinations of elastic modulus, Poisson's ratio, and the angle of internal friction of the backfill. The maximum pressure and maximum moment on top of the culvert obtained from numerical modeling are adjusted close to the numbers shown in the report by the Commonwealth of Kentucky Transportation Cabinet, Department of Highways, Division of Bridge Design (Figure 7).

Table 1. Material Properties

Material	Elastic Modulus E		Poisson's Ratio υ	Mass Density		Cohesion C		Friction Angle
	(psf)	(MPa)		(pcf)	(kg/m^3)	(psf)	(kPa)	ϕ
Concrete	5.43E+08	26000	0.35	156	2499			
EPS	1.33E+04	0.64	0.1	1.26	20			
Russell Clay	3.98E+05	19	0.25	123	1970	5.30E+02	25	26.2°
Shale Bedrock	2.32E+08	11100	0.29	169	2700	8.02E+05	38400	14.4°

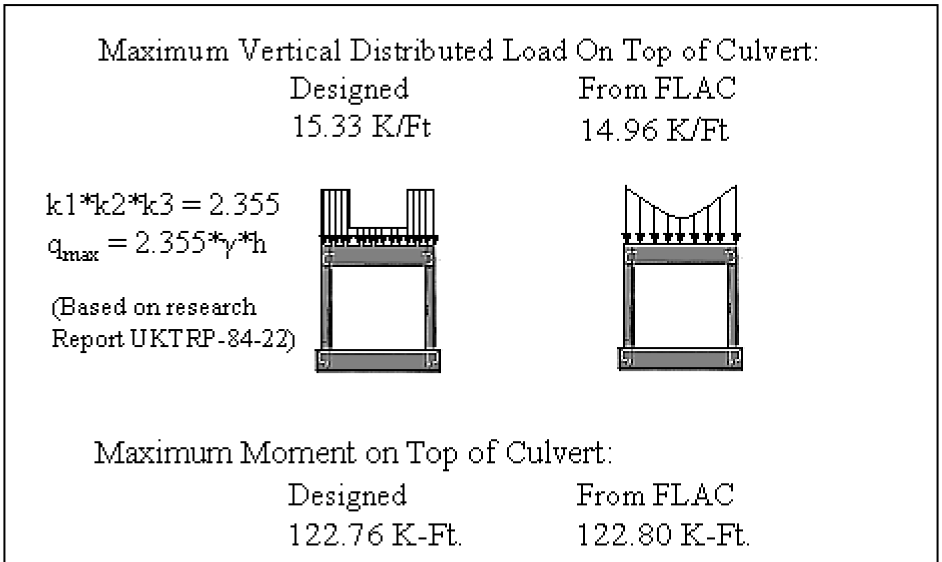

FIG. 7. Calibration of the numerical model

Analyses of Stresses on Culvert Using Different Sizes of geofoam

To investigate the effects on the earth pressure in a backfill using the imperfect ditch method, geofoam is placed above the culvert directly. Two sets of parametric studies were used to investigate stress distributions with different combinations of elastic modulus, Poisson's ratio, cohesion, and friction angle for backfill under two different sizes of geofoam (Figures 4 and 5). Typical results, corresponding to design loads and in-situ data, are shown in Figures 8 through 10.

The numerical results show that the maximum pressure at the top of culvert, with geofoam width 1.5 times the culvert width, is reduced to 3.01 kips/ft, which is 20.1 percent of the maximum pressure without geofoam. When width of geofoam equals the width of culvert, the maximum pressure at the top of culvert is reduced to 2.79 kips/ft, which is 18.7 percent of the

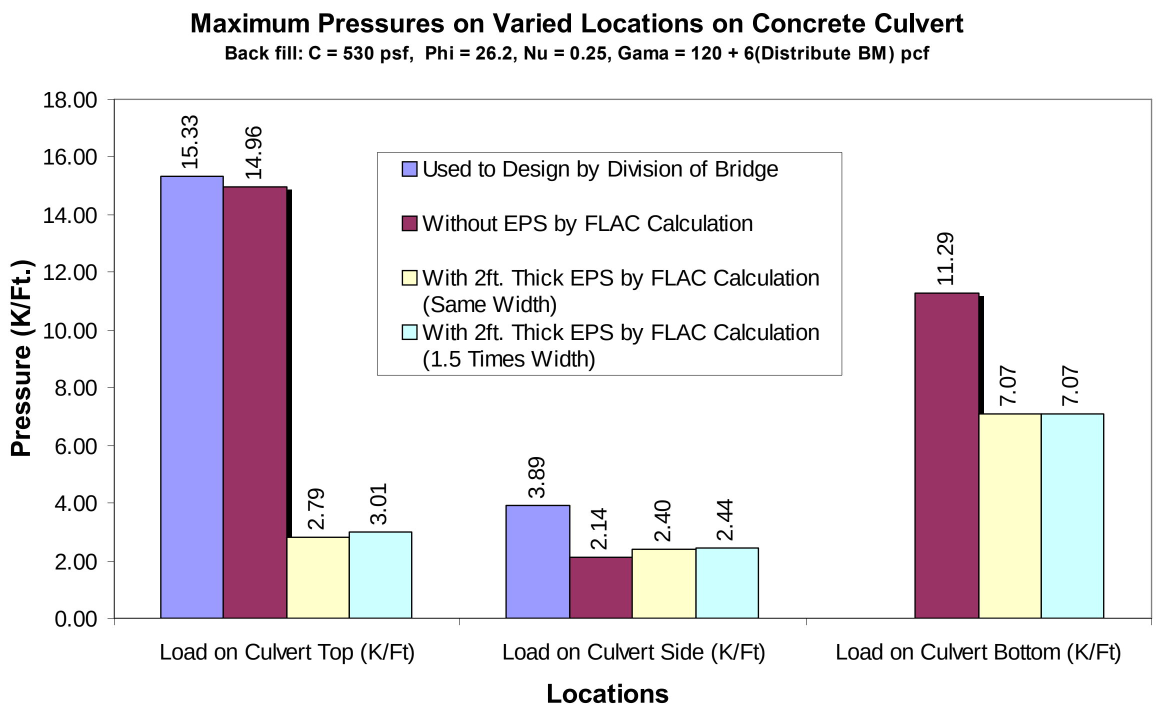

FIGURE 8. Prediction of maximum pressures on culvert with and without geofoam

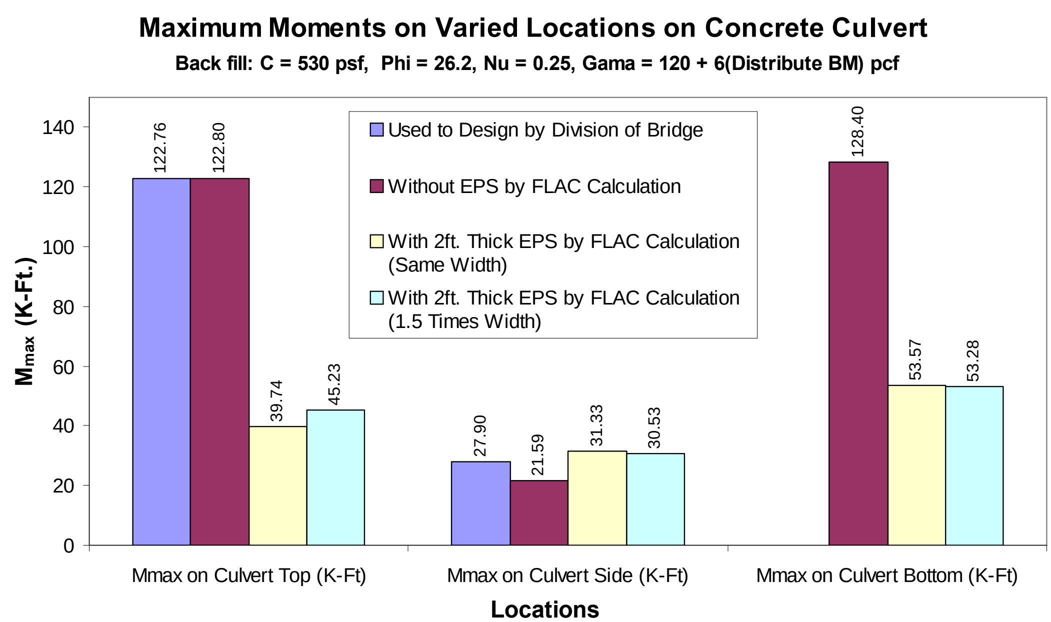

FIGURE 9. Prediction of maximum moments on culvert with and without geofoam

maximum pressure without geofoam (Figure 8). The maximum moment on the top of culvert is decreased to 39.7 kip-ft/ft, which is 32.4 percent of the maximum moment without geofoam

(Figure 9). The interesting point is that the maximum moment is smaller when geofoam width is the same as the culvert width (Figure 9). This fact supports that narrower ditch creates a larger arching effect.

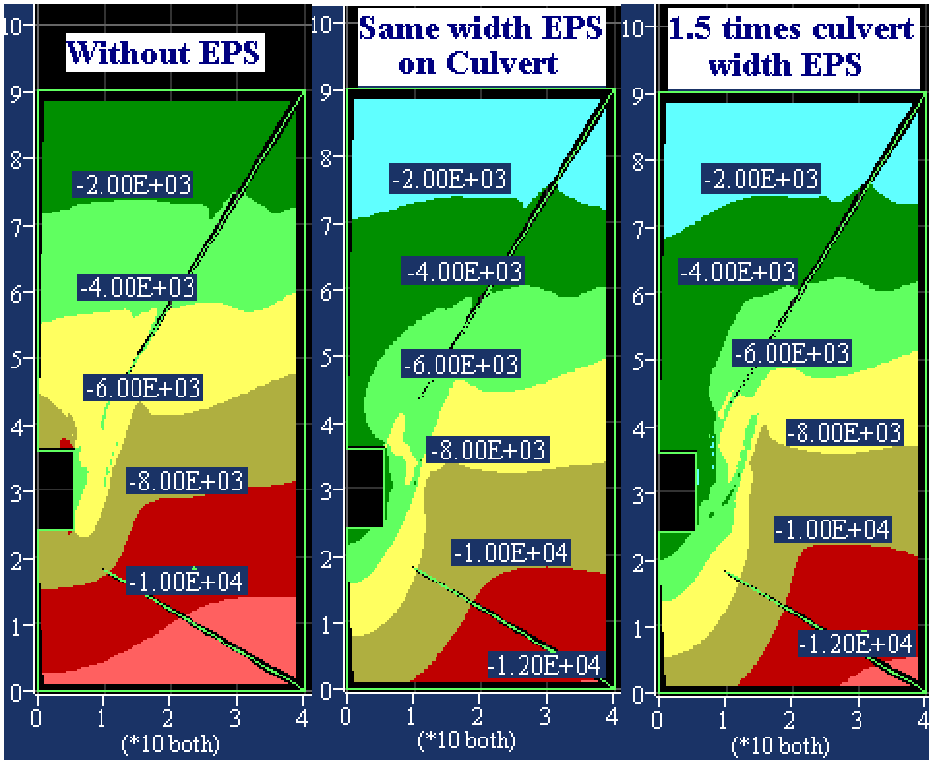

FIGURE 10. Contours of maximum principal stress with and without EPS on the top of culvert (psf)

The maximum pressure at the bottom of culvert is reduced to 7.1 kips/ft, when the geofoam width is either 1.5 times or equal to the culvert width, which is 62.6 percent of the pressure without geofoam (Figure 8). The maximum moment on the bottom of culvert is decreased to 53.57 kip-ft/ft, when width of geofoam equals width of culvert, which is 41.8 percent of the maximum moment without geofoam (Figure 9).

The maximum pressure on the sidewall of culvert is increased to 2.40 kips/ft, which is 12.1 percent more than the pressure without geofoam, when geofoam width equals culvert width. In the situation where width of geofoam is 1.5 times the width of culvert, the maximum pressure on the sidewall of culvert is increased to 2.44 kips/ft, which is 14.1 percent more than the maximum pressure without geofoam (Figure 8). But, comparing with the design load used by the Kentucky Transportation Cabinet, those values are still 38.4 percent (for the same geofoam width as culvert width) and 37.3 percent (for the geofoam width being 1.5 times the culvert width) lower than design load, respectively. The maximum moment on the sidewall of the culvert was a 41.4

percent more when the widths of geofoam and the culvert are the same. That value is 9.4 percent higher than the design value used by the Kentucky Transportation Cabinet (Figure 9).

The stress reduction is also observed from contours of maximum principal stress as shown in Figure 10. Comparing stress contours between with and without geofoam, the lower stress zone is extended to culvert top, side, and bottom for the situations with geofoam. The wider the geofoam, the deeper the lower stress area is projected in this specific case.

INSTRUMENTATION

Instrumentation includes strain gages, pressure cells, and inverted settlement plates. Three sections were chosen to install these gages (Figure 11). Among three sections, different sizes of geofoam were placed at two sections of the culvert. Wider geofoam (1.5 times of culvert width) was placed on top of segment A. Narrow geofoam (Same width as culvert width) was placed on top of segment B. The third segment (Segment C) was used as reference segment. The positions (Figure 12) to be installed strain gages and pressure cells were decided by theoretical analysis and numerical calculation. Two inverted settlement plates were installed on segments A and B to measure geofoam deformation.

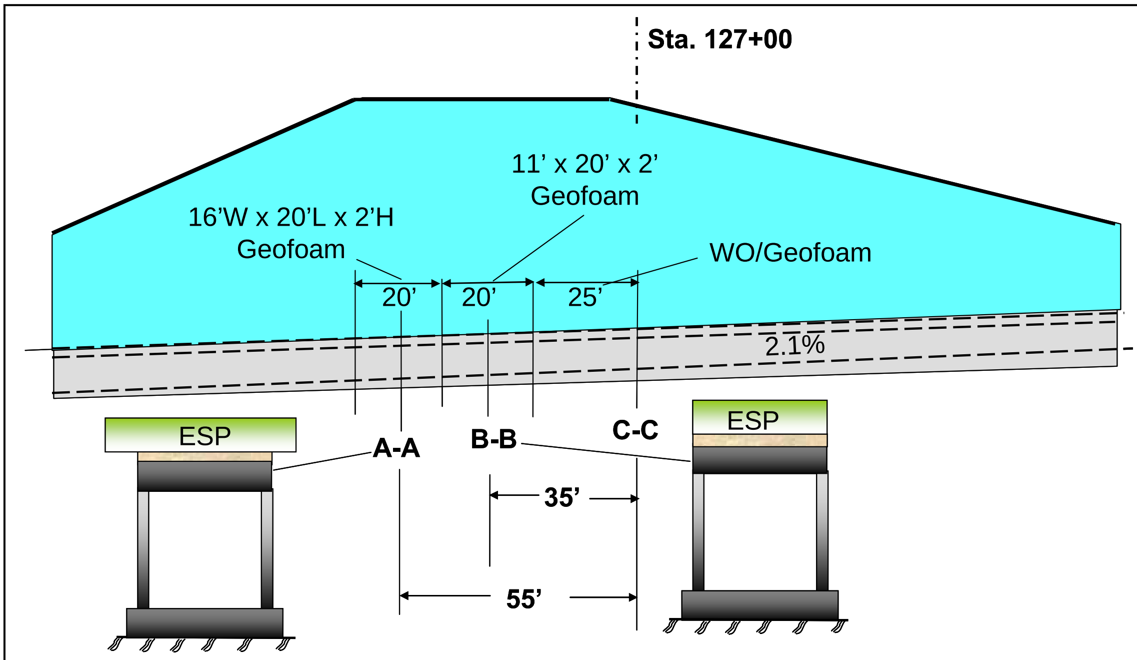

Figure 11. Three instrumented sections.

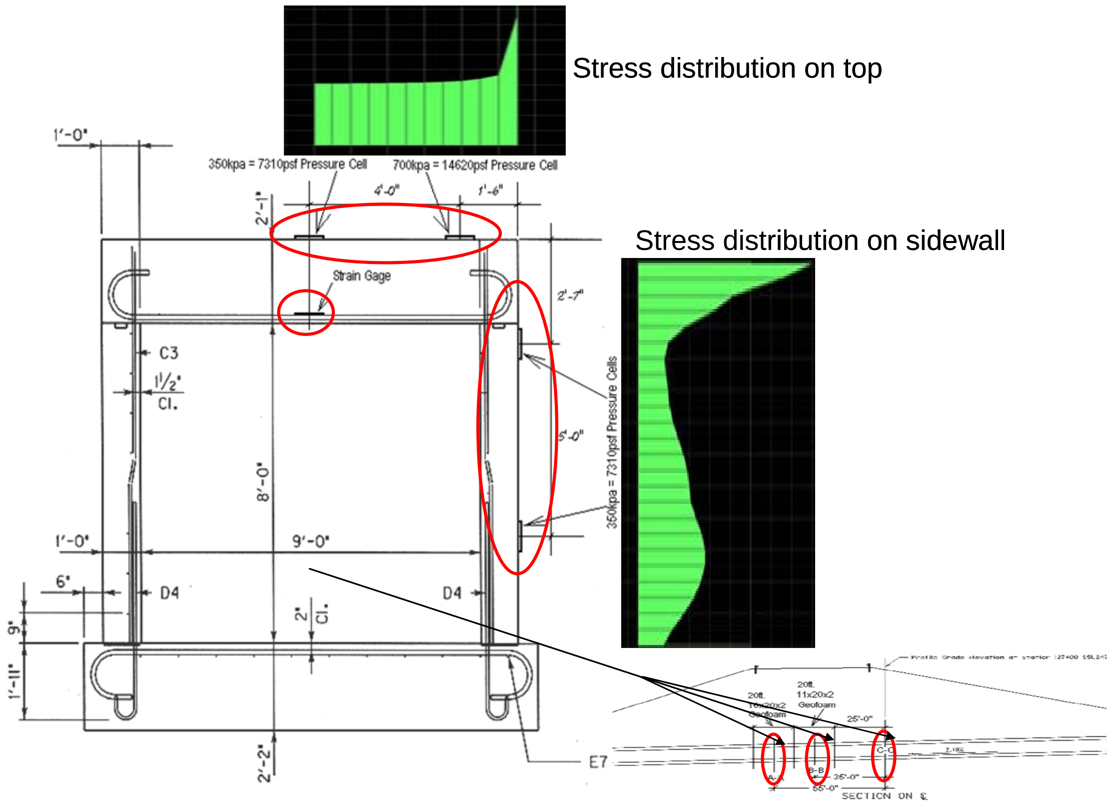

Figure 12. Positioning pressure cells and strain gage.

Strain Gage Installations

Strain gages were mounted on reinforced bars (Figure 13). They were calibrated and certified by manufacture. Three reinforced bars with strain gages were embedded to the bottom of culvert top slab (Figures 12 and 14). The strain gage wire was laid through the top of the culvert slab (Figure 15), protected by PVC conduit, and grouped to a switch box on a wing wall at the culvert outlet (Figure 16). The strain readout unit was GK-403 by Geokon.

Pressure Cell Installations

On each section (Total three sections), two pressure cells (Figure 17) were installed on top slab and sidewall respectively (Figure 12). Total twelve (12) pressure cells were installed on this culvert. Four bolts were used to fix each pressure cell on top slab and sidewall (Figure 18). The electric cable was protected by PVC conduit (Figure 19), collected to bottom of culvert (Figure 20), and grouped to switch box on wing wall at the culvert outlet (Figure 16). The pressure readout unit was also GK-403 by Geokon.

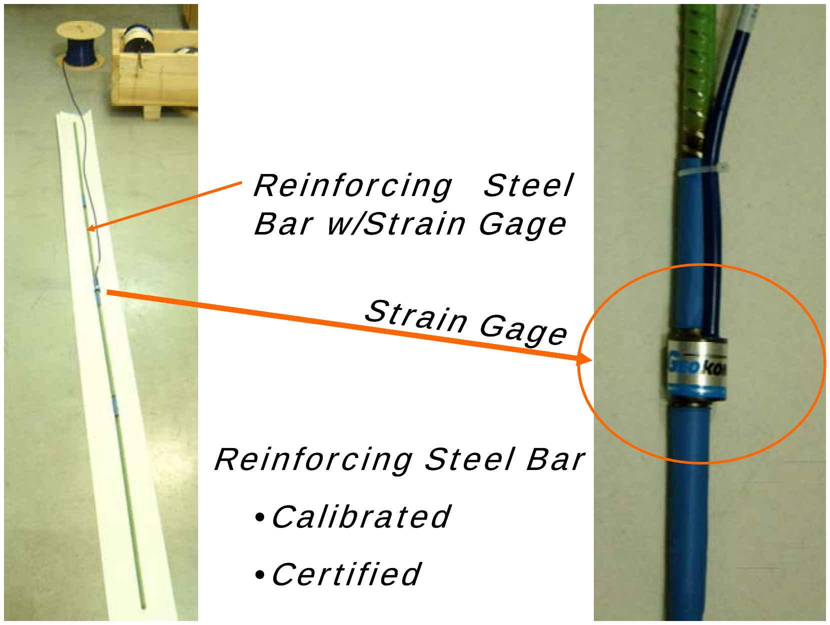

Figure 13. Strain gage is mounted on reinforced bar.

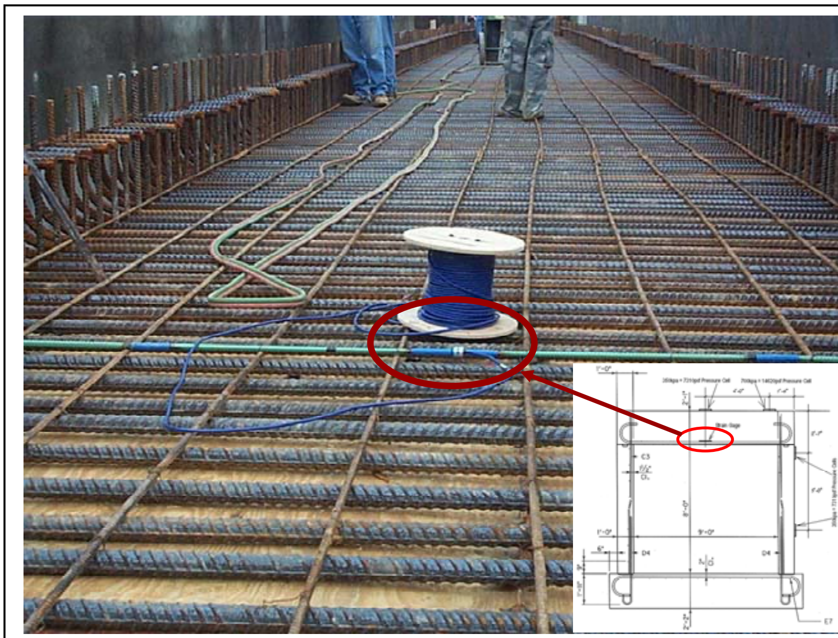

Figure 14. Strain gage position on top slab.

Figure 15. Strain gage wiring.

Figure 16. Grouped wires and reading station

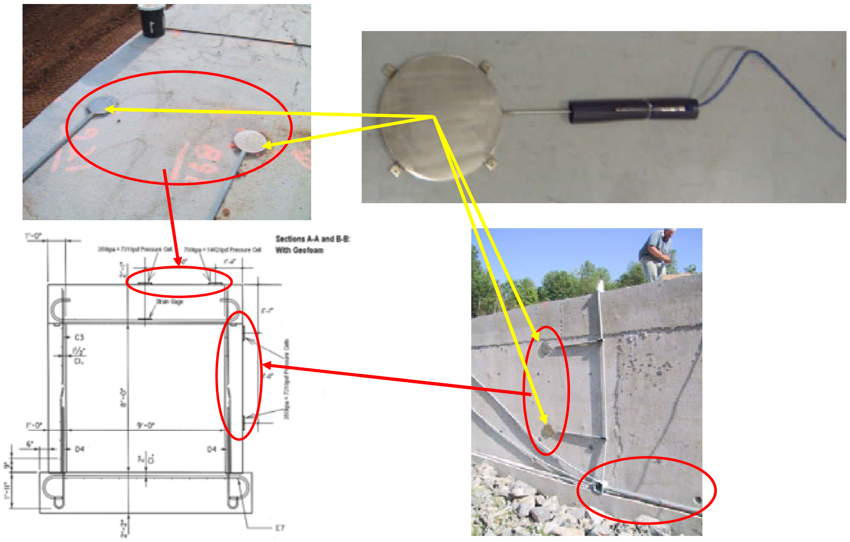

Figure 17. Pressure cells installation.

Figure 18. Pressure cells installation detail.

Figure 19. PVC conduits protect electric cables.

Figure 20. Wires are protected and guided to culvert bottom.

Geofoam Installation

Geofoam is an ultra lightweight material. The density of geofoam used in the Jamestown project was 1.35 pounds per cubic foot only. A block sized at 2 feet thick, 4 feet wide, and 16 feet long was carried by two men easily (Figure 21). The geofoam is laid on one (1) foot thick sand (Figure 22), which helped geofoam to have uniform contact between geofoam and top slab of culvert. Two different sizes of geofoam were installed on top of culvert to study width effect on stress reduction. The center line of wider segment, 16-ft x 20-ft x 2-ft was at 55-ft apart from culvert center; the center line of narrow segment, 11-ft x 20-ft x 2-ft was at 35-ft apart from culvert center (Figures 11 and 23).

Figure 21. Geofoam easy installation.

Figure 22. The geofoam is laid on one foot thick sand.

Figure 23. Geofoam on position.

Inverted Settlement Platform Installations

Two inverted settlement platforms (Figure 24) were last installed on two sections with geofoam (Figure 25). The 3-ft x 3-ft x ½-in steel plates with 5-ft steel rod were placed at the top of geofoam in order that settlement on the geofoam could be measured from inside the culvert (Figure 26).

Figure 24. Inverted settlement platform.

Field Sampling and Testing

Thin-walled tube samples and bag samples of soil and backfill materials around the buried structure were obtained during construction (Figure 27). Liquid and plastic limits, gradation, specific gravity, moisture-density, unconsolidated-undrained and consolidated-undrained triaxial tests with pore pressure measurements, and consolidation were performed on collected samples and backfill materials. Actual soil properties are were used to correct parameters utilized in previous numerical models.

Figure 25. Two inverted settlement platforms are installed on geofoam.

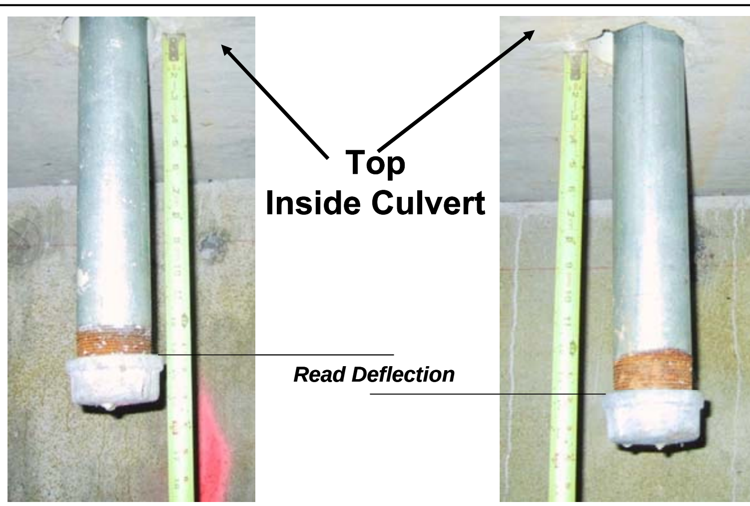

Figure 26. Settlement reading inside culvert.

Figure 27. Field Sampling.

DATA PRESENTATION AND DISCUSSION

Strain datum readings were started on October 14, 2004, when three strain gages were laid on bottom of top slab. Readings of earth pressure on culvert top slab and sidewall and settlement for geofoam were started on May 19, 2005, when all twelve (12) pressure cells and two (2) inverted settlement platforms were installed. Since then, weekly or bi-weekly datum collection has continued based on the rate of embankment construction.

Strains on Bottom Ceiling of Culvert

Datum collection from strain gages were started after the concrete was poured and before forms were removed. Figure 28 shows all strain data collected from three strain gages on sections A, B, and C respectively. Strains were set up relative to zero at around 200 days when the contractor was ready to start filling on the top of culvert. Before that point, strain waves were observed. Those waves recorded strain changes after concrete forms were removed. Figure 29 shows strain changes as fill height increases. Strains on all three sections A, B, and C increased similarly before the fill height reached 10 feet. Strain on section C, which worked as

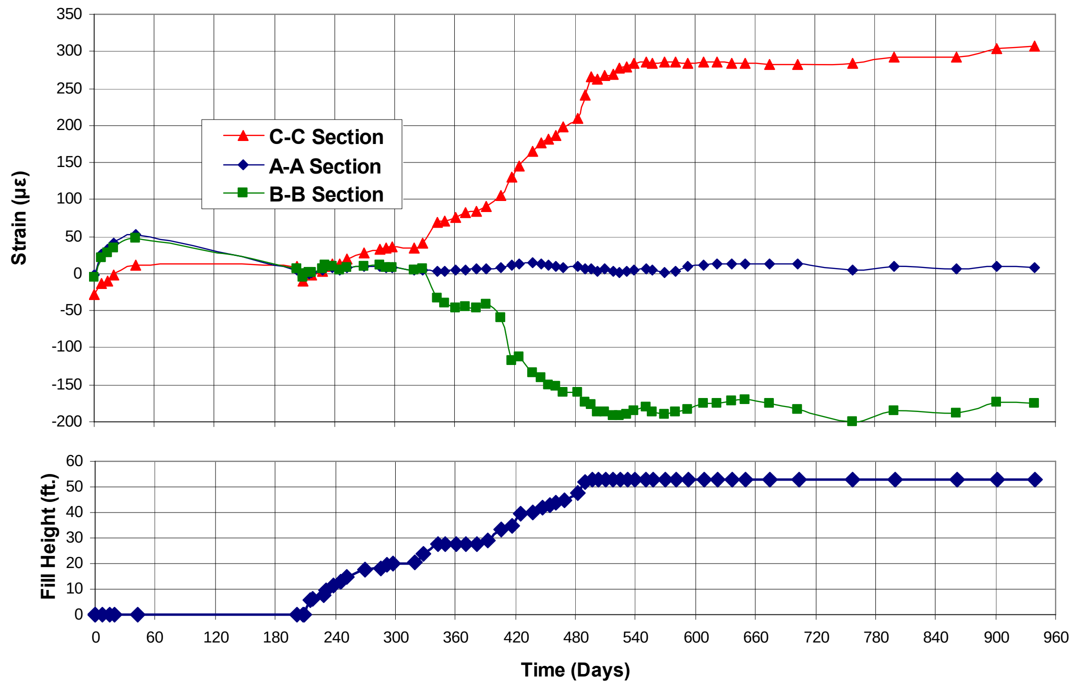

Figure 28. Strains on Top Slab of Culvert.

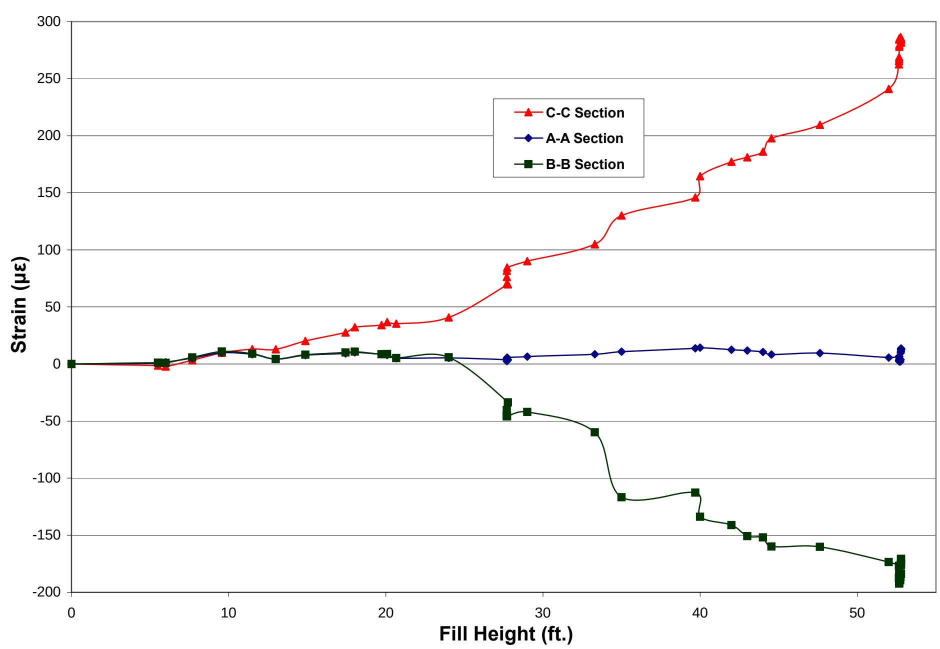

Figure 29. Strain on Top Slab of Culvert vs. Fill Height.

reference section without geofoam, diverged from strain measurements from the other two gages and kept increasing after the fill height reached 10 feet. The final reading for that strain reached 306.40 με, which is 41.76 times higher than strain on section A (7.34 με). Strain on section A slightly varied between 2.19 and 13.52 με. That reached 7.34 με as the date of this report. Geofoam, measuring 1.5 times of the width of the culvert, was placed on this section. It is shown later that there was a large difference in recorded strains at sections with and without geofoam. Strain on section B reached compressive strain, -175.25 με. Because of the arching effect, the possibility existed at Section B where geofoam was used that strains reached a compressive state. Strain on section C, which did not contain geofoam on top of the culvert, still increases even after 450 days after completion of embankment construction (Figure 28). Whereas strain on section A, where geofoam is placed on top of culvert, ceases increasing, even decreases in final reading (Figure 28).

Earth Pressures on Top Culvert and Sidewall

All twelve pressure cells worked properly. Stresses on pressure cells were initialized after they installation. Figure 30 shows earth pressures at different sections on top of the culvert.

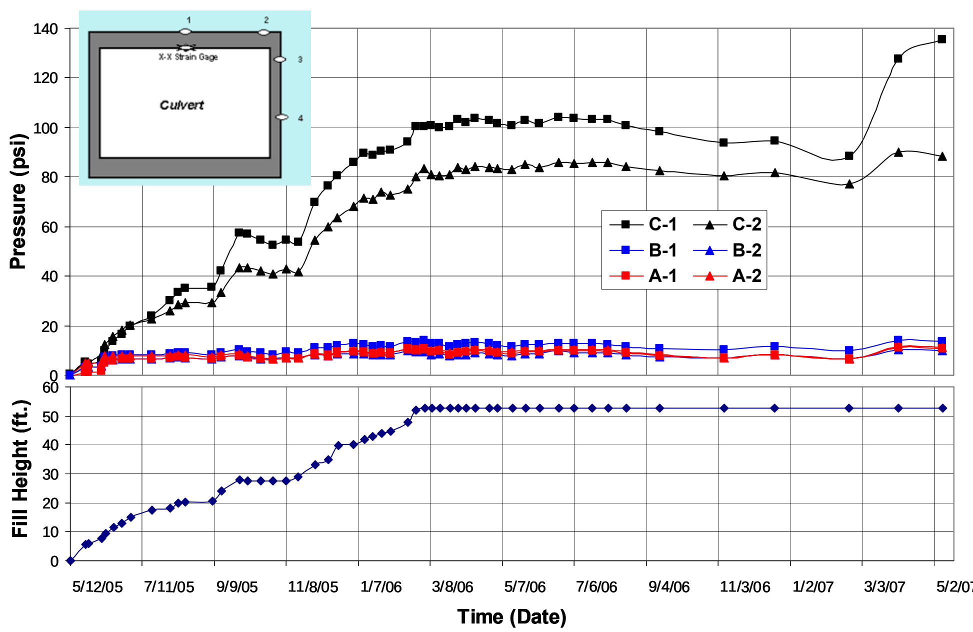

Figure 30. Pressures on top of culvert.

Stresses measured from all three sections increased in similar rates before the fill height reached 5 feet. That indicated only the self weight of the fill affected pressures on the top of the culvert. After the fill height reached 10 feet, pressure increases on three sections occurred at different rates. On section C, which worked as the reference section without geofoam above the culvert, the pressures increased continuously as fill height increased. Whereas on sections A and B, which contained the 2-foot thick geofoam material placed in a trench, pressures increased very slowly. Past 35-feet of fill height, the rate of pressure increase on top the culvert at section C declined, but still kept increasing with a much higher rate than ones observed on the sections A and B. Pressures on sections A and B were remained almost constant after the fill height reached

40 feet. Based on theoretical and numerical analyses, pressure on pressure cell C-2 was higher than pressure on cell C-1 since the point at the C-2 position was firmer than the point at the C-1 position. However, actually measured pressures were different than those obtained from those analyses. More detail investigation is needed for this situation.

In situ measured pressures on the top culvert shown in Figure 30 verified the fact that compressible geofoam had a considerable effect in reducing the pressure on top of the culvert. Pressures at points where geofoam was placed reached a much lower pressure level when compared to the pressures measured on the culvert points where geofoam had not been used. They were about 15 percent of the pressures at the points where no geofoam was used. That was a significant reduction.

Pressures on the outside sidewall of the culvert are shown in Figure 31. Similar trends in sidewall pressures at both sections with and without geofoam on top of the culvert were observed. They were at the same level as current pressure readings. Pressure on one point of section A was slightly higher than pressures on other points. Little differences in sidewall pressures between points on the sections with and without geofoam on the top of culvert were observed.

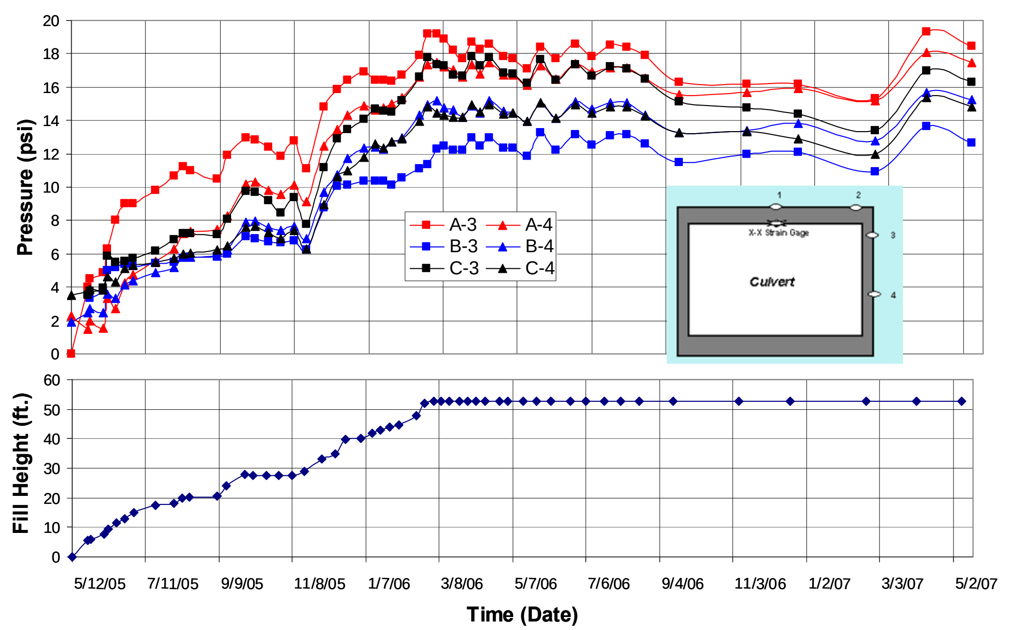

Figure 31. Pressures on sidewall of culvert.

Figure 32 shows pressures acting on the top and sidewall of the culvert at section C. Pressures on top the culvert are much higher than ones on the sidewall. The horizontal pressure—the average pressure from two pressure cells –acting on the sidewall is only 0.176 times the lower pressure measured on the top of the culvert. In contrast, at section B, the pressures acting on the top and sidewall of the culvert are near the same level and range from about 10 to 16 psi (Figure 33). On section A, pressures acting on the sidewall are obviously higher than ones acting on the top of the culvert (Figure 34). The difference in their average values is about 7 psi. Obviously, geofoam created positive arching at both sections A and B and caused a tremendous reduction in pressures acting on the top of the culvert at those two sections.

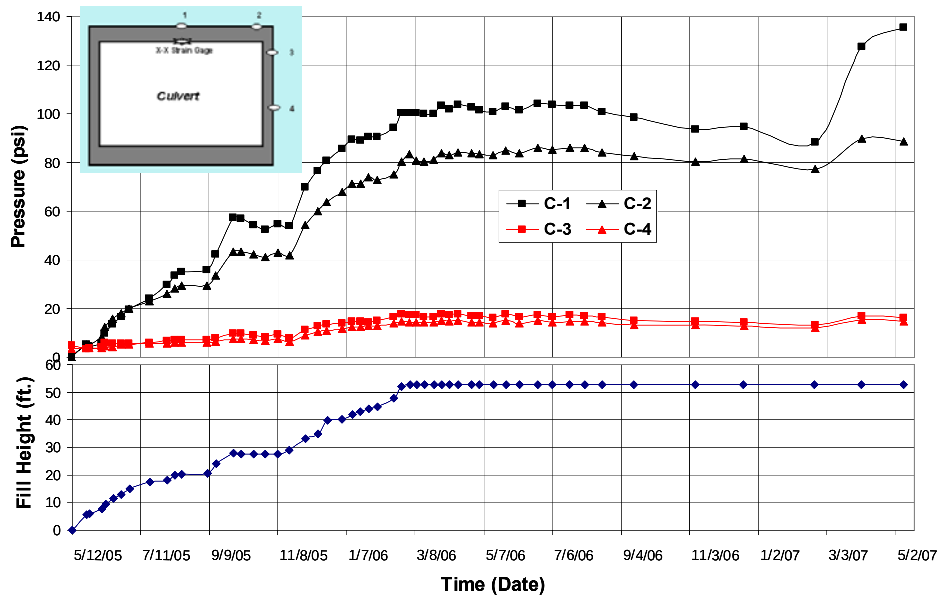

Figure 32. Pressures of top culvert and sidewall on section C.

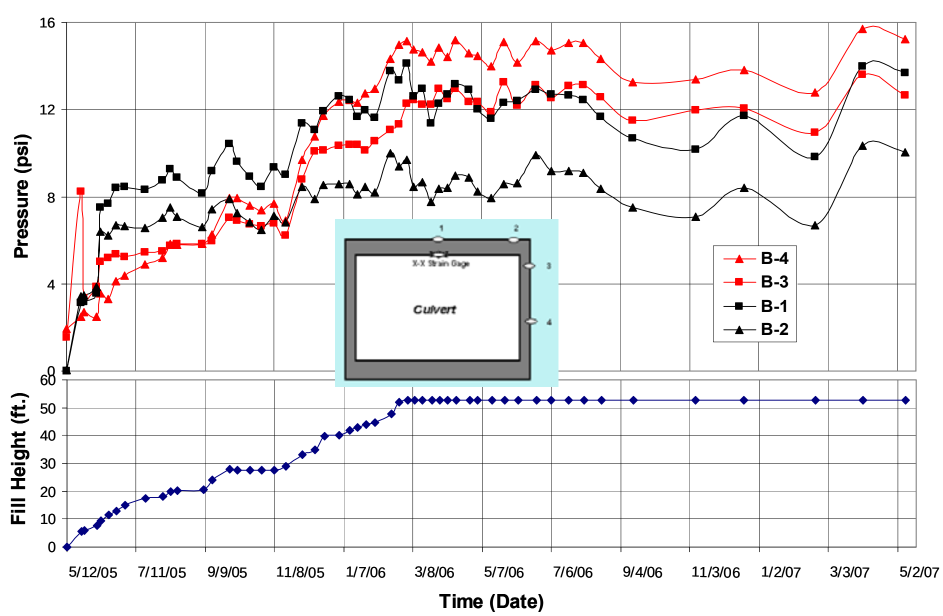

Figure 33. Pressures of top culvert and sidewall on section B.

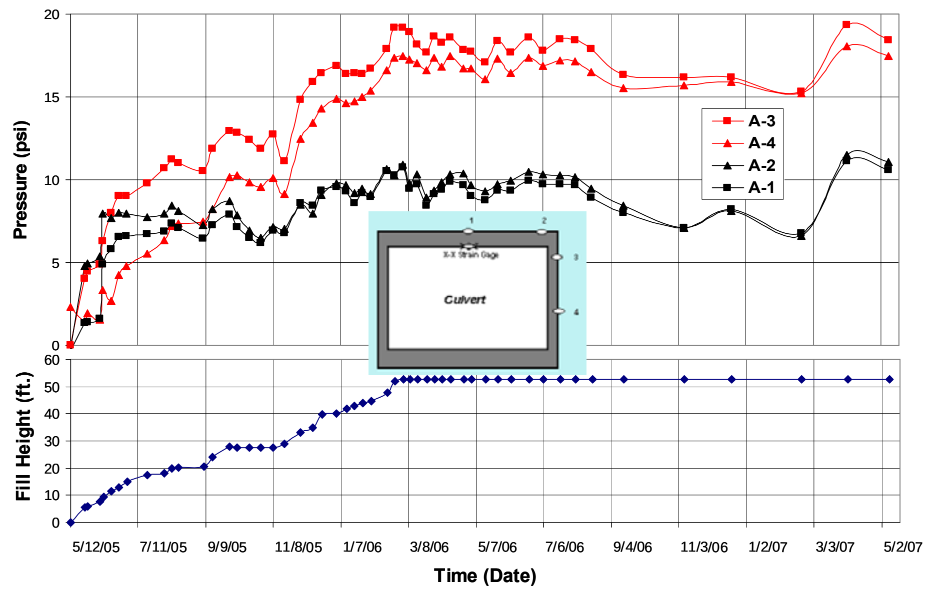

Figure 34. Pressures of top culvert and sidewall on section A.

Geofoam Settlement

Geofoam settlement data obtained from two inverted settlement platforms are shown in Figure 35. Settlements obtained from the two inverted settlement platforms are almost identical. The maximum settlement observed to date on section A reached 13.63 inches. Ignoring any small deformation of the sand, the deformation of the geofoam is about 57 percent of its original thickness of two feet. The deformations of both geofoam sections continue at much reduced rates. Long-term monitoring of the settlements will be very valuable in observing the behavior of the geofoam in this type of geofoam application.

Stress and Strain Relationship

Figure 36 shows the typical stress-strain curves versus time at section C, where geofoam was not installed. Strain increases as pressure increases on the top culvert since pressure on the sidewall is obviously smaller than pressure on the top of the culvert. Positive strain-- about 300 $\mu\varepsilon$--on the bottom ceiling slab prevails on this section. There is very small positive strain (about 8 $\mu\varepsilon$) on the bottom ceiling slab at section A (Figure 37). This strain fluctuates as pressure changes around this section. On the other hand, strain on section B (Figure 38) is very sensitive. As pressure on the sidewall starts jumping (see line ①–① in Figure 38), strain plunged to negative values on the bottom ceiling slab at section B. Since that point, the strain continues decreasing and reaches a negative value of 175 $\mu\varepsilon$. This indicates that compressive deformation occurs on the bottom ceiling slab at this section due to positive arching effect.

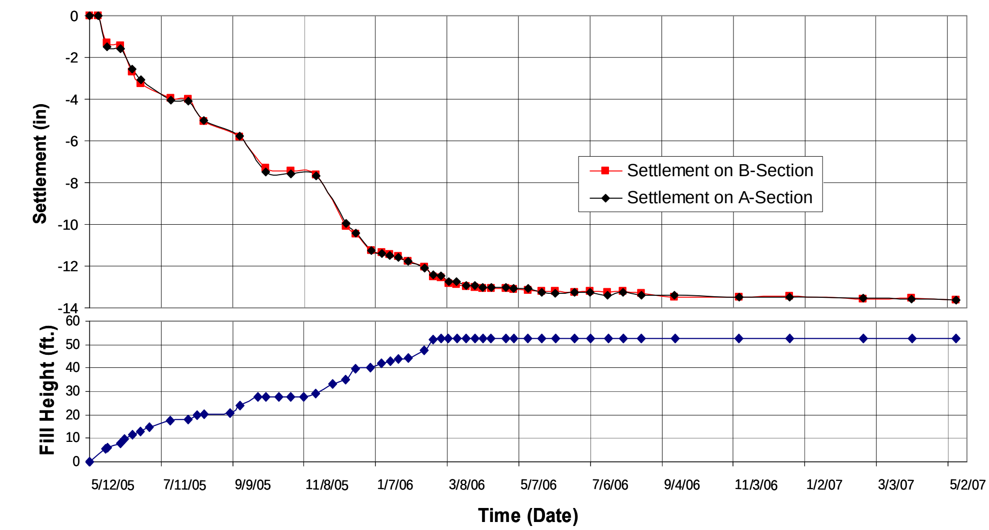

Figure 35. Geofoam settlements on sections A and B.

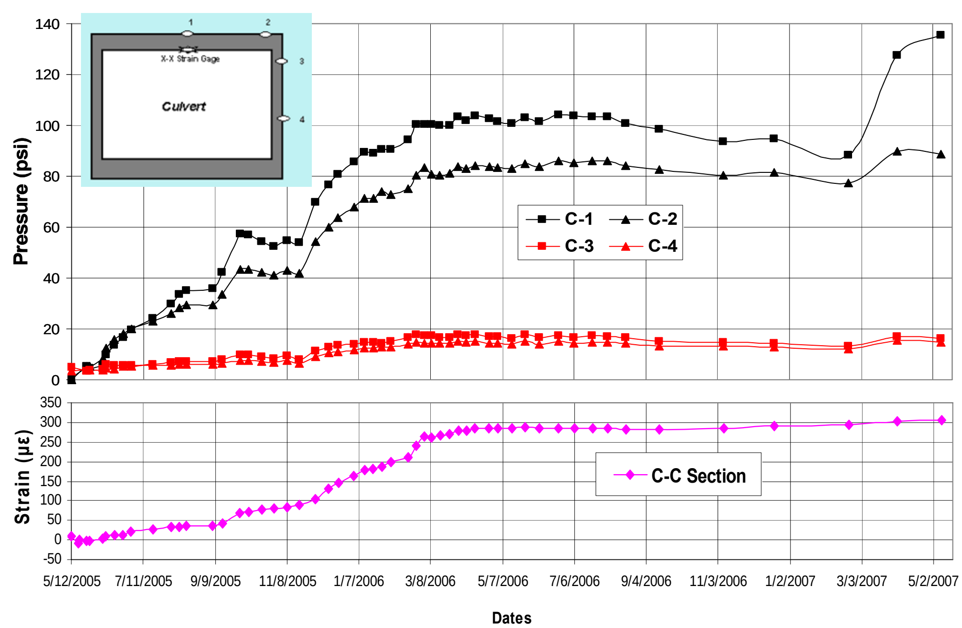

Figure 36. Stresses and strain varied on section C.

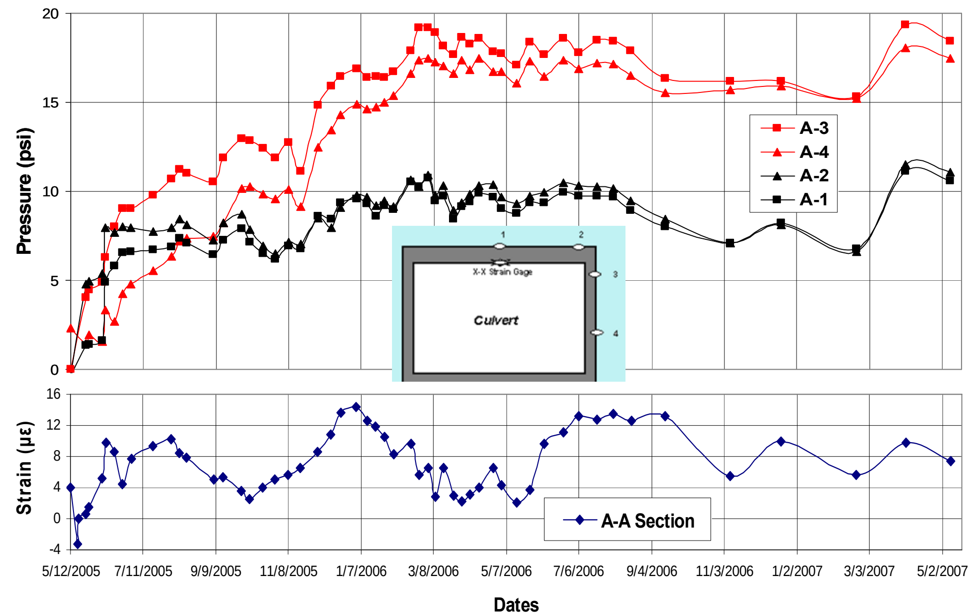

Figure 37. Stresses and strain varied on section A.

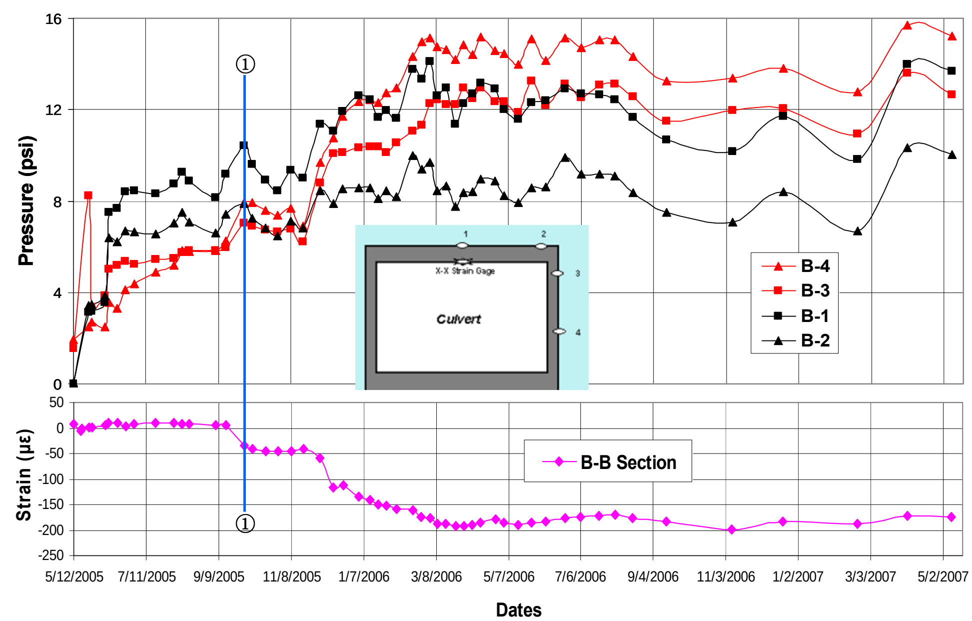

Figure 38. Stresses and strain varied on section B.

Stress on Culvert and Geofoam Settlement

As shown in Figure 39, curves of stress and geofoam settlement varied with time at section A. Although the pressure at the top of the culvert fluctuates, the rate of geofoam is decreasing with an increase in time. Pressure on top of the culvert reaches the first peak value of 10.6 psi and oscillates between 6.8 psi and 11.5 psi (see line ①–① in Figure 39). Geofoam settlement increases from 12.1 inches to 13.6 inches in the period of February 17, 2006 and May 9, 2007. The settlement rate has decreased to about 0.02 inch/month. At section B, the geofoam settlement and pressure fluctuation curves (as function of time) are very similar to those of section A, as shown in Figure 40.

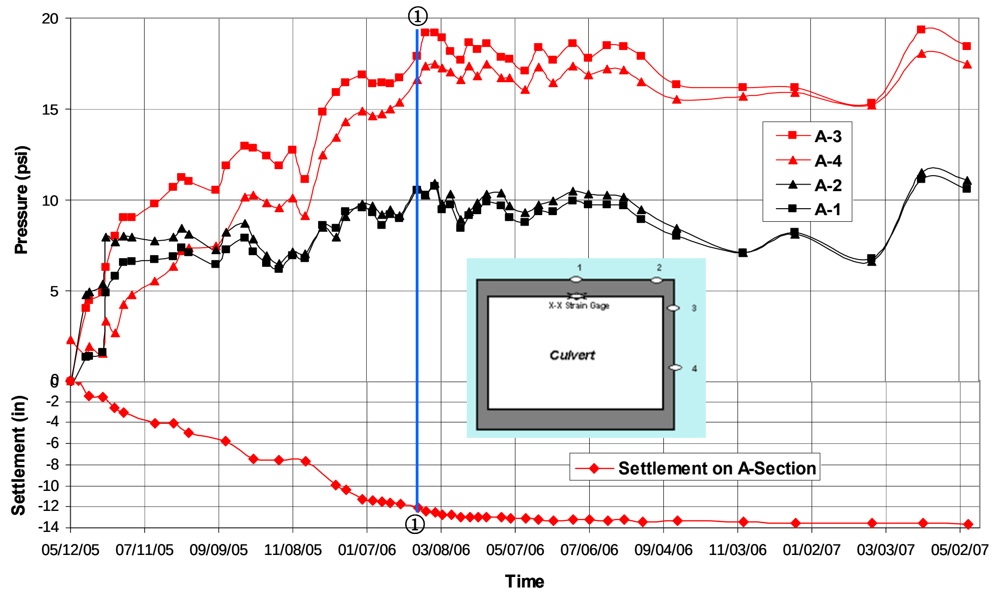

Figure 39. Trends of stresses and geofoam settlement on section A.

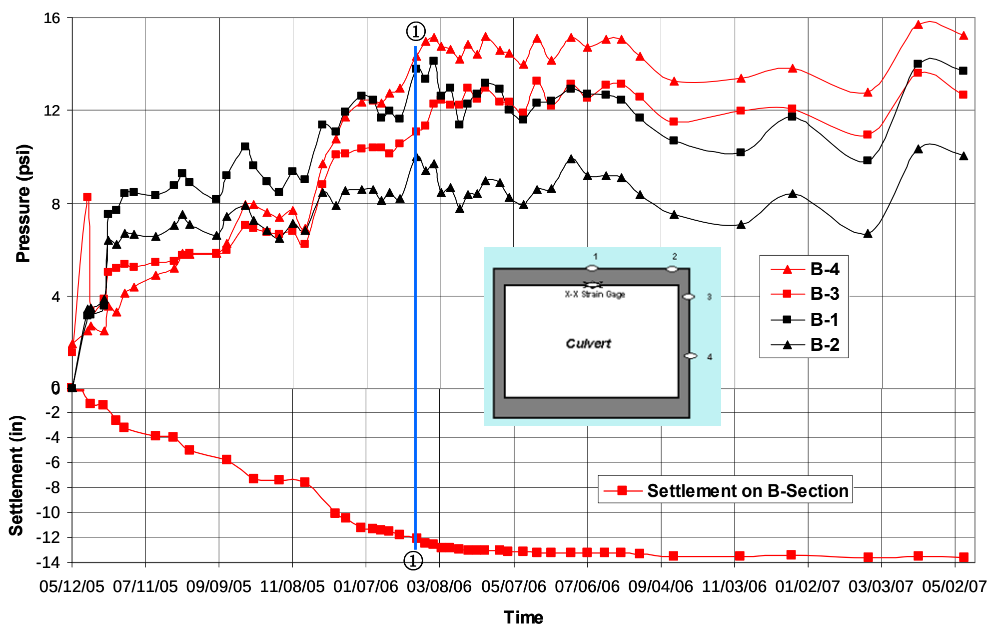

Figure 40. Trends of stresses and geofoam settlement on section B.

COMPARING DESIGNED, NUMERICAL, AND FIELD DATA

Pressure Comparison

As shown in Figure 41, measured pressures acting on top of the culvert are lower than pressures predicted from the numerical model. This was true for all the cases including with and without geofoam on top of the culvert and for different sizes of geofoam. At the section without geofoam, and using an average value of the final five readings (to date) from the two pressure cells located on top of culvert, the measured pressure was 13.79 K/Ft., which is 7.8 percent lower than the predicted value of 14.96 K/Ft. Measured pressure on top of the culvert, where the geofoam width was equal to the width of the culvert, was 53.7 percent of the pressure predicted from the numerical model. In others words, the in-situ pressure that was reduced by using geofoam is larger than the value predicted by the numerical model. From a numerical modeling viewpoint, it is conservative. The main reasons that caused this are, as following:

1. Geofoam is an elasto-plastic material. Instead of using elasto-plastic model in the FLAC calculation, the elastic model with a low value of Young's modulus was used for geofoam.

2. In actuality, the problem is 3-dimensional. The arching effect should be obtained from both directions. In the numerical model, a plain strain model was assumed in the current research. It only accounts for one directional arching effect. Using a 3-dimensional numerical model will yield results that are closer to measured values than those predicted from a 2-dimensional model.

At the section where the width of the geofoam was 1.5 times the width of the culvert, the measured pressure, 1.27 K/Ft., at the top of the of the culvert was lower than the pressure where the width of the geofoam was equal to the width of the culvert. Also, the in-situ measured pressure on top of the culvert is lower than the pressure predicted by the numerical model. For future application, if geofoam is used in a similar situation, a pressure as low as 20 percent of the traditional design load could be used for the design of the top slab.

Pressures predicted from the numerical model and measured in-situ pressures acting on the sidewalls at sections without geofoam and with the wider geofoam layer are nearer the same value (see Figure 41). At the section without geofoam, the measured pressure is 2.08 K/Ft., which is 97.2 percent of the predicted value of 2.14 K/Ft. At the section with the wider geofoam layer, the measured pressure is 2.42 K/Ft., which is 99.2 percent of the predicted value of 2.44 K/Ft. This is even closer than pressures on the section without geofoam. Measured pressure on the section with smaller width of geofoam is 1.90 K/Ft., which is 79.2 percent of the predicted value of 2.40 K/Ft. All of the predicted and in-situ measured values are lower than the design load of 3.89 K/Ft., which was the value used by the Commonwealth of Kentucky Transportation Cabinet, Department of Highways, Division of Bridge Design.

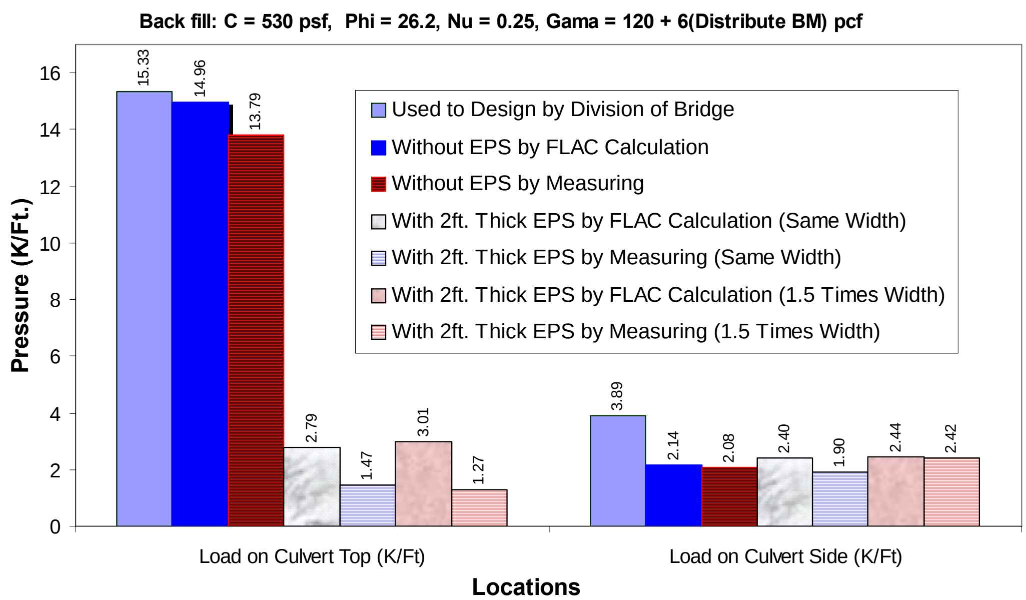

Figure 41. Maximum pressure comparison among designed, predicted, and measured data (use average final five readings as measured data).

Moment Comparison

Assuming that the measured pressures on the top and sidewall of the culvert act as uniform distributed loads on the top of the culvert and sidewall, respectively, maximum moments on the top slab and sidewall may be calculated roughly. Those moments, grouped with designed and predicted moments, are shown in Figure 42. At the section without geofoam, the maximum moment is larger than the designed and predicted moments since load distribution, which is shown in Figure 7, is not considered.

Predicted maximum moments at sections at the geofoam sections are higher than maximum moments calculated from measured pressures. This is true for moments on the top of the culvert and sidewall. For maximum moments on the sidewall, predicted maximum moments at sections containing the geofoam are larger than the maximum moment at the section without geofoam. However, the calculated maximum moments using measured pressures are still lower than maximum moments used in design. For the worst case, where the wider layer of geofoam was used on top of the culvert, the maximum moment on the sidewall is 69.3 percent of the design moment of 27.90 K-Ft. Considering both actual pressure and design moment on the sidewall, the load used in designing the side wall is still safer even when geofoam was used on top of the culvert.

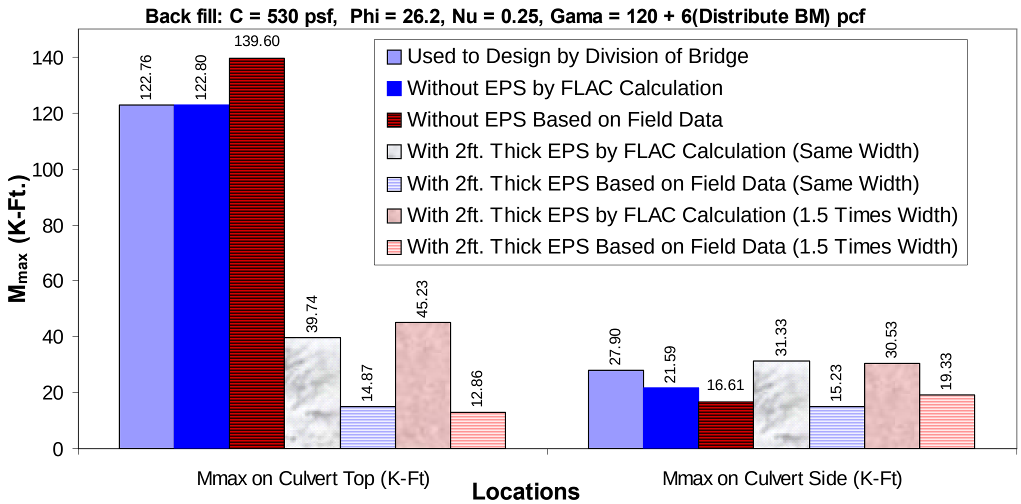

Figure 42. Maximum moment comparison among designed, predicted, and calculated by measured data.

CONCLUSIONS AND DISCUSSION

Strong evidence obtained from both numerical model (FLAC 4.0) analysis and in-situ test data indicates that geofoam is an ideal elasto-plastic material for reducing vertical loads on top of a rigid culvert resting on an unyielding foundation. In the numerical model analysis, the "calibrated" model helps to obtain more reasonable and closer results to in-situ data. Data from three instrumented sections constructed with and without geofoam, and with different sizes of geofoam, provide first hand information to support the use of numerical model analysis.

Results from both numerical analysis and in-situ data show that geofoam has a great effect in reducing the vertical soil pressures above a culvert. The load on the top of culvert can be reduced to 20 percent of traditional design load after two (2) feet thick geofoam is placed on top of the culvert. Results from numerical model are more conservative when compared to actual test data obtained from field measurements.

Recorded geofoam settlements show how the effect of positive arching can be created by large geofoam deformation, which is much greater than deformations of adjacent soil columns. Geofoam deformations observed to date measured about 57 percent of its original height. Stresses on the top of culvert where geofoam was placed have reached a relatively stable level which is expected at the yield point of the geofoam. This technology can be used in an application that requires controlled pressure on a rigid underground structure.

Whether geofoam is used or not used, the model analysis and test data show that the earth pressure acting on the sidewall does not change significantly. Although the pressure acting on the sidewall is slightly higher when geofoam is used on top of the culvert only, the value is still below the design value used by the Kentucky Transportation Cabinet.

A linear-elastic model was used to simulate the geofoam stress-strain behavior in this numerical analysis. As noted earlier, geofoam exhibits desirable elasto-plastic behavior during compression (Figure 2). Geofoam creates a larger deformation (than many other of types of compressive materials), which results in a bigger positive arching effect under elasto-plastic model when stress on geofoam is beyond elastic range. This positive arching effect will reduce pressure on the top of the culvert even more. In-situ test data provides strong evidence supporting this analysis.

RECOMMENDATIONS

Geofoam deformations are occurring at a very low decreasing rate. Key questions are: When and will these deformations stop? If the geofoam deformations continue in the future, then what effect will the deformations have on the vertical and sidewall pressures acting on the culvert? Will creep occur along the shear zones along the column of soil located directly above the rigid culvert? To answer these important questions, it is recommended that long-term monitoring of all instrumentation at this site continue for several years. This includes the inverted settlement platforms which will provide deformation measurements of the geofoam, strain gages, and pressure cells. A vital and extremely important part of this research is to determine the long-term applicability of the imperfect trench method for reducing stresses on culverts.

From this study, it is obvious that the effect caused by positive arching creates a stress reduction on deep buried rigid structures on unyielding foundations. However, what are the effects on vertical pressures of “shallow” buried rigid structures when geofoam is used on these structures? What is clear line between deep and “shallow” buried structures? To date, only results from numerical model have been analyzed. Instrumentation of other sites, especially at sites where the fill cover may be shallow, is recommended to obtain the necessary in situ data to answer these questions.

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REFERENCES

Allen, D. and B. Meade. (1984) “Analysis of Loads and Settlements for Reinforced Concrete Culvert,” *Research Report*, UKTRP-84-22.

Handy, R. L., and G. Spangler. (1973) “Loads on Underground Conduits”, *Soil Engineering*, Third Edition, 1973.

Hoeg, K. (1968) “Stresses Against underground Structural Cylinders,” *Journal of the Soil Mechanics and foundation Division*, ASCE, Volume 94, No. SM4, 833 – 858.

Penman, A. D. M., J. A. Charles, J. K. Nash, and J. D. Humphreys. (1975) “Performance of Culvert Under Winscar Dam,” *Geotechnique*, Volume 25, No. 4, 713 - 730.

Spangler, M. G. (1958) “A Practical Application of the Imperfect Ditch Method of Construction,” *Proceedings of Highway Research Board*, Volume 37.

Sun, L., T. Hopkins and T. Beckham. (2005), “Stress Reduction by Ultra-Lightweight Geofoam for High Fill Culvert: Numerical Analysis,” *Geotechnical Applications for Transportation Infrastructure: Featuring the Marquette Interchange Project in Milwaukee, Wisconsin, Proceedings of the 13th Great Lake Geotechnical and Geoenvironmental Conference*, May 13, 2005, Milwaukee, Wisconsin.

Sun, L., T. Hopkins and T. Beckham. (2006) “Load Reduction by Geofoam for Culvert Extension: Numerical Analysis,” in *Geotechnical Engineering in the Information Technology Age. Proceedings of Geocongress 2006, Atlanta*, February-March 2006, CD Proceedings, ISBN 0-7844-0803-3, D. J. DeGroot, et al., Eds. Reston, Virginia: ASCE.

Vaslestad, J., T. H. Johansen and W. Holm. (1993) “Load Reduction on Rigid Culverts Beneath High Fills”. *Transportation Research Record*, 1415, 58 – 68.

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