Demonstration of a Physical Modeling Method to Simulate Expansive Soil Behavior

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ABSTRACT
A method to physically model the swelling pressure applied by expansive soils onto underground structures was developed to understand the soil-loading pattern and measure the effectiveness of soil expansion mitigation solutions. The test apparatus used an engineered material to simulate the fundamental one-dimensional expansive soil-loading curve obtained from standard oedometer swell testing. The engineered material was able to model the soil-structure interaction matching the soil pressure to structure rigidity. Mitigation techniques used in industry such as placing a deformable/frangible material between the soil and the structure could be tested in the same test apparatus with the results compared to the non-mitigated structure. The testing results showed the effects of modifying the structure design, the mitigation solution, or both. This physical modeling method can be used to optimize and structurally test geotechnical structures designed in expansive soil environments.

RÉSUMÉ
Une méthode pour modèle physique de la pression de gonflement appliquées par les sols gonflants sur les structures souterraines a été développé pour comprendre la structure du sol de chargement et de mesurer l'efficacité des solutions de sol expansion d'atténuation. L'appareillage d'essai utilisé un matériau conçu pour simuler les fondamentaux à une dimension courbe expansive sol obtenues lors des essais de chargement oedométrique houle standard. Le matériau d'ingénierie a été en mesure de modéliser l'interaction sol-structure correspondant à la pression du sol à la structure de rigidité. techniques de gestion utilisées dans l'industrie comme le placement d'un matériau déformable / rupture entre le sol et la structure pourrait être testé dans l'appareil de test avec les résultats par rapport à la structure non-atténuée. Les résultats des tests ont montré l'effet de modifier la conception de la structure, la solution d'atténuation, ou les deux. Cette méthode de modélisation physique peut être utilisée pour optimiser et tester structurellement structures géotechniques conçus dans des environnements sol expansif.

1 INTRODUCTION

Expansive soils can transmit destructive forces to engineered structures through their inherent ability to swell as moisture content increases. If not adequately designed, building foundations, retaining walls, tunnels, or utility vaults can fail when exposed to the swelling pressure developed by such soils.

Much time and effort has been spent over the last half century researching and testing the properties of expansive soils, both on the molecular level and macroscopic level (Curtis, 1971; Dhowian, 1990; Fredlund, 1983; Holtz et al, 1956; Yoshida et al, 1983; Nelson et al, 1992). Such analyzes have provided a framework for the design engineer to predict the swelling loads imparted on infrastructure in contact with expansive soil. However, there are few constitutive models within industry-accepted numerical simulation tools that adequately combine the swelling behavior of expansive soils with the structural response of engineered materials.

Modeling or simulating the interaction between the soil and structure is important in situations involving expansive soils. The pressure exerted by expansive soils decreases as the structure deforms or moves. Therefore, the final design pressure on the structure is highly dependent on the rigidity of the structure. In order to design an economic and efficient structure, engineers must be able to accurately predict or model the soil-structure interaction.

A method was developed by the authors to simulate the expected soil-structure interaction through physical testing. Such testing allows for 1) real-time soil-structure behavior (deflections and pressures), 2) timely results where years' worth of in-ground testing soil swelling can be simulated in a few hours, and 3) possible quality control/structure optimization based on testing to failure and modifying the structure based on its performance. By testing structures with different methods to mitigate the expansive soil loading, the authors were able to show the effects of mitigation method quantitatively.

2 BACKGROUND

An expansive soil is characterized by its ability to swell on a macroscopic level as it imbibes water within the range of the shrinkage limit and plastic limit of the soil. A high percentage of the montmorillonite clay, typically >50%, is needed to show macroscopic material deformations of the clay due to water content change. When the montmorillonite clay percentage is below 50%, the individual clay crystals may swell, but there is not enough material to cause noticeable volumetric changes.

Tests have been developed to quantify the swelling potential of a soil. ASTM D4546 Standard Test Method for One Dimensional Swell or Collapse of Cohesive Soil, commonly known as the oedometer test, is a standard test used to determine the vertical strain induced in a soil sample as it is allowed to take in free water. Multiple tests can be conducted at different overburden pressures to generate a curve relating vertical strain, ε_z, on the y-axis to overburden stress, σ_z, on the x-axis. Gysel (1987) found that the data from oedometer swell tests can be approximated by a straight line on a semi-log plot as shown in Figure 1. Equation [1] provides the expression for this line where σ is the one-dimensional stress, ε is the one-dimensional strain, σ_{sw} is the swell pressure, and ε_{fs} is the free swell strain. This approximation was the basis used by the authors to simulate the loading behavior of expansive soil on structures.

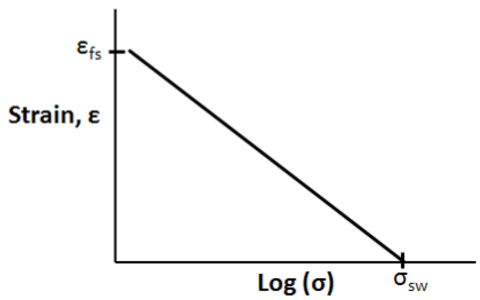

Figure 1. Vertical strain versus overburden stress

$$\varepsilon = \frac{-\varepsilon_{fs}}{Log(\sigma_{sw})} Log(\sigma) + \varepsilon_{fs} \qquad [1]$$

Many other factors in addition to vertical strain and overburden pressure must be taken into account when developing the design pressures in expansive soil. Factors such as initial moisture content, final moisture content, shrinkage limit, plastic limit, structure shape, structure orientation, and the loading history will impact the soil expansion potential. Geotechnical engineers with experience in a particular expansive soil region can judge how all of these factors affect the final design pressure of a structure.

The design engineer has tools to mitigate expansive soil effects. One common method involves removing expansive soil and replacing it with a non-expansive soil. A second involves treating expansive soils with lime to change the soil chemistry and make it less expansive. The first case relies on the cost effective importation of non-expansive materials and disposal of expansive materials. The second relies on proper treatment methods being implemented correctly.

A third, more costly, method to mitigate the swelling pressures developed is to design structures to withstand the expansive clay loading by increasing the thicknesses and strengths of the material used in construction.

Another option involves including a frangible or deformable material, which will now be referred to as the inter-layer, between the soil and the structure. The inter-layer material allows the soil to expand, thereby lowering the resulting pressure on the structure. The combination of the deformation allowed by the inter-layer material and the resulting structural load redistribution reduces the applied soil swelling pressure.

Due to the difficulties in modeling expansive soil behaviour, the soil-membrane-structure interaction is difficult to predict. In an effort to advance the understanding of this interaction, a testing system was devised and used for demonstration testing on relatively flexible structures. Furthermore, the testing method was able to test mitigation approaches, specifically deformable/frangible material, to determine the reduction in load realized by the test specimen. From this information, designers can evaluate the cost trade-offs associated with mitigation solutions such as deformable/frangible material installation versus stronger structure designs.

3 TEST METHOD

3.1 Test Fundamentals

To simulate the expansive soil behavior on a structure, it is assumed that the soil-loading curve shown in Figure 1 can be developed for the ideal case (lab testing using oedometer results) and the in situ case where depth, compaction, moisture contents, and plasticity factor into the stress/strain relationship. From this initial data, the strain and swell pressure applied by the expanding soil to the structure is defined by the line shown on the Figure 1 stress-strain plot. Neglecting edge effects for rectilinear structures, the applied pressure on a perfectly rigid structure would fall at the intersection of the stress strain curve with the x-axis (σ_{sw}). This data point is referred to as the maximum swell pressure.

On the extreme opposite end of the spectrum, a perfectly compliant structure allows for the maximum soil swell strain (ε_{fs}). The ability of the compliant structure to allow free swell results in zero swell pressure applied to the structure.

Most soil and structures will not meet the perfectly rigid or perfectly compliant assumptions. As a result, the pressure distribution along any face lie along multiple points along the oedometer curve. For example, a rectangular structure may be fairly rigid near the corners causing high swell pressures in these regions; however, the midspan of the rectangular structure may be capable of sustaining large deformations that reduce the soil's induced swell pressure.

There are multiple methods to analyze or test structures according to this swell behavior. A closed form theoretical approach would involve solving for the beam equation shown in Figure 2. The well-known differential equation for the deflection of the beam is shown in Equation [2]. The unique difference between the expansive soil loading equation (see Equation [3]) and typical beam equations is that the load is a function of deflection (or y in this notation). Since the load is a function of y instead of x, the closed form solution is more difficult to solve analytically.

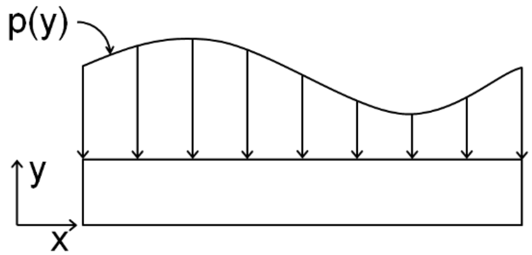

Figure 2. Beam loaded with a pressure, p, as a function of deformation, y.

$$\frac{1}{EI}\,{}^{\partial^4 y}\!/_{\partial x^4} = p(x) \qquad [2]$$

$$\frac{1}{EI}\,{}^{\partial^4 y}\!/_{\partial x^4} = p(y) \qquad [3]$$

A method to physically test the structure could involve elaborate pressure application devices such as hydraulic or electric linear actuators. A feedback control loop would be needed to ensure that the pressure applied matched the soil behavior as the structure deflected with different magnitudes at different locations. In terms of logistics, only a fixed number of pressure application devices could be used in such testing creating a discretization of the in situ uniformly varying load.

The approach proposed in this research uses a deformable material that mirrors the stress-strain curve of the particular expansive clay in question. For instance, lets assume we have a soil that will swell (deform) up to 2.4 inches when unconfined and has a confined expansion pressure of 16 psi. If a material existed that applied 16 psi when compressed 2.4 inches, and applied nearly zero pressure when it was allowed to relax 2.4 inches, the material would be capable of simulating the maximum and minimum points of the stress-strain curve for this particular soil. Furthermore, if at points along the deformation curve between zero and 2.4 inches applied a similar pressure as the same stress-strain curve expected from the soil, this material could simulate the complex soil-structure interaction expected in expansive soils.

To better explain the method used to match the engineered material characteristics to the soil data, it is helpful to plot both sets of data where stress is plotted along the y-axis and strain is converted to deformation and plotted on the x-axis. Let σ equal the swell pressure of the soil, σ_{sw} equal the maximum expected swell pressure under full confinement, δ equals the deformation of the soil, and δ_{fs} equals the maximum free swell of the soil when not confined. Figure 3 shows the graph of the soil behavior when plotted with σ on the y-axis and δ on the x-axis following Equation [4] where σ_{sw} is 16 psi and δ_{fs} is 2.4 inches.

$$\sigma = \sigma_{sw}^{\left(\frac{\delta_{fs}-\delta}{\delta_{fs}}\right)} \qquad [4]$$

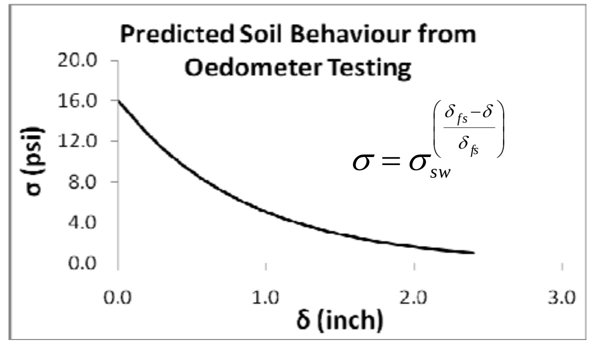

Figure 3. Ideal soil behavior using σ_{sw}=16 psi and δ_{fs}=2.4 inches

The compression plot of the engineered material must be the mirror image of the soil plot and follow Equation [5] where σ_{eng} is the stress in the engineered material. Unlike the soil, the engineered material will only create the maximum pressure when it is compressed fully. Another, possibly more convenient method to plot the behavior of the engineered material is to plot the relaxation curve (compress the engineered material 2.4 inches and set the deflection at this point equal to zero). As the engineered material is allowed to relax the pressure decreases. Both plots are shown in Figure 4. Notice how the compression curve mirrors the soil curve while the relaxation curve matches the soil curve

$$\sigma_{eng} = \sigma_{sw}^{\left(\frac{\delta}{\delta_{fs}}\right)} \qquad [5]$$

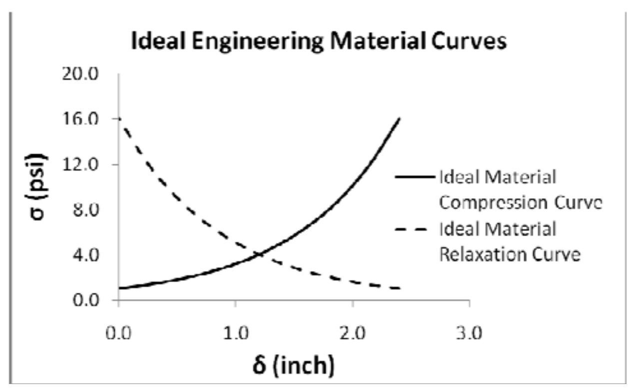

Figure 4. Ideal material compression and relaxation curves

3.2 Engineered Material Analysis

Derivation of the ideal engineering material characteristics led to material testing of foam/rubber, which will be referred to simply as foam herein. Most solid materials and honeycomb composites do not provide the needed modulus of elasticity to practically simulate expansive soil loading. A highly deformable material was desired to reduce the test apparatus size and material costs. For the assumed expansive soil, the combination of at least 2.4

inches of deflection at 16 psi of pressure is needed. This narrowed the pool of possible materials to soft and very soft foams.

A Zwick Universal Testing Machine was configured in the compression configuration for material testing. To simulate the nearly static loading in future testing, the foam was compressed at a rate of 0.1 inches/min. The actual thicknesses of the foam tested varied; therefore, strain data was used initially to compare the data. From the strain plots, the data was extrapolated to determine the needed thickness of foam to match the 16-psi loading desired at 2.4 inches of deflection. Although, over a dozen different foam materials were tested, a plot of four well-known materials is shown in Figure 5 with the ideal curve shown in bold.

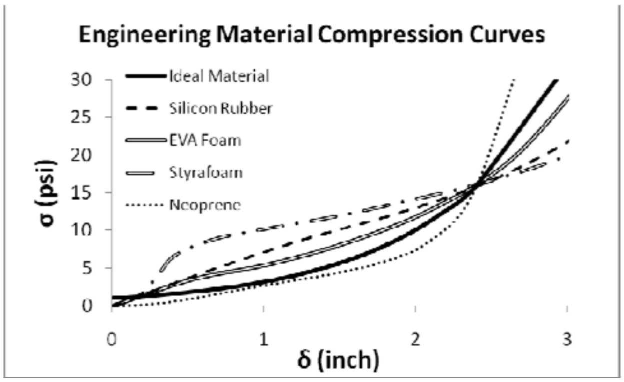

Figure 5. Foam stress-strain data

The initial results showed that a few different foam materials could be used to simulate the expansive soil behavior. Ethylene vinyl acetate (EVA) foam was selected as a reasonable fit to the ideal material curve.

Custom foams can be manufactured by adjusting the ratio of initial constituents and the curing properties. Composite foam sandwiches, where foams of different stiffnesses are combined to generate a completely new material curve, could also be generated. These methods of fine tuning the foam's material properties are beyond the scope of this research.

Upon acquisition of the EVA foam, quality testing was performed on each sample. First, the initial geometry of the foam was checked since variations in material thickness were measured between shipments. Second, compression testing was conducted on each sample used for testing. Such testing data was used to verify the pressure applied during each test. Finally, cyclic testing was conducted on the foam. The results of cyclic testing showed that the EVA compression data changed only slightly between the first two compression cycles, and further cycles showed almost no change. The results of the cyclic testing are shown in Figure 6.

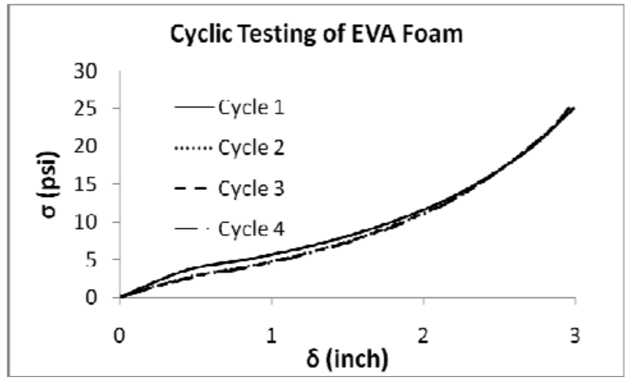

Figure 6. Foam cyclic testing results

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To prove the concept of simulating expansive soil loading, a square test specimen was used. The square test specimen better demonstrates a spectrum of deformations; high deformations can be seen in the middle of the square faces while small deformations occur at the corners. Wood was used to build the test specimen due to its ability to withstand high deformations under lower loads than building materials such as concrete.

The test apparatus was designed to load the structure in two dimensions only. This assumption is accurate if the square structure can be considered a plane strain section.

The final design of the test apparatus is shown in Figure 7. Each wall is constructed from two steel I-beams fastened together with plates. The structural steel I-beams are significantly more rigid than the structure tested to ensure that the deflections recorded are of the test specimen, not the test apparatus. Rubber wheeled casters were fastened to the bottom of the I-beams to allow free convergence of the test apparatus walls.

Within one set of the plates used to fasten the I-beams together, brass acme nuts were inserted that accepted threaded acme rod. In the opposing set of plates, a through-hole was bored where a radial bearing and a fixed shaft collar were placed on the outside of the plate. A total of eight acme all-thread rods were used to control the displacement of the I-beams. A threaded rod was positioned at each of the four corners of the test apparatus walls to maintain even loading.

Brackets were attached to the test apparatus at key locations to mount measurement sensors. String-pot linear extensometers were mounted to two adjacent I-beams with the strings attached to the opposing I-beams to measure the gross convergence of two test apparatus walls. Similarly, extensometers were mounted to two adjacent I-beams such that the movement of the test specimen inside the test apparatus could be monitored and recorded. Finally, five indication rulers were adhered to the test apparatus walls to measure the deflection of the foam used to load the test specimen. The readings from these rulers were used to determine the pressure applied at 5 points along the test specimen walls at various snap-shots during the load application phase of testing.

a)

b)

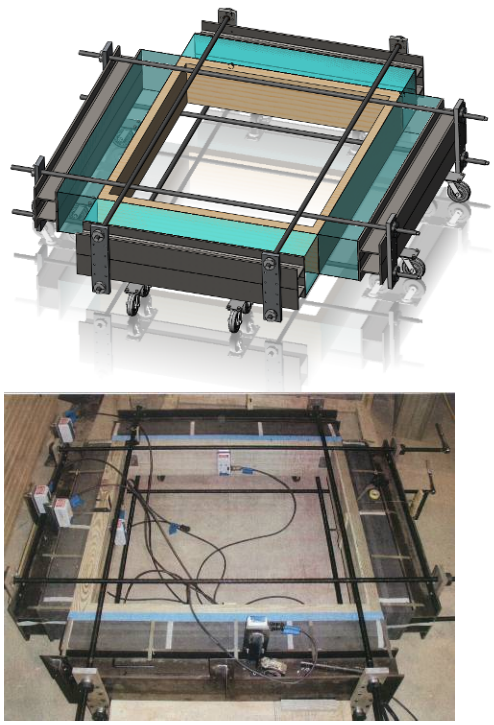

Figure 7. Test apparatus designed to simulate expansive soil loading a) CAD model, b) Physical test apparatus

3.3 Test Procedure

The testing began by loading a test specimen constructed of wood into the test apparatus with the all-thread rods removed. The load application foam was adhered loosely to the test apparatus walls as they were pushed in contact with the test specimen walls. The all-thread rods were added and tightened until there were no air gaps between the test specimen, load application foam, and I-beam apparatus walls. More string-pot extensometers were added inside the test specimen to measure structure deflection. All of the sensors were wired into a data acquisition system for recording at a rate of 1 Hz.

The testing began with two individuals, one assigned to four all-thread rods on one wall, marking the initial positions of the threaded rod. Each individual would spin their four rods in a nearly simultaneous manner. After every inch of test apparatus wall convergence, measurements were taken of the foam compression along the walls of the test apparatus. This testing method continued until failure of the test specimen was achieved.

For the first test, the test specimen was loaded such that it was in direct contact with the loading foam; this simulates direct expansive soil/structure interaction. For the second test, a deformable/frangible material was adhered to the outside of the test specimen. For this case, 1 inch of deformable/frangible material covered the entire outer surface of the wood test specimen. The second test simulates the condition where a deformable/frangible material is placed along the outside of a structure expected to experience expansive soil loads to help control expansive pressure loading. As the soil begins to swell, the deformable/frangible material would allow some soil movement, thereby decreasing the final pressure experienced by the structure.

Again, test specimen 2 was loaded into the test apparatus similarly to test specimen 1. The foam along the walls of the test apparatus was converged carefully onto the deformable/frangible material so as not to prematurely load the system before beginning the test.

4 RESULTS

The test apparatus was able to successfully use the foam material to apply a non-uniform pressure to the test specimen. Figure 8a shows the foam compression profile (which can be converted to a pressure profile using the foam compression data) along one side of the test specimen for the test where the soil is in direct contact with the test specimen (Specimen 1). Each curve represents another five turns of the all-thread rods with the final curve showing 5 inches of convergence (2.5 inches on each wall). Figure 8b shows the same foam compression profiles for the test specimen where one inch of deformable/frangible material is placed between the soil and the test specimen (Specimen 2). Each curve on this graph represents another 6 turns of the all-thread rods with the final curve showing 7 inches of convergence (3.5 inches on each side).

a)

b)

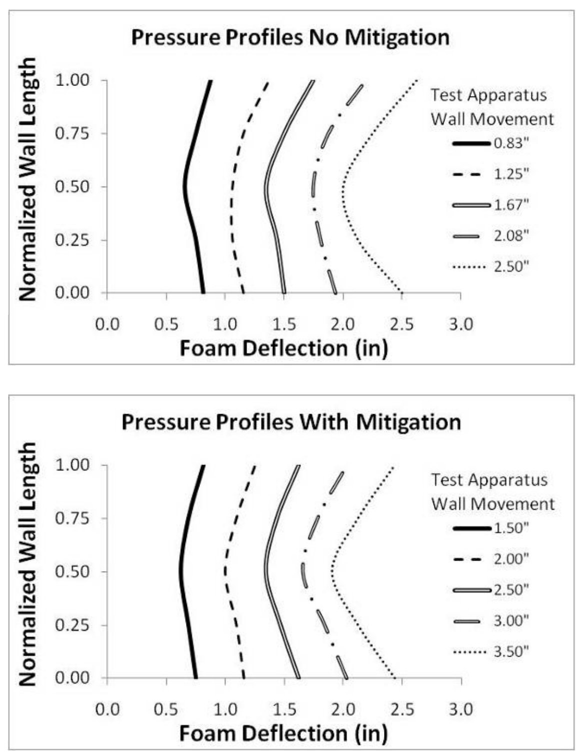

Figure 8. Foam displacement profiles at different stages during the test with a) showing the test without mitigation techniques and b) showing the test with 1” of deformable foam placed around the test apparatus

As the test specimen walls were loaded by the EVA foam, the center of the walls began to deflect more than the edges. This created the non-uniform pressure distribution expected by expansive soils. At the design load for the first test (2.4" of test apparatus wall movement), the edges of the structure were loaded to 16 psi (or 2.4" of deflection) while the center of the structure was only loaded to 12 psi (or 2" of deflection). The center of this structure deflected 0.5" at the design load expected for this soil scenario.

The first test specimen was loaded to nearly 3 inches of displacement on each side before the test was ended due to localized wood cracking. The second test specimen was capable of being loaded up to nearly 4 inches of deflection on each side since the load on the test specimen was reduced by the one inch of deformable/frangible material. At the design load for the second test (2.4" of test apparatus wall movement), the edges of the structure were loaded to 9 psi (or 1.6" of deflection) while the center of the structure was only loaded to 7 psi (or 1.3" of deflection). The center of this structure deflected 0.28" at the design load expected for this soil scenario.

There are significant differences between the two tests. The first test resulted in test specimen deflections of nearly two times the deflections shown in the mitigated test. Figure 9 shows the wood deflection of the test specimen wall at the mid-span versus the test apparatus I-beam movement. The slope of the curve for the mitigation solution is shallower than the first curve indicating less loads were transferred to the structure. This results in an overall lower structural loading for the mitigated solution.

The second test allowed the I-beams to converge another inch on all sides; the exact thickness of the deformable/frangible material placed along the test specimen.

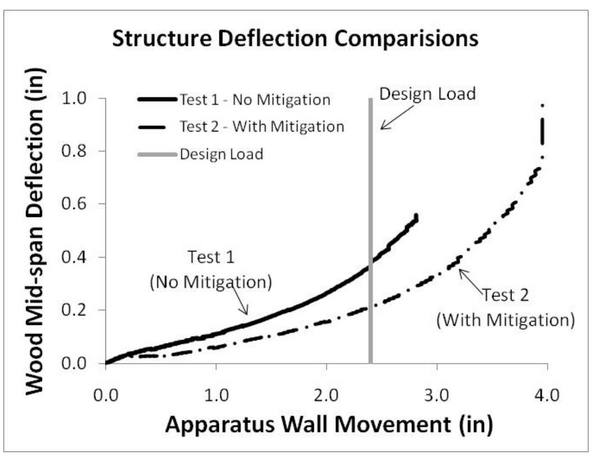

Figure 9. Test comparisons between mitigated and non-mitigation structure designs

The second test ended in dramatic fashion with one wall from the test specimen fractured down the center, as expected for a square, wooden test specimen. Figure 10 shows the complete failure of one of the walls of the test specimen. After failure, the potential energy stored in the foam behind that wall was relieved, and the foam relaxed to its original thickness.

Figure 10. Test specimen failure

5 CONCLUSION

This paper has presented a testing method that can be used to economically simulate expansive clay loading on structures. The method demonstrated that the use of manufactured materials, in this case an EVA foam, with compression properties similar to the expansive properties of a specific clay, can be used to simulate the soil-structure interaction. The testing demonstrated that the apparatus could be used to simulate direct soil on structure loading and simulate the benefits of placement of a frangible material between the structure and soil.

The apparatus, while useful, can be refined so that it can be applicable to larger and more complex structure shapes. It is the desire of the authors that other investigators may find opportunities to use this, or similar concepts, in future expansive clay research.

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