Developing Guidelines for the Use of Lightweight Materials in Culvert Preservation

Report Number: KTC-24-27

DOI: https://doi.org/10.13023/ktc.rr.2024.27

Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

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Research Report
KTC-24-27

Developing Guidelines for the Use of Lightweight Materials in Culvert Preservation

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May 2024

1. Report No. KTC-24-27	**2. Government Accession No.**	**3. Recipient's Catalog No**
4. Title and Subtitle Developing Guidelines for the Use of Lightweight Materials in Culvert Preservation		**5. Report Date** May 2024 **6. Performing Organization Code** KTC-24-27
7. Author(s): Charlie Sun and Kean Ashurst		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Kentucky Transportation Center College of Engineering University of Kentucky Lexington, KY 40506-0281		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** SPR 22-625
12. Sponsoring Agency Name and Address Kentucky Transportation Cabinet State Office Building Frankfort, KY 40622		**13. Type of Report and Period Covered** **14. Sponsoring Agency Code**
15. Supplementary Notes Prepared in cooperation with the Kentucky Transportation Cabinet		

16. Abstract

This study addresses challenges that arise during highway embankment construction on road widening projects when additional fill is placed above existing culverts. Researchers conducted reduced-scale model laboratory tests to simulate culvert behavior under different loading conditions and to determine how well lightweight materials (LWMs) perform when subjected to changing loads. Testing showed that proximity of LWM to the culvert's top surface strongly influences the magnitude of strain reductions or increases. Placing LWMs with relatively low elastic modulus closer to the culvert's top surface led to reduced culvert ceiling strain and increased culvert wall strain. LWMs with relatively high elastic modulus generally increased both culvert ceiling and wall strain. Researchers conducted over 12,000 numerical simulations to analyze culvert behavior under a range of loading conditions involving LWMs. Simulations underwrote the development of empirical formulas that can be used by practitioners to design LWM installation profiles above culverts. Following the development of empirical formulas, researchers developed a user-friendly web app practitioners can use to efficiently identify the best LWM installation profile for individual projects. Adopting the insights, methodologies, and tools presented in this study will enhance infrastructure resilience and sustainability on highway widening projects.

17. Key Words roadway widening, culvert, lightweight material, Geofoam, Pudgee, reduced-scale model laboratory test, numerical simulation, FLAC, empirical formula, regression		**18. Distribution Statement** Unlimited with approval of the Kentucky Transportation Cabinet	
19. Security Classification (report) Unclassified	**20. Security Classification (this page)** Unclassified	**21. No. of Pages** 102	**19. Security Classification (report)**

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Acknowledgements

We extend our heartfelt gratitude to the esteemed members of the Study Advisory Committee (SAC) for their invaluable guidance and unwavering support throughout this study. Their expertise, advice, and contributions have been instrumental in shaping the direction and outcomes of our research.

Special recognition goes to Mr. Erik Scott, Geotechnical Support & Review Branch, Division of Structural Design at the Kentucky Transportation Cabinet. His exceptional contributions, dedicated leadership, and valuable insights have significantly enriched this study.

We also acknowledge and express our gratitude to all SAC members for their unwavering support, commitment, and expertise. Each member's contributions, regardless of size, have played a vital role in successfully completing this research.

Additionally, we would like to express our thanks to Dr. Nisal Peiris, Research Engineer at KTC and Assistant Professor at the Department of Civil Engineering, College of Engineering, University of Kentucky, for generously providing the data acquisition system and guiding its use. We also extend our gratitude to Mr. Tim Jones, transportation technician at KTC, and Mr. Habib Unluoglu, graduate student at the Department of Civil Engineering, College of Engineering, University of Kentucky, for their valuable assistance in running the reduced-scale model laboratory test.

Finally, we sincerely thank Dr. Chris VanDyke for his thorough review and constructive edits of the manuscript, which greatly enhanced the quality of our work.

Executive Summary

Preservation of existing culverts plays a critical role in highway embankment construction. On road widening projects, preservation of these structures is challenging because they are subjected to higher loads from added fill material. To mitigate the impacts of higher loads on culverts, lightweight materials (LWMs) can be installed above the culvert. However, practitioners need better guidance on LWM installation profiles for culverts in highway widening projects.

This report lays out practical guidelines, empirical formulas, and a user-friendly design procedure — operationalized via a web-based app — that practitioners can use to develop LWM installation profiles for existing culverts under widened embankments. Researchers developed guidance based on reduced-scale model laboratory tests and over 12,000 numerical simulations. The combination of laboratory testing and numerical simulation is a cost-effective and robust method for studying culvert behavior under different loading conditions.

Laboratory tests analyzed the impacts of dry play sand, brown silty clay, Pudgee, Geofoam, cellular concrete blocks, and lightweight aggregates on the maximum bending strains of culvert ceiling and walls. Despite Pudgee's higher mass density, it resulted in greater culvert ceiling strain reductions than the Geofoam. The proximity of material to the culvert's top surface strongly influences the magnitude of strain reductions or increases. Placing LWMs closer to the culvert's top surface typically led to greater strain reductions. In most installation profiles, Pudgee and Geofoam inclusions increased culvert wall strain. Cellular concrete and lightweight aggregates generally increased both culvert ceiling and wall strains.

Applying empirical formulas derived from numerical simulations can guide development of LWM installation profile designs that will enhance long-term infrastructure resilience. The proposed design method incorporates a systematic approach for assessing culvert loads and load ratios. This method involves defining target reduction ratios, drawing on soil mechanics principles to delineate search regions, and achieving optimal load reduction within designated regions.

The web-based app will advance the state of the art for designing effective LWM installation profiles. Its user-friendly interface, algorithm integration, and collaboration features make it a valuable tool for engineers, researchers, and industry professionals who work on LWM installation profile design. Adopting the insights, methodologies, and tools presented in this study will enhance infrastructure resilience and sustainability on highway widening projects.

Section 1 Introduction

Transportation agencies often preserve existing culverts when highway embankments are constructed as part of road widening projects (Figure 1.1). At some existing sites, culvert ceiling and wall thicknesses were reduced in a stepped-down manner along culvert for sections located beneath embankment slopes. This design approach resulted in these culvert sections being intended for smaller loads compared to those acting on sections under the main embankment. During road widening, significantly larger loads are exerted on these weaker portions of the culvert due to the added weight of fill material. To mitigate the effects of increased loads in these areas, lightweight materials (LWMs) can be placed around the culvert. The Kentucky Transportation Cabinet (KYTC) has implemented this construction method on several projects, including stepped-down culverts on I-75 and I-64 interstate widening.

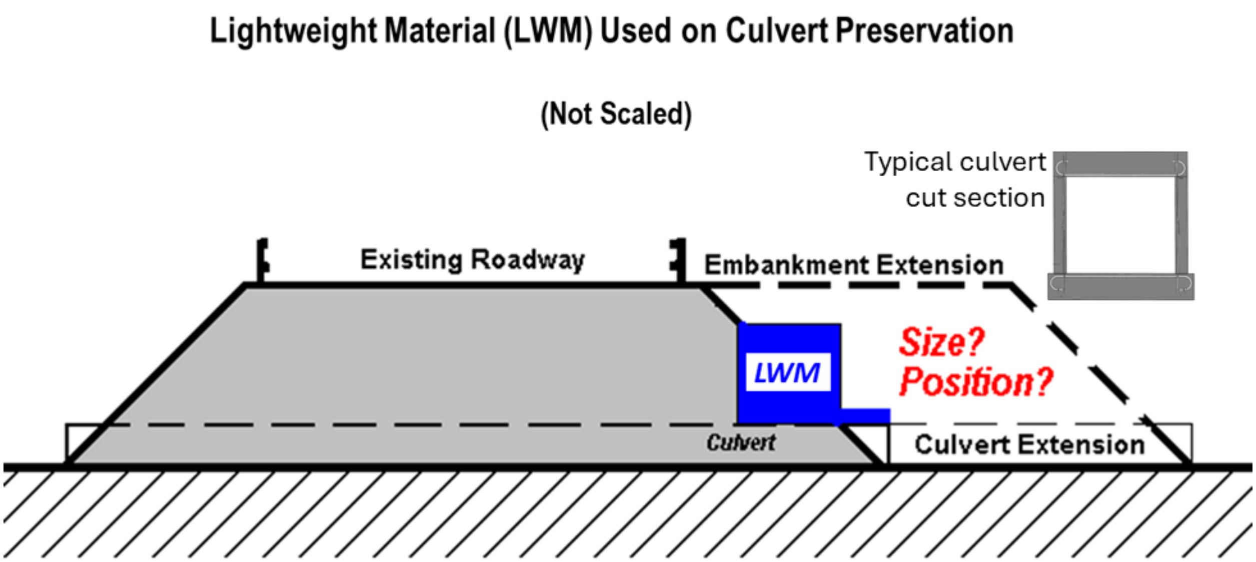

Figure 1.1 Lightweight Material Used for Culvert Preservation

According to Spangler's research, [1] the supporting strength of a buried structure primarily depends on three factors:

1. The structure’s inherent strength
2. The distribution of vertical load and bottom reaction
3. The magnitude and distribution of lateral earth pressures, which may act against a structure's sides.

The second and third factors are influenced significantly by the bedding character on which the structure is founded and the backfill placed against the culvert sides. The relative stiffness of the buried structure and the materials placed around it dictate the magnitude and distribution of earth pressures on the structure.

To mitigate large vertical earth pressures on buried structures, Marston’s imperfect ditch method of construction can be utilized.[2] This method helps minimize the load on a culvert under an embankment. Expanded polystyrene (EPS, or Geofoam — a lightweight material used in geotechnical earthwork) can be installed as the compressible material in the ditch above the culvert to promote positive arching.[3] EPS has low stiffness and favorable elastic-plastic behavior. When the embankment is constructed, the soft zone compresses more than its surrounding fill, inducing positive arching above the culvert.

Without the use of the imperfect ditch — backfilled with a compressible material like EPS — areas of high stress concentrations exist at the top and bottom of the culvert. Placing EPS above the culvert significantly reduces the concentrated stresses at the top and bottom.[4][5] Stress reductions are influenced by the size of the EPS and the distance between the top of the culvert and the EPS.

This report lays out practical guidelines, empirical formulas, and a user-friendly design procedure — operationalized via a web-based app — that practitioners can use to develop LWM installation profiles for existing culverts under widened embankments. We examined LWMs, including cellular concrete, lightweight aggregates, and recycled tires to determine how effective they are at reducing loads on a culvert. Analyses considered a range of factors, including the stiffness of LWMs, size of LWMs, distance between the LWM and culvert, and different backfill soils.

Section 2 Project Scope

This report proposes practical guidelines and empirical formulas for evaluating the amount of pressure applied to existing culverts under widened embankments. We adopted a multifaceted approach to develop these guidelines and formulas, which involved using test data, in-situ measurements, and numerical simulation. The report focuses on examining different installation profiles of LWMs placed within new and/or existing embankment limits. As part of this project, we:

- Conducted reduced-scale model laboratory tests to validate theoretical models
- Carried out detailed numerical simulations to analyze different scenarios
- Developed precise empirical formulas based on collected data
- Optimized coefficients in these formulas to ensure they are accurate and reliable
- Developed a user-friendly design procedure

Additionally, we designed a web app to facilitate implementation of guidelines and formulas. Applying the guidance from this report and available in the web app will help practitioners identify acceptable lightweight fill installation profiles that effectively distribute loads and mitigate pressures on existing culverts.

Section 3 Reduced-Scale Model Laboratory Test

Reduced-scale model laboratory tests have several benefits over developing full-scale models or conducting field tests. First, they are cost-effective. Building and testing a reduced-scale model is often less expensive than constructing a full-scale model or conducting field tests. Testing these models is thus a more feasible option, especially when there are budget constraints. Second, reduced-scale models can be tested more quickly than full-scale models. This enables faster analysis and decision making, which are particularly important when time constraints are an issue. Third, small-scale testing can help identify potential problems early, reduce the risk of failure in full-scale applications, lower costs, and improve safety. Fourth, conducting some tests at full scale is not feasible or practical due to technical limitations or resource availability, making reduced-scale models a valuable alternative. Finally, reduced-scale models are often used in research and development to study the behavior of materials, structures, or systems under different conditions, motivating new discoveries and innovations in engineering.[6]

We used reduced-scale model laboratory tests to simulate culvert behavior under different loading conditions to clarify how they will perform and how LWMs behave when subjected to changing loads. During our testing, we systematically varied parameters such as the stiffness and size of LWMs, distance between LWM and the culvert, and the properties of backfill soils. This systematic approach lets us evaluate the impact of each factor on overall culvert performance and the effectiveness of LWMs in enhancing culvert structural capabilities.

3.1 Design and Fabricate Reduced-Scale Culvert Models

Culverts measuring 10 ft. x 10 ft., with top and bottom panels 14 in. thick and side walls 12 in. thick, are commonly used in Kentucky. For laboratory testing, we designed and fabricated culvert models at a 1:20 scale. The scaled-down models were 6 in. high x 6 in. wide (Figure 3.1).

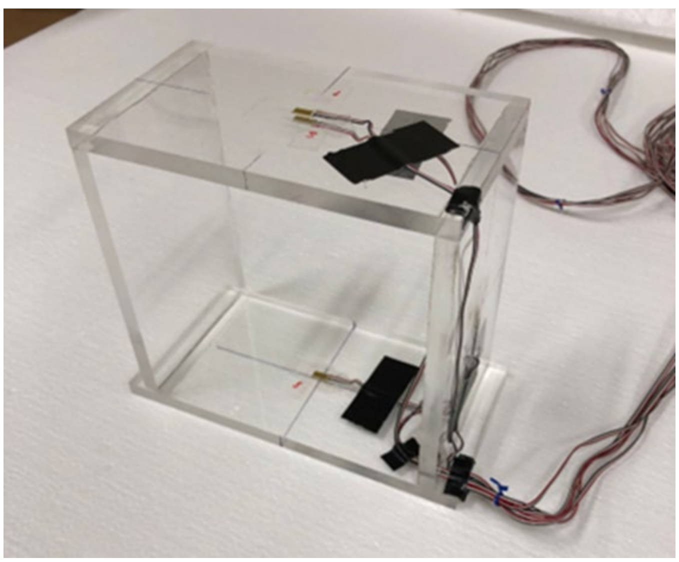

Figure 3.1 Reduced-Scale Plexiglass Culvert Model

On two reduced-scale culvert models, the thicknesses of top and bottom panels and the two side walls were 3/8 inch. On a third model, these components were 1/2 inch thick. All components had a uniform depth of 3.8 inches. All models were constructed using plexiglass. The models with thinner panels and side walls (3/8 inch) experienced functionality issues after a certain number of tests. We traced this issue to a problem with connection points between the top panel and the side wall. The model with thicker panels and side walls (1/2 inch) performed flawlessly, highlighting the importance of structural integrity in model construction.

To monitor performance, nine (9) strain gauges were strategically installed on the reduced-scale culvert model. Four (4) gauges were positioned on the top panel, four (4) were affixed to the side wall, and the last gauge was attached to the bottom panel.

3.2 Design and Construct a Loading Frame for Reduced-Scale Model Testing
We designed and constructed a loading frame appropriate for reduced-scale model testing and suitable for frequent loading-unloading test situations, ensuring ease of assembly and disassembly. The loading procedure was designed to be efficient and observable. The loading frame had the following dimensions:

- Height: 3 ft. 2 in.
- Width: 3 ft. 1 in.
- Depth: 8 in.

Three sides of the frame were made of wood and two sides were made of glass. Two pieces of tempered glass (dimensions: 3 ft. square and 1/2 inch thick) were used to create transparent windows at the front and back of the frame so we could observe testing. To facilitate assembly and disassembly, wood frames on two sides were cut in half, providing access inside the frame when handling the culvert model, LWMs, and soils (Figure 3.2). This design feature lets us easily manipulate components and conduct tests within the frame.

Figure 3.2 Loading Frame

To ensure tests were repeatable and accurate, we meticulously drew a grid pattern on one the loading frame's glass faces (Figure 3.3). The grid consisted of rectangles 2 in. wide and 3 in. tall. Spacing vertical lines 2 in. apart, ensured consistent compaction points. Precision was critical for achieving uniform compaction across the soil surface during testing. We spaced horizontal lines 3 in. apart to facilitate even load distribution during each loading step. This ensured the load was uniformly applied across the culvert model. A single horizontal line 3.5 in. below the culvert's top surface acted as a separator between two-step loading processes, allowing for controlled loading before the load height reached the culvert's top surface.

To facilitate identification and tracking of loading levels, each horizontal line was labeled with its corresponding elevation level. This labeling system enabled precise monitoring of the loading process and ensured the desired loading conditions were achieved consistently throughout testing (Figure 3.3).

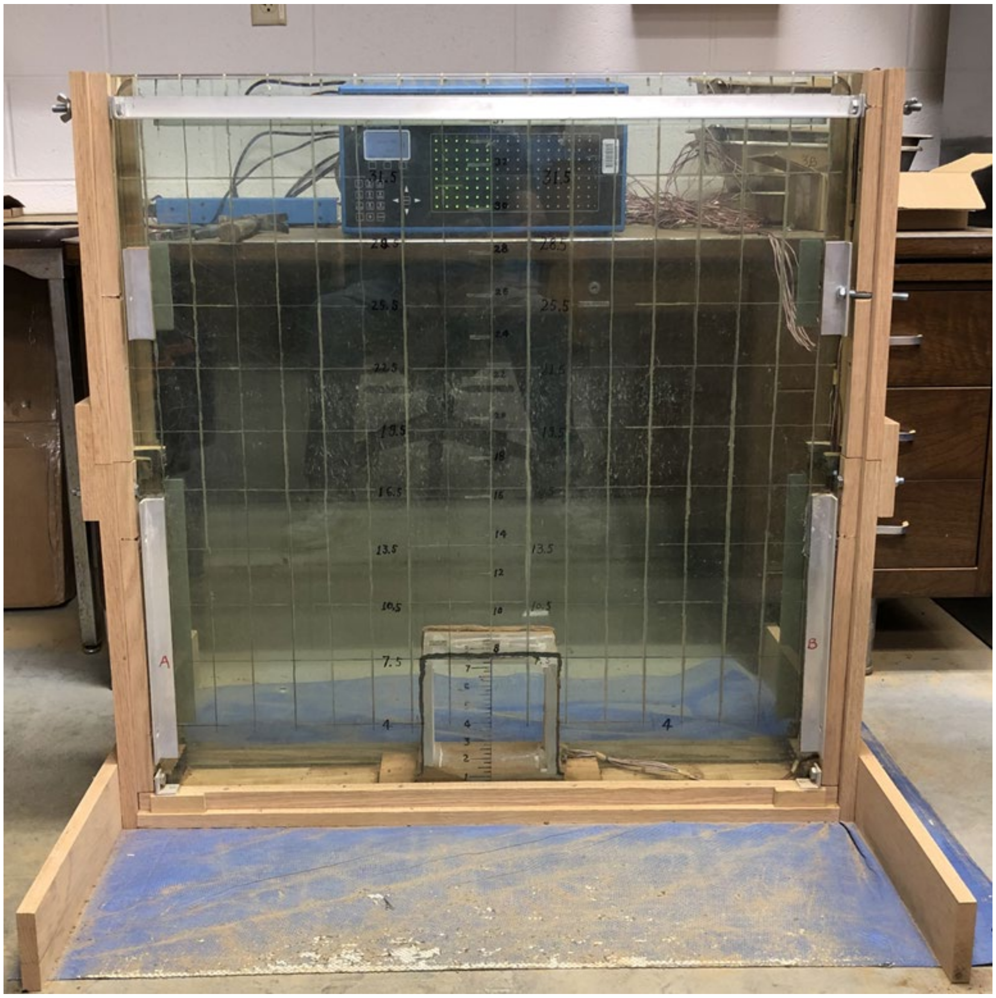

Figure 3.3 Front Glass with Grid Pattern and Elevation Labels

3.3 Data Acquisition System

The StrainSmart® Data Acquisition System 7000 is a comprehensive solution for stress testing analysis. It features high channel density and can handle up to 128 channels in a 4U height, 19-in. rack-mountable scanner. The system accommodates sensors such as strain gauges, strain-gauge-based transducers, thermocouples, and LVDTs. Its Ethernet interface allows for flexible positioning and synchronization of scanners (Figure 3.4).

Figure 3.4 StrainSmart® Data Acquisition System 7000

This system's measurement accuracy is ±0.05% of full scale and 0.5 microstrain resolution. It also offers scan rates of up to 2,048 samples per second and includes nonvolatile data storage, self-calibration capability, and RJ-45 input connectors. Additionally, the system supports interchangeable sensor input cards with analog input cards, reducing assembly time and cabling costs.

StrainSmart® software simplifies test setup for different transducers. It automatically outputs test data in engineering units based on input parameters for sensors, materials, and instrumentation hardware. The software can store test setups and measurement data for offline display or integration into databases, word processors, and spreadsheets. It also accounts for unique strain gauge characteristics and measurement system errors, ensuring accurate and reliable strain measurements.[7]

3.4 Tools for Soil Loading and Unloading

All tools utilized during testing had to fit in the 4-in. space between the loading frame's two glass faces. In addition to the standard small soil scoop and a manually operated standard soil compaction hammer weighing 5.5 lb. with a 12-in. drop height, a 20-oz. plastic cup and a custom-made 72-oz. metal sheet cup were used for soil loading and unloading (Figure 3.5). The custom metal sheet cup offered a more efficient method of loading and unloading soil. Compact hand trowels, brushes, hammers, wrenches, and other tools (as depicted in Figure 3.5) were used to load and unload soil as well as to assemble and disassemble the frame as necessary throughout testing.

Figure 3.5 Tools Used for Soil Loading and Unloading

3.5 Materials Used in Reduced-scale Model Laboratory Test

Testing focused on how LWM installation profiles affect loads on the culvert. To analyze their impacts, we varied the size of LWMs and adjusted the distance between the materials and the culvert's top surface. The primary load on the culvert originates from soils. LWMs can potentially reduce this load. Soils used during testing were brown silty clay and play sand. LWMs included Pudgee (a commercial soft foam simulation product by Dynamic System, Inc.), Geofoam, cellular concrete, and lightweight aggregates. Table 3.1 summarizes LWM and soil properties.

Table 3.1 Materials Used in Reduced-Scale Model Laboratory Test

Material	Elastic Modulus E (psf)	Poisson's Ratio (U)	Mass Density (pcf)	Cohesion C (psf)	Friction Angle (φ)	Moisture Content (%)
Play sand	835417.37	0.25	95.00		41.00	< 5
Brown silty clay	417708.69	0.30	108.05	1994.56	20.00	14.50 – 19.69
Pudgee	1440.00	0.10	12.35			
Geofoam	13300.00	0.10	1.35			
Cellular concrete (45)	22600000.00	0.20	45.00			
Lightweight aggregates	12850000.00	0.15	52.80			

3.6 Test Procedures

Our testing procedures ensured systematic and precise management of soil and LWMs. These are described in the subsections below.

3.6.1 Culvert Model Installation and Strain Gauge Cable Connection

Prepare the clean interior of the loading frame. Place the culvert model along the centerline on top of a 1/2-in.-thick wooden platform. This raises the bottom of the culvert model, improving its visibility. To prevent soil from infiltrating the culvert model, use mineral-based non-hardening clay to seal small gaps between the culvert model and the frame's glass faces (Figure 3.3). Carefully guide the nine pairs of strain gauge cables from the culvert model at the inside frame bottom to the side frame corner and then out of the top of the loading frame. Ensure the cables are neatly arranged and free from obstructions.

Once the cables are positioned, connect them to the appropriate ports on the StrainSmart® Data Acquisition System 7000. Follow manufacturer instructions for proper cable connection. This step is crucial for monitoring and recording strain data effectively throughout testing. Next, read the deformation data using the data acquisition system. This measures initial readings and establishes a baseline for later deformation measurements.

3.6.2 Load and Compact Soil on First Two Layers below Culvert Model Top Surface

Begin soil loading by using a 20-oz. plastic cup and a custom-made 72-oz. metal sheet cup. Load soil up to the 4-in. elevation line and level it using appropriate tools. Compact soil along each vertical line twice, covering two rows with each row along the front and back glass faces of the loading frame. Record the deformation data measured by the data acquisition system. Load the second layer of soil up to the 7.5-in. elevation line, aligning it with the top surface line of the culvert model. Compact the second layer of soil following the same procedure used for the first layer. Record deformation data at this loading level to evaluate changes or responses under this soil load.

3.6.3 Load and Compact Soil above the Top Surface of Culvert Model

This section involves three loading cases:

a. Soil loading without LWM
b. Soil loading with lightweight block material placed
c. Soil loading with digging and burying lightweight aggregate or block material

Each case employs a unique loading strategy. Soil loading without LWM serves as a baseline. Adding lightweight block material and lightweight aggregate material introduces variations into the loading approach, which enables assessments of their impact on the culvert model's performance under different conditions.

3.6.3.1 Soil Loading Without Lightweight Material

The process begins at the 7.5-in. elevation line. Each layer of soil is added in 3-in. lifts until an elevation of 34.5 in. is reached. Once each lift is placed, compact the soil along each vertical line twice, covering two rows along the loading frame's front and back glass faces, similar to the procedure described in Section 3.5.2. With the first lift, avoid compacting soil directly above the culvert model to prevent impact damage. Compensate for missed compaction at one lift by applying it at the next higher level. After each round of compaction, record deformation data. These data measure the culvert's response under loading.

3.6.3.2 Soil Loading with Lightweight Block Material Placed – Direct Placement

Following the procedure outlined in Section 3.6.3.1, compact and level the layer designated for lightweight block material installation at the expected elevation. Place the lightweight block accordingly. Continue with 3-in. lifts and compact soil at each level. Avoid direct compaction above the lightweight block area when placing the first lift to prevent impact damage or unexpected deformation. Compensate for missed compaction by applying it at the next higher level. Record deformation data after each round of compaction to measure the culvert's response under loading.

3.6.3.3 Soil Loading with Lightweight Aggregate or Block Material – Dig-And-Bury
Consistent with steps outlined in Section 3.6.3.1, compact and level the soil layer up to the elevation for the top surface of lightweight aggregate or block material. Then, remove soil from the designated area for the lightweight aggregate or block material and install it in this space. Proceed with equal 3-in. lifts and soil compaction at each level, including the first lift, based on the characteristics of lightweight aggregate. For the compaction of lightweight blocks, follow the procedures outlined in Section 3.6.3.2. Record deformation data after each round of compaction to monitor the culvert's response under loading.

3.6.4 Soil and Lightweight Material Unloading
Once the soil reaches an elevation of 34.5 in., compact the final layer of soil and record deformation data. Carefully remove soil from the loading frame using trowels and cups. As soil is extracted to the level of the LWM's top surface, record the deformation data. Continue removing soil and LWM until reaching the culvert's top surface. At this point, take another deformation reading. Complete the unloading process by clearing remaining soil from the loading frame. Then take the final deformation reading. Thoroughly clean the inside and outside of the frame to prepare for the next testing cycle.

3.7 Analysis of Test Results
We conducted a series of tests using different combinations of LWMs and soils. Using different soil types revealed how soil properties affect the loads on the culvert. Similarly, experimenting with different LWMs provided insights into how materials with different stiffnesses impact culvert loads. Varying LWM size and the distance between the material and culvert's top surface let us identify optimal conditions for reducing culvert loads.

3.7.1 Loading with Dry Play Sand
We used dry play sand, whose properties are more stable than silts or clays, in the preliminary tests to assess the impact of LWMs on the culvert model. This phase focused on testing Pudgee and Geofoam under the load exerted by dry play sand. These tests sought to document how LWMs influence the behavior of the culvert model under different loading conditions.

3.7.1.1 Preliminary Tests with Pudgee at Varied Thicknesses Directly on Culvert Top Surface
We placed Pudgee directly on the culvert's top surface in three thicknesses (0.875 in., 1.80 in., and 2.675 in.). For all levels of thickness, the Pudgee had a width of 6.75 in. We conducted an initial reference test using only sand as the fill material to establish a baseline. Following this, we carried out three additional tests by placing the different thicknesses of Pudgee directly on the culvert top surface. Pudgee was installed following procedures outlined in Section 3.6.3.2.

Once the fill height reached 16.5 in. maximum bending strains experienced by the culvert ceiling were lower when Pudgee inclusions were used compared to the sand-only loading condition (Figure 3.6). Thicker Pudgee inclusions were associated with greater reductions in strains at their respective points. The legend in Figure 3.6 indicates the condition represented by each line-symbol combination. For example, the yellow line with triangles captures the maximum bending strains recorded when a 6.75 in. wide x 0.875 thick Pudgee inclusion was installed. There was no compaction above the culvert top until the 13.5-in. elevation, resulting in the culvert ceiling experiencing negative strain. Compaction was done above this elevation, resulting in higher strains. Data at elevations of 10.5 in. and 13.5

in. for the three tests involving Pudgee were excluded due to the area above the Pudgee not being compacted according to the procedures outlined in Section 3.6.3.2.

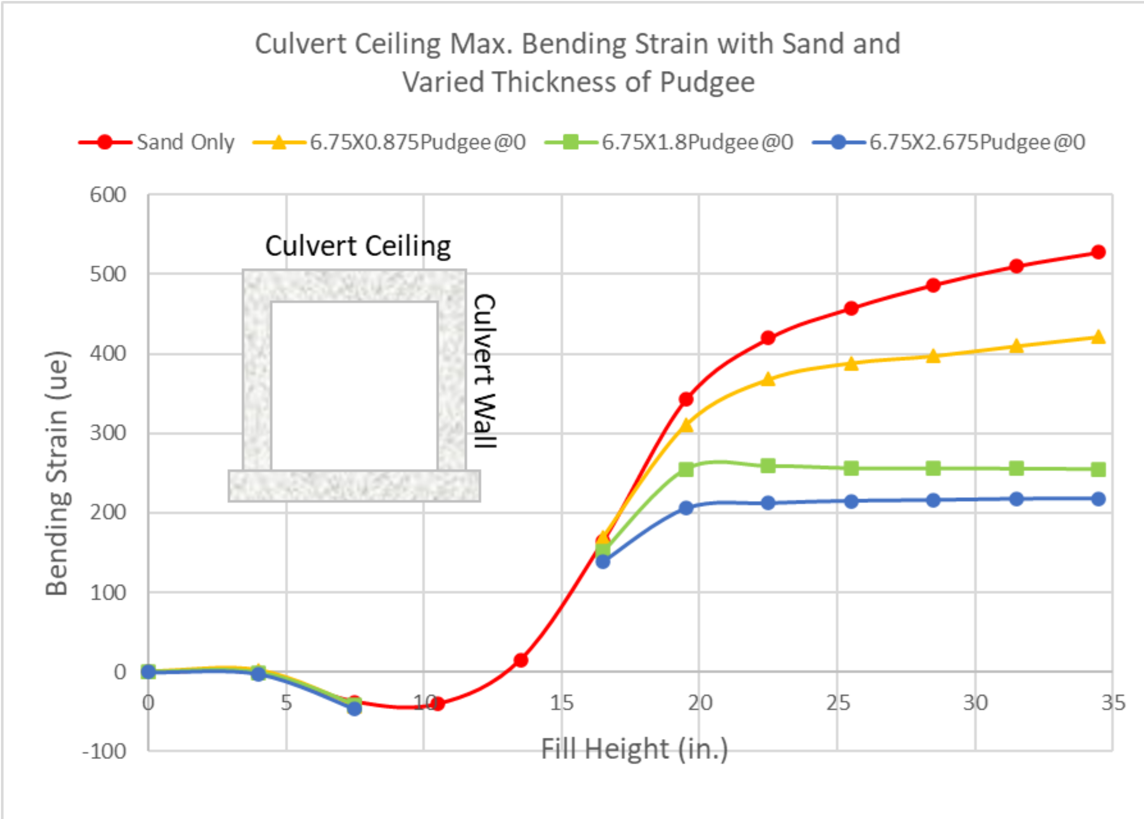

Figure 3.6 Culvert Ceiling Maximum Bending Strains — Sand Only and Pudgee Inclusions

Culvert wall maximum strains exhibited the opposite trend. When a Pudgee inclusion was installed, strains were higher than those observed with the sand-only loading condition (Figure 3.7). The strain curve for the sand-only condition increases continuously until the elevation exceeds 16.5 in., at which point the deformation on the culvert ceiling displays a larger increase due to normal compaction above the culvert's top surface. The larger increase in deformation on the culvert ceiling leads to negative strain due to the semi-rigid connection between the culvert ceiling and wall. As the thickness of the Pudgee inclusion increased, so did measured strain. This underscores the importance of being cautious when using Pudgee as a fill material, as it can increase the culvert wall's maximum bending strain. Data for elevations of 10.5 in. and 13.5 in. for the three tests involving Pudgee were excluded due to the area above the Pudgee inclusion not being compacted according to the procedures outlined in Section 3.6.3.2.

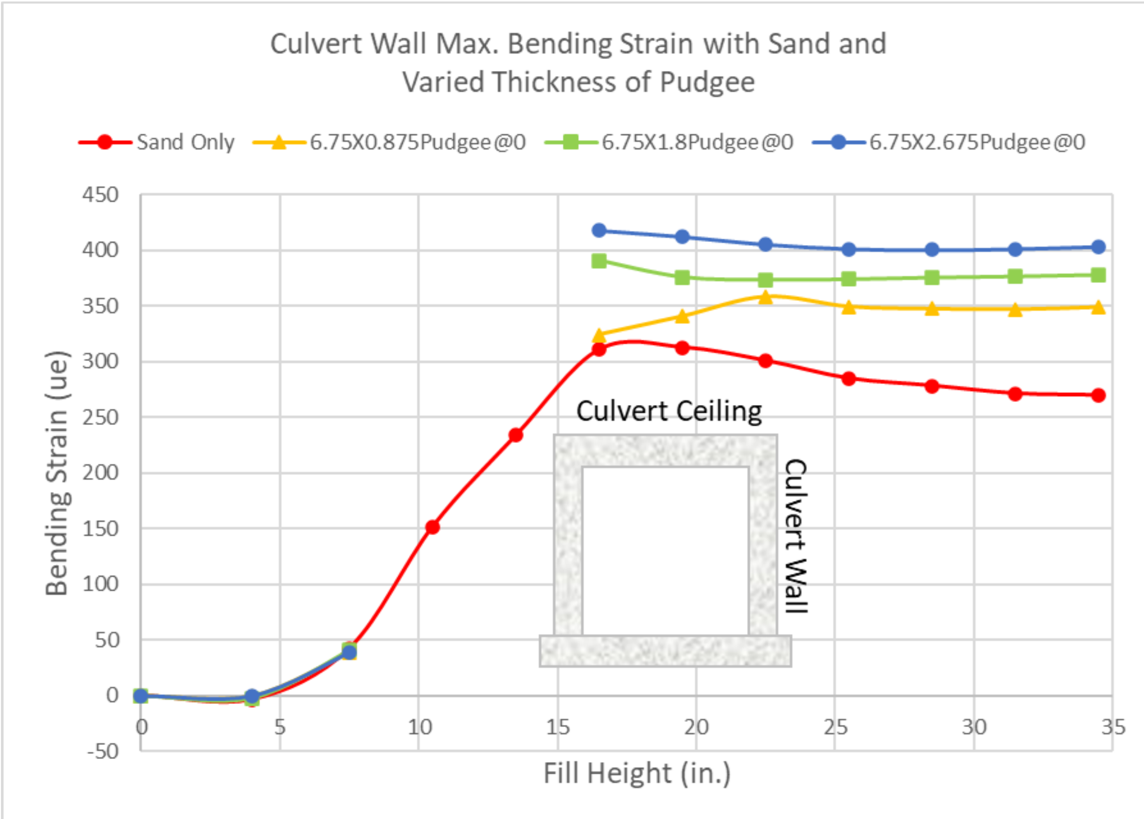

Figure 3.7 Culvert Wall Maximum Bending Strains — Sand Only and Pudgee Inclusions

3.7.1.2 Tests with Pudgee at Different Installation Profiles Above the Culvert

For the next batch of tests, we varied Pudgee width (6.75 in., 10.1 in., and 13.5 in.) but held its thickness fixed (1.9 in.). We also varied the distance between the culvert's top surface and the bottom of the Pudgee (0.0 in., 3.0 in., 6.0 in., 12.0 in.). Baseline data reported in the previous section for the sand-only loading condition serve as a point of comparison. We conducted 12 tests by placing the different sizes of Pudgee at four different positions for each Pudgee inclusion.

Once fill height reached 16.5 in., maximum bending strains experienced by the culvert ceiling were lower when a Pudgee inclusion was used than under the sand-only loading condition (Figure 3.8). Holding the size of the Pudgee inclusion constant, we found that the closer the inclusion was placed to the culvert's top surface, the greater the strain reduction. However, strain reduction was not always directly proportional to Pudgee inclusion width. In our tests, a Pudgee inclusion width of 10.1 in. placed 0.0 in. from the culvert's top surface yielded the largest strain reduction. Some data points were excluded due to the area above the Pudgee inclusion not being compacted according to the procedures outlined in Section 3.6.3.2.

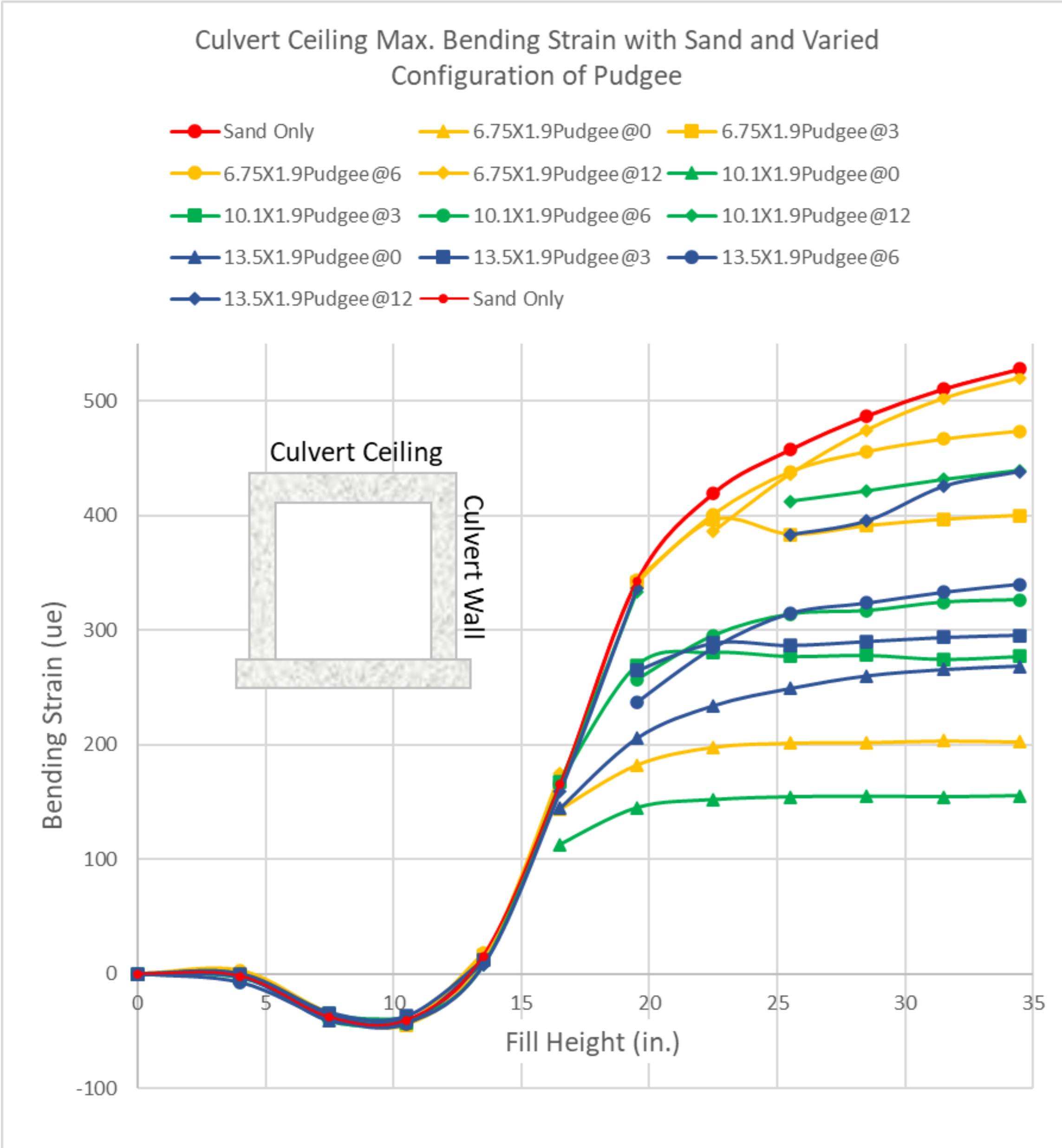

Figure 3.8 Culvert Ceiling Maximum Bending Strains — Sand Only and Pudgee Inclusions

Culvert wall maximum strains exhibited diverse trends. When a Pudgee inclusion was used, culvert wall strains were higher or similar to those measured under the sand-only loading condition. Figure 3.9 visualizes these trends and underscores the importance of exercising caution when using Pudgee inclusions as they can increase the culvert wall's maximum bending strain. Some data points were excluded due to the area above the Pudgee inclusion not being compacted according to the procedures outlined in Section 3.6.3.2.

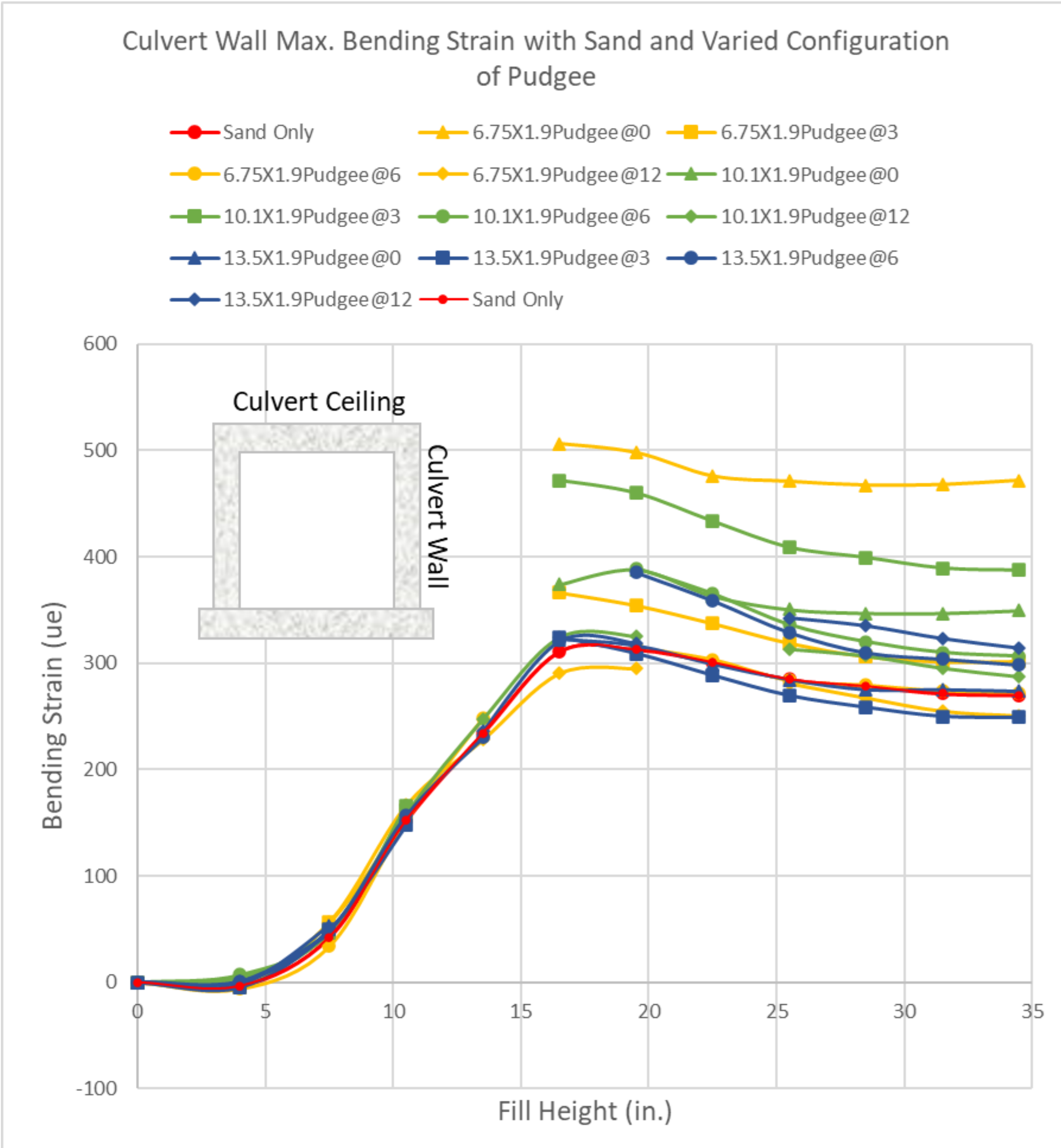

Figure 3.9 Culvert Wall Maximum Bending Strains — Sand Only and Pudgee Inclusions

3.7.1.3 Tests with Geofoam at Different Elevations Above the Culvert

This section reports on the performance of Geofoam, an LWM often used in US highway construction. For all tests discussed in this section, the Geofoam specimen was 6.75 in. x 2.75 in. We varied the distance between the bottom of the Geofoam and the culvert's top surface (0.0 in., 3.0 in., 6.0 in.).

Compared to the sand-only loading condition, Geofoam reduced culvert ceiling strain (Figure 3.10). Geofoam placed 0.0. in. above the culvert's top surface yielded the largest reduction in strain. Our observations align with theoretical expectations, which predict an inverse relationship between strain reduction and the distance between Geofoam and the culvert's top surface. Some data points were excluded due to incomplete compaction above the Geofoam.

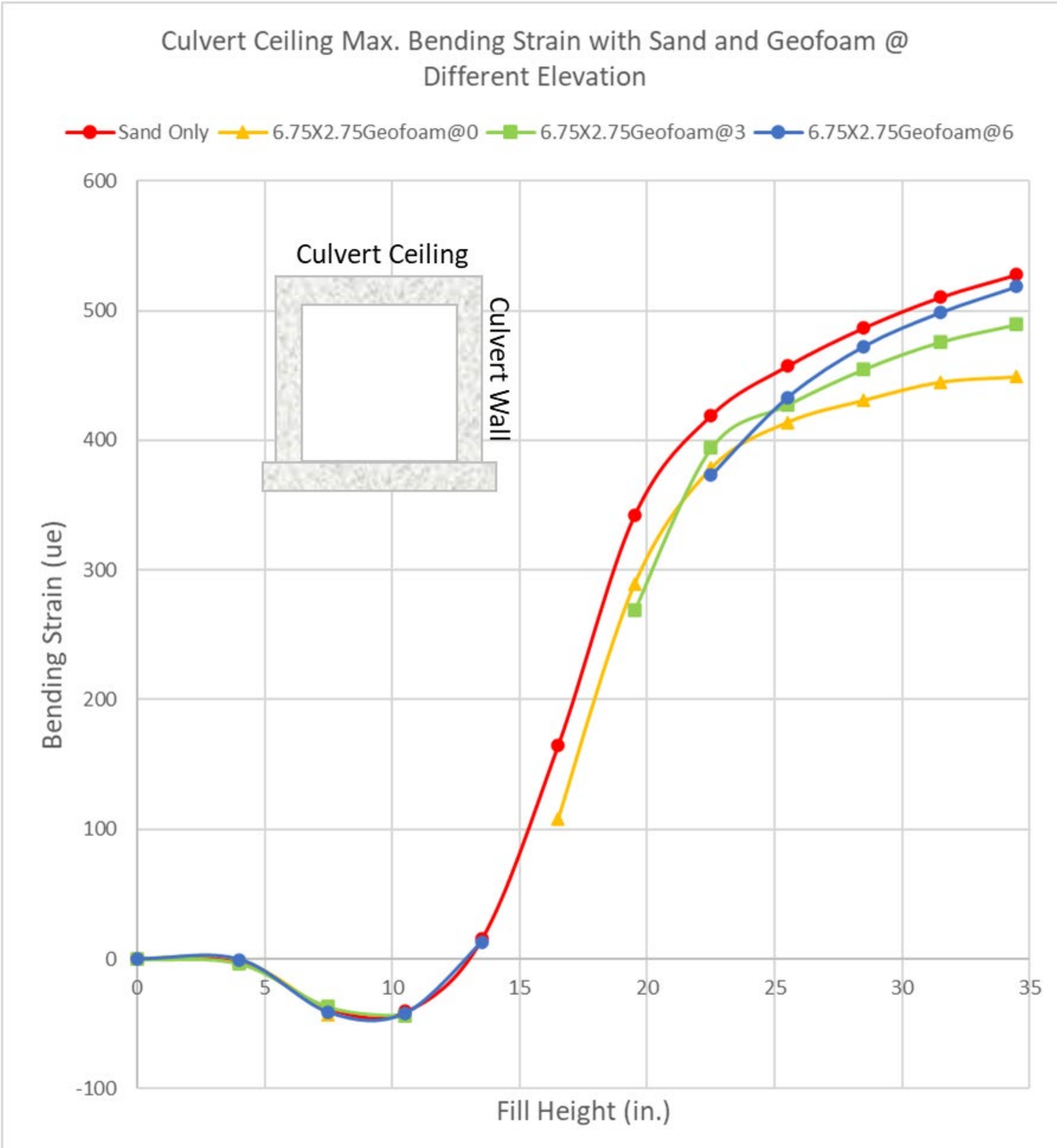

Figure 3.10 Culvert Ceiling Maximum Bending Strains — Sand Only and Geofoam Inclusions

Geofoam produced higher culvert wall maximum strains than the sand-only loading condition, with the most significant increases observed for Geofoam installed near the culvert's top surface (Figure 3.11). Geofoam placed 6.0 in. above the culvert's top surface exhibited trends similar to the sand-only loading condition. Some data points were excluded from analysis due to incomplete compaction above the Geofoam.

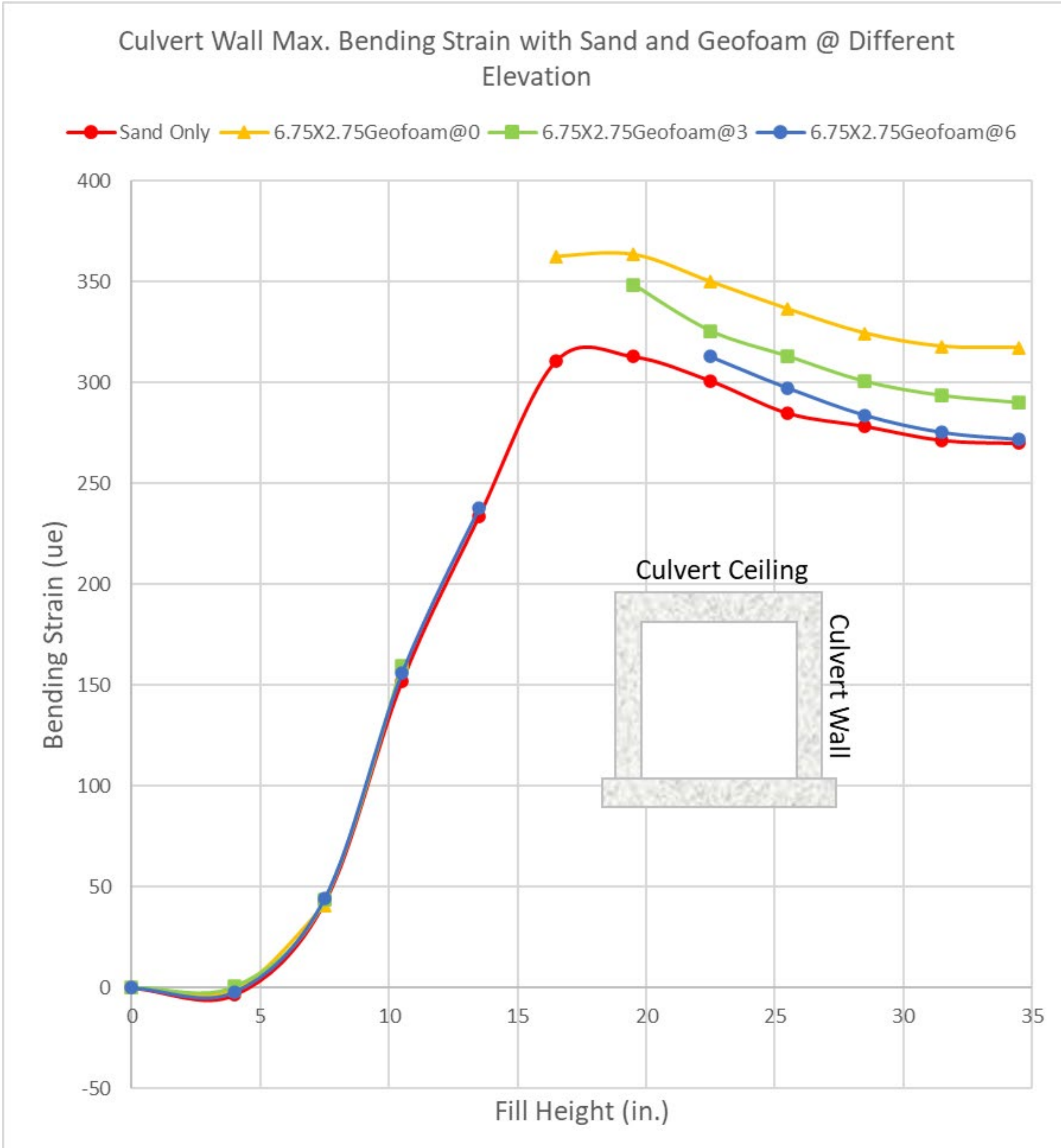

Figure 3.11 Culvert Wall Maximum Bending Strains — Sand Only and Geofoam Inclusions

3.7.1.4 Comparison of Strain Changes between Pudgee and Geofoam

Figure 3.12 compares test results for Pudgee and Geofoam inclusions of the same size (6.75 in. x 2.675 in.) placed the same distance (0.0 in.) above the culvert's top surface. Despite a higher mass density, Pudgee yielded greater reductions in culvert ceiling strain. This demonstrates that the self-weight of LWM is not the sole determinant of load reduction — the material's elastic modulus also plays a significant role. For instance, at a fill height of 34.5 in., we observed a 58.71% strain reduction with Pudgee compared to a 14.96% reduction for Geofoam. Pudgee's lower elastic modulus contributes to a larger arch effect, which redistributes the load to adjacent areas, effectively reducing the load beneath the LWM.

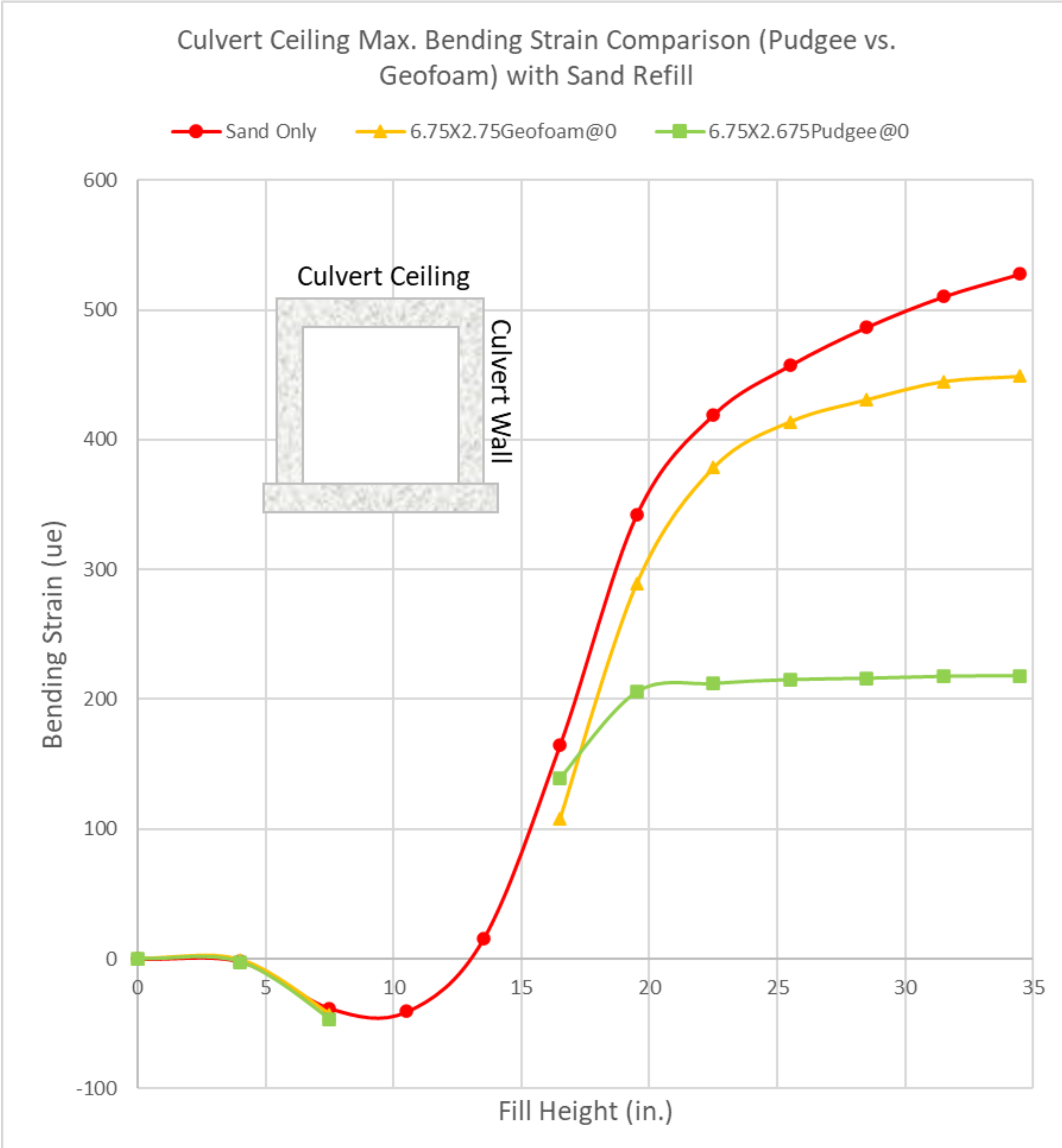

Figure 3.12 Culvert Ceiling Maximum Bending Strains — Pudgee and Geofoam Inclusions, and Sand Refill

Figure 3.13 compares the effects of Geofoam and Pudgee inclusions on culvert wall strain. At a fill height of 34.5 in, the Pudgee inclusion resulted in a 44.15% increase in strain, while Geofoam inclusion yielded a 17.59% increase. This is attributable to the arch effect discussed above.

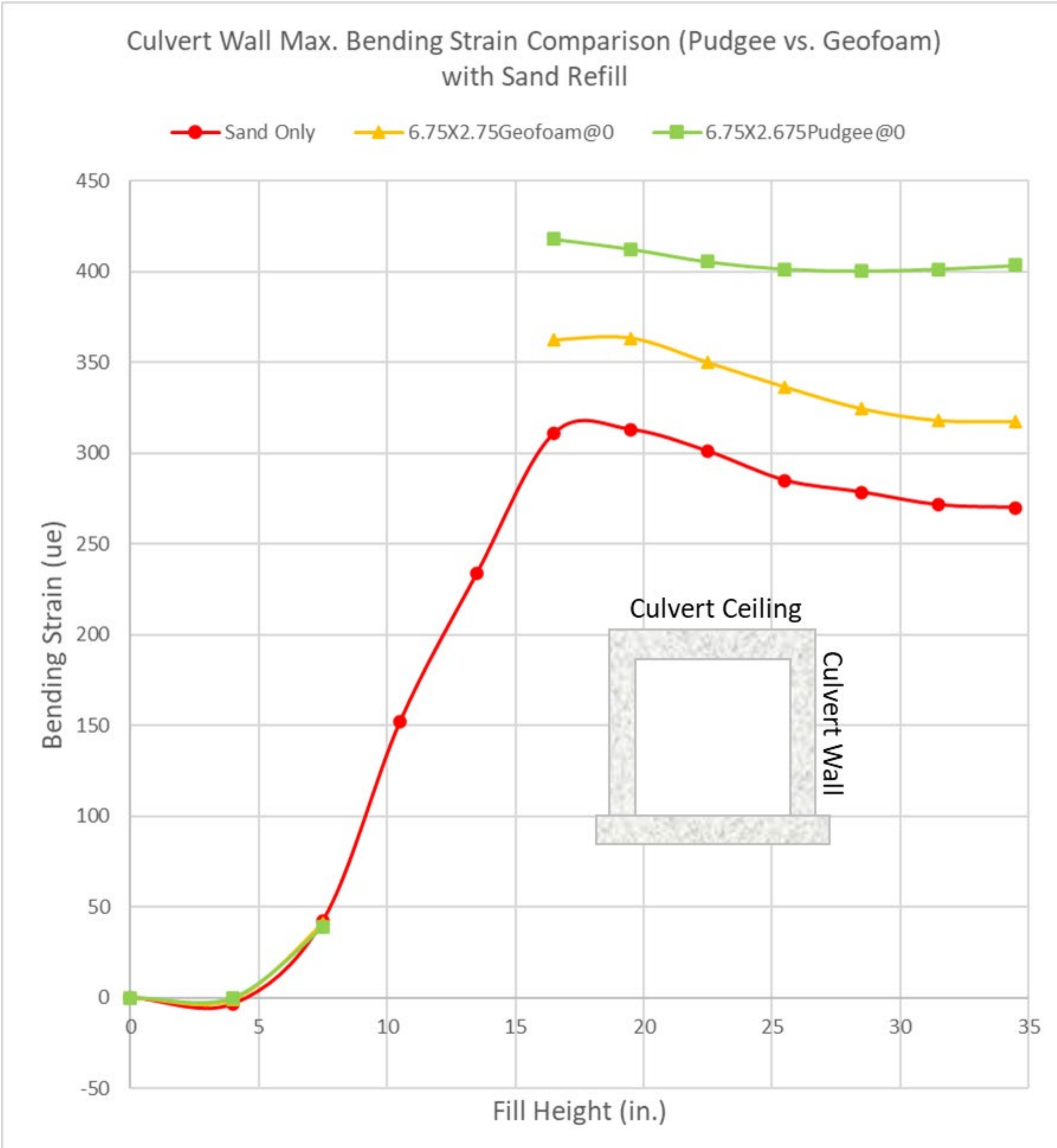

Figure 3.13 Culvert Wall Maximum Bending Strains — Pudgee and Geofoam Inclusions, and Sand Refill

3.7.2 Loading with Brown Silty Clay

Brown silty clay is commonly used as fill material in highway embankments due to its widespread availability and practicality. The series of tests described in the subsections below used brown silty clay as the loading material. Testing involved applying loads using four LWMs: Pudgee, Geofoam, cellular concrete, and lightweight aggregates. Our results offer insights into changes in culvert ceiling and wall bending strains when using more practical LWMs with different installation profiles.

3.7.2.1 Tests with Pudgee at Different Installation Profiles Above the Culvert

For testing, we varied the widths of Pudgee inclusions (6.75 in., 10.1 in., 13.5 in.) but held the thickness constant at 1.9 in. We varied the distance between the culvert's top surface and the bottom of the Pudgee inclusion (0.0 in., 3.0 in., 6.0 in., 12.0 in.). Before evaluating Pudgee's performance, we conducted a reference test using only brown silty clay as the fill material to establish a baseline (i.e., soil-only loading condition).

For all 12 tests in which Pudgee inclusions were used, culvert ceiling bending strains were less than those measured under the soil-only loading condition (Figure 3.14). This trend is especially noticeable for fill heights greater than 16.5 in (Figure 3.14). Soil compaction began at an elevation of 13.5 inches, resulting in strain increases above this height.

Holding the size of Pudgee inclusion constant, the closer the material was placed to the culvert's top surface, the greater reduction in strain. Strain reductions were directly proportional to the Pudgee inclusion's width when the distance between the top of the culvert and Pudgee was less than 6.0 in. But this trend shifts for Pudgee inclusions placed at least 6.0 in. from the culvert's top surface. At a distance of 12.0 in. above the culvert's top surface, the smallest-width Pudgee inclusion (6.75 in.) yielded the largest reduction in strain. We observed the overall largest strain reduction for the 13.5-in. Pudgee placed 0.0 in. above the culvert's top surface. Some data points were excluded due to the area above the Pudgee inclusion not being compacted according to outlined procedures.

In all cases, we measured higher culvert wall strains when Pudgee inclusions were used than under the soil-only loading condition. The strain curve for the soil-only loading condition (in red) continuously increases until the elevation exceeds 16.5 in., where the deformation on the culvert wall decreases due to normal compaction above the culvert's top surface. This larger increase in deformation on the culvert ceiling leads to negative strain due to the semi-rigid connection between the culvert ceiling and wall.

When the distance between the culvert's top surface and Pudgee inclusion was smaller (0.0 in., 3.0 in.), increases in strain were directly proportional to the inclusion width. However, this trend shifts at the 6.0-in. distance, eventually reversing at the 12.0-in. distance. When the Pudgee inclusion was placed 12.0 in. above the culvert's top surface, the smallest inclusion (6.75 in.) yielded the largest increase in strain.

Figure 3.15 visualizes these trends and reaffirms the importance of exercising caution when using Pudgee inclusions because they can increase the culvert wall maximum bending strain. Some data points were excluded due to incomplete soil compaction above the Pudgee inclusion.

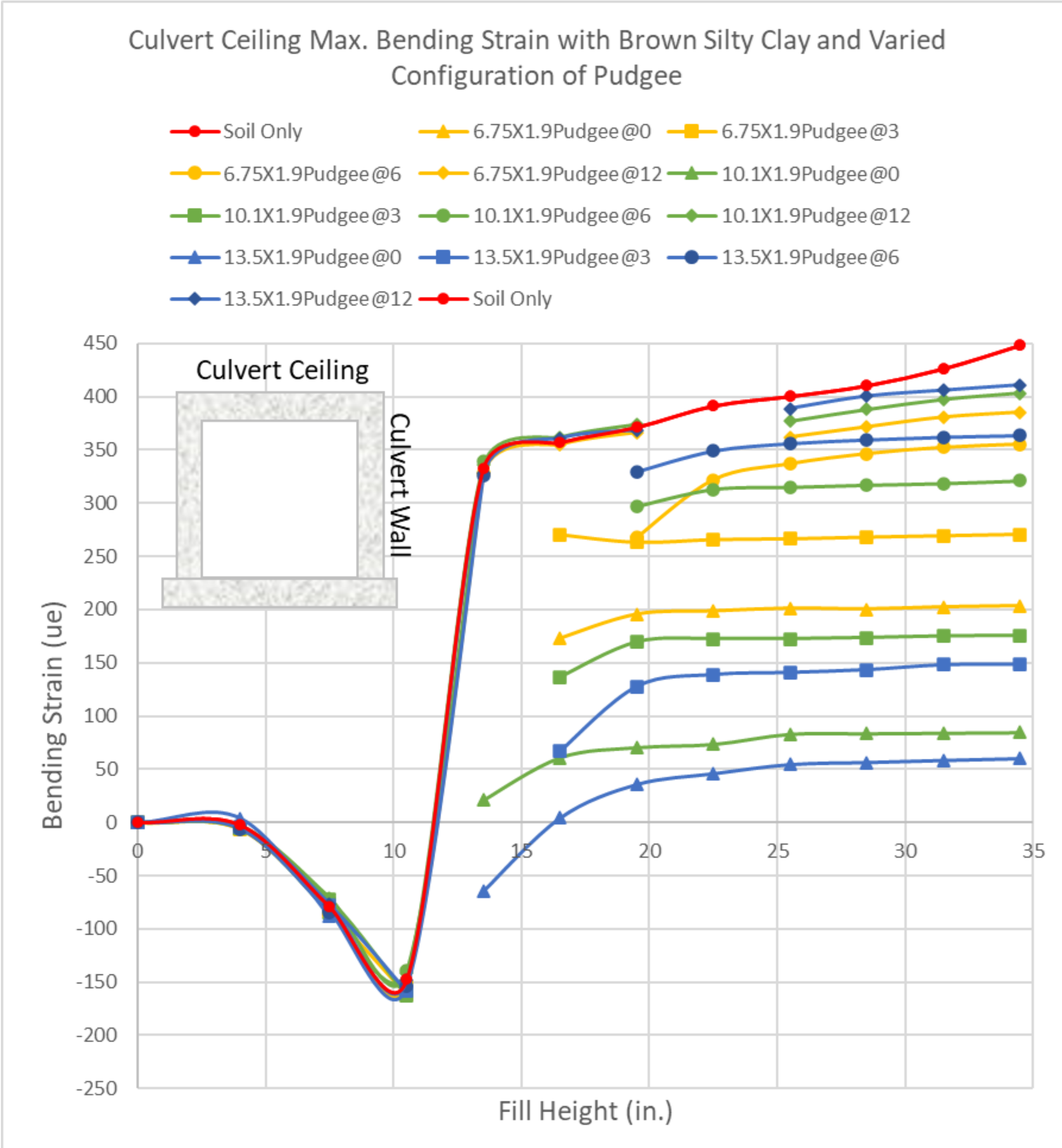

Figure 3.14 Culvert Ceiling Maximum Bending Strains — Soil Only and Pudgee Inclusions

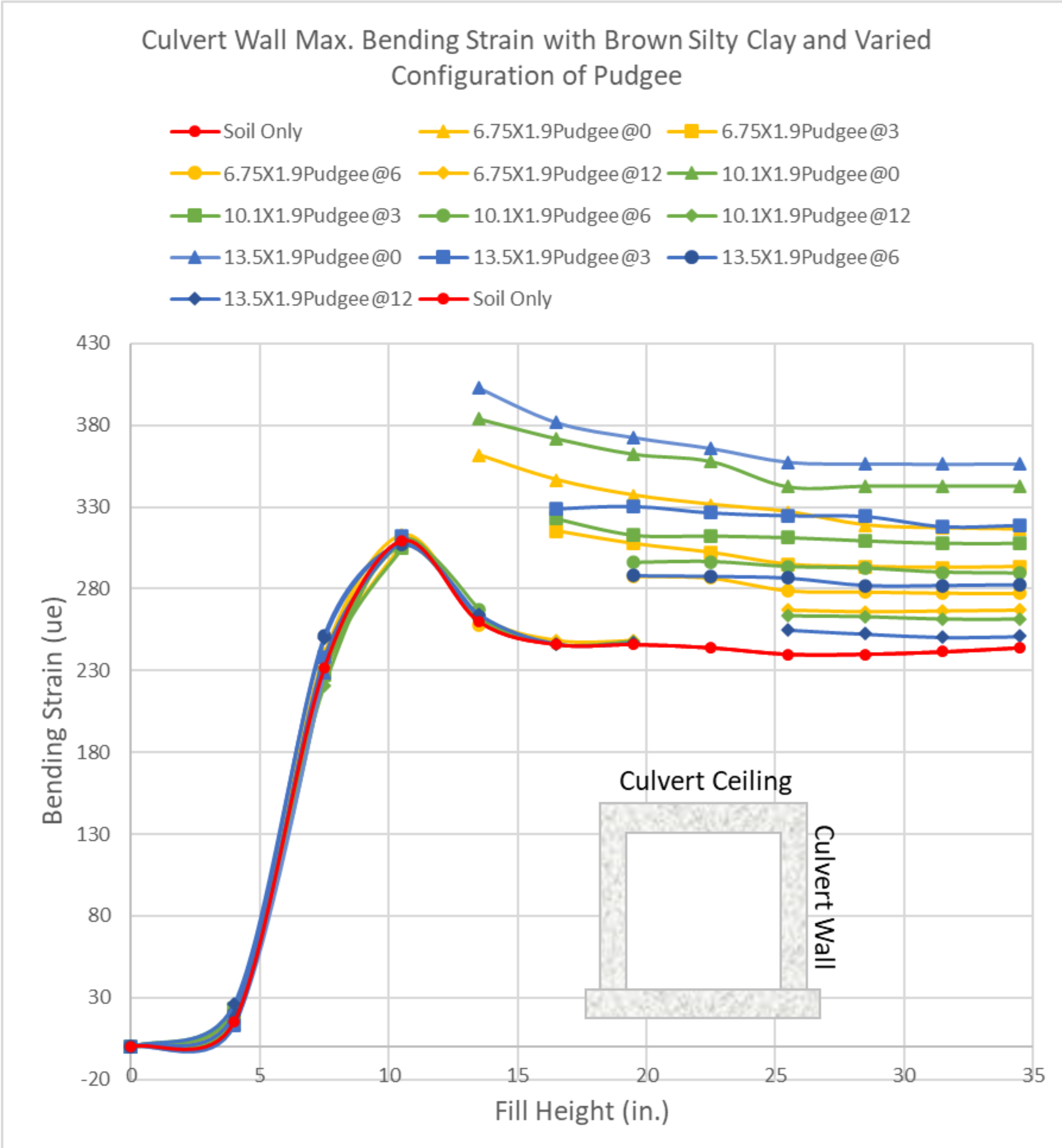

Figure 3.15 Culvert Wall Maximum Bending Strains — Soil Only and Pudgee Inclusions

3.7.2.2 Tests with Geofoam at Different Elevations Above the Culvert

For Geofoam testing, we used a single size of Geofoam inclusion (10.25 in. x 6.0 in.) placed at four different distances (0.0 in., 3.0 in., 6.0 in., 12.0 in.) above the culvert's top surface. Baseline data from previous tests using only brown silty clay as fill material (i.e., soil-only loading condition) were used for comparisons.

Compared the soil-only loading condition, we measured lower culvert ceiling strains when Geofoam inclusions were used, with the greatest reductions seen when Geofoam was installed directly above the culvert's top surface. As the distance between the Geofoam inclusion and the culvert's top surface increased, the magnitude of strain reductions decreased. At a distance of 12.0 in., we observed little difference in strains between the Geofoam involved and soil-only loading conditions.

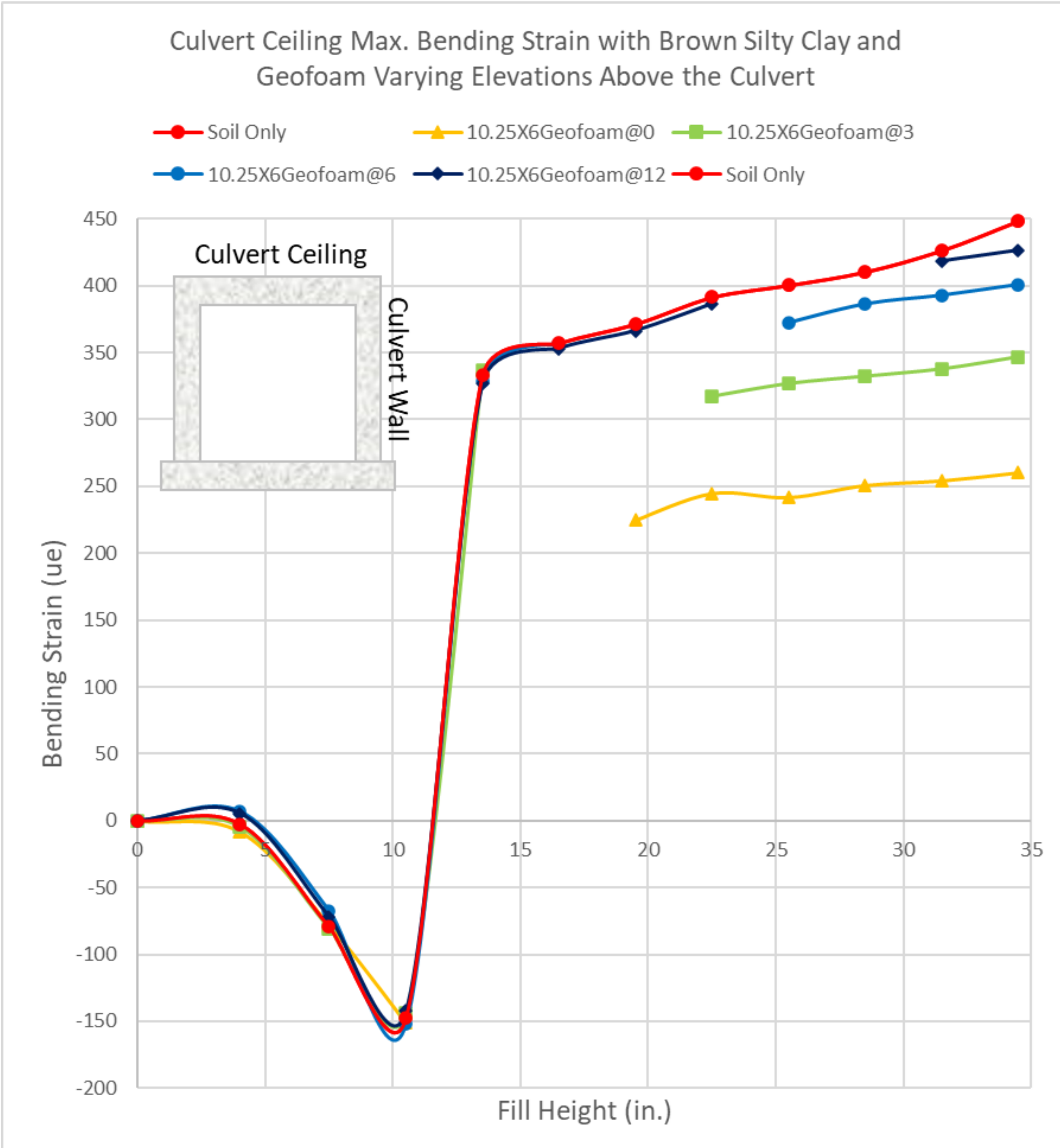

Figure 3.16 Culvert Ceiling Maximum Bending Strains — Soil Only and Geofoam Inclusions

As the distance between the Geofoam inclusion and the culvert's top surface decreased, the culvert wall maximum strain increased, similar to the trend described in Section 3.7.1.3 (Figure 3.17).

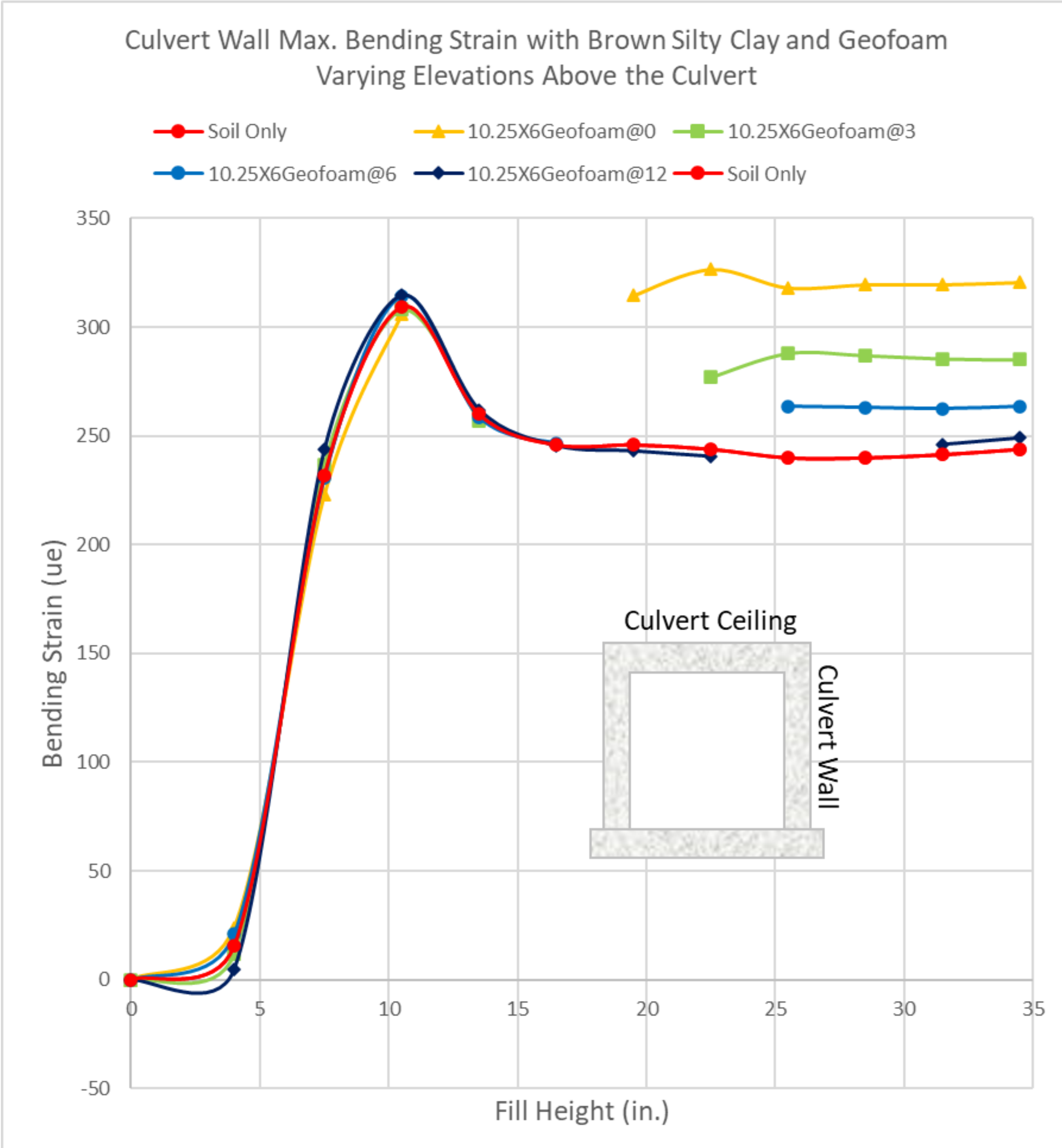

Figure 3.17 Culvert Wall Maximum Bending Strains — Soil Only and Geofoam Inclusions

3.7.2.3 Tests with Cellular Concrete: Variations in Installation Profile Above the Culvert Using Procedures from Section 3.6.3.2

Our tests used three different sizes of cellular concrete block (6.5 in. x 3.0 in., 6.5 in. x 6.0 in., 10.25 in. x 6.0 in.). The bottoms of these blocks were placed at four different distances above culvert's top surface (0.0 in., 3.0 in., 6.0 in., 12.0 in.). Baseline data from previous tests using the soil-only loading condition were used for comparisons.

Culvert ceiling maximum bending strains tended to be higher for cellular concrete block involved than for the soil-only loading condition (Figure 3.18).

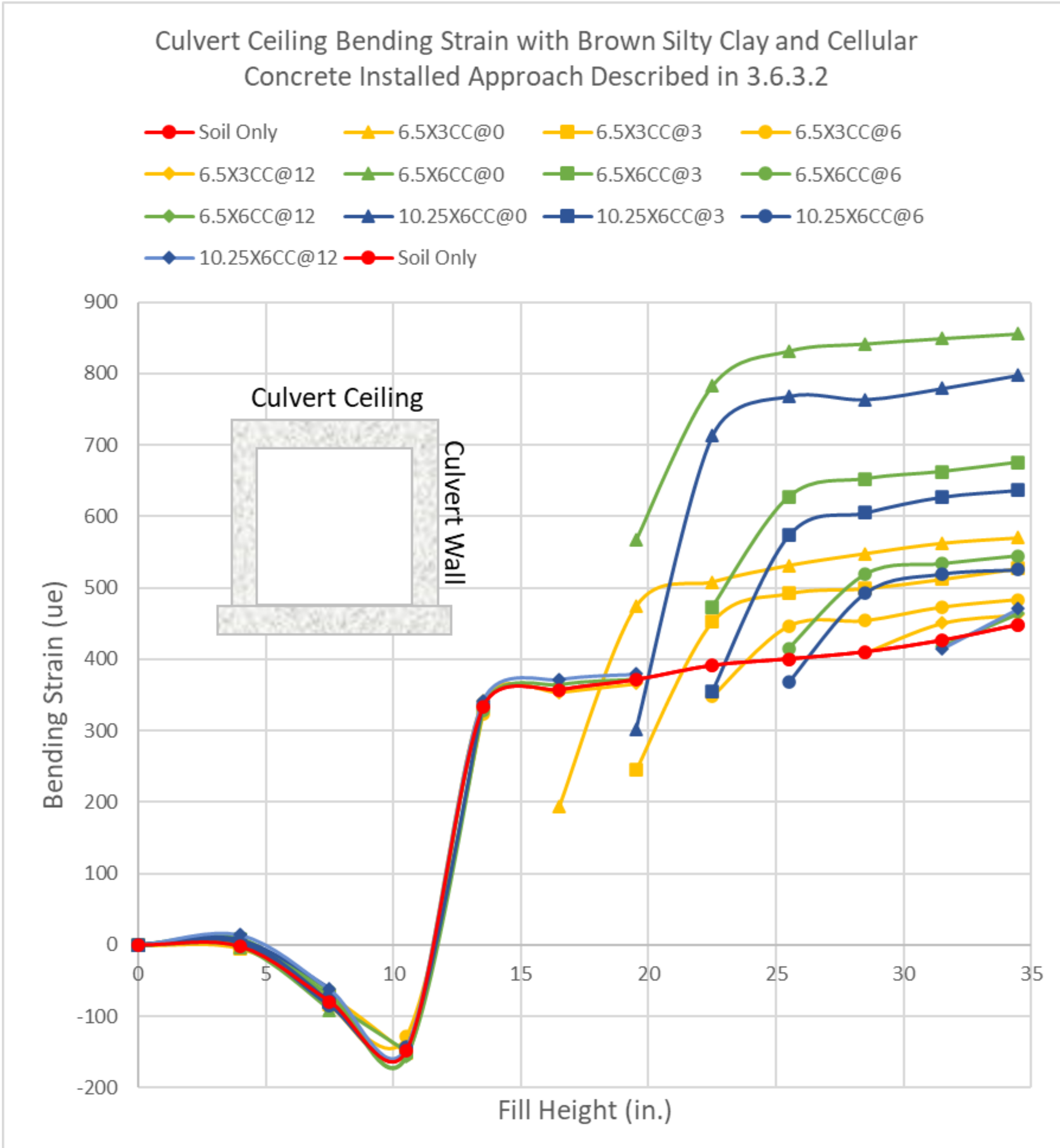

Figure 3.18 Culvert Ceiling Maximum Bending Strains — Soil Only and Cellular Concrete Block

Holding the size of cellular concrete block constant, the closer the block was to the culvert's top surface, the greater the measured increase in strain. We observed the largest strain increases with the 6.5 in. x 6.0 in. cellular concrete block (neither from the smallest size of 6.5 in. X 3.0 in., nor from the largest size of 10.25 in. X 6.0 in.) when the distance between the bottom block and the culvert's top surface was 0.0 in. One possible explanation for this trend is that cellular concrete is stiffer than the surrounding soil, causing significantly less deformation and potentially creating a negative arch effect. A negative arch effect increases loading in the area under the cellular concrete block. Compared to cellular concrete block with a size of 6.5 in. x 6.0 in., the 6.5 in. X 3.0 in. block creates less differential deformation on the surrounding soil because it is less thick. The block sized 10.25 in. x 6.0 in. shelters a larger area underneath the cellular concrete block and reduces load redistribution.

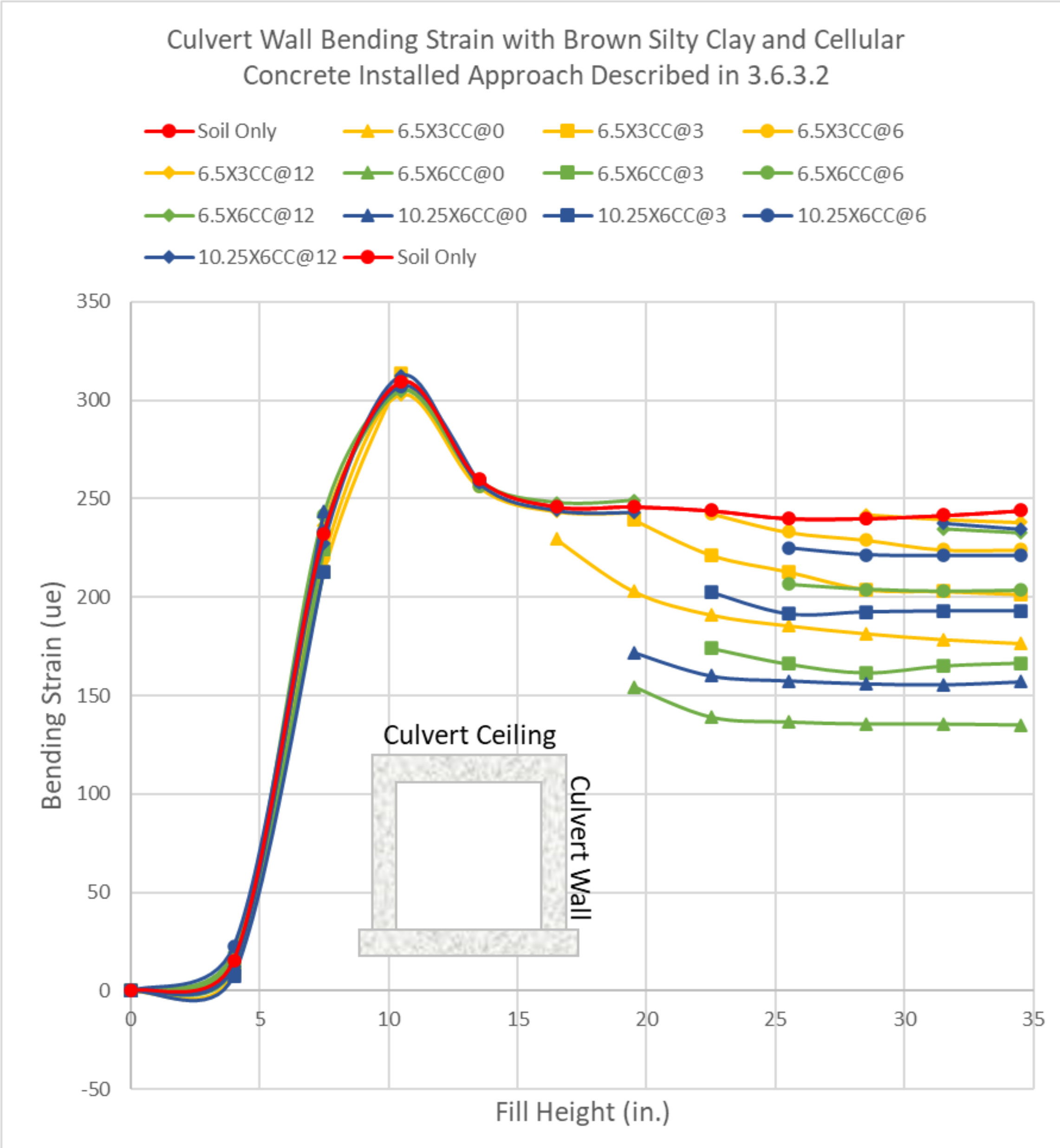

Figure 3.19 Culvert Wall Maximum Bending Strains — Soil Only and Cellular Concrete Block

Culvert wall maximum bending strains were lower with cellular concrete blocks than under the soil-only loading condition (Figure 3.19). Load redistribution due to the negative arch effect caused by cellular concrete block explains why culvert wall and ceiling maximum strains exhibited opposite trends.

3.7.2.4 Tests with Cellular Concrete: Variations in Installation Profile Above the Culvert Using Procedures from Section 3.6.3.3

This section reports test results for the dig-and-bury method of installing cellular concrete blocks. We used three different widths of cellular concrete block (6.5 in., 10.25 in., 13.25 in.). Block thickness was held constant at 6.0 in. for all tests. The vertical distance between the culvert's top surface and the bottom of the block varied (0.0 in., 3.0

in., 6.0 in., and 12.0 in.). We compared the performance of different block – distance combinations to the soil-only loading condition.

Culvert ceiling maximum bending strains were higher when cellular concrete blocks were used than under the soil-only loading condition (Figure 3.20). This differs slightly from the cases shown in Figure 3.18 and results from soil being compacted before the dig-and-bury steps.

Similar to the results reported in Section 3.7.2.3, when the size of the concrete block was held constant, we observed greater strain increases when the block was placed nearer to the culvert's top surface. The largest strain increase was observed when the smallest size of cellular concrete block was placed 0.0 in. above culvert's top surface. This is due to smaller blocks creating more negative arch effect, which increases culvert ceiling strain. Larger blocks shelter a bigger area underneath them, which reduces load redistribution.

We saw a similar trend in maximum strains for the culvert wall. In all tests involving cellular concrete blocks, we saw greater strains than under the soil-only loading condition (Figure 3.21). This divergence from observations reported in Section 3.7.2.3 is due to the dig-and-bury method resulting in more compaction above the culvert. When the dig-and-bury method is employed, deformations on the culvert ceiling and wall are built up before soil is dug out. These deformations are not fully released once digging is complete. Added load from the block installation accumulates on both the culvert ceiling and wall, which increases both culvert ceiling and wall strains.

Results discussed in this section and the previous one highlight that the method used to install LWMs influences loadings on the culvert, even when the same LWM is used. The culvert wall is most affected. The dig-and-bury method generated higher loadings on the culvert wall due to increased compaction at lower elevations. Unlike elastic or discrete materials, brown silty clay does not exhibit elastic recovery after deformation caused by loading. Even if the load is reduced, the structure remains deformed.

With the dig-and-bury installation method, when part of the brown silty clay is excavated, the surrounding soil stays in place, preserving most of the deformation. Subsequent loading from the LWM combines with this existing deformation, significantly increasing culvert wall strain. The levels of strain induced by the two installation methods — direct placement and dig-and-bury — differ significantly.

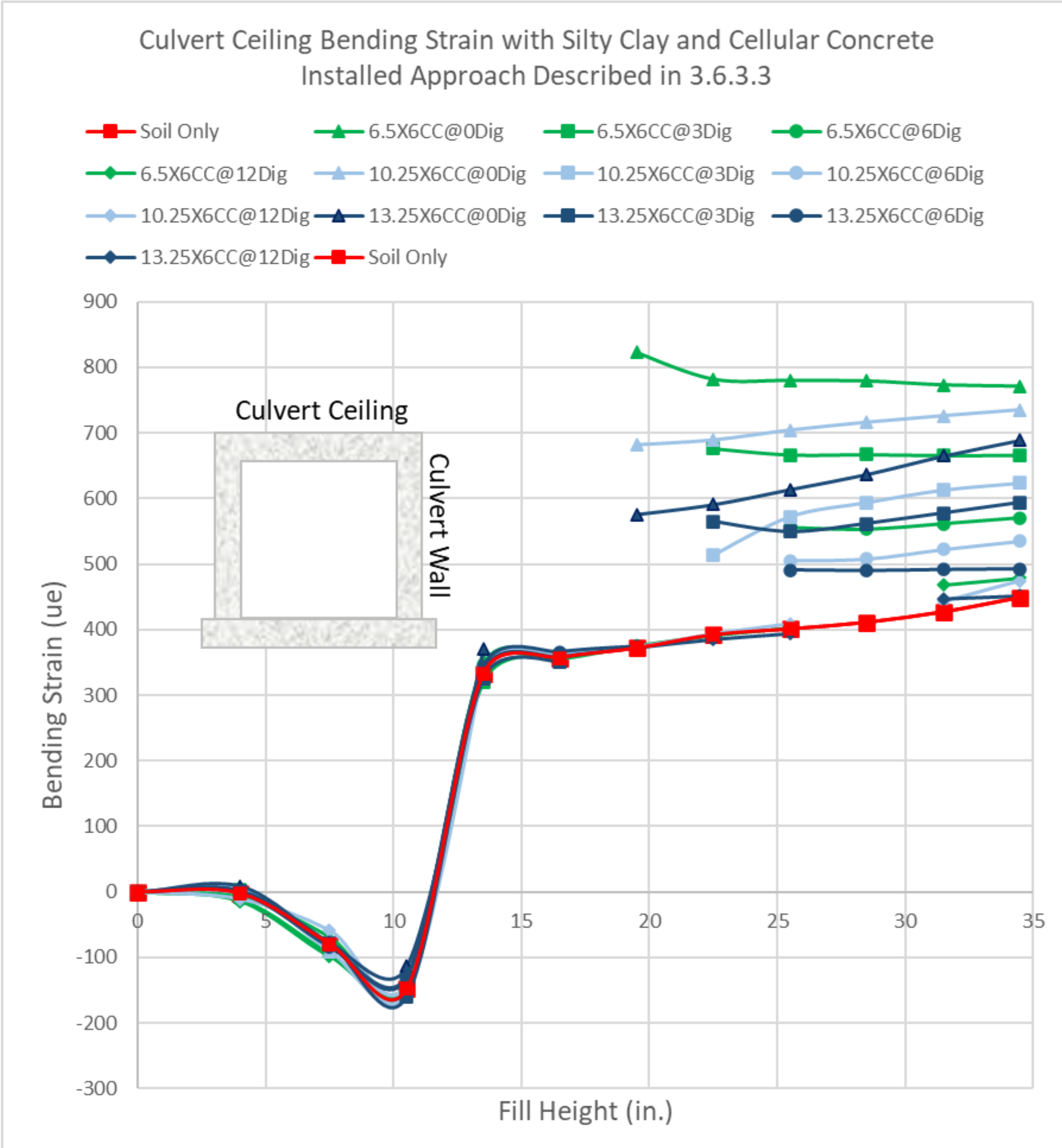

Figure 3.20 Culvert Ceiling Maximum Bending Strains — Soil Only and Cellular Concrete Block

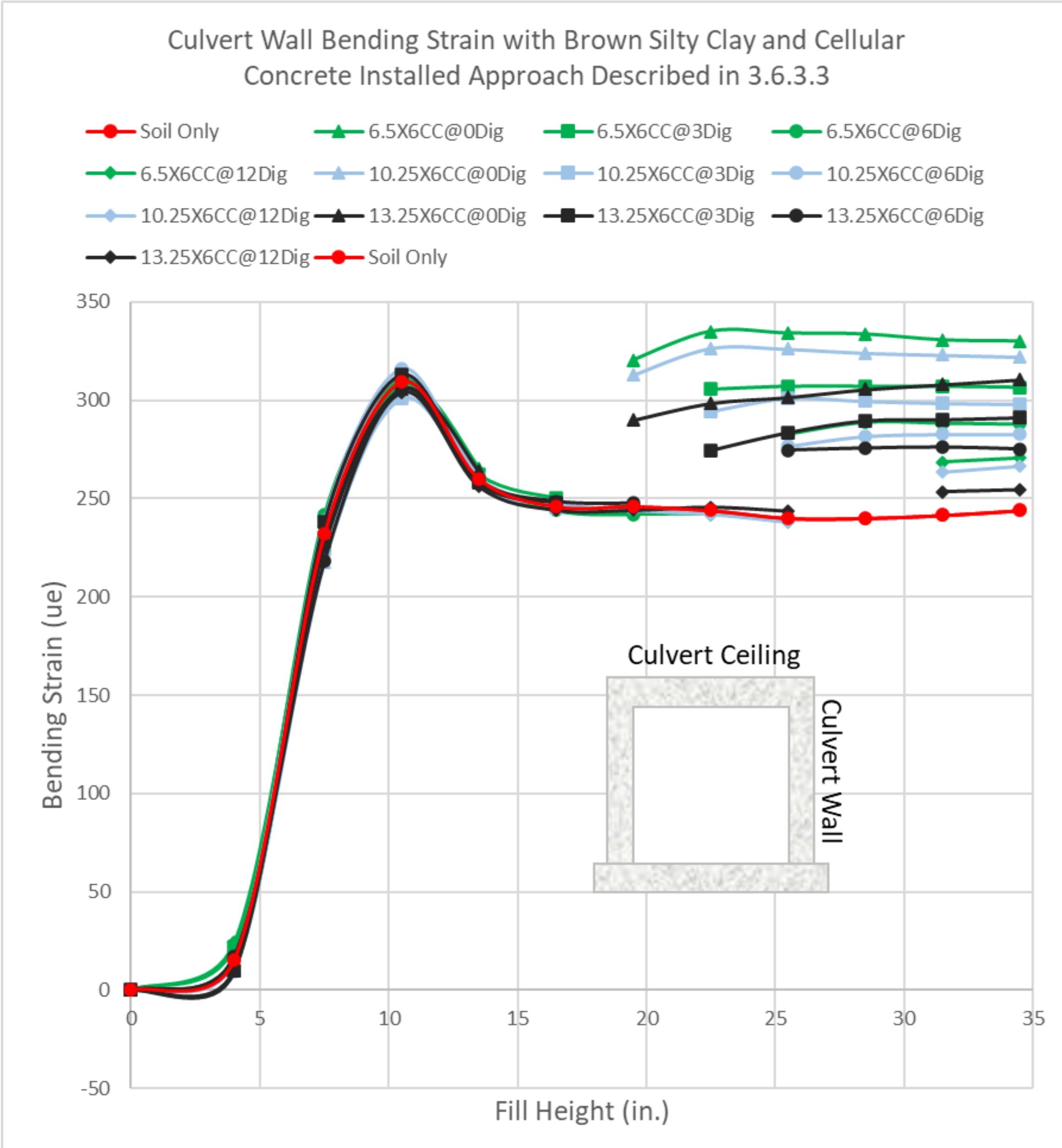

Figure 3.21 Culvert Wall Maximum Bending Strains — Soil Only and Cellular Concrete Block

3.7.2.5 Tests with Lightweight Aggregates at Different Installation Profiles Above the Culvert

We conducted these tests using lightweight aggregates in three sizes (13.5 in. x 6.0 in., 13.5 in. x 12.0 in., 20.0 in. x 12.0 in.) placed at three different distances above the culvert's top surface (0.0 in., 3.0 in., 12.0 in.). We compared results for lightweight aggregates to those obtained under the soil-only loading condition.

Across testing configurations, culvert ceiling maximum bending strains tended to be higher when lightweight aggregates were used than under the soil-only loading condition. We attribute this to the negative arch effect caused by the higher elastic modulus of lightweight aggregates and more compaction before the dig-and-bury installation. But maximum strains at points where compaction on lightweight aggregates starts were lower than those produced under the soil-only loading condition. Notably, maximum strains generated by two sizes of lightweight aggregate

(13.5 in. X 12.0 in., 20.0 in. X 12.0 in.) placed 12.0 in. above the culvert's top surface were less than strains under the soil-only loading. In these situations, the self-weight of lightweight aggregates plays a dominant role.

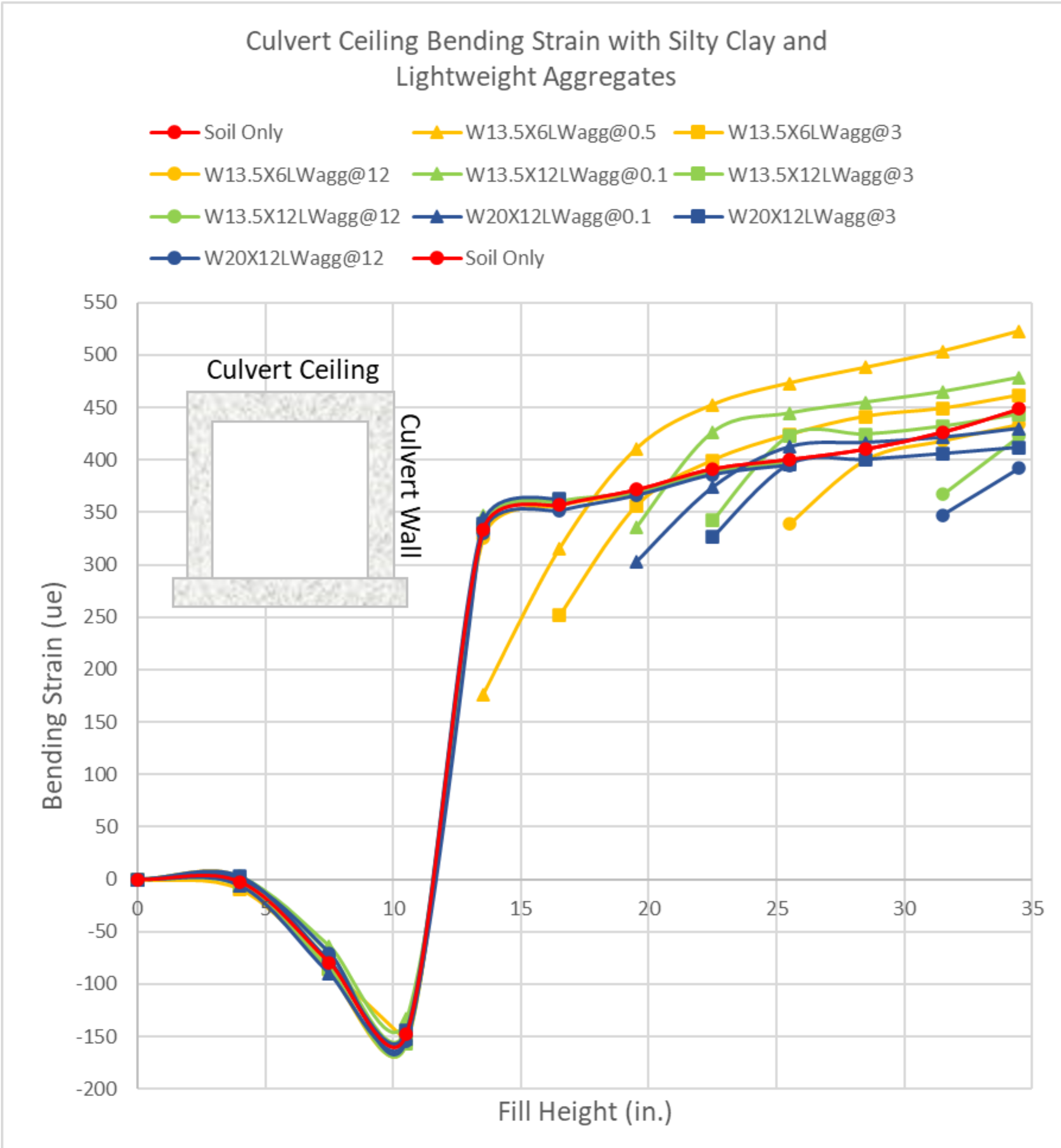

Figure 3.22 Culvert Ceiling Maximum Bending Strains — Soil Only and Lightweight Aggregates

Holding the size of the lightweight aggregates constant, we saw that strains increased the closer aggregates were placed to the culvert's top surface. The smallest size of lightweight aggregate installed 0.0 in. above the culvert's top surface yielded the highest increases in strain. Larger sizes of lightweight aggregate shelter a larger area underneath, create less negative arch effect, and result in less culvert ceiling strain.

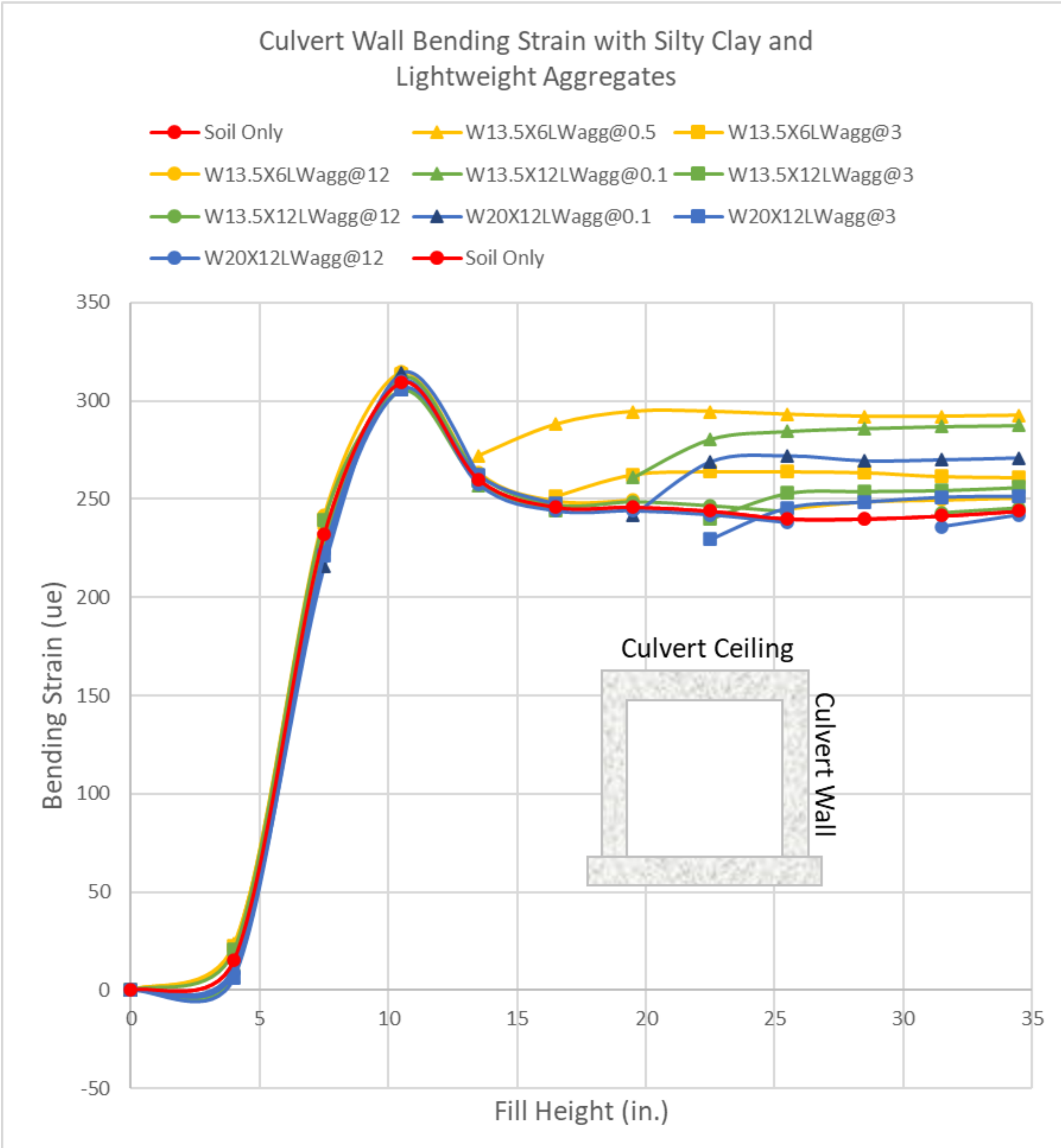

Figure 3.23 Culvert Wall Maximum Bending Strains — Soil Only and Lightweight Aggregates

Maximum strains observed for the culvert wall were generally higher with lightweight aggregates than under the soil-only loading condition (Figure 3.23). These trends are akin to the results documented in the previous section for cellular concrete blocks installed using the dig-and-bury method. With this installation method, deformations on the culvert ceiling and wall accumulate before soil is excavated, and these deformations are not fully released by excavation. Added load from the lightweight aggregates accumulates on both the culvert ceiling and wall, which results in higher strains for both the ceiling and wall, except when larger lightweight aggregate inclusions were placed 12.0 in. above the culvert's top surface — for this cases there was barely any strain reduction.

3.8 Summary on Reduced-Scale Model Laboratory Test

Our tests analyzed the impacts of dry play sand, brown silty clay, Pudgee, Geofoam, cellular concrete blocks, and lightweight aggregates on culvert ceiling and wall maximum bending strains. Despite Pudgee's higher mass density, it resulted in greater culvert ceiling strain reductions than Geofoam. The proximity of material to the culvert’s top surface strongly influences the magnitude of strain reductions or increases. Generally, placing LWMs closer to the culvert’s top surface led to greater strain alterations. In most installation profiles Pudgee and Geofoam inclusions increased culvert wall strain. Cellular concrete and lightweight aggregates generally increased both culvert ceiling and wall strains. These findings provide valuable insights for determining the optimal method for using lightweight materials to reduce culvert loads.

Section 4 Numerical Simulation

Numerical simulation involves using mathematical models and computational techniques to analyze real-world systems or phenomena by breaking down complex problems into solvable equations. In this project, leveraging numerical simulation offered numerous benefits. Interactions among the new embankment, buried LWMs, and the existing culvert are complex, and numerical simulation accurately captured this complexity by considering factors like soil properties, material behavior, and loading conditions.

Numerical simulation provides a cost-effective alternative to full-scale physical tests by virtually simulating different scenarios. With numerical simulation, we can quickly test different design installation profiles and scenarios and easily modify parameters such as LWM type and placement, embankment height, and soil properties to assess their impact on culvert pressure. Simulations generate data that can be used to develop empirical formulas for practical LWM profile design.

4.1 FLAC – A Commercial Tool for Advanced Numerical Simulation

Fast Lagrangian Analysis of Continua (FLAC) is robust numerical modeling software used extensively in geotechnical engineering and rock mechanics. It simulates material behavior under diverse loading and boundary conditions. FLAC employs the finite difference method to tackle problems related to soil and rock mechanics, such as slope stability analysis, excavation support design, and studies on underground structure interaction.

Previous Kentucky Transportation Center (KTC) projects verified FLAC's effectiveness. It accurately predicted loads on a 9.0 ft. wide x 8.0 ft. high culvert embedded under 52.0 ft. of fill, including Geofoam, on US 127 in Russell County, Kentucky.[5] Additionally, FLAC successfully compared loads on a culvert with two different inclusions — Geofoam and cellular concrete — required for highway widening on I-75 in Grant County, Kentucky.[8] Moreover, it accurately predicted loads on a three-sided culvert with shallow Geofoam filling on KY 1447 in Jefferson County, Kentucky.[9]

4.2 Approach and Methodology in Numerical Simulations

In our numerical simulations, the dimensions of the culvert opening were set at 10.0 ft. wide x 10.0 ft. high, with specific thicknesses for the ceiling, bottom, and walls. Dimensions related to LWMs were scaled based on culvert width, which helped generate dimensionless parameters for empirical formulas. Next, we generated a finely divided geometrical model that precisely captures the physical components of the culvert, embankment, surrounding soil layers, and layout of LWMs. This process involved delineating geometric features and attributing material properties based on the culvert and surrounding environment's conditions.

Next, we transformed the geometrical model into a finite difference grid, discretizing the entire domain into smaller grids to enable efficient numerical computations. Grid generation is crucial, particularly in areas of material discontinuities, to ensure simulation accuracy.

For the soils and LWMs considered, appropriate constitutive models were employed to describe their mechanical behavior under diverse loading conditions. This included utilizing models such as the Mohr-Coulomb model for soils and elastic models for LWMs.

We imposed boundary conditions and encompassing constraints and supports to simulate interactions among the culvert, embankment, and surrounding soil layers. We conducted simulations based on the defined model setup, which encompassed the size and placement of LWMs, material properties, and loading conditions. FLAC iteratively solves governing equations to calculate system response, with a specific focus on culvert ceiling and wall moments.

Once simulations were complete, we performed sensitivity analyses to pinpoint key parameters that significantly impact culvert behavior and moment variations. Numerical simulations were validated and verified by comparing them to field test data from previous studies, ensuring our model is accurate and reliable enough for real-world engineering applications.

4.3 Materials Involved in Numerical Simulations

To capture a broad spectrum of geotechnical scenarios, numerical simulations included a range of soils and LWMs. Soil selection encompassed different Young's modulus values, representing a continuum from relatively soft soils with low plasticity (e.g., low plasticity soil-clay) to extremely rigid soils (e.g., uniform gravel). This range is crucial as it is representative of typical soil variations encountered on real-world geotechnical projects.

Simulations also evaluated the effects of incorporating LWMs used in contemporary engineering. We performed detailed assessments of Geofoam (both soft and normal states), shredded tire chips, lightweight aggregates, and cellular concrete. Each material has unique properties and behaviors, which influence factors like load distribution, deformation characteristics, and overall structural performance. Table 4.1 lists the properties of all soils and LWMs evaluated in our simulations.

Table 4.1 Materials Used in Numerical Simulations

Material Type	Material	Young's Modulus (psf)	Poisson's Ratio	Density		Cohesion (psf)	Friction Angle
				(pcf)	(slug/ft^3)		
LWM	Soft Geofoam	7,200.90	0.050	1.261	0.0392		
LWM	Geofoam	13,299.48	0.100	1.287	0.0400		
LWM	Shredded tire chips	21,096.00	0.230	32.499	1.0101		
LWM	Lightweight aggregates	835,475.00	0.250	52.765	1.6400		
LWM	Cellular concrete	22,600,000.00	0.200	45.000	1.3986		
Soil	Low plasticity soil-clay	41,775.00	0.250	118.645	3.6876	125.31	24.00
Soil	Russell clay	397,733.30	0.250	118.722	3.6900	529.50	26.20
Soil	Uniform-coarse soil-sand	522,233.30	0.250	99.911	3.1053	0.00	34.00
Soil	Uniform gravel	835,475.00	0.250	99.911	3.1053	0.00	34.00

4.4 Developing the Numerical Simulation Model

The first step in model development was defining key parameters and variables. This included specifying culvert dimensions and properties (width, height, ceiling, bottom, and wall thickness) and properties of the surrounding soils and LWMs. Parameters related to the LWMs (length, thickness, distance from the culvert top, fill height) were defined in relation to the culvert width.

We then constructed a detailed geometrical model to represent physical aspects of the culvert, embankment, surrounding soil layers, and placement of LWMs. This involved generating geometric features for each component and assigning appropriate material properties based on real-world conditions. The geometrical model was converted into a finite difference grid, where the entire domain was discretized into smaller grids to facilitate numerical computations and ensure the accuracy and efficiency of simulations.

Appropriate constitutive models were selected for simulating the mechanical behavior of soils and LWMs under different loading conditions. For soils, models such as the Mohr-Coulomb model were used; elastic models were suitable for LWMs. Boundary conditions, including constraints and supports, were applied to simulate interactions among the culvert, embankment, and surrounding soil layers.

We derived our numerical simulation model from an embankment cross section that incorporates a culvert (Figure 4.1(a)). Figure 4.1(b) illustrates a section along the road, encompassing the culvert. This section is theoretically infinite on its left and right sides. In light of the symmetric conditions of geometry and loading, a half section from Figure 4.1(b) was utilized. Figure 4.1(c) illustrates the numerical simulation model generated following assignment of boundary conditions.

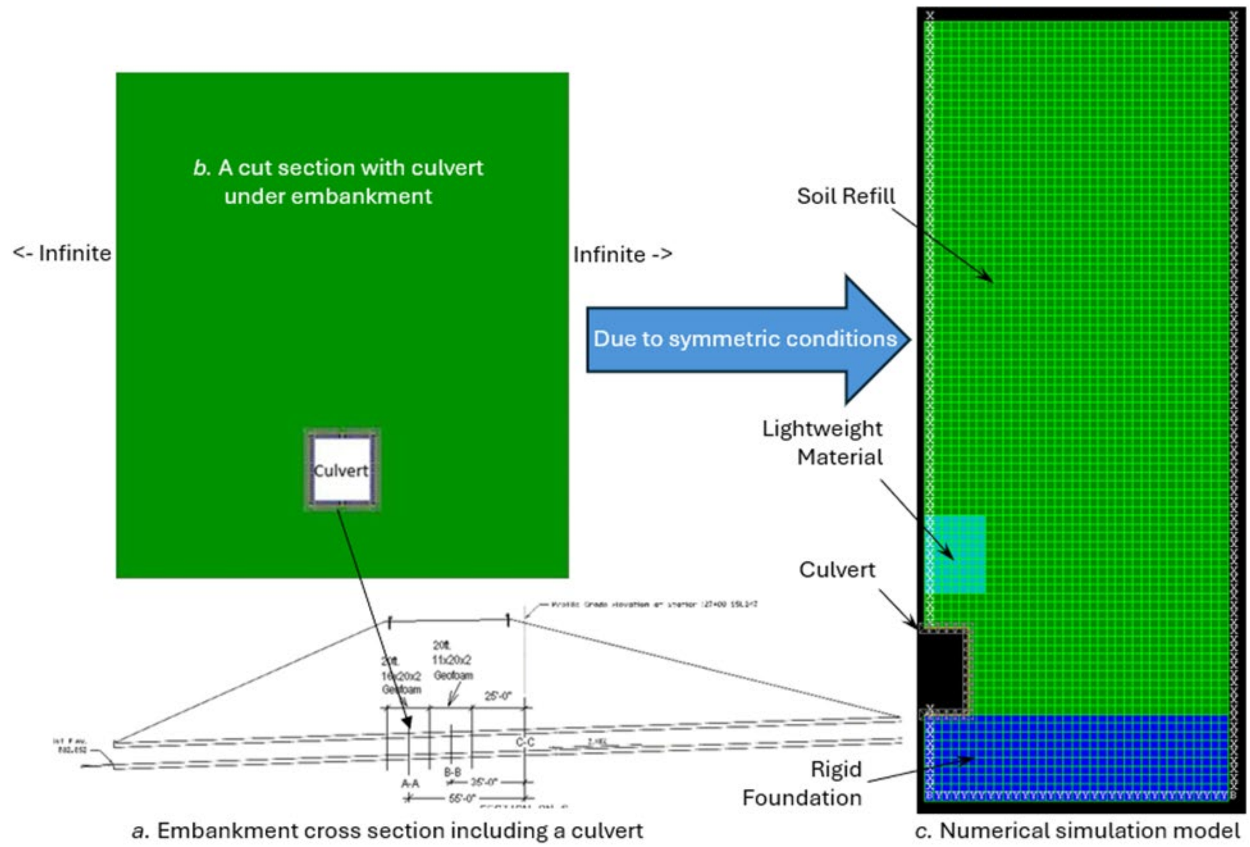

Figure 4.1 Numerical Simulation Model Depicting an Embankment with an Embedded Culvert

4.5 Calibrating the Numerical Simulation Model

Calibration enhances a numerical model's ability to replicate real-world scenarios accurately. It is an iterative process that involves fine-tuning model parameters and inputs to align with observed data. Calibration improves a model's predictive capabilities and reliability for engineering applications.

For calibration of our numerical simulation model, we leveraged long-term in-situ data obtained from a previous study (Sun et al. 2011).[5] This study utilized a 2-foot-thick layer of Geofoam as the LWM. It had a Young's modulus of 13,300 psf, Poisson's ratio of 0.1, and a density of 1.35 pcf. In-situ soil properties were also well-documented, with a Young's modulus of 397,733.3 psf, Poisson's ratio of 0.25, density of 118.722 pcf, cohesion of 529.5 psf, and a friction angle of 26.2 degrees. The fill height above the culvert's top surface was 52.0 feet.

During calibration, we adjusted the stiffness parameters of the culvert's ceiling, walls, and bottom and fine-tuned connections between the soil, culvert, and Geofoam. We made these adjustments to achieve loading ratios that closely matched observed data from the in-situ study. Our calibrated model yielded loading ratios of 21.68% on the culvert ceiling and 128.09% on the culvert wall, which were calculated by comparing the maximum moments under soil and Geofoam loading to the soil-only loading condition. These ratios were consistent with measurements from the in-situ data, validating the accuracy and practicality of our numerical simulation model.

4.6 Conducting Numerical Simulations and Analysis

Our numerical simulations explored culvert behavior under a range of conditions (see Table 4.1 for soil and LWM parameters):

- Six different lengths of LWM (L/W = 1.0, 1.4, 2.0, 3.0, 4.0, 5.0, where L = Length of lightweight material - see L in Figure 4.2, which is parallel to culvert cut section; W = Width of culvert)
- Five different thicknesses of LWM (t/W = 0.2, 0.5, 1.0, 2.0, 4.0, where t = Thickness of lightweight material),
- Six different distances between the bottom of the LWM and the top of the culvert (d/W = 0.0, 0.25, 0.5, 1.0, 2.0, 4.0, where d = Distance between LWM bottom and culvert top)
- Six different fill heights (h/W = 0.2, 0.5, 1.0, 2.0, 4.0, 7.0, where h = Fill height)

We conducted 12,480 simulations due to the interdependent relationships among the thickness of the LWM, distance from the bottom of the LWM to the culvert's top surface, and fill height (see Figure 4.2). Initially, we determined 21,600 simulations would be needed (calculated as 4 x 5 x 6 x 5 x 6 x 6). Adjusting this number optimized computational resources while ensuring comprehensive coverage of relevant scenarios.

The final data points generated through numerical simulations served as the foundation for developing empirical formulas. Results from all numerical simulations are documented in the supplemental file, *Numerical Simulation Results.pdf*. Simulations shed light on critical factors influencing the culvert load under varying conditions of LWM use:

- Size of LWM
  - The size of the LWM significantly impacts culvert loads. As LWM size increases, it has a larger impact on altering the load distribution on the culvert.
- Distance from Culvert Top
  - Proximity of the bottom of the LWM to the culvert's top surface intensifies the impact, amplifying the alterations in load distribution.
- Effect of Young's Modulus
  - LWMs with lower Young's moduli exhibit a positive arch effect. This effect helps reduce loads on the culvert's top surface while potentially increasing loads on the culvert wall, especially for shorter lengths of LWM.
- Impact of Hard Young's Modulus
  - LWMs with higher Young's moduli exhibit a negative arch effect. This effect can offset load reductions from the LWM's self-weight, potentially increasing loads on the culvert ceiling. However, it reduces loads on the culvert wall in most scenarios.
- Complexity of Load Calculation
  - Calculating culvert loads when incorporating LWMs is a complex task due to interactions among soil, culvert structure, and the properties of LWMs. The size of the LWM and its distance from the culvert's top surface

are critical variables and must receive careful consideration in any analysis of the impacts of LWM integration.

70			
d	t_{LWM}	h_{Fill}	H
0	2	68	70
1	2	67	70
3	2	65	70
8	2	60	70
14	2	54	70
21	2	47	70
29	2	39	70
37	2	31	70
45	2	23	70
55	2	13	70
66	2	2	70
0	5	65	70
1	5	64	70
3	5	62	70
8	5	57	70
14	5	51	70
21	5	44	70
29	5	36	70
37	5	28	70
45	5	20	70
54	5	11	70
63	5	2	70
0	10	60	70
1	10	59	70
3	10	57	70
8	10	52	70
14	10	46	70
21	10	39	70
28	10	32	70
35	10	25	70
42	10	18	70
49	10	11	70
58	10	2	70
0	20	50	70
1	20	49	70
3	20	47	70
8	20	42	70
14	20	36	70
21	20	29	70
28	20	22	70
35	20	15	70
42	20	8	70
48	20	2	70
0	40	30	70
1	40	29	70
3	40	27	70
8	40	22	70
14	40	16	70
21	40	9	70
28	40	2	70

50

40			
d	t_{LWM}	h_{Fill}	H
0	2	38	40
1	2	37	40
3	2	35	40
8	2	30	40
14	2	24	40
24	2	14	40
36	2	2	40
0	5	35	40
1	5	34	40
3	5	32	40
8	5	27	40
14	5	21	40
23	5	11	39
33	5	2	40
0	10	30	40
1	10	29	40
3	10	27	40
8	10	22	40
14	10	16	40
21	10	9	40
28	10	2	40
0	20	20	40
1	20	19	40
3	20	17	40
8	20	12	40
13	20	7	40
18	20	2	40

27

20			
d	t_{LWM}	h_{Fill}	H
0	2	18	20
1	2	17	20
3	2	15	20
7	2	11	20
11	2	7	20
16	2	2	20
0	5	15	20
1	5	14	20
3	5	12	20
7	5	8	20
13	5	2	20
0	10	10	20
1	10	9	20
3	10	7	20
8	10	2	20

15

10			
d	t_{LWM}	h_{Fill}	H
0	2	8	10
1	2	7	10
3	2	5	10
6	2	2	10
0	5	5	10
1	5	4	10
3	5	2	10

7

7			
d	t_{LWM}	h_{Fill}	H
0	2	5	7
1	2	4	7
3	2	2	7
0	5	2	7

4

4			
d	t_{LWM}	h_{Fill}	H
0	2	2	4

Interdependent Relationship among t, d, and h

t - Lightweight Material (LWM) Thickness (ft.)

d - Distance between Culvert Top and LWM Bottom (ft.)

h - Fill Height above LWM (ft.)

H - Total Height above Culvert (ft.)

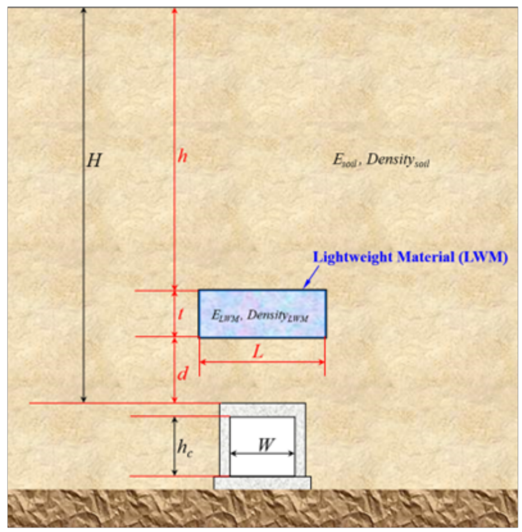

Figure 4.2 Relationships Among Fill Height, LWM Thickness, and Distance Between LWM and Culvert

Section 5 Development of Empirical Formulas

This section describes the development of empirical formulas from data generated through numerical simulations and analysis. Empirical formulas are valuable for engineers and practitioners attempting to optimize the installation profiles of LWMs above culverts and enhancing infrastructure resilience under changing loading conditions, such as those encountered during highway widening projects.

5.1 Data Overview

Our dataset included 12,480 data points generated through numerical simulations (see Section 4). Each data point represented a unique combination of parameters related to LWM use and soil loads, providing a comprehensive understanding of how different factors influence loads on the culvert.

5.2 Formulating Empirical Formulas

The empirical formulas capture relationships between key parameters and the load on the culvert. Experimenting with power, exponential, and polynomial functions revealed that a polynomial function provided the most accurate representation for our purposes. Equation 5.1 is the formula for calculating the load on the culvert in the absence of LWMs.

$$
\begin{aligned}
Load = a_{00} + &\left[a_{10} + a_{11}\left(\frac{E_{soil}}{E_0}\right) + a_{12}\left(\frac{E_{soil}}{E_0}\right)^2 + a_{13}\left(\frac{E_{soil}}{E_0}\right)^3\right] \\
&* \left[a_{20} + a_{21}\left(\frac{\gamma_{soil}}{\gamma_0}\right) + a_{22}\left(\frac{\gamma_{soil}}{\gamma_0}\right)^2 + a_{23}\left(\frac{\gamma_{soil}}{\gamma_0}\right)^3\right] \\
&* \left[a_{30} + a_{31}\left(\frac{h}{W}\right) + a_{32}\left(\frac{h}{W}\right)^2 + a_{33}\left(\frac{h}{W}\right)^3\right] \qquad (5.1)
\end{aligned}
$$

where:

E_{soil} = Young's modulus for soil

γ_{soil} = Soil density

h = Fill height

(normalized using constants E_0 = 500,000 psf, γ_0 = 1 slug/ft^3, and W = 10.0 ft. for dimensionless purposes)

The formula includes 13 coefficients ($a_{00}, a_{10}, a_{11}, a_{12}, a_{13}, a_{20} \dots a_{33}$) that are determined through regression.

Equation 5.2 is the formula for calculating the load ratio on the culvert when LWM is installed above the culvert's top surface.

$$
\begin{aligned}
Ratio = a_{00} + &\left[a_{10} + a_{11}\left(\frac{t}{W}\right) + a_{12}\left(\frac{t}{W}\right)^2 + a_{13}\left(\frac{t}{W}\right)^3\right] \\
&* \left[a_{20} + a_{21}\left(\frac{L}{W}\right) + a_{22}\left(\frac{L}{W}\right)^2 + a_{23}\left(\frac{L}{W}\right)^3\right] \\
&* \left[a_{30} + a_{31}\left(\frac{E_{LW}}{E_0}\right) + a_{32}\left(\frac{E_{LW}}{E_0}\right)^2 + a_{33}\left(\frac{E_{LW}}{E_0}\right)^3\right] \\
&* \left[a_{40} + a_{41}\left(\frac{\gamma_{LW}}{\gamma_0}\right) + a_{42}\left(\frac{\gamma_{LW}}{\gamma_0}\right)^2 + a_{43}\left(\frac{\gamma_{LW}}{\gamma_0}\right)^3\right] \\
&* \left[a_{50} + a_{51}\left(\frac{E_{soil}}{E_0}\right) + a_{52}\left(\frac{E_{soil}}{E_0}\right)^2 + a_{53}\left(\frac{E_{soil}}{E_0}\right)^3\right] \\
&* \left[a_{60} + a_{61}\left(\frac{\gamma_{soil}}{\gamma_0}\right) + a_{62}\left(\frac{\gamma_{soil}}{\gamma_0}\right)^2 + a_{63}\left(\frac{\gamma_{soil}}{\gamma_0}\right)^3\right]
\end{aligned}
$$

$$* \left[a_{70} + a_{71}\left(\frac{d}{W}\right) + a_{72}\left(\frac{d}{W}\right)^2 + a_{73}\left(\frac{d}{W}\right)^3\right]$$
$$* \left[a_{80} + a_{81}\left(\frac{h}{W}\right) + a_{82}\left(\frac{h}{W}\right)^2 + a_{83}\left(\frac{h}{W}\right)^3\right] \quad (5.2)$$

where:
t = LWM thickness
L = LWM length
E_{LWM} = LWM Young's modulus
γ_{LWM} = LWM density
E_{soil} = Young's modulus for soil
γ_{soil} = Soil density
d = Distance between the bottom of LWM and the top of the culvert
h = Fill height
(normalized using constants E_0, γ_0, and W as in Equation 5.1)

Equation 5.2 contains 33 coefficients ($a_{00}, a_{10}, a_{11}, a_{12}, a_{13}, a_{20} \ldots a_{83}$) that are determined through regression analysis.

5.4 Coefficient Optimization in Empirical Formulas

We determined coefficients for Equations 5.1 and 5.2 through regression analysis, which minimizes differences between predicted and actual values. Regression analysis was conducted iteratively, with coefficients adjusted to achieve the best possible fit to the numerical simulation data. This process involved mathematical optimization algorithms that systematically adjusted the coefficients until the resulting empirical formulas aligned closely with observed data points. Fine-tuning coefficients through regression analysis ensured the empirical formulas provide reliable and accurate predictions for culvert loads under different conditions.

When determining coefficients for empirical formulas, a crucial metric we use is the coefficient of determination (R^2). This statistical measure is calculated as:

$$R^2 = 1 - \frac{\text{Sum of Squared Residuals (SSR)}}{\text{Total Sum of Squares (TSS)}} = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \quad (5.3)$$

where:
y_i = Predicted value from the empirical formula
$\hat{y}_i$ = Value from numerical simulation
$\bar{y}$ = Average value of the total simulation data

SSR (Sum of Squared Residuals) quantifies the discrepancy between predicted and observed values, while TSS (Total Sum of Squares) measures variability in the data.

R^2 is measured on a scale from 0 to 1 and captures the proportion of variance in the dependent variable (culvert load or load ratio) explained by the model's independent variables (e.g., soil properties, LWM characteristics, dimensions). Higher R^2 values indicate a model effectively captures and predicts the observed variability in the data, indicating a stronger correlation between the predicted and actual values. Table 5.1 lists R^2 values for different combinations of soils and LWMs.

Table 5.1 Regression Summary for Coefficient Optimization in Empirical Formulas

Case	R^2	
	Culvert Ceiling	Culvert Wall
Soil Only	0.9927	0.9880
All Data	0.8291	0.7279
3 Soft Lightweight Materials	0.8859	0.8094
3 Soft Lightweight Materials + 3 Normal Soils	0.9252	0.8356
Soft Geofoam + 3 Normal Soils	0.9262	0.8455
Normal Geofoam + 3 Normal Soils	0.9349	0.8543
Shredded Tires + 3 Normal Soils	0.9230	0.8323
Lightweight Aggregates	0.8733	0.6037
Cellular Concrete	0.8829	0.6040
3 Soft Lightweight Materials + Low Plasticity	0.9271	0.8117
Soft Geofoam + Low Plasticity	0.9459	0.9013
Geofoam+Low Plasticity	0.9305	0.8887
Shredded Tires+Low Plasticity	0.9719	0.7356
3 Soft LW + Russell	0.9501	0.8768
3 Soft LW + Soil Sand	0.9400	0.8769
3 Soft LW + Uniform Gravel	0.9213	0.8529

An R^2 value above 0.7 or 0.8 is considered robust for scientific and engineering studies. All R^2 values for the culvert ceiling formula regression exceeded 0.8290, with the lowest value being 0.8291 (All Data). R^2 values for the culvert wall formula regression were modestly lower, especially for *Lightweight Aggregates* (0.6037) and *Cellular Concrete* (0.6040) cases. In situations with lower R^2 values, caution is needed when utilizing the empirical formula as they may have limited predictive accuracy.

Substituting optimized values (see Appendix A) for the 13 coefficients in Equation 5.1 and the 33 coefficients in Equation 5.2 yielded empirical formulas for culvert load and culvert load ratio. Practitioners can use these formulas to forecast culvert behavior under different loading conditions.

Section 6 Design Method Utilizing Empirical Formulas

We developed a multistep design procedure that can be used to assess culvert loads and load ratios under diverse conditions. Applying this procedure helps ensure the reliability and effectiveness of LWM installation profile design.

6.1 Establishing Target Reduction Ratio

The first step in establishing target reduction ratios due to the increase in fill height is to determine the existing loads on the culvert ceiling and wall. This involves gathering data on the culvert and soil fill, including culvert dimensions, fill height, and soil properties. Once this information is in hand, Equation 5.1 is used to calculate the existing loads on the culvert ceiling and wall.

Next, we simulate the effects of the new fill height and adjusted soil properties resulting from highway widening. We again use Equation 5.1 but substitute in the new fill height and soil property values to calculate the new loads on the culvert ceiling and wall. The new loads reflect the altered conditions caused by the increased fill height.

The target reduction ratios — denoted as $R_{Ceiling}$ and R_{Wall} — are calculated using Equation 6.1. Target reduction ratios quantify the extent of load reduction achieved through new fill heights and soil properties. This information can guide the optimization process for LWM installation profiles and highway widening design strategies. These ratios are critical indicators of whether proposed design changes will effectively mitigate culvert loads.

$$R = \frac{Load_{Existing}}{Load_{WithNewFill}} \tag{6.1}$$

6.2 Defining Search Region Using Soil Mechanics

Adding new fill material above an existing embankment can significantly alter the distribution of loads on a buried culvert. In Figure 6.1, the yellow area represents the active zone as defined by soil mechanics principles. The active zone is the soil region that sees notable changes in stress and deformation due to external loading. When a structure is buried in the active zone, it is vulnerable to soil movements and pressures.

Behavior in the active zone adheres to fundamental soil mechanics principles, including soil pressure distribution, shear strength, and stress-strain relationships. For culverts, the active zone's behavior is critical and influences the amount of pressure exerted on the culvert. On highway widening projects that involve the placement of additional fill material, the active zone around the buried culvert sees heightened stress levels, which increases pressure on the culvert walls and ceiling. Failure to consider these factors adequately during design and construction can result in structural challenges.

Fill material in the yellow area contributes to loads on the culvert's ceiling and walls. Finding combinations of LWMs and soil within this zone that offset the additional load from the new fill is key to optimizing the LWM installation profile. Areas outside the yellow zone can be disregarded.

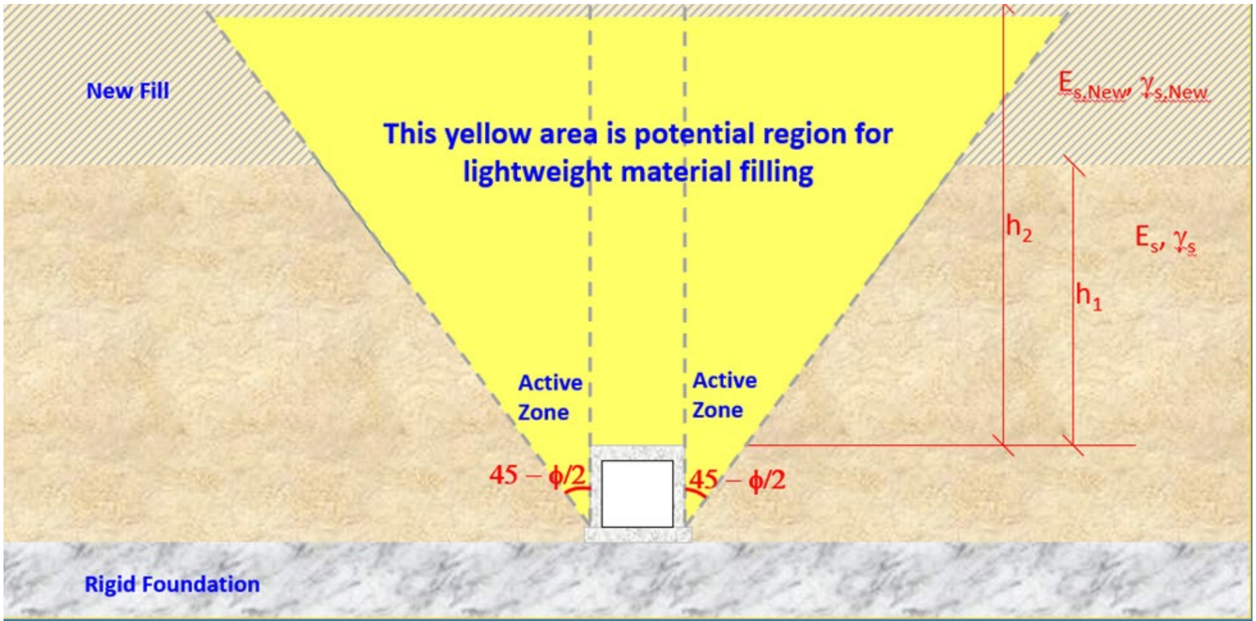

Figure 6.1 Active Zone Under Fill Materials Extending from the Lowest Level of the Culvert

6.3 Achieving Optimal Reduction Ratio in the Designated Region

Equation 6.2 is used to determine the minimum thickness of LWM required for effective load reduction.

$$t_{min,LWM} = \frac{\gamma_{new,Soil} * (h_{new} - h_{existing})}{\gamma_{existing,Soil} - \gamma_{LWM}} \quad (6.2)$$

where:
$t_{min,LWM}$ = Minimum required thickness of lightweight material
h_{new} = New fill height
$h_{existing}$ = Existing fill height
$\gamma_{new,Soil}$ = Density of the new fill soil
$\gamma_{existing,Soil}$ = Density of the existing soil
γ_{LWM} = Density of LWM

The LWMs layer is initiated from the top of the culvert, with the minimum length set equal to the culvert's width (see Figure 6.2). The starting thickness ($t_{start,LWM}$) is determined as follows:

$t_{start,LWM} = 0.66 * t_{min,LWM}$, if $E_{LWM} < E_{Soil}$, or
$t_{start,LWM} = 1.05 * t_{min,LWM}$, if $E_{LWM} > E_{Soil}$.

where:
E_{LWM} = modulus of elasticity of the lightweight material
E_{Soil} = modulus of elasticity of the soil

Substituting all relevant variables into Equation 5.2 returns load reduction ratios for both the culvert ceiling and wall. If both of these ratios are less than or equal to the required target reduction ratios computed with Equation 6.1, the current size and position of the LWM offsets the additional load from the new fill. If the ratios do not meet these criteria, increase the size of LWM and repeat the comparison.

The maximum length of LWM is constrained in the active zone (Figure 6.3), ensuring effective load distribution. Maximum thickness ($t_{max,LWM}$) is defined according to the following criteria:

$t_{max,LWM} = 1.05 * t_{min,LWM}$, if $E_{LWM} < E_{Soil}$
$t_{start,LWM} = 1.55 * t_{min,LWM}$, if $E_{LWM} > E_{Soil}$.

Varying the distance between the bottom of the LWM and the culvert's top surface throughout the potential region and repeating the aforementioned procedures identifies all installation profiles that satisfy target load reduction ratios. These installation profiles are viable options for installing LWM to achieve optimal load reduction.

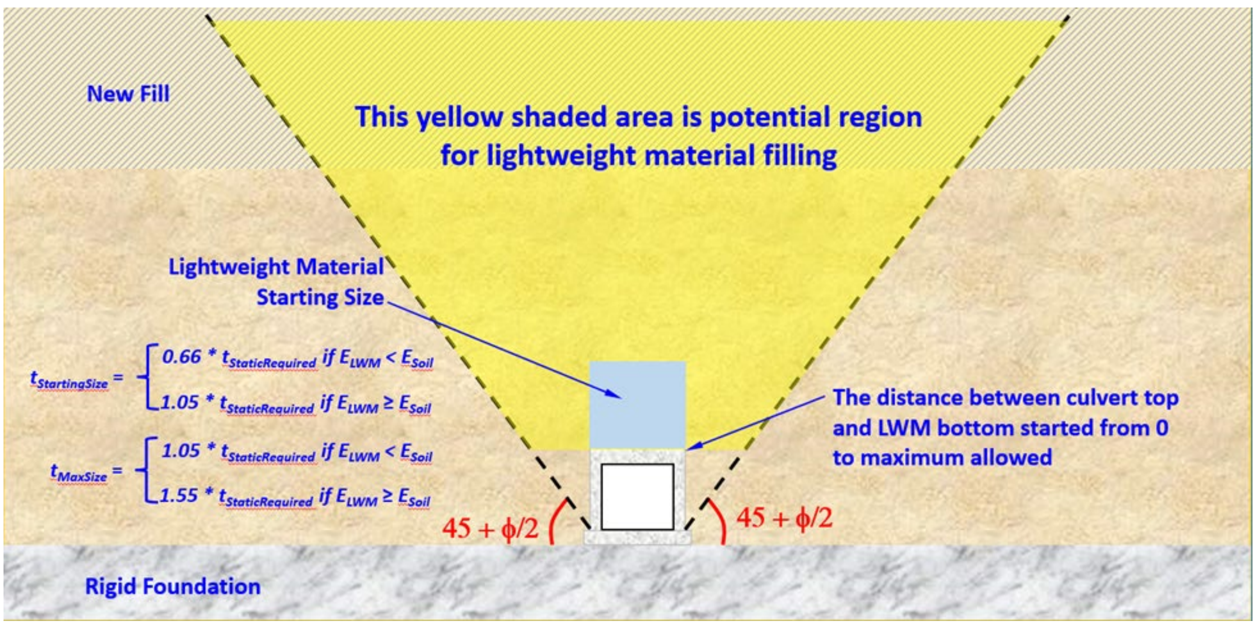

Figure 6.2 Initial Size and Positioning of LWM Layer Atop the Culvert

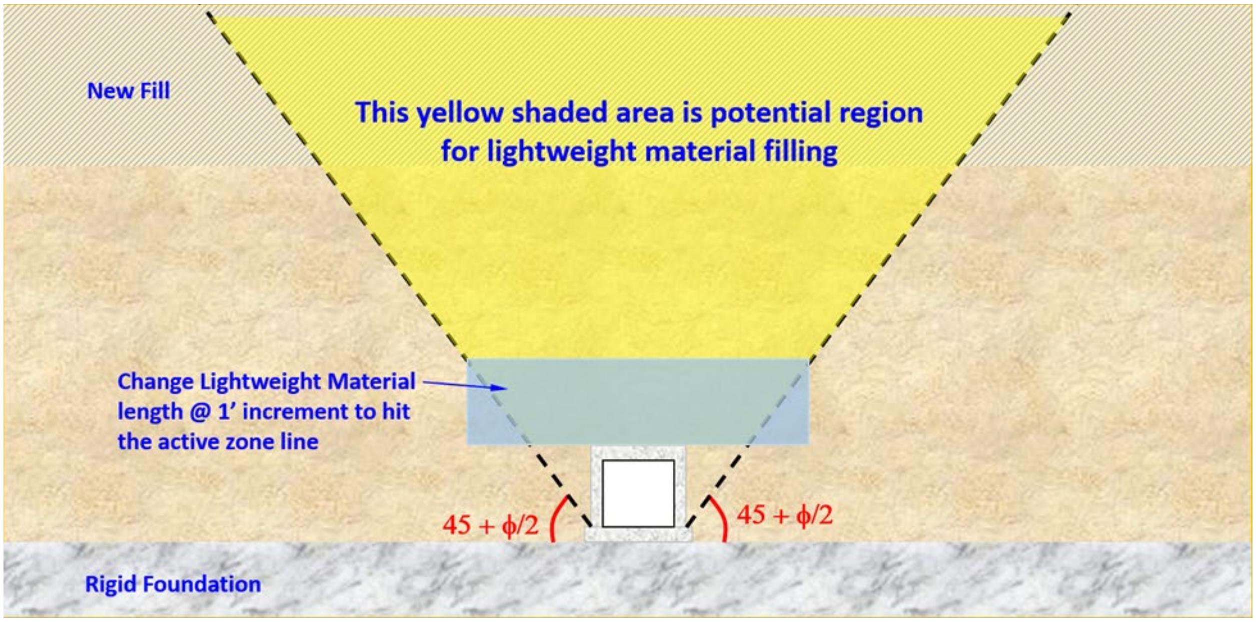

Figure 6.3 Maximum Length of the LWM is Determined by Active Zone

Section 7 Development of Lightweight Material Installation Profile Design Web App

We developed a web app that facilitates the efficient design of LWM installation profiles for culverts exposed to additional load from new fill placed above existing embankments. It can be used by engineers, researchers, and industry professionals engaged in highway widening projects and LWM installation profile design.

7.1 User Interface Design

The web app user interface features interactive elements such as input fields for culvert dimensions, existing fill height, new fill height, soil properties, and LWM specifications. Dropdown menus, parameter auto-distribution based on input, and checkboxes are strategically employed to improve user interaction and simplify parameter selection.

Figure 7.1 showcases the interface, where users can input essential conditions and parameters for generating a LWM installation profile. In the *Existing Condition* section, users specify details such as the existing fill height, culvert size, and soil properties. If the soil used for new fill is the same as the existing fill, users can click on the button labeled *Use Same Soil for New Fill*. Clicking this button automatically populates boxes in the *New Fill Condition* section with the existing soil properties. If the new fill will be a different soil type, users can manually input the corresponding soil properties in this section.

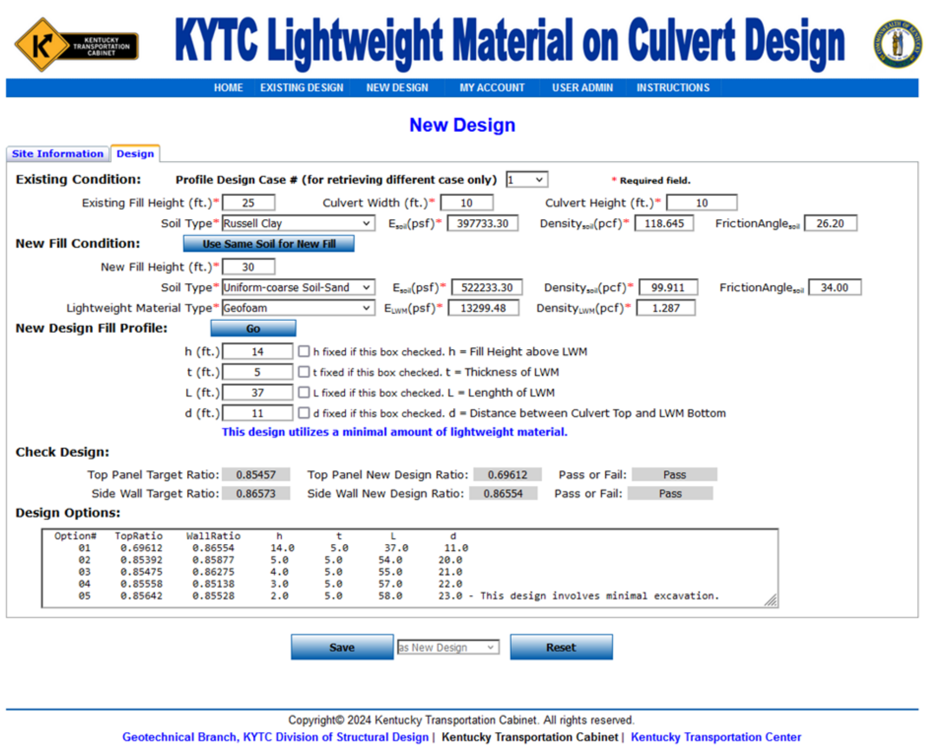

Figure 7.1 Web App Interface

Once the user enters all data in the *Existing Condition* and *New Fill Condition* sections, they click the *Go* button in the *New Design Fill Profile* section. Clicking this button initiates creation of the LWM installation profile. The results include multiple option sets for parameters like Fill Height above LWM (h), Thickness of LWM (t), Length of LWM (L), and Distance between Culvert Top and LWM Bottom (d). Design options listed in the box at the bottom of the screen range from utilizing the minimal amount of LWM to designs involving minimal excavation.

7.2 Algorithm Integration

The web app is powered by sophisticated algorithms that calculate the optimal LWM installation profile based on user inputs and the established search strategy. These algorithms incorporate equations derived from our numerical simulations and empirical formulas to determine the minimum required thickness and length of LWMs required to offset additional loads from new fill materials.

7.3 Features and Capabilities

The web app offers several features to assist users in designing effective installation profiles:

- ***Input Parameters***
  - Users can input culvert dimensions, existing fill height, new fill height, soil properties (density, modulus of elasticity, and friction angle), and LWM specifications (density and modulus of elasticity), along with some fixed parameters.
- ***Optimization Algorithms***
  - The app utilizes optimization algorithms to calculate the minimum required thickness and length (which is parallel to culvert cut section) of LWMs to achieve desired load reduction ratios.
- ***Load Reduction Analysis***
  - The app provides detailed load reduction analysis, including calculated load reduction ratios for the culvert ceiling and walls based on the selected LWM installation profiles.
- ***Flexible Design Options***
  - Users can adjust parameters and experiment with different scenarios to identify the most suitable LWM installation profile for their project.
- ***Output and Recommendations***
  - The app generates comprehensive output reports and recommendations based on the analysis, assisting users in making informed design decisions. Clicking on the *Print Design Form* button compiles all input and design options into a single design form in PDF format.

7.4 Accessibility and Collaboration

The web app can be accessed from desktops, laptops, and tablets. Multiple users in the same group can work on design iterations collaboratively and share project data securely. The app represents an important step forward in designing LWM installation profiles for highway widening projects. Appendix B includes a user's manual that has comprehensive instructions, guidelines, and illustrative examples to ensure the proper utilization of the web design app.

Section 8 Conclusions and Further Work

Developing LWM installation profiles for culverts exposed to greater loads from new fill in highway widening projects is critical for preserving their structural integrity and durability. Through reduced-scale model laboratory tests, numerical simulations, and development of empirical formulas, we have made significant progress in understanding culvert behavior under varying loading conditions and optimizing LWM installation profiles.

Empirical formulas illuminate factors that influence culvert loads and load ratios and guide practical applications in LWM installation. Incorporating these formulas into a systematic design procedure facilitates efficient evaluations of culvert loads and development of effective LWM installation profiles that mitigate pressures on existing culverts. The web app lets engineers, researchers, and industry professionals design optimal LWM installation profiles tailored to individuals project needs. The app's intuitive interface, algorithm integration, and collaborative features make it a valuable tool for developing LWM installation profile designs.

Future research can focus on several areas to improve LWM installation profile design above existing culverts:

- ***Validation and Calibration***:
  - Further validation and calibration of empirical formulas and numerical simulation models using field data and long-term monitoring could enhance their accuracy and reliability in practical applications.
- ***Advanced Material Analysis***:
  - Investigating the behavior of new LWMs and innovative construction techniques can spur the development of more efficient and sustainable culvert support systems.
- ***User Feedback and Iterative Improvement***:
  - Gathering user feedback and incorporating iterative improvements into the web app would ensure its continued effectiveness and relevance in the field.

Addressing these areas will advance the design of LWM installation profiles above existing culverts and lay the foundation for improving the resilience and sustainability of infrastructure modified during road widening projects.

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Appendix A Optimized Coefficients for Empirical Formulas

Optimized Coefficients for Empirical Formulas

Position	DataType	a_{00}	a_{10}	a_{11}	a_{12}	a_{13}	a_{20}	a_{21}	a_{22}	a_{23}
Top	Overall	1.0034029	0.8445051	1.1754572	-0.5380450	0.0743849	2.7817858	0.2932433	-0.1199173	0.0138638
	AllSoilsAnd3Soft	1.1875848	1.6646076	1.0509547	-0.4926910	0.0689180	2.7838705	-0.1034930	0.0283574	-0.0014034
	ThreeSoilsAnd3Soft	2.1899487	2.5191749	0.3937379	-0.1771902	0.0245469	2.9052807	-0.0274766	0.0077388	-0.0004086
	ThreeSoilsAndSoftGeofoam	2.2791194	2.5337440	0.3533841	-0.1589520	0.0219615	2.9111277	-0.0328963	0.0080288	-0.0003993
	ThreeSoilsAndGeofoam	2.3124644	2.5230943	0.4177136	-0.1899724	0.0262999	2.9122822	-0.0215273	0.0068388	-0.0003730
	ThreeSoilsAndShreddedTires	1.5185604	1.7636620	0.4825243	-0.2207348	0.0310403	2.3726015	-0.0429161	0.0121428	-0.0006425
	AllSoilsAnd2Hard	1.0162440	0.3074963	1.5631863	-0.6350110	0.0837512	2.8553165	0.1774932	-0.0750264	0.0070920
	ThreeSoilsAnd2Hard	1.0112737	0.2017910	1.5810468	-0.6436284	0.0856724	2.8493204	0.2592883	-0.1071288	0.0113933
	ThreeSoilsAndLightAggregates	0.9977426	0.1762480	1.4832382	-0.7073761	0.1381133	2.8693391	0.2358810	0.1340696	-0.0108003
	ThreeSoilsAndFoamConcrete	1.0072945	0.1623573	1.5870204	-0.6438703	0.0845926	2.8637527	0.1032088	-0.0787331	0.0089964
	LowPlasticityAnd3Soft	1.058239027	0.386600238	1.022583664	-0.423683823	0.055496425	2.704399963	-0.042003319	0.045269227	-0.00275392
	LowPlasticityAndSoftGeofoam	1.083990715	0.379336536	1.021524769	-0.442052806	0.05882053	2.701847841	-0.188241921	0.059102543	-0.00320783
	LowPlasticityAndGeofoam	1.054955028	0.404288326	1.032792986	-0.37542938	0.046236161	2.706961677	-0.12517958	0.084449599	-0.005614
	LowPlasticityAndShreddedTires	1.035065153	0.382235753	1.018271433	-0.436430629	0.058510423	2.697179472	0.157616091	0.019153697	-0.001897675
	RussellClayAnd3Soft	2.198750784	2.545261848	0.413395486	-0.190325364	0.026213223	3.050504085	0.019298289	0.00092036	-0.000147316
	Coarse Soil-SandAnd3Soft	2.368578098	3.275285855	0.477723053	-0.215626174	0.030163103	2.97377749	-0.040297402	0.009324722	-0.000461669
	Uniform GravelAnd3Soft	1.039818557	1.253412151	0.841008882	-0.406627676	0.058321788	2.793572045	0.100196575	-0.069500299	0.008711439
	SoilOnly	-0.2497654	113.3336264	3.2889274	-9.9547762	0.0569846	-0.2889616	-0.0468726	-0.0675398	-0.0025262
Wall	Overall	1.0046391	0.8436546	0.8673948	-0.3963347	0.0606957	0.9026313	0.1321415	-0.0406792	0.0001058
	AllSoilsAnd3Soft	0.9662810	0.8912235	0.7735959	-0.3418300	0.0512595	0.2950067	0.0748643	-0.0269393	0.0015908
	ThreeSoilsAnd3Soft	0.9509332	0.9780998	0.6856993	-0.3256976	0.0510395	0.3566838	0.0628358	-0.0235740	0.0014370
	ThreeSoilsAndSoftGeofoam	0.9272370	1.3266286	0.6355872	-0.2671922	0.0420199	0.5648832	0.0190486	-0.0156597	0.0010358
	ThreeSoilsAndGeofoam	0.9404182	0.8697467	0.7837580	-0.3684182	0.0556784	0.4013311	0.0511664	-0.0212638	0.0012751
	ThreeSoilsAndShreddedTires	0.9803517	0.8629986	0.7052397	-0.4023582	0.0665750	0.0439650	0.1702873	-0.0578358	0.0051165
	AllSoilsAnd2Hard	0.9594520	2.6303841	0.9567949	-0.2121932	0.0102401	2.8283383	-0.8274029	0.0556572	0.0001728
	ThreeSoilsAnd2Hard	0.9824768	1.1005382	0.6566480	-0.1998522	0.0112346	1.4109081	-0.4943075	0.0296211	0.0000544
	ThreeSoilsAndLightAggregates	1.0067933	0.8949852	3.9526450	0.0916026	0.0078562	0.2167515	-0.5777004	0.0358800	0.0000573
	ThreeSoilsAndFoamConcrete	0.1753820	2.0474525	-0.1120292	0.0748046	-0.0112210	0.9858573	-0.0990631	0.0135560	-0.0005133
	LowPlasticityAnd3Soft	0.966183006	0.582325483	2.339573914	-0.808715571	0.092596293	1.892846792	-0.175501058	-0.01749588	0.000186467
	LowPlasticityAndSoftGeofoam	0.960575144	0.699799855	2.478769527	-0.949756709	0.117634187	0.267643686	0.125770527	-0.042856611	0.002374146
	LowPlasticityAndGeofoam	0.978195898	0.499643616	1.760910072	-0.587953275	0.065332473	0.959920891	0.654032917	-0.196508391	0.000786429
	LowPlasticityAndShreddedTires	0.957179623	0.689693318	3.962717726	-0.886908256	0.069855942	4.749204173	-0.719965305	0.022757668	0.000568036
	RussellClayAnd3Soft	0.974075411	0.796301661	1.020329493	-0.463445258	0.067206956	0.170390917	0.247882544	-0.076480464	0.006663988
	Coarse Soil-SandAnd3Soft	0.948789459	0.825936539	0.559267956	-0.26803234	0.042277257	0.374497407	0.040698414	-0.020173255	0.00135972
	Uniform GravelAnd3Soft	0.936537681	0.799705052	0.25878664	-0.16627132	0.031117671	0.824692785	0.00692107	-0.03890351	0.002745822
	RussellClayAndGeofoam	0.9684479	0.6191055	1.0023286	-0.4541110	0.0649127	0.1329347	0.0916729	-0.0268971	0.0021098
	Coarse Soil-SandAndGeofoam	0.9319605	0.9252003	0.8138561	-0.3827307	0.0579305	0.5174738	0.0231099	-0.0176027	0.0011844
	Uniform GravelAndGeofoam	0.9071811	1.3454069	0.5807410	-0.3384736	0.0586137	0.8670782	-0.0568495	-0.0167353	0.0014674
	SoilOnly	-0.2423038	83.2518378	-40.5730537	14.1349751	0.0804482	-0.0221089	-0.1557254	-0.0630058	-0.0025236

a_{30}	a_{31}	a_{32}	a_{33}	a_{40}	a_{41}	a_{42}	a_{43}	a_{50}	a_{51}	a_{52}	a_{53}
0.1111802	-0.3482605	0.1691133	-0.0035955	0.1497443	0.1843495	-0.0634877	-0.1053486	0.3534439	0.1904847	0.2833855	-0.1710732
0.0994245	-0.3038592	0.1708148	-0.0035417	0.1503469	0.1653773	-0.0431331	-0.1057450	0.3894546	0.0556827	0.3517900	-0.1785083
0.2389457	-0.1832224	0.1752668	-0.0034298	0.0953036	0.1500034	-0.0184116	-0.1232269	0.2951902	0.0722223	0.4121752	-0.2112141
0.2497812	-0.1830665	0.1752690	-0.0034298	0.0984377	0.1501255	-0.0184068	-0.1232267	0.2978227	0.0703183	0.4048765	-0.2075591
0.2530589	-0.1828481	0.1752767	-0.0034296	0.0991766	0.1501571	-0.0184054	-0.1232267	0.2971469	0.0716750	0.4086884	-0.2091424
0.1941659	-0.1844603	0.1752146	-0.0034322	0.1497517	0.1198185	-0.0266399	-0.1139610	0.2238575	0.0446486	0.4547668	-0.2270021
0.1087824	-0.3522439	0.1683155	-0.0035866	0.1877349	0.2137236	-0.0582983	-0.1381825	0.8353419	-0.2489967	0.1442769	-0.0329417
0.1088407	-0.3521380	0.1688242	-0.0035977	0.1878957	0.2138412	-0.0582945	-0.1384001	0.8361796	-0.2482385	0.1445874	-0.0336496
0.2095571	-0.1659367	0.3827380	-0.2206634	0.1747886	0.1946417	-0.0791433	-0.1199264	0.9217884	-0.2057697	0.1541980	-0.0487298
0.1088407	-0.3521379	0.1688239	-0.0035979	0.1879221	0.2138780	-0.0582426	-0.1383295	0.8330705	-0.2511562	0.1423398	-0.0344625
0.150454292	-1.857162389	0.107895017	-0.005495953	0.204990636	-1.977652655	-0.084889055	2.056122289	0.567707535	0.208449363	0.284886449	-0.170947822
0.158864438	-1.857041268	0.107896761	-0.005495928	0.213626544	-1.977314128	-0.084875784	2.056122809	0.571732919	0.208785684	0.284914549	-0.170945474
0.160301341	-1.856900751	0.107901976	-0.005495768	0.212332433	-1.977360168	-0.084877354	2.056122757	0.58217052	0.20965765	0.284987401	-0.170939388
0.145676739	-1.857356857	0.107886813	-0.005496299	0.203509555	-1.982336404	-0.092905327	2.044639232	0.544603561	0.206519424	0.284725203	-0.170961294
0.112241847	-0.136929695	0.178859244	-0.003376468	0.203161461	0.185903114	-0.014233797	-0.158380971	0.398212337	0.239090413	0.327759705	-0.1331658
0.100036507	-0.067012331	0.169869732	-0.002982143	0.112060863	0.220198509	-0.032161377	-0.176129353	0.19304712	0.261419748	0.383990233	-0.214479789
0.145697183	-0.133091374	0.122113448	-0.002284069	0.128752755	0.159337994	-0.076371579	-0.08251176	0.348806392	0.182902236	0.271492947	-0.187318064
-0.7732124	-107.2998318	-0.7760954	0.0533288								
0.2093287	-0.1144905	0.0000423	-0.0000260	0.2372313	0.0988596	-0.0012398	-0.1361156	0.1435151	-0.0004205	0.5942244	-0.2985250
0.2315379	-1.1775240	0.0000423	-0.0000260	0.2131348	0.0777938	-0.0012382	-0.0864958	0.1846598	-0.0005264	0.5395662	-0.2701148
0.2485439	-0.7837991	0.0000423	-0.0000260	0.1941745	0.0776119	-0.0012383	-0.0865626	0.1383789	-0.0005264	0.5588358	-0.2795926
0.2615277	-0.7819736	0.0000423	-0.0000260	0.1683337	0.0774499	-0.0012383	-0.0865629	0.1140002	-0.0005266	0.5746890	-0.2884990
0.2577830	-0.7812791	0.0000423	-0.0000260	0.1923117	0.0776000	-0.0012383	-0.0865626	0.1110335	-0.0005264	0.6520173	-0.3241994
0.1914408	-0.8075129	0.0000423	-0.0000260	0.1788925	0.0762249	-0.0012386	-0.0868662	0.2358101	-0.0005266	0.5117211	-0.2565982
0.4185634	-0.1220906	0.0000416	-0.0000371	0.4457479	0.1127177	-0.0012361	-0.2150256	0.5204887	-0.0004334	-0.5726032	0.3035548
0.1189961	-0.0634669	0.0000421	-0.0000173	0.3122011	0.1133829	-0.0012340	-0.1685943	2.2540595	-0.0004282	5.6042478	-2.7711663
0.0543661	-0.0257158	0.0000422	-0.0000173	0.5536445	0.1600129	-0.0012250	-0.1941188	4.9236992	-0.0004282	-0.0362439	0.0409874
0.2011719	-0.0466669	0.0000424	-0.0000103	0.3042080	0.1164318	-0.0012335	-0.1687007	-0.7660207	-0.0004281	10.8180735	-5.2542543
0.044237803	-0.736233653	4.22705E-05	-2.59971E-05	0.371677035	0.134532125	-0.001231958	-0.040989196	0.174748808	-0.000420514	0.59795848	-0.298446293
0.058511274	-0.724048313	4.22705E-05	-2.59971E-05	0.349936882	0.134420139	-0.001231959	-0.040989206	0.183492015	-0.00042051	0.598673821	-0.298431421
0.05465803	-0.476087712	4.22706E-05	-2.59971E-05	0.507548431	0.135244347	-0.001231956	-0.040989085	0.233394605	-0.000420486	0.602755023	-0.298346479
0.025663339	-0.149968876	4.22706E-05	-2.59971E-05	0.388417597	0.134439324	-0.001231966	-0.041019121	0.144325782	-0.000420529	0.595467279	-0.298498176
0.437675775	-2.07910351	4.22679E-05	-2.59971E-05	0.232635405	0.083921946	-0.001236402	-0.079861956	0.187510775	-0.000525877	0.752312085	-0.243833414
0.208557718	-0.686149839	4.22681E-05	-2.59971E-05	0.187394636	0.076133928	-0.001238641	-0.089517353	0.142086516	-0.000526386	0.580794304	-0.304094614
0.159185906	-0.169211482	4.22682E-05	-2.59971E-05	0.19632263	0.074479779	-0.001239216	-0.091448897	0.082541419	-0.000527793	0.573396399	-0.288629593
0.2984979	-0.7712816	0.0000423	-0.0000260	0.2311050	0.0778527	-0.0012383	-0.0865621	0.1154136	-0.0005263	0.7472413	-0.3054809
0.2806554	-0.7755257	0.0000423	-0.0000260	0.1870112	0.0775656	-0.0012383	-0.0865627	0.1086856	-0.0005264	0.6604720	-0.3243111
0.2607865	-0.7806998	0.0000423	-0.0000260	0.1809412	0.0775259	-0.0012383	-0.0865627	0.0936438	-0.0005270	0.4808991	-0.1960277
-3.5141691	-123.1256953	2.6148411	0.0052406								

Optimized Coefficients for Empirical Formulas 2

a_{60}	a_{61}	a_{62}	a_{63}	a_{70}	a_{71}	a_{72}	a_{73}	a_{80}	a_{81}	a_{82}	a_{83}
-0.0145892	0.1018647	1.7142694	-0.2872573	1.0991525	-0.3932656	0.0377430	-0.0004154	-1.0380511	-0.1631254	0.0434255	-0.0039248
-0.0086313	0.1115508	1.7042555	-0.2887834	1.3499758	-0.3630476	0.0333661	0.0004052	-1.0218027	-0.1310253	0.0314852	-0.0027497
-0.0114928	0.0967763	1.6694633	-0.2715374	1.8473928	-0.1810325	0.0098290	0.0012746	-0.9674337	-0.0421702	0.0086469	-0.0007605
-0.0117522	0.0962073	1.6680801	-0.2719016	1.8479182	-0.1663967	0.0072122	0.0013338	-0.9624753	-0.0337784	0.0066277	-0.0005964
-0.0116618	0.0963486	1.6685044	-0.2750157	1.8474209	-0.1783075	0.0124086	0.0008610	-0.9645376	-0.0320687	0.0067896	-0.0006140
-0.0196653	0.0802528	1.6319316	-0.2424164	1.7145873	-0.2737487	0.0121946	0.0024005	-1.0149924	-0.1250938	0.0268593	-0.0022570
0.0411522	0.2230824	1.8990929	-0.4209182	1.2080597	-0.2425982	-0.0309626	0.0065256	-1.3526366	0.3101164	-0.0788116	0.0073646
0.0412272	0.2232269	1.8992158	-0.4217397	1.2047460	-0.2699267	-0.0128011	0.0042085	-1.3518098	0.3145782	-0.0852891	0.0081706
0.0324719	0.2054417	1.8787523	-0.3524506	1.2955753	-0.9419983	0.2334312	-0.0186812	-1.7186330	1.1703615	-0.2776545	0.0220213
0.0409717	0.2226025	1.8978995	-0.4235290	1.2153088	-0.2024239	-0.0421987	0.0071908	-1.3687371	0.1962326	-0.0607262	0.0065020
-0.035935501	0.023688795	1.452901443	-0.032072844	0.667238764	-0.377738504	0.08009098	-0.005507477	-1.919709259	0.390525001	-0.08683562	0.006969799
-0.035810581	0.024149448	1.454600141	-0.025808746	0.67144491	-0.376781533	0.082488353	-0.005818743	-1.92665239	0.369124011	-0.078006691	0.005999556
-0.035649099	0.02474472	1.456785288	-0.018251441	0.659070114	-0.425295651	0.104339939	-0.008207741	-1.881977951	0.662203537	-0.151788618	0.012201163
-0.036498618	0.021612206	1.445241793	-0.060421158	0.677591476	-0.353430412	0.062202386	-0.003362146	-1.94307175	0.185432415	-0.041578201	0.003581778
0.005240497	0.175811175	2.021599435	-0.406437946	1.663784334	-0.218236811	0.022371648	0.000223787	-0.903714724	-0.043478175	0.011854442	-0.001064942
-0.030488048	0.116862535	1.90888515	-0.248792194	1.709991793	-0.132424641	0.003790488	0.001364218	-1.155724077	-0.040173971	0.006853405	-0.000602023
-0.015725762	0.098334765	1.703296132	-0.321679132	1.107893297	-0.271354182	0.004681679	0.001897427	-0.973091279	-0.303349815	0.060378923	-0.004871613
-0.1115932	-0.1071206	8.4568515	0.0449029	1.3253654	-0.0170688	-0.2042748	0.0308302	-0.0062218	0.0395648	-0.0022149	-0.0001185
-0.0227577	0.0289440	6.6580971	-0.2371403	2.4959323	0.0798030	-0.3739166	0.0532005	0.0264114	0.0854697	-0.0045747	-0.0002662
-0.0227502	0.0289620	6.3908004	-0.2556451	2.9689713	0.0433674	-0.3939207	0.0570532	0.0277542	0.0638499	-0.0010132	-0.0004824
-0.0227477	0.0289668	5.6413831	-0.2680250	2.1940297	0.1120555	-0.2951453	0.0410270	0.0504886	0.0581929	-0.0005233	-0.0004699
-0.0227365	0.0290036	6.8628823	-0.2823084	4.0202790	-0.0546490	-0.4880271	0.0732225	0.0257103	0.0440432	-0.0028363	-0.0000792
-0.0227754	0.0288940	6.2757041	-0.1963463	5.4185707	-0.4130717	-0.5527529	0.0821748	-0.0229526	0.1127730	0.0071525	-0.0020311
-0.1078557	-0.1011868	14.5548459	0.0348396	-0.0018825	-0.0533129	0.0199889	-0.0018736	0.0762744	0.0129264	-0.0046593	0.0002276
-0.1031568	-0.0942282	12.3825613	0.0253022	0.0217052	-0.0670229	0.0244726	-0.0023365	0.1365599	-0.0041290	0.0002631	0.0002706
-0.1041908	-0.0957705	5.1497170	0.0263273	-0.2255952	0.0722123	-0.0209228	0.0008964	0.1342666	0.0195736	0.0005136	0.0010688
-0.1058049	-0.1015842	8.7341395	0.0250829	-0.2500240	-0.0741919	0.0265577	-0.0024877	0.4708520	-0.0018284	0.0001273	-0.0000901
-0.111563129	-0.107018616	10.14085742	0.045077899	1.432893503	-0.035010658	-0.172772687	0.024444548	0.081577942	0.051570136	-0.007890116	0.00028743
-0.111595599	-0.107128757	14.18104316	0.045372431	1.946006969	-0.09379972	-0.2326419	0.035432765	0.126431424	0.094152708	-0.015105446	0.000621767
-0.111552121	-0.106981273	15.18366551	0.045445422	0.462120536	-0.224562425	0.036287271	-0.001917145	0.110549233	0.04781171	-0.0103686	0.000725528
-0.111546225	-0.106961325	6.975178455	0.044847133	0.377729678	0.380888371	-0.207713179	0.024065336	0.073203137	0.013144539	0.00538109	-0.001069882
-0.022717919	0.029154985	6.151729304	-0.261249314	1.902448963	0.326257483	-0.396176545	0.050039861	-0.009383522	0.054433974	-0.006738413	0.000256234
-0.022745997	0.028983051	5.78227129	-0.25896247	4.974862766	-0.244561382	-0.451372584	0.067552158	0.043359133	0.05634198	0.000895649	-0.000617574
-0.022757722	0.028924141	5.073005458	-0.261852738	4.120425107	-0.596556275	-0.273240784	0.051668475	0.078514076	0.062263902	0.004203932	-0.001007102
-0.0227360	0.0290068	8.0304177	-0.2749472	3.8914206	0.4553335	-0.6939932	0.0870011	-0.0024124	0.0698531	-0.0089679	0.0003645
-0.0227339	0.0290169	6.5769461	-0.2840290	2.9778298	-0.1864109	-0.2565145	0.0403342	0.0379481	0.0414598	-0.0022536	-0.0001120
-0.0227351	0.0290106	7.7026139	-0.2779305	2.0966826	-0.3609983	-0.0911261	0.0202935	0.0361371	0.0209125	0.0005254	-0.0002463

Appendix B KYTC Lightweight Material on Culvert Design Web Application User's Manual

October 2023

2023

User’s Manual

KYTC Lightweight Material on Culvert Design Web Application

Charlie Sun and Christopher Van Dyke

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1. INTRODUCTION

The Lightweight Material on Culvert Design web application[1], developed by the Kentucky Transportation Cabinet (KYTC) and accessible at http://lightweightonculvert.uky.edu/, serves as a specialized platform dedicated to the submission of lightweight material profile designs for culverts into the KYTC centralized database. This web application has been meticulously designed to streamline the exploration of various lightweight material arrangements within specified embankment boundaries, thereby simplifying the task of identifying feasible and efficient lightweight fill configurations. Users are empowered to conveniently attach accompanying images and documents directly within the application.

Anticipated to be primarily utilized by two (2) key user groups, namely KYTC Engineers/Officers and Designers (comprising vendors and contractors) engaged in highway expansion projects, this web application empowers primary users (Designers) to submit lightweight material profile designs for culverts seamlessly via the online platform. The central office, in turn, efficiently processes and assesses these digital submissions, facilitating clear and open communication between designers and the central office throughout the entire process of submitting and accepting lightweight material profile designs for culverts.

To facilitate user understanding and maximize the utility of the web application, the following sections provide an extensive overview of its features and offer comprehensive guidance on their utilization. Visual representations of the web application's diverse graphical user interfaces are also included to enhance clarity and user-friendliness.

[1] Referred to hereafter in this guide as *web application*.

2. OVERALL WEB PAGE SETTING

All functioning web pages on the web application are divided into three sections — **Header**, **Main Content**, and **Footer** (Figures 1).

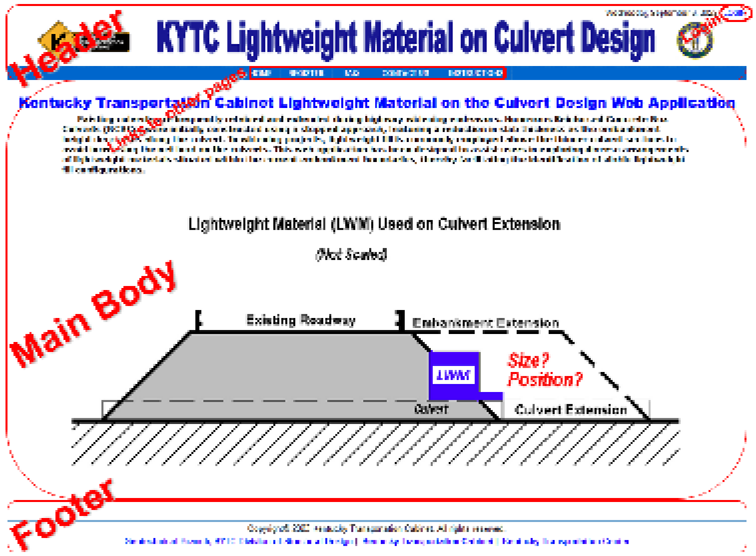

Figure 1. Overall web page setting: Links to other pages and LOGIN page are in Header Portion

2.1 Header

The **Header** is fixed at the top of each page and has two different settings for before and after login. The contents present before *and* after login include web title, date and time, and links to **HOME** and **INSTRUCTIONS**. Before login, there are also links to **LOGIN** (upper right corner of the page), **REGISTER**, **FAQ**, and **CONTACT US**. After login, the user's first name appears on the top line and the **LOGIN** link is replaced with **LOGOUT** in the top right corner. Links for **EXISTING DESIGN**, **NEW DESIGN** and **MY ACCOUNT** appear for users who are registered as Designers and Central Office Lightweight Material on Culvert Design manager. Additional link, **USER ADMIN** appears for Central Office Lightweight Material on Culvert Design manager.

2.2 Main Content

The **Main Content** section of each page hosts the different functioning pages, which are illustrated in detail later.

- 2 -

2.3 Footer

The **Footer** contains links to related web sites such as **Geotechnical Branch, KYTC Division of Structural Design**, **Kentucky Transportation Cabinet**, and **Kentucky Transportation Center**.

3. USER AS A NON-REGISTERED USER

Non-registered user can register as **Designer** and receive instant approval from the web application's management system. The functions described below are available to non-registered users in the **Header** section.

3.1 HOME – *Default Page of Web Application*

The **HOME** link is the first link in the **Header**'s last line (Figure 1). Clicking this link loads the web application's home page (Figure 1). This is the web application's default page and briefly introduces the application.

3.2 REGISTER – *Get Approval Instantly from Web Application Management System*

The **REGISTER** link is the second link in the **Header**'s last line (Figure 1). After clicking this link, user is asked to supply personal information to create their account (Figure 2). If a red asterisk appears next to a field, the user must provide the required information to complete their registration. Required information includes **First Name**, **Last Name**, **Email** (which is used as the **Login ID** by the user and for all correspondence email sent by administrators), **Password** (created by the user), **Phone Number**, **Street Address**, **City**, **State**, **Zip Code**, **Country**, and **Organization**. ***Designer*** is the only option for user **Designation** for now. If registrant's email domain contains "gmail" or "yahoo", or does not exist in current user database, they will be assigned as a **UserTBA** temporarily and wait further verification by administrator from web application. The **UserTBA** can view all the existing designs in different stages, such as **Initiated, Submitted, Accepted,** and **All Existing Designs**. Some information (e.g., **Fax Number**, **Web Site**, and **Description**) is optional. Information supplied by the user is confidential and maintained in the web application management system. Passwords are encrypted and stored in the web application management system as well.

After the user enters all the required information and clicks the **Register** button, the page shown in Figure 3 appears. This page informs the user: "*An activation link has been sent to your email address. Please follow the instructions in the email to activate your account.*"

- 4 -

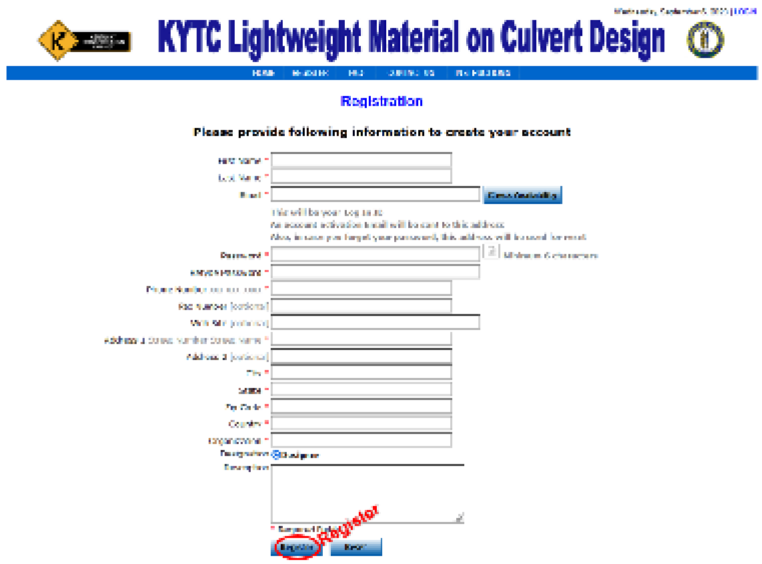

Figure 2. REGISTRATION screen

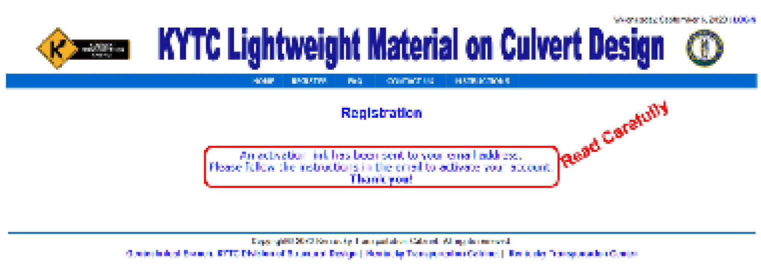

Figure 3. Information after Register button is clicked

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Figure 4 is an image of the email sent to the user.

Account Activation for KYTC Lightweight Material on Culvert Design Inbox ×

KYTC Lightweight Material on Culvert Design <KTC.Research@uky.edu> 9:43 AM (14 minutes ago)
to me

Dear Charlie,

Thank you for signing up for a KYTC Lightweight Material on Culvert Design account! You are temporarily approved as UserTBA until your account has been verified by an administrator. The KYTC Lightweight Material on Culvert Design Administrator will inform you when you are approved as a Designer.

With user privilege as a UserTBA, KYTC Lightweight Material on Culvert Design will let you view Lightweight Material on Culvert Design information stored on KYTC Lightweight Material on Culvert Design database.

Please activate your account by clicking on this link Activate Account

If you did not sign up for this account, take no action, and no account will be created.

Thank You.

KYTC Lightweight Material on Culvert Design Administrator

Figure 4. Email provides a link to activate user’s account

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A user can immediately activate their account by clicking on the link provided in the email. The **Activation** page (Figure 5) informs the new user of their account activation status. If activation is successful, the registered user may click on the **LOGIN** link, which is located on the upper right corner of the page, to log into the system by using **LOGIN** page (Figure 10).

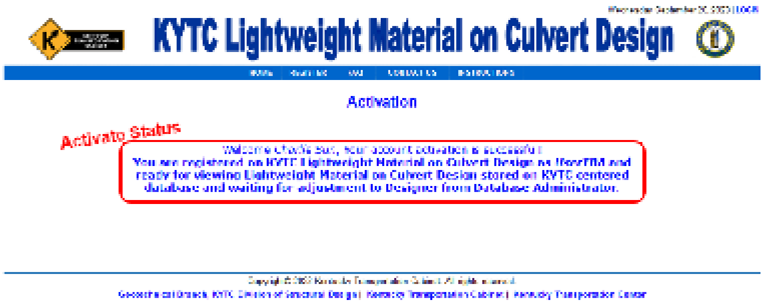

Figure 5. Screen after activating user's account

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3.3 FAQ – *Frequently Asked Questions*

FAQ link is the third link in the **Header's** last line (Figure 1). This link provides straightforward answers to frequently asked questions about the web application (Figure 6).

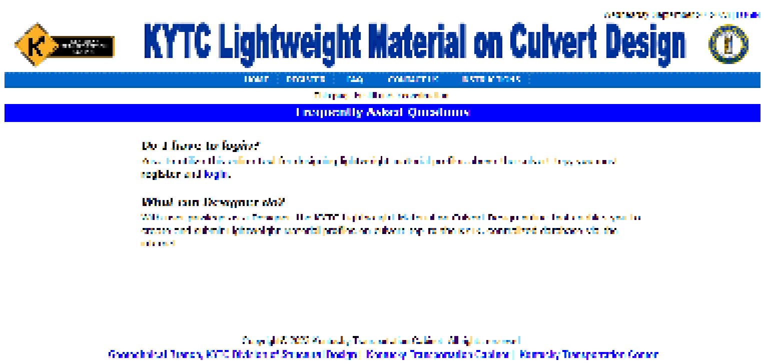

Figure 6. **FAQ** page provides straightforward answers to frequently asked questions about the web application

3.4 CONTACT US – *Communicating with Web Application Administrator*

The **CONTACT US** link is the fourth link in the **Header's** last line (Figure 1). The **CONTACT US** page offers a portal for users to communicate with a system administrator (Figure 7). The users may either use physical address to send regular mail; or they may supply the required information and click the **Send** button. Clicking the **Send** button generates an email that is sent by the system to both the sender and the web application administrator.

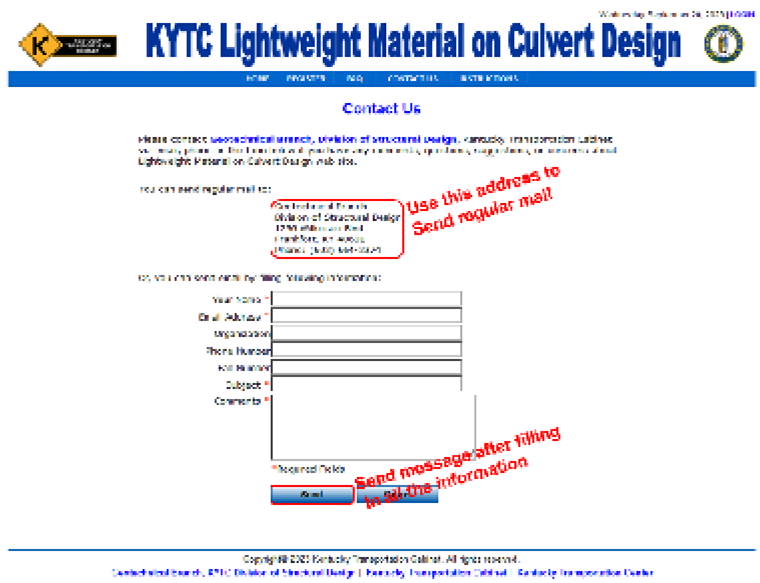

Figure 7. CONTACT US screen

3.5 INSTRCTIONS

The INSTRUCTIONS link is the Header's final link (Figure 1). Under this link, users find a *Quick Start Guide* and a *User's Manual* (Figure 8). The *Quick Start Guide* presents brief instructions for using this web application; the *Manual* provides more detailed instructions. Users can view it online or download a copy for printing.

Figure 8. INSTRUCTIONS screen

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4. USER AS A DESIGNER

Designer is a registered user and belongs to a major group on the web application. They can instantly activate their account after registering and following directions shown on the screen. If the **Designer** does not activate their account, the administrator can send them a notification email with the activating link or activate the account on their behalf. Personal information can be modified by clicking on the **MY ACCOUNT** link. In contrast to unregistered users, a **Designer** enjoys enhanced access privileges. They can view **Initiated, Submitted, Accepted,** and **All Existing Designs** (as depicted in Figure 9). **Designers** are also empowered to submit their own designs, share designs with fellow **Designers** within the same group, upload attachments, and submit their designs online.

Figure 9. Designers can view all the designs at different stages

4.1 LOGIN

Figure 10 displays the **LOGIN** page. This page is the gateway for registered users to access the web application. A **Designer** may **Log In** by entering their email address, password into the appropriate fields in the **Login** area, and clicking on **Sign In** button.

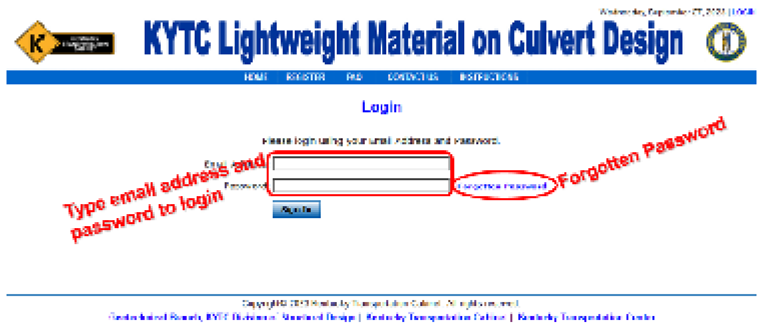

Figure 10. **LOGIN** page

4.2 FORGOTTEN PASSWORD

If a user forgets their login password, they can click **Forgotten Password** link shown in Figure 10. Clicking this link takes the user to a page where they can reset their password (Figure 11). On the **Forgotten Password** page, a user enters their registered email address and clicks the **Reset Password** button. This creates a temporary, randomly generated password and emails it to the user. An instance instruction is shown on screen (Figure 12) and the email like one in Figure 13 is sent to user. Once the user logs in with their temporary password, the user is prompted to immediately proceed to the **MY ACCOUNT** page and update their password.

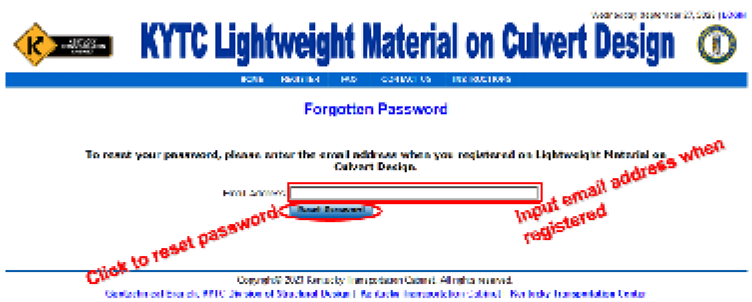

Figure 11. Reset Password screen

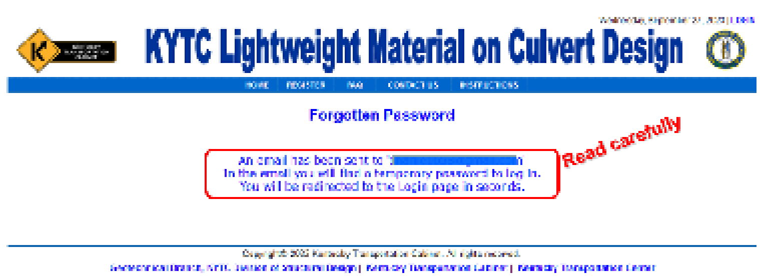

Figure 12. Brief instruction is shown on screen

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Figure 13. Temporary password created and included in email

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4.3 Starting Page after LOGIN

The INSTRUCTIONS page (Figure 9) appears following login. The **Designer** has access to new links like **EXISTING DESIGN**, **NEW DESIGN**, and **MY ACCOUNT**. When you hover your mouse over the **EXISTING DESIGN** link, you'll see dropdown links for **Design Initiated**, **Submitted**, **Accepted**, and **All Existing Designs**. A **Designer** can edit their own and their group's existing designs which have not been submitted from the design list; they can have the new design by clicking on **NEW DESIGN** link; and they can modify their personal information by clicking on **MY ACCOUNT** link.

4.4 EXISTING DESIGN

Sub-links for **Design Initiated**, **Submitted**, **Accepted** and **All Existing Designs** will show up when user's mouse hover over the link **EXISTING DESIGN** (Figure 9). Each sub-link will open a corresponding list per design status. Figure 14 shows a list including all existing designs currently housed in the web application when the sub-link **All Existing Designs** is clicked. All titles of columns function like "**sort by**" key when any title is clicked. The list in Figure 14 is sorted by column of **County**, which is default sort order. The first clicking on any title will bring list sorted ascending by this column; the second clicking on same title will bring list sorted descending by this column. Keeping clinking on same title will bring the list sorted back and forth between ascending and descending by this column. In the **String Included** cell, when any string or number is entered and the **Search Design** button is clicked, all designs that include that string in **County, Route No., Soil Type, LWM Type, Submit By**, or equal that number in **District, Culvert Width, Culvert Height, Existing Fill Height, New Fill Height, Soil Elastic Modulus, Soil Density, LWM Elastic Modulus**, and **LWM Density** will be displayed.

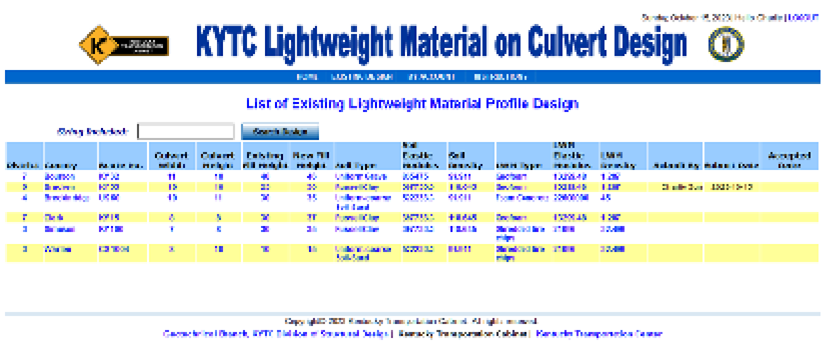

Figure 14. List of all existing designs sorted by County when the sub-link **All Existing Designs** is clicked

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Users can view site detail information by clicking on an item in any column, such as **District, County, Route No., Culvert Width, Culvert Height, Existing Fill Height, Soil Type, Soil Elastic Modulus, Soil Density, LWM Type, LWM Elastic Modulus,** or **LWM Density** from the list in Figure 14. Three (3) tabs are visible to users on the view design page —**Site Information, Design,** and **Attachments**.

4.4.1 Site Information – Shows site information

Figure 15 displays contents under the first tab, **Site Information**. Within this tab, you will discover site information encompassing details such as location, coordinates, route number, speed limit, milepost, and more.

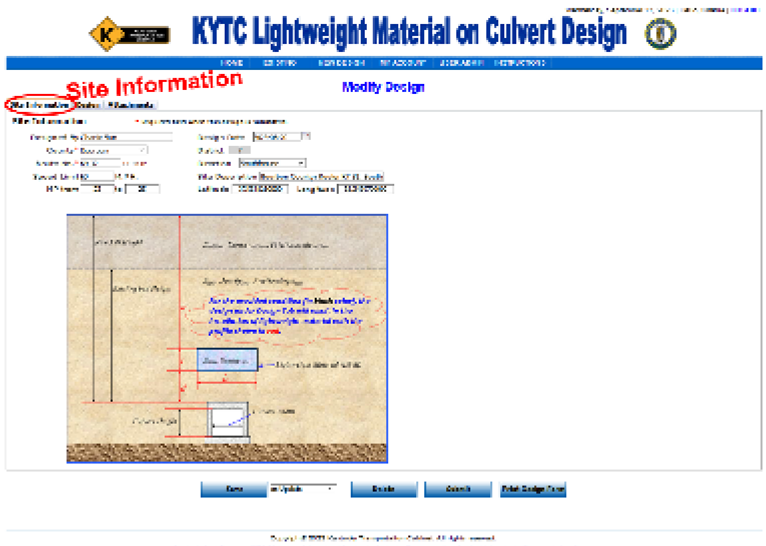

Figure 15. Site detail information for project site

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4.4.2 Design – Shows design for lightweight material installation profile

Figure 16 showcases the content found within the second tab, named **Design**. This tab comprises various sections, including Existing Condition, New Fill Condition, New Design Fill Profile, and Design Options. In Existing Condition, you can find details regarding the existing fill height, culvert size, and soil properties. New Fill Condition encompasses information on the new fill height, soil properties, and lightweight material (LWM) properties. The design option listed beneath the Go button is one utilizing a minimal amount of lightweight material, while the set at the bottom of the Design Options list aims to minimize excavation. Furthermore, there is a Print Design Form button that allows you to generate a design sheet for the current design in PDF format.

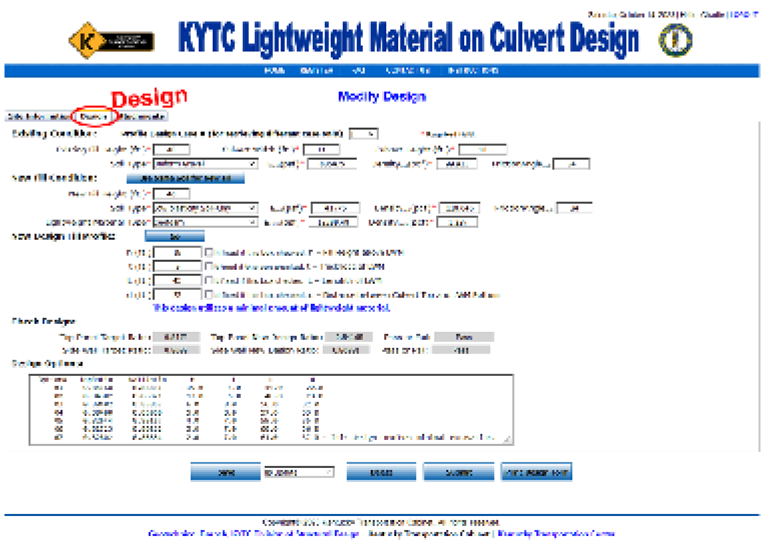

Figure 16. The Existing Condition, New Fill Condition, New Design Fill Profile, and Design Options shown under **Design** tab

4.4.3 Attachments – Shows uploaded attachments by Designer

On the **Attachments** tab, the user may view or download attachments about this design uploaded by the Designer (Figure 17). Clicking on a file name will view this attachment.

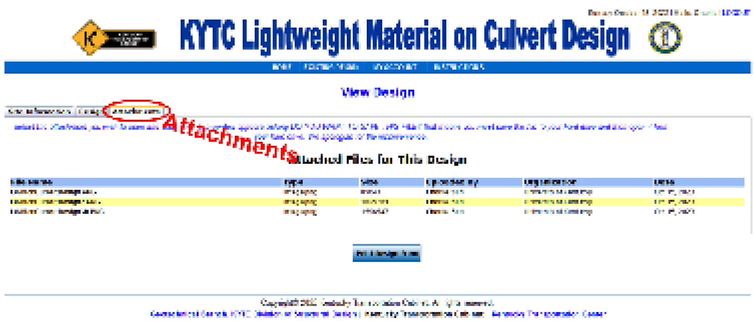

Figure 17. Layout under **Attachments** Tab

4.5 NEW DESIGN – ***Create and Submit a new profile design for lightweight material installation***

The **Designer** can start a new profile design for lightweight material installation profile by clicking the **NEW DESIGN** link. The page displayed in Figure 18 appears once a user clicks this link. The tabs, **Site Information** and **Design** are presented upon opening the link. The figure displayed under the **Site Information** tab illustrates information needed for lightweight material installation design.

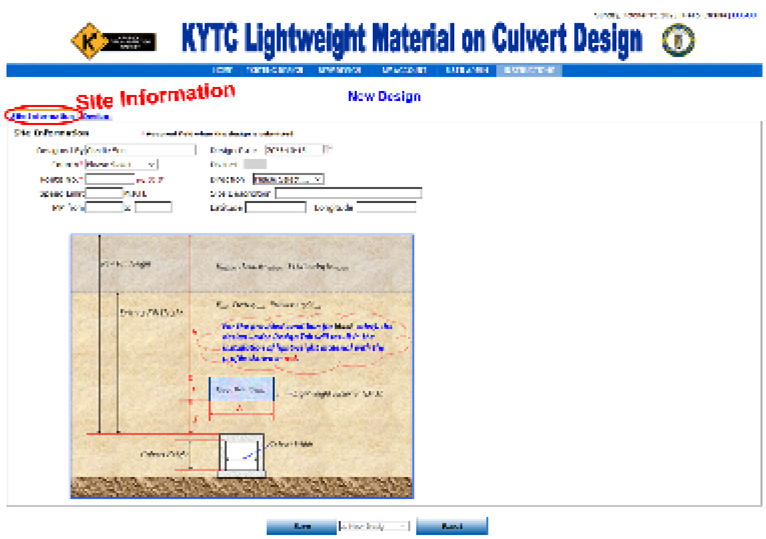

Figure 18. Screen for inputting a new site information

The tabs contain three kinds of entry fields:

1. Required Fields are denoted with *
   - Required fields must be completed to get design results and save their data.
2. Field with gray background
   - Ignorable fields will be automatically filled by application when user inputs corresponding information.
3. Fields without any mark:
   - Optional fields — information can be entered into them, or they can be left blank.

4.5.1 Site Information – Entering site information

Upon clicking the **NEW DESIGN** link, certain fields are conveniently pre-selected or come with default values for ease of use. The **Designed By** field is pre-filled with user's name, while the **Design Date** automatically displays the current date.

Additionally, the **District** field is automatically populated once a **county** selection is made. The **Site Description** is thoughtfully pre-filled based on the information entered in the **County**, **Route No.**, and **Direction**. If necessary, the information within the **Site Description** field can be edited to ensure its accuracy.

4.5.2 Design – Entering design parameters and populating design results

This tab serves as an interface to input essential conditions and parameters for generating a lightweight material installation profile. The existing condition includes details such as the Existing Fill Height, culvert size, and soil properties.

If the soil used for the new fill matches that of the existing fill, a convenient option labeled Use Same Soil for New Fill is provided. Clicking this button automatically populates the new fill condition with the existing soil properties. However, if a different soil is to be used in the new fill, the user can manually input the corresponding soil properties in the new fill condition section.

In addition to soil properties, crucial details for the new fill condition encompass the New Fill Height and the properties for the lightweight material (LWM). Once all necessary data is entered, clicking on the Go button initiates the creation of design results for the lightweight material installation profile. These results include multiple option sets for parameters like Fill Height above LWM (*h*), Thickness of LWM (*t*), Length of LWM (*L*), and Distance between Culvert Top and LWM Bottom (*d*). The set immediately below the Go button corresponds to the design that utilizes the minimal amount of lightweight material, while the set at the bottom of the Design Options list corresponds to the design involving minimal excavation.

Figure 19 provides an illustrative example of the data entered, and it represents the moment when the Go button has been clicked to initiate the design process for a new site.

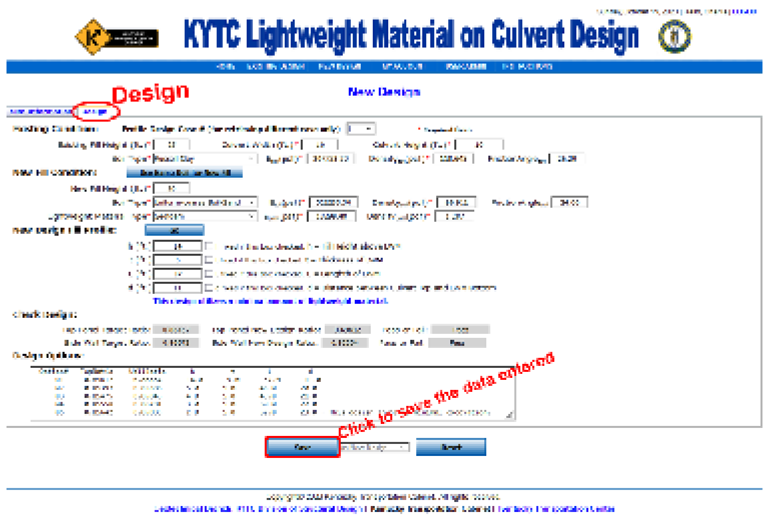

Figure 19. Example of data entered for a new design

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4.5.3 Save Button

Clicking the Save button saves a design for lightweight material installation profile after all required data have been entered and the **Go** button has been clicked. One more tab, one dropdown list, and three more buttons are brought up after the Save button is clicked (Figure 20). Users can upload attachments to the server by using functions on the **Attachments** tab. They can save the design ***as Update, as New Case***, or ***as New Site*** by choosing the appropriate option in the dropdown list. Users can delete the current design by clicking **Delete**, submit current design by clicking **Submit**, and print out the Design Form by clicking **Print Design Form**.

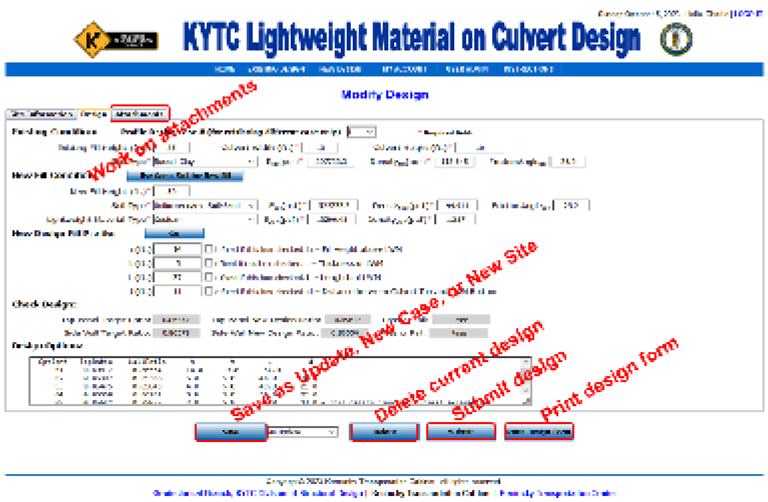

Figure 20. More functions show up after Save Button is clicked

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4.5.4 Attachments – Uploading and managing Attachments

After saving a design data and results, Designers can upload attachments (e.g., pictures; .PDF, .doc, or .zip files) using the page shown in Figure 21 and following these steps:

1. Click **Browse** to identify a file to upload.
2. Click **Upload** to send the selected file to the web application server.

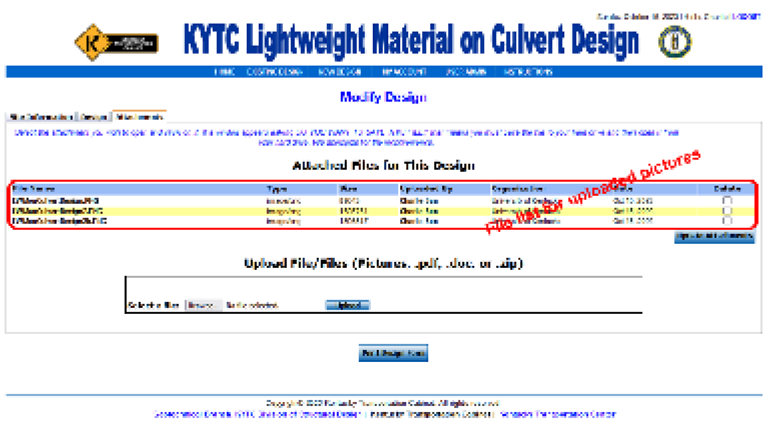

Figure 21. Upload and manage attachments under **Attachment** tab

4.5.5 Save Option Dropdown List

The **Save Option Dropdown List** encompasses three distinct save options, namely ***as Update***, ***as New Case***, and ***as New Design***. By selecting ***Save as New Case***, users can append a new case to the existing design while preserving some site information. On the other hand, opting for ***Save as New Design*** establishes an entirely new site, initialized with certain shared data from the current site.

4.5.6 Delete Button

Clicking the **Delete** button deletes the current site information. It begins a new design for lightweight material installation profile after deleting.

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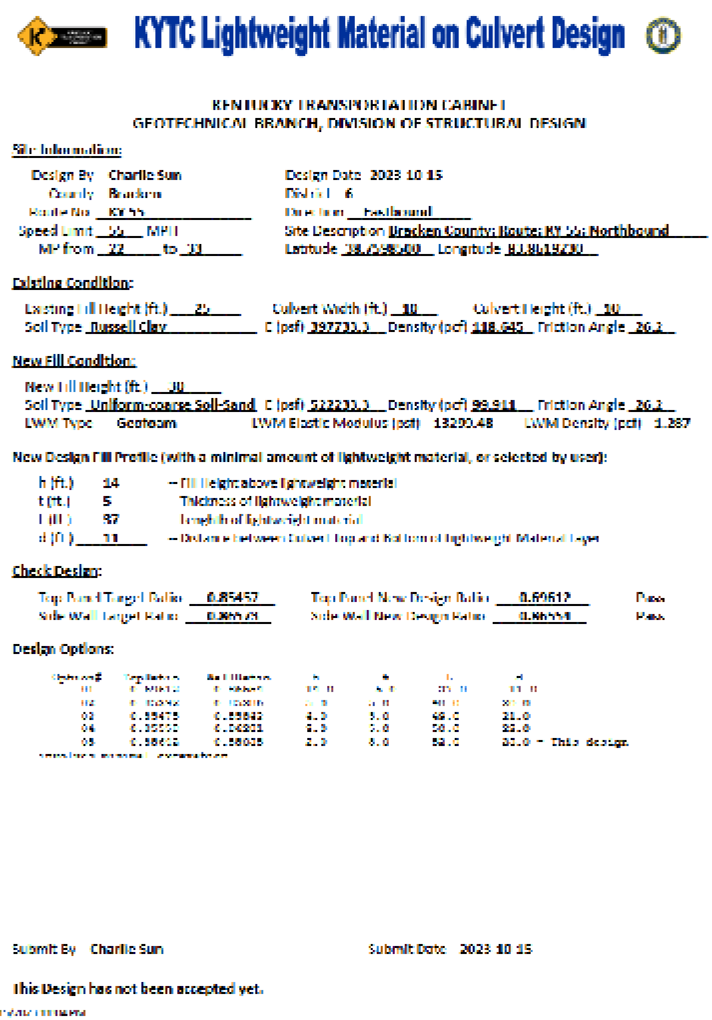
4.5.7 Submit Button

Users will send a design for lightweight material installation profile to Central Office Lightweight Material on Culvert Design (LWMCD) Manager after they click the **Submit** button. When users successfully submit their survey form, emails with the **Design Form** attached as a PDF file are sent to the **Central Office LWMCD Manager** and **Designer**. The message "*Your Lightweight Profile Design has been successfully submitted. Thank you.*" appears onscreen. All the information for the current design is locked. No one can make changes.

4.5.8 Print Design Form Button

Clicking the **Print Design Form** button creates a PDF version of the **KYTC Lightweight Material on Culvert Design Form** (Figure 22). Users can save this file on their local hard drive or open it onscreen using software for viewing PDFs (e.g., Adobe Reader or Acrobat) and save it later. The printed form is identical to the form sent to **Central Office LWMCD Manager**.



KYTC Lightweight Material on Culvert Design

KENTUCKY TRANSPORTATION CABINET
GEOTECHNICAL BRANCH, DIVISION OF STRUCTURAL DESIGN

Site Information:

Design By Charlie Sun — Design Date 2023 10 15
County Bracken — District 6
Route No KY 55 — Direction Eastbound
Speed Limit 55 MPH — Site Description Bracken County; Route: KY 55; Northbound
MP from 22 to 33 — Latitude 38.7598500 Longitude 83.8619230

Existing Condition:

Existing Fill Height (ft.) 25 — Culvert Width (ft.) 10 — Culvert Height (ft.) 10
Soil Type Russell Clay — C (psf) 397733.3 — Density (pcf) 118.645 — Friction Angle 26.2

New Fill Condition:

New Fill Height (ft.) 30
Soil Type Uniform-coarse Soil-Sand — C (psf) 522233.3 — Density (pcf) 99.911 — Friction Angle 26.2
LWM Type Geofoam — LWM Elastic Modulus (psf) 13200.48 — LWM Density (pcf) 1.287

New Design Fill Profile (with a minimal amount of lightweight material, or selected by user):

h (ft.) 14 -- Fill Height above lightweight material
t (ft.) 5 Thickness of lightweight material
L (ft.) 57 Length of lightweight material
d (ft.) 11 -- Distance between Culvert Top and Bottom of Lightweight Material Layer

Check Design:

Top Panel Target Ratio 0.85457 — Top Panel New Design Ratio 0.69612 — Pass
Side Wall Target Ratio 0.86573 — Side Wall New Design Ratio 0.86558 — Pass

Design Options:

Option#	Top Ratio	[illegible]	h	t	L	d
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
03	0.55475	0.85842	4.0	5.0	48.0	21.0
04	0.35550	0.86801	6.0	5.0	50.0	26.0
05	0.38612	0.88035	2.0	6.0	52.0	30.0 -- This design

[illegible]

Submit By Charlie Sun — Submit Date 2023 10 15

This Design has not been accepted yet.

[illegible]

Figure 22. **KYTC Lightweight Material on Culvert Design Form in PDF format**

4.6 MY ACCOUNT -- *Modify Personal Information*

Clicking **MY ACCOUNT** brings up the page depicted in Figure 23. A registered user can update their profile and change their password or contact information on this page (except for their email address, which serves as the user ID).

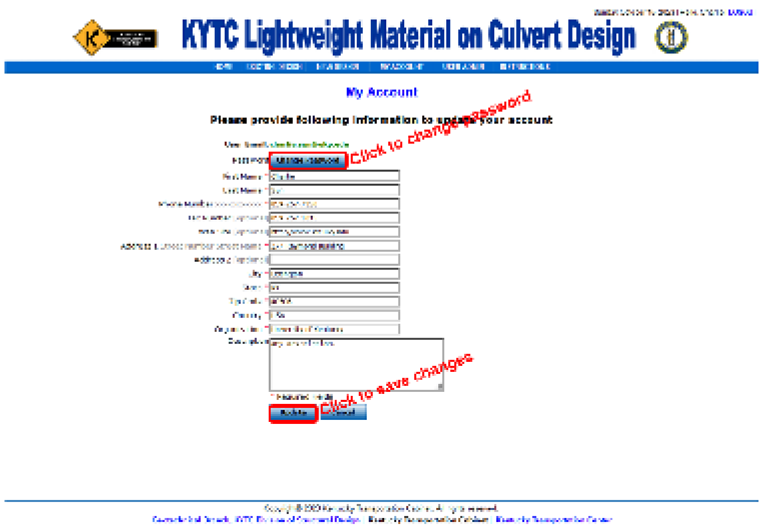


Figure 23. Update user's account from **MY ACCOUNT** link

5. USER AS A CENTRAL OFFICE LWMCD MANAGER

The **Central Office LWMCD Manager** has the most user privileges in the web application. In addition to the links **Designers** can access, the **Central Office LWMCD Manager** sees the following links on the **Header** after logging in: **USER ADMIN →** (**User Admin, User List** and **Groups**) – see Figure 24. The **Central Office LWMCD Manager** has final authority to accept or request changes for design. **USER ADMIN →** (**User Admin, User List** and **Groups**) links to pages for maintaining all the information of registered users and groups. On these pages, new users can be added and information for existing users can be modified. On all pages listing existing sites, the **Central Office Manager** can activate or archive sites. Attachments can be managed on the **Attachments** tab. To learn how to navigate privileges available to **Designers**, refer to the following sections:

4.3 Starting Page after LOGIN
4.5 NEW DESIGN – ***Create and Submit a new profile design for lightweight material installation***

Figure 24. **Header** – after a **Central Office Manager** logs in

5.1 Screen for Managing Existing Design List

On the page listing existing designs, the **Central Office LWMCD Manager** can archive or activate a lightweight material profile design by checking or unchecking the archive checkbox and clicking the **Update** Button (Figure 25). The **Central Office LWMCD Manager** can click on **Retrieve Archive** or **Retrieve All** to view different groups of lightweight material profile designs.

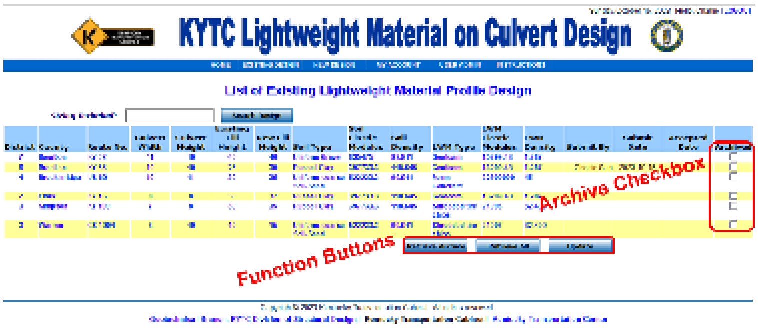


Figure 25. Archive/active designs by a **Central Office Manager**

5.2 Screen for Managing Attachments

The **Central Office LWMCD Manager** can review or download attachments that have been uploaded by the **Designer** on the design page's **Attachment** tab. Following review, they can decide whether to delete the attachment by checking the appropriate box. Upon making their selection(s), **Central Office LWMCD Manager** should proceed by clicking the **Update Attachments** button to complete the necessary action (Figure 26).

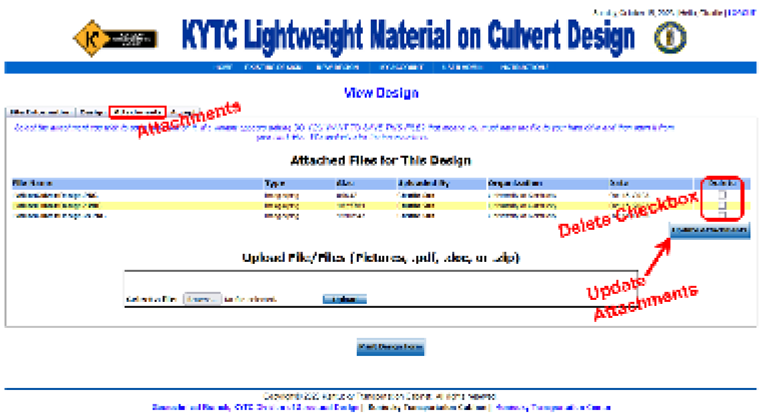


Figure 26. Manage attachments by **Central Office Manager**

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5.3 Accept or Request Changes – *Central Office LWMCD Manager's Decision*

After the **Central Office LWMCD Manager** logs in, if a lightweight material installation profile design is awaiting their acceptance, the portion of **Central Office Manager's Decision** under **Accept** tab will be active (Figure 27). After deciding to **Accept** or **Request Changes**, the **Central Office LWMCD Manager** fills out the corresponding information and clicks the **Submit** button. Once submitted, individual emails containing the **Design Form** in PDF format are sent to the **Designer** who submitted the profile design. A copy of this email is sent to the **Central Office LWMCD Manager** for recordkeeping purposes.

If the **Central Office LWMCD Manager** requests changes, emails which include suggestions or modifications for further consideration are sent to the **Designer**.

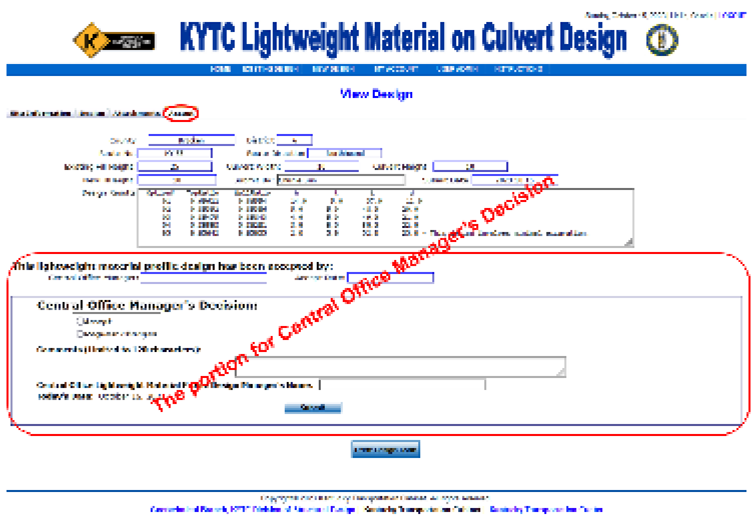

Figure 27. **Central Office Manager** submits their decision

5.4 USER ADMIN – *User Administration*

In the **Header** section, the **Central Office LWMCD Manager** has access to **USER ADMIN → User Admin**. Clicking on this link brings up the **User Administration** page. This page contains three tabs — **Pending Designer**, **All Existing Users**, and **Add New User**. Figure 28 displays the **Pending Designer** tab, which lets the **Central Office LWMCD Manager** approve or delete pending requests for **Designer** by clicking the corresponding buttons.

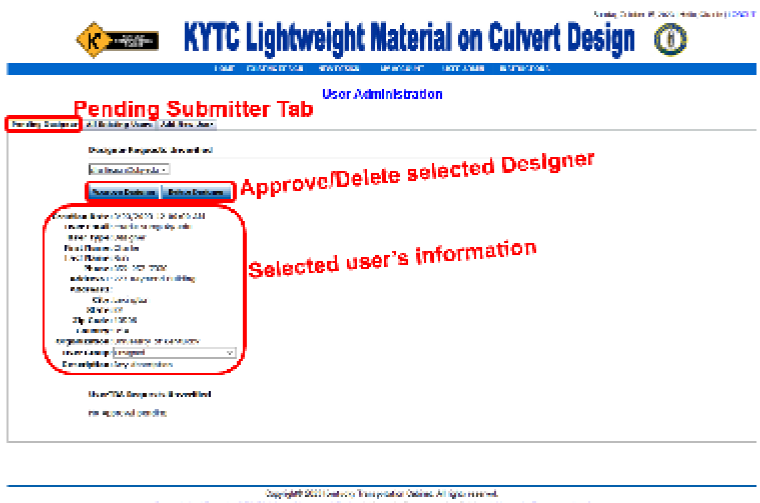

Figure 28. **User Administration** page with **Designer** in pending

5.4.1 Pending Designer – Approve/Reject Pending Designer

The area on this tab depends on whether **Designer** requests are pending. These situations arise only when a user has registered on web application management system but not activated their account yet. If there are users who have not activated their accounts, dropdown lists appear. When the dropdown list under **Designer Requests Unverified** is clicked and a user is selected, the user information appears as seen in Figure 28.

The **Central Office LWMCD Manager** may approve a **Designer**'s request by selecting correct user group and clicking the **Approve Designer** button. They can reject or delete a request by clicking the **Delete Designer** button. If a **Designer** is approved, the web application management system sends an email to the **Designer** notifying them of the approval. If there are no requests pending, "No Approval pending" appears under **Designer Requests Unverified**.

5.4.2 All Existing Users – Maintain All Registered User's Information

A second tab — **All Existing Users** — provides the **Central Office Manager** with a dropdown list of all existing registered users. When a user is selected from the dropdown list, their personal information appears beneath the dropdown list, which the **Central Office LWMCD Manager** can modify (Figure 29). The **Central Office LWMCD Manager** can save changes to a user's profile by clicking the **Update** button; change their status by clicking the **Change Status** button; or reset their password by clicking the **Reset Password** button. Clicking the **Reset Password** sends the selected user an email with a new password automatically generated by the system.

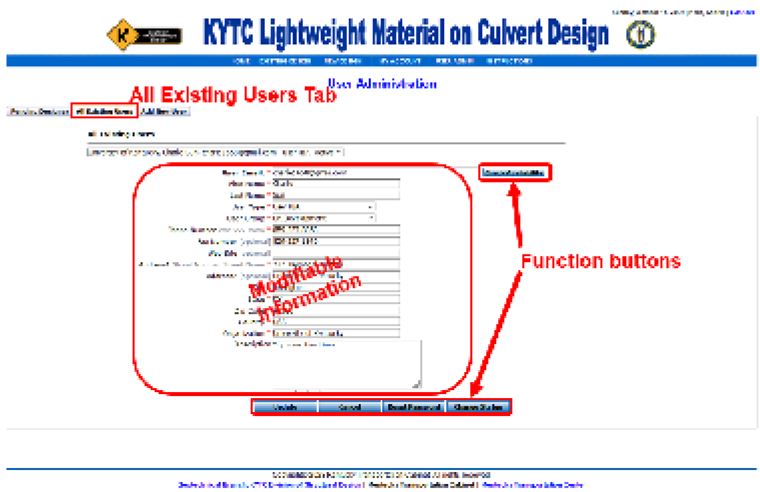

Figure 29. User info appears when user is selected on **All Existing Users** tab

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5.4.3 Add New User -- Add/Invite New User

Clicking the **Add New User** button lets the **Central Office LWMCD Manager** registering and activating a new user on their behalf (Figure 30). This user does not need to activate their account and can directly login to the web application via the **LOGIN** link. This page looks nearly identical to the **Registration** page seen in Figure 2 except the **Central Office LWMCD Manager** can select **User Type** and **Group** for the invited user directly. No activation from user's side is needed. After clicking **Register**, the web application management system instantly sends an email to the invited user that includes the **LOGIN** link.

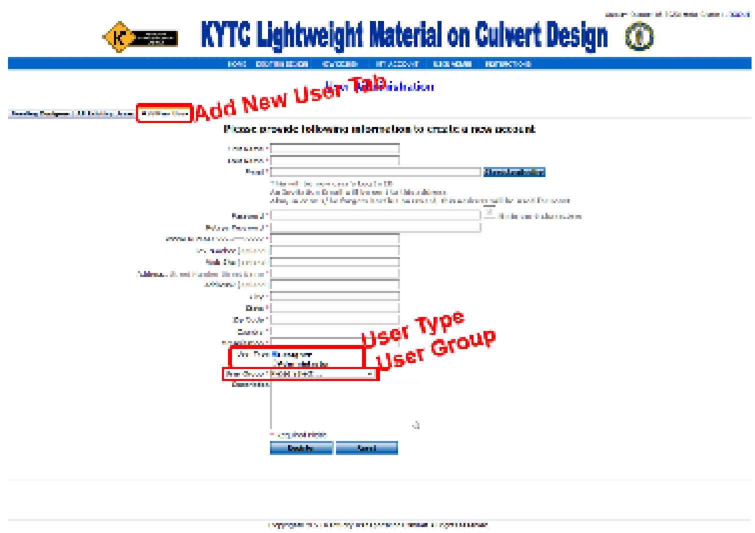

Figure 30. **Add New User** tab lets **Central Office Manager** to add/invite new users

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5.5 USER List

The **Central Office LWMCD Manager** has access to the **USER ADMIN → User List** link in the **Header**. Clicking this link takes the **Central Office LWMCD Manager** to the **User List** page (Figure 31). On this page, the **Central Office LWMCD Manager** can search users by using any string included in any fields. All titles of columns function like "**sort by**" key when any title is clicked. The **Central Office LWMCD Manager** can copy users' email addresses by selecting the checkboxes in front of users and clicking the button of **Copy Selected Email Addresses**. They can go to user detail page and modify their data by clicking on a user.

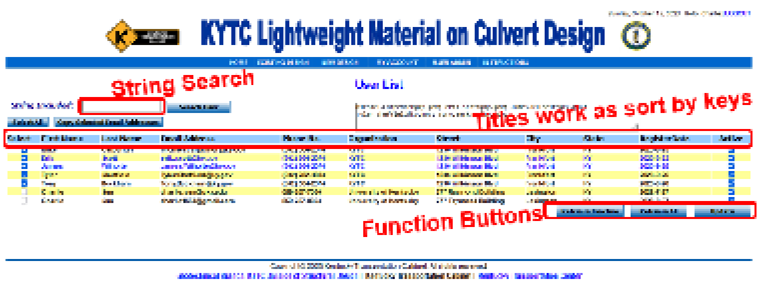

Figure 31. **USER ADMIN → User List** page provides **Central Office Manager** an interface maintaining user information and copy user email addresses

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5.6 GROUP ADMIN – *Group Administration*

The **Central Office LWMCD Manager** has access to the **USER ADMIN → Groups** link in the **Header**. Clicking this link takes the **Central Office LWMCD Manager** to the **User Group List** page (Figure 32). On this page, the **Central Office LWMCD Manager** can modify existing groups' information and add new groups.

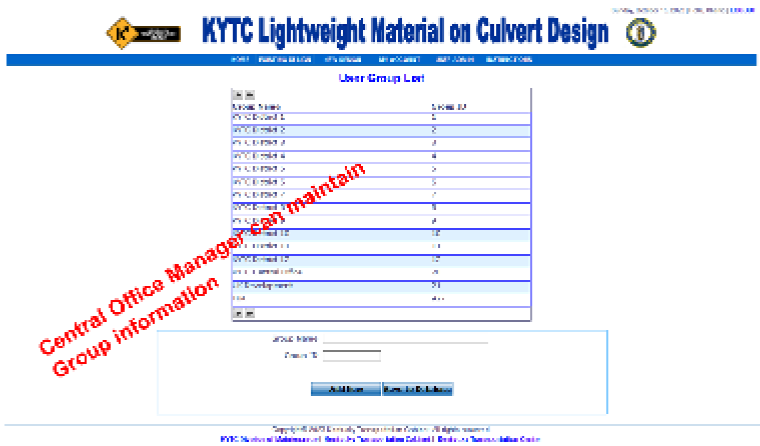

Figure 32. **USER ADMIN → Groups** page provides **Central Office Manager** an interface maintaining group information

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6. USER AS AN ADMINISTRATOR

An **Administrator** is an assistant to the **Central Office LWMCD Manager** in the web application. The **Administrator** can perform all functions available to the **Central Office LWMCD Manager** except receiving email when the Designer submits a lightweight material installation profile design. Only the **Central office LWMCD Manager** will get this email.

7. LOGOUT

The **LOGOUT** link appears in the upper right corner of every page of the web application. When a user clicks a **LOGOUT** link, the system deletes all session variables, and a fresh session begins. The user is then redirected to the original **HOME** page. To reenter the site, the user must click the **LOGIN** link in the upper right corner of the page and enter their **Email Address** and **Password**.

If you have questions or need assistance with the KYTC Lightweight Material on Culvert Design web application, please contact:

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