# Design Considerations and Applications of Lightweight Materials for Earthquake-Resistant Infrastructure

**Steven F. Bartlett, Ph.D., P.E. University of Utah**

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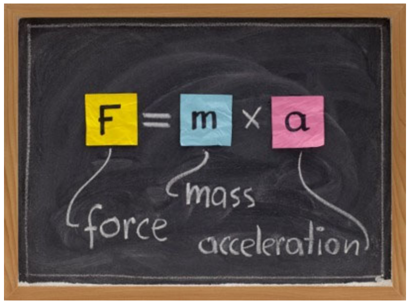
# Topics

- Introduction
- Material Properties
- Applications
- Design Considerations

# Introduction – Lightweight Materials Advantages

- Low inertial forces




  - small m (mass) produces small $F_i$
- High strength to weight ratio
- Energy Loss
  - Compressible → Increased Damping
- Manufactured materials with low variability in mechanical properties

# Material Properties – EPS and Cellular Concrete

## EPS

- Weight
  - 0.7 to 2.85 pcf
- Compressive Strength
  - 5 to 60 psi (10% strain)
  - 2.2 to 18.6 psi (1% strain)
    - Elastic Range
- Young's Modulus
  - 220 to 1,860 psi

## LCC

- Weight
  - 20 to 45 pcf
    - Typical constructed values
- Compressive Strength
  - 50 to 400 psi
- Young's Modulus
  - 220 to 275 ksi

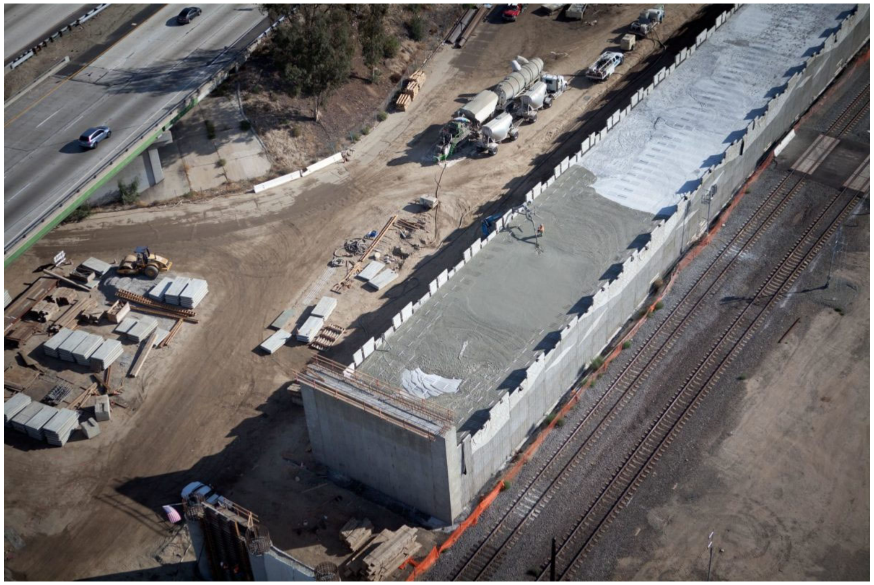
# Material Properties – Strength to Weight Comparison

- Stiff Clay = 75 kN/$m^2$ / 18 kN/$m^3$ = 4.2
- Med. Dense Sand at 5 m = 74 kN/$m^2$ / 22 kN/$m^3$ = 3.4
- EPS = 40 kN/$m^2$ / 0.196 kN/$m^3$ = 204
  - For strength in elastic range (i.e., strength at 1 percent strain)
- LCC = 333 kN/$m^2$ / 3.9 kN/$m^3$ = 85
  - For ultimate strength

# Applications

- Roadway construction over soft soils / reclaimed land
- Rail embankment
- Bridge abutments and under fill
- Accelerated bridge construction
- Retaining and buried wall backfill
- Culverts, pipelines and buried structures
- Slope stabilization
- Leeves and dikes
- Landscaping and vegetative green roofs

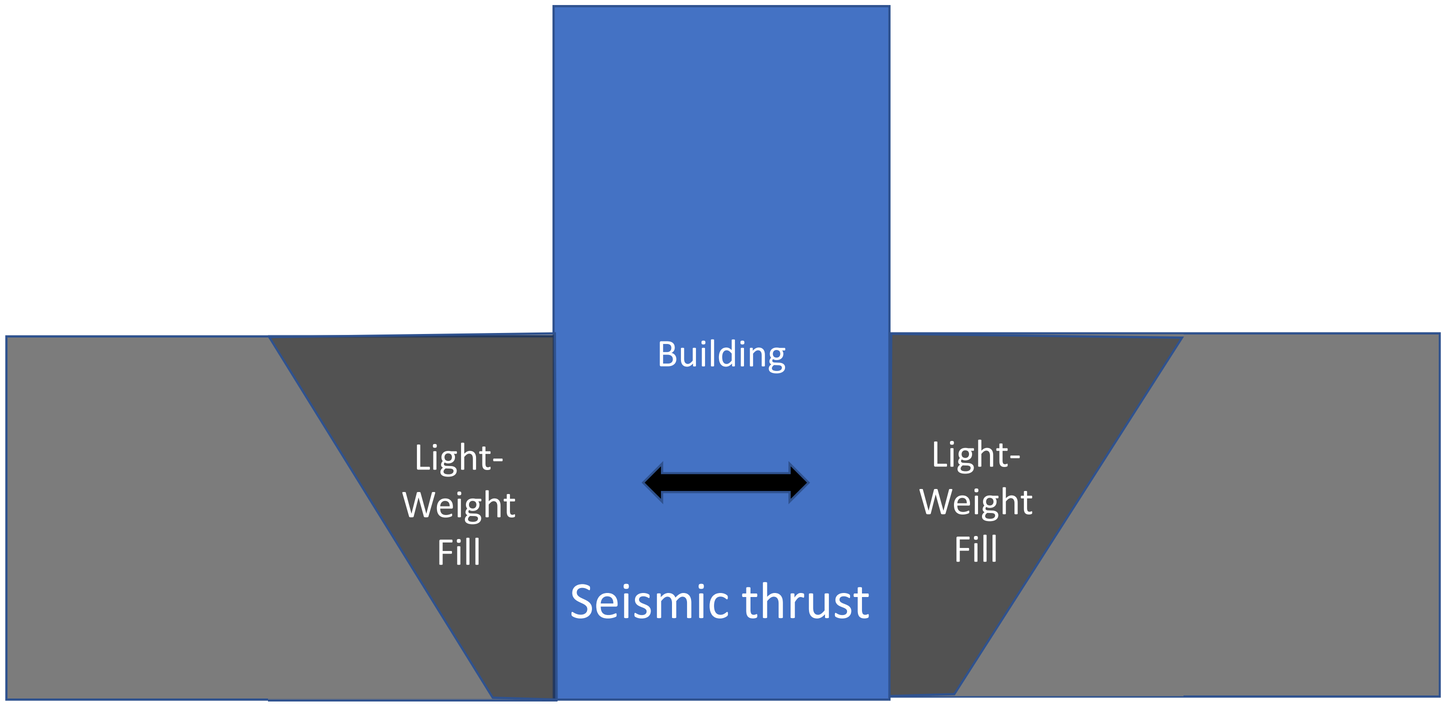
# Lightweight Embankments and Fills



LCC embankment - Colton Crossing, California
Photo courtesy of Cell-Crete.com

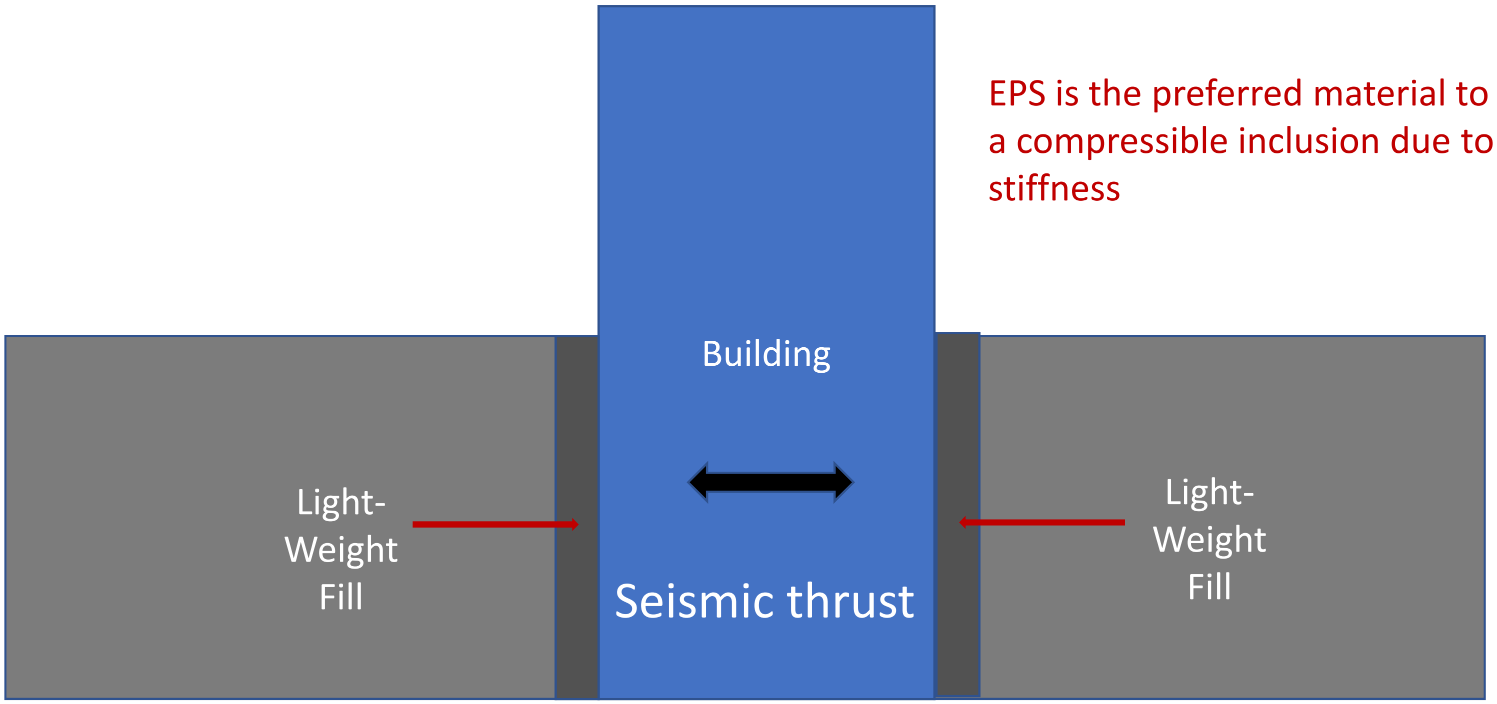
Geofoam embankment –
Utah Transit Authority Light Rail System
Salt Lake City, Utah

# Seismic Advantages – Backfill for Buried Walls – Mass Reduction




Seismic thrust greatly reduced due to low unit weight and compressibility of light-weight materials

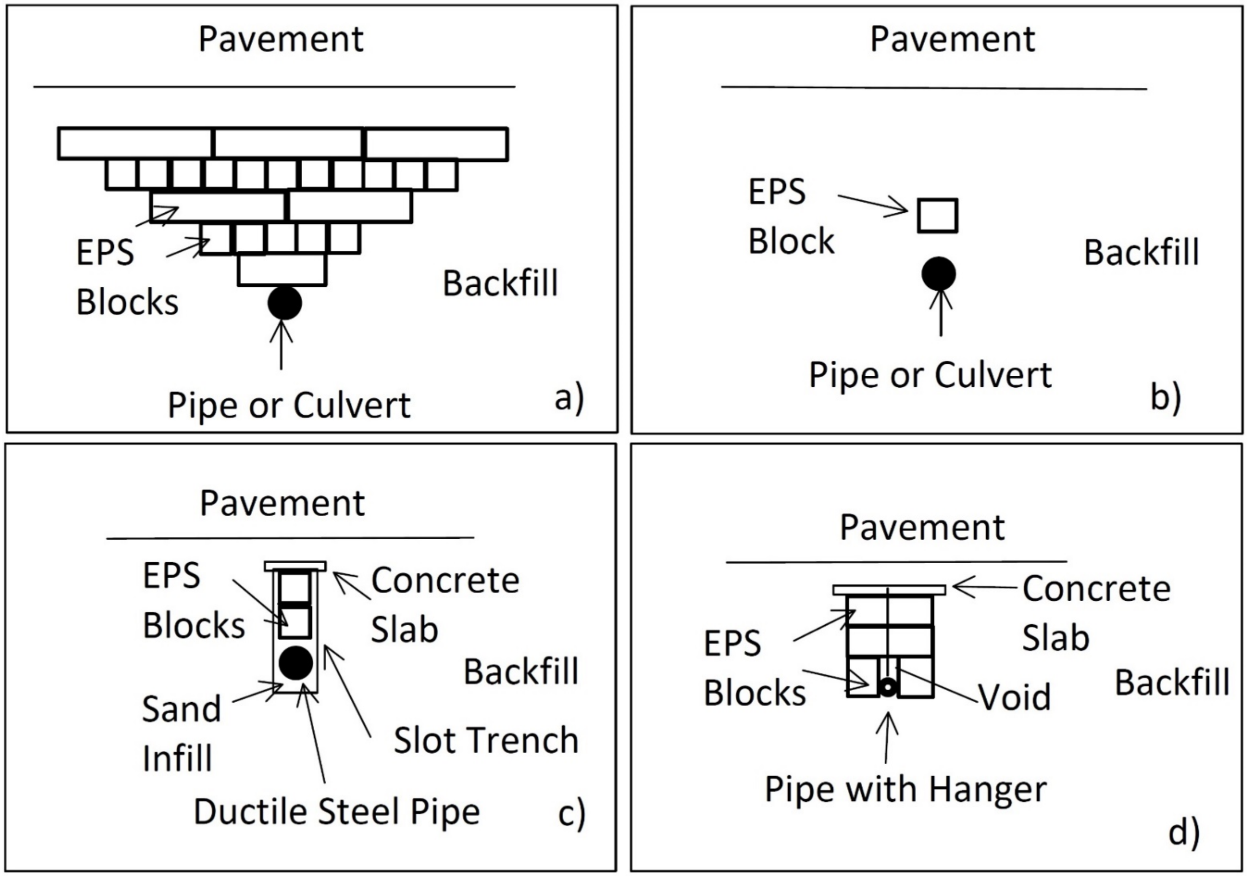
# Seismic Advantages – Backfill for Buried Walls – Compressible Inclusion



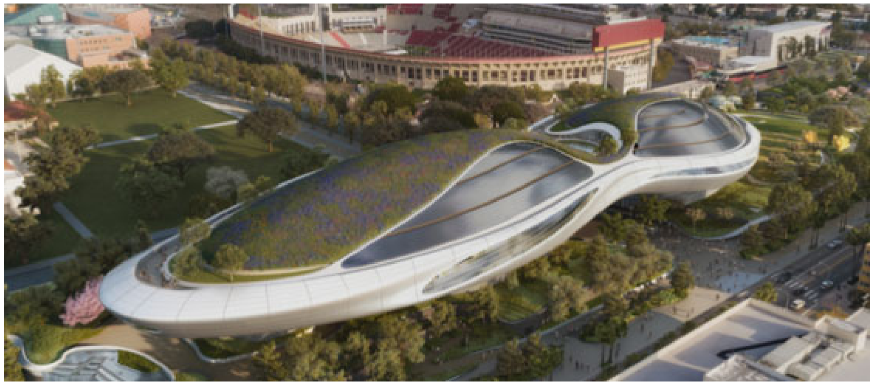

EPS is the preferred material to produce a compressible inclusion due to its low stiffness

Seismic thrust greatly reduced due to low unit weight and compressibility of light-weight materials

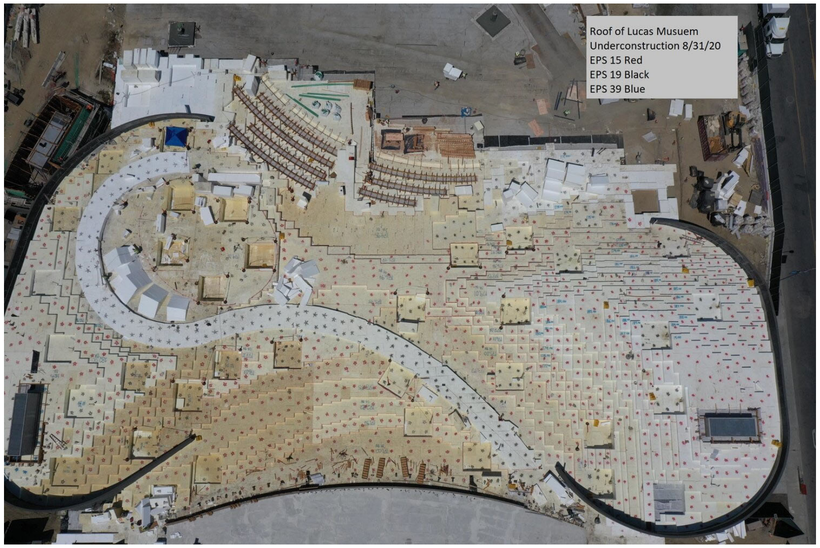
# Pipeline Protection Strategies



# Light-Weight Green Roofs

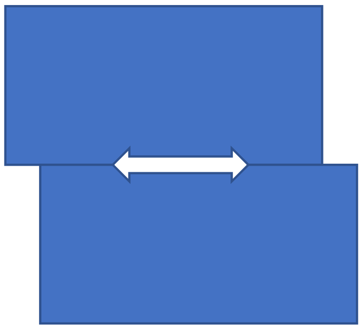


Conceptual View of Lucas Museum
Los Angles California

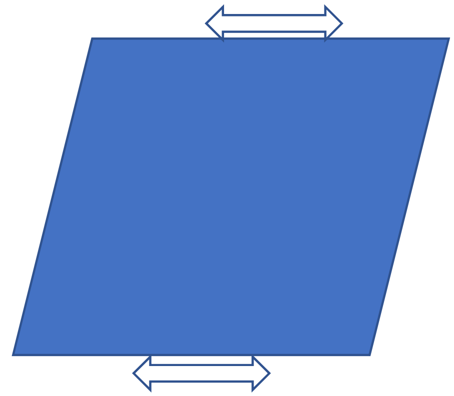



EPS Placement Lucas Museum
Los Angles California – Over Parking Structure

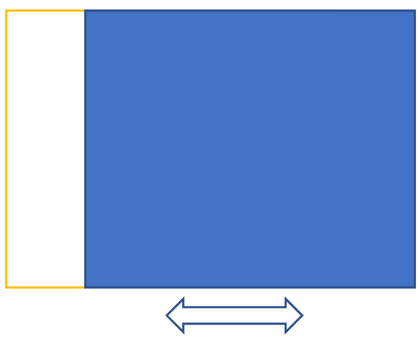
# Modes of Seismic Excitation / Failure



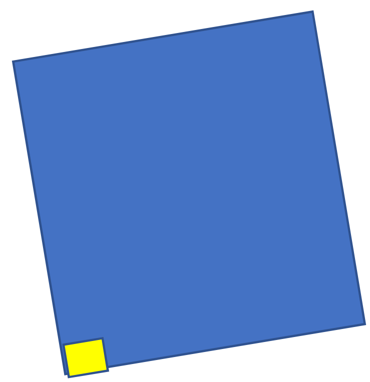
Interlayer Shear / Sliding



Horizontal Sway and Overstressing

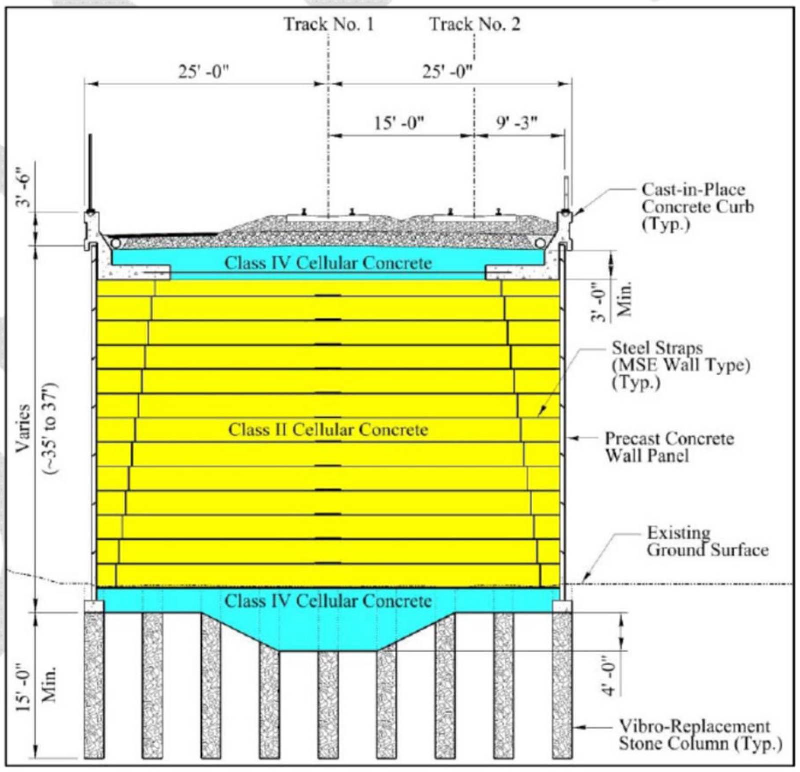


Basal Sliding



Rocking and Uplift

# Design Considerations – LCC Embankment




LCC embankment - Colton Crossing, California

- (1) 8.5-foot wide concrete ties with ballasted track section [12 inches ballast/18 inches sub ballast],

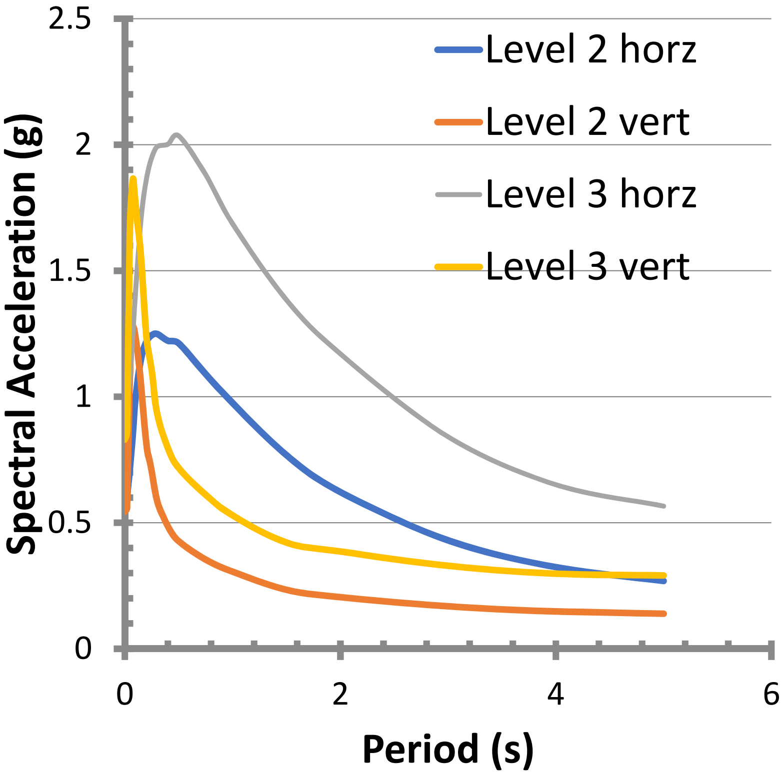
  (2) 3-foot thick upper layer of Class IV cellular concrete,

  (3) variable thickness of Class II cellular concrete,

  (4) 2.5-foot thick Class IV layer of cellular concrete with a 4-foot deep shear key embedded in the foundation soils (at higher embankment sections),

  (5) vibro-replacement stone columns approximately 15 ft deep in the foundation soils

# Design Considerations – Spectral Accelerations




1. Level 1 – The embankment structure should remain intact with no permanent deformation (i.e. the seismic loads must remain within the elastic range of the stress-strain curve of the embankment).
2. Level 2 – The embankment structure should be repairable, with only minor permanent deformation.
3. Level 3 – The embankment structure must not collapse after experiencing permanent deformations.

AREMA (2010)

# Design Considerations – Design Time Histories

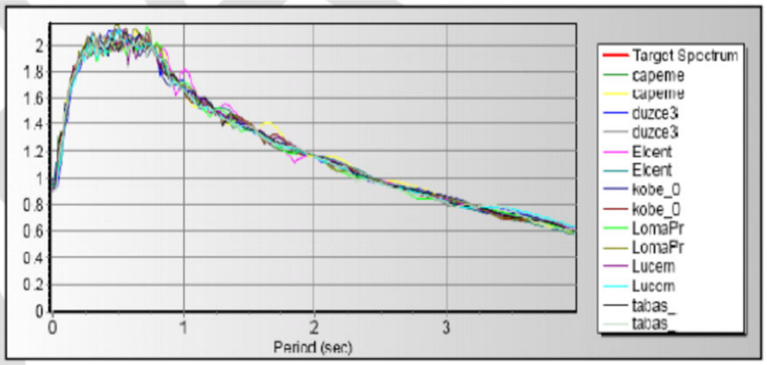



**Figure 4. Spectrally matched time histories for Level 3 horizontal response spectra.**

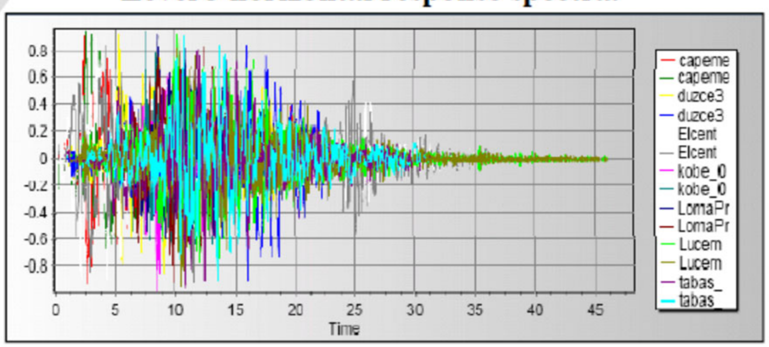
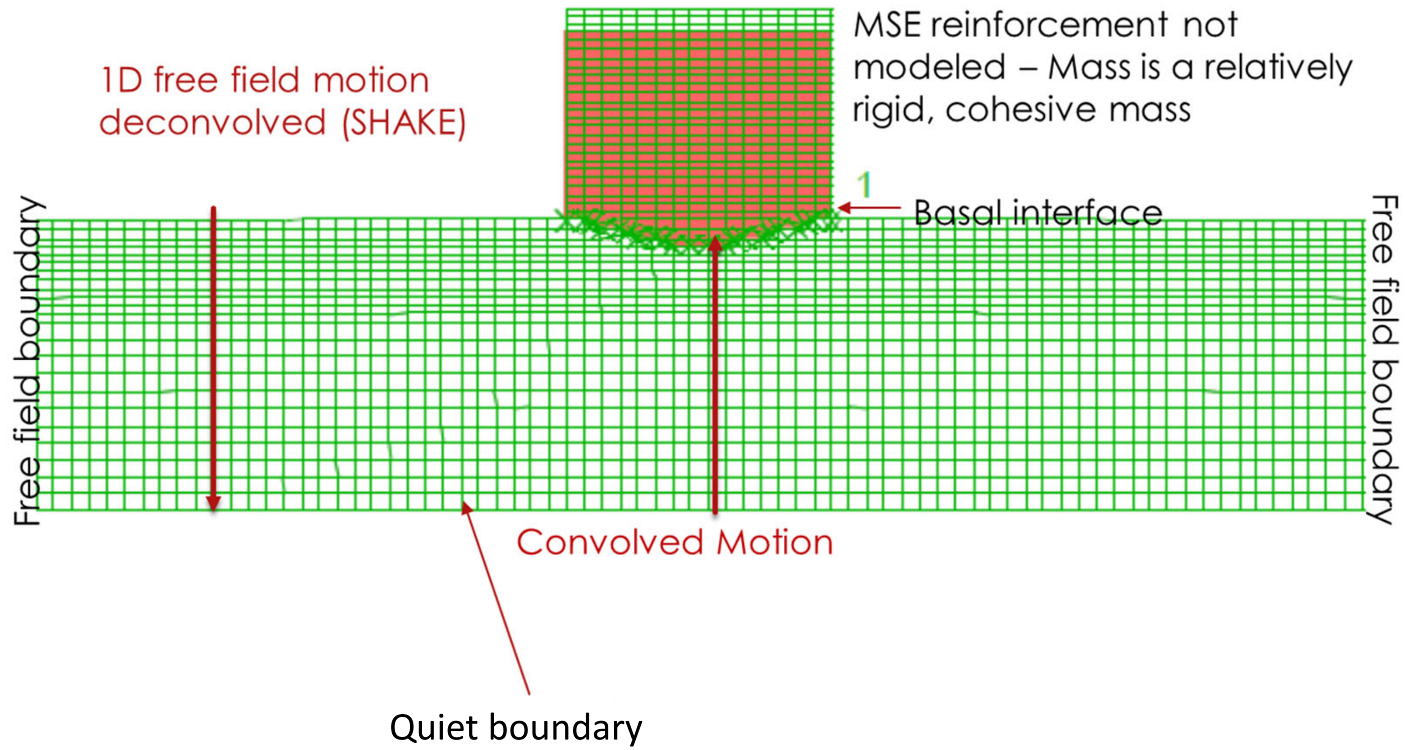



**Figure 5. Comparison of spectrally-matched time histories with Level 3 target spectrum.**

# Design Considerations – Numerical Model



# Design Considerations – Colton Crossing Summary

- Evaluations suggest that the LDCC embankment remained in the elastic range for AREMA Level 1 and 2 earthquakes and will not exceed the peak shear strength under any of the AREMA Level 1, 2 and 3 earthquakes.

- Reinforcement of the LDCC mass is recommended to prevent the potential for minor cracking resulting from excitation.

- Interlayer sliding and overstressing of LCC due to sway did not occur.
- Estimated basal sliding of the tallest section of the embankment is expected to range from 1 to 4 inches at the Level 2 earthquake, and from 4 to 7 inches at the Level 3 earthquake.

- The presence of basal shear key was integral to limit basal sliding for the AREMA Level 3 event. Higher strength LCC is also recommended near the top and base of the embankment.

- Rocking mode is not significant and any minor overstressing from such should be addressed by higher strength LCC in basal layer.

# Design Considerations – Freestanding EPS Embankments

Shake Table Test – EPS Development Org. - Japan

Geofoam embankment –
Utah Transit Authority Light Rail System
Salt Lake City, Utah

# Design Considerations - Steps of Simplified Approach for Interlayer Shear and Sliding and Basal Sliding

| | |
|---|---|
| **Calculate** | Fundamental period of the EPS embankment |
| **Develop** | Design acceleration response spectrum |
| **Determine** | Design acceleration and inertial forces at the base and top of embankment |
| **Determine** | Determine the internal sliding and shear forces within the embankment |
| **Compare** | Internal sliding force and shear forces with available resistance |
| **Calculate** | Factor of Safety |

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# Simplified Approach – Calculate Fundamental Period of Embankment as SDOF System

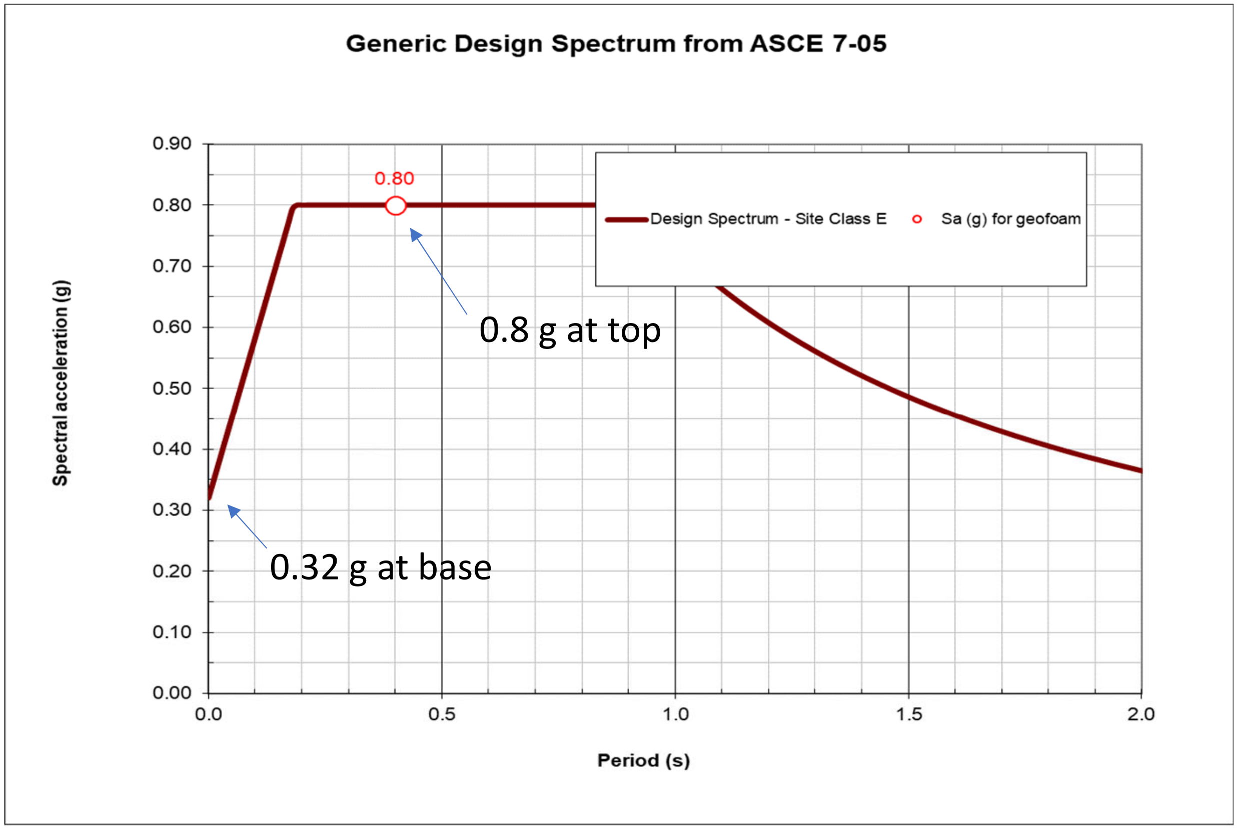
flexural, shear and axial stiffness of the beam are considered in this equation

$$T_0 = 2\pi\left[\left(\frac{\sigma'_{v_0}H}{gE_{t_i}}\right)\left(4\left(\frac{H}{B}\right)^2 + \left(\frac{12}{5}\right)(1+\nu) + 1\right)\right]^{0.5}$$

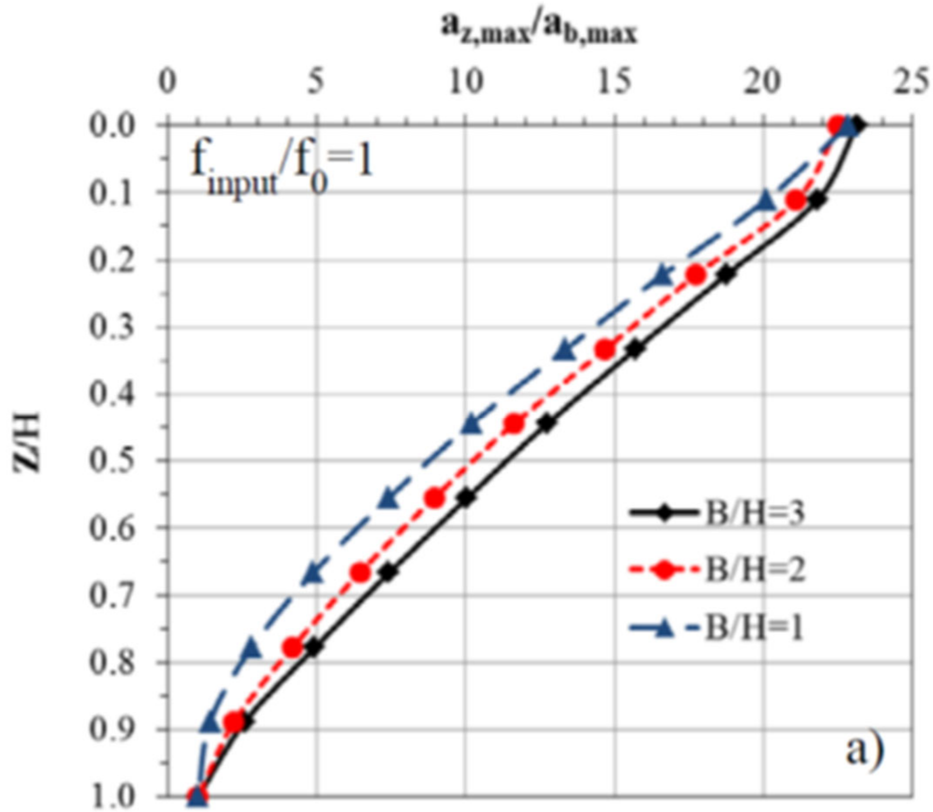
(Hotta. 2001)

To = fundamental period
$\sigma'_{v_0}$ = *effective vertical stress*
*H = height of embankment*
*g = acceleration of gravity*
*B = width of embankment*
$E_{t_i}$ = *Youngs modulus of LDCC*
$(\nu)$ = *Poisson's ratio*

# Simplified Approach – Determine Design Acceleration and Inertial Forces the Base and Top of the Embankment



Simplified Approach (Sliding Only)
Acceleration Amplification within Embankment from Numerical Models

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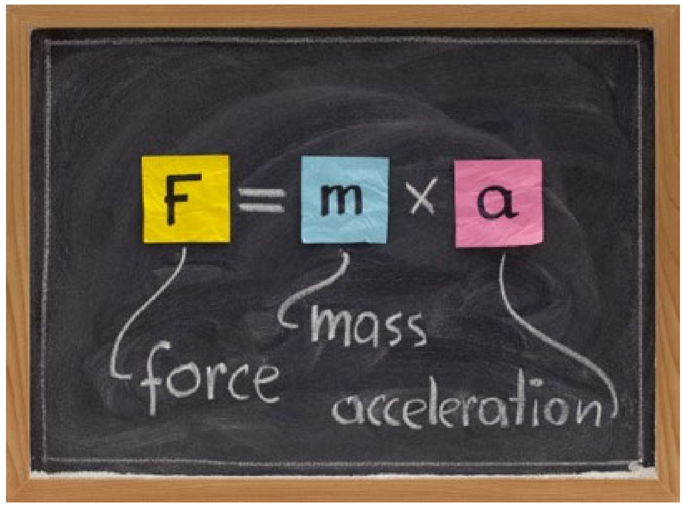
## Simplified Approach – Determine Design Acceleration and Inertial Forces the Base and Top of the Embankment




m = lumped mass (i.e., mass of embankment above potential sliding plane)
a = acceleration in embankment at potential sliding or shear plane with acceleration linearly interpolated from top of embankment to bottom.

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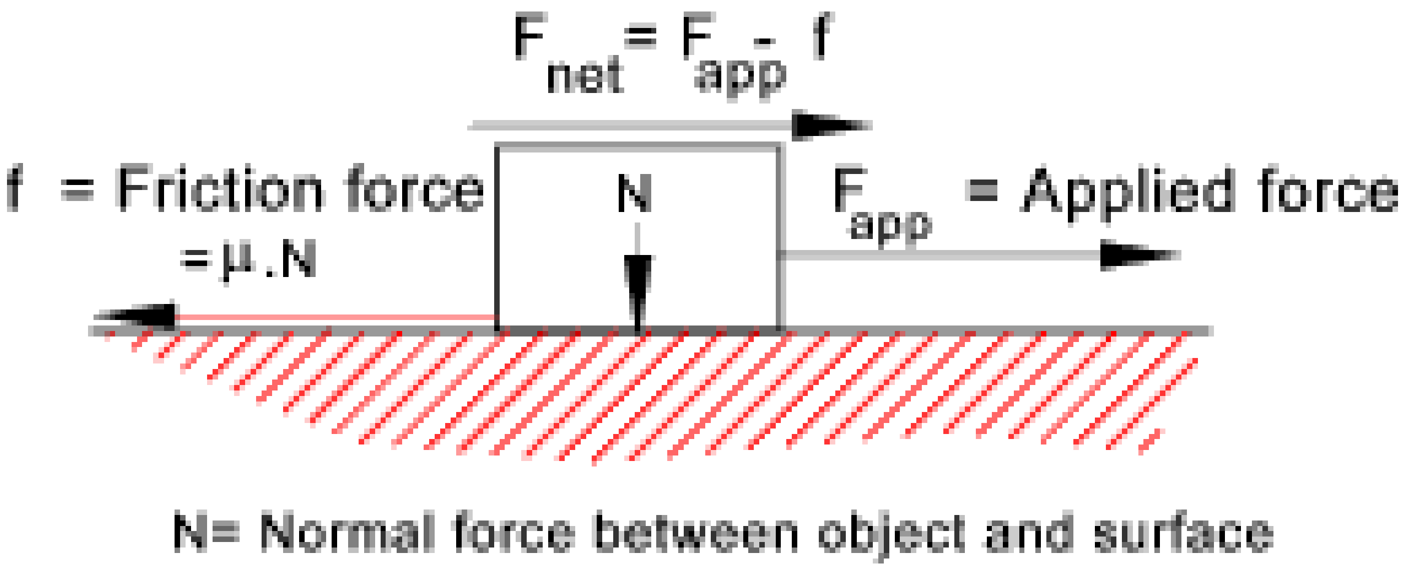
# Simplified Approach - Sliding Stability – Force Diagram




**FS = capacity / demand**
**FS = f / Fapp**

# Shear Keys to Prevent Sliding and Example Calculation


| | | | | | | | |
|---|---|---|---|---|---|---|---|
| H = | | | 5 | m | | | |
| Block height = | | | 1 | m | | | |
| number of interfaces | | | 5 | | | | |
| normal stress | | | 23 | kPa | | | |
| interface friction | | | 0.8 | (geofoam - geofoam) | | | |
| interface friction | | | 0.6 | (geofoam - soil) | | | |
| geofoam shear strength | | | 23.0 | psi (EPS 19 used in shear key) | | | |
| geofoam shear strength | | | 157.3 | kPa | | | |
| | | | | | | | |
| interface # | $S_a$ (g) | mass/unit area (kg/m$^2$) | inertial force (N/m$^2$) | frictional resisting force (N/m$^2$) | shear key coverage (%) | cohesive resisting force (N/m$^2$) | FS sliding (w/key) |
| | | | | | | | |
| 5 | 0.800 | 2304 | 18088 | 18082 | 0.0 | 0 | 1.00 |
| 4 | 0.704 | 2304 | 15918 | 18082 | 0.0 | 0 | 1.14 |
| 3 | 0.608 | 2304 | 13747 | 18082 | 0.0 | 0 | 1.32 |
| 2 | 0.512 | 2304 | 11576 | 18082 | 0.0 | 0 | 1.56 |
| 1 | 0.416 | 2304 | 9406 | 18082 | 0.0 | 0 | 1.92 |
| 0 | 0.320 | 2304 | 7235 | 13561 | 0.0 | 0 | 1.87 |

# Design Considerations - Summary of EPS Embankment Evaluations

- Horizontal accelerations of 0.5 to 0.6 g applied at the fundamental period of the embankment are necessary to initiate interlayer sliding and basal sliding. Geofoam embankments appear to be relatively stable under most earthquake loadings.

- Simplified techniques based on SDOF system are recommended for seismic evaluations of routine projects, However, for large, nearby earthquakes and irregular embankment geometries, discrete block models should be considered.

- Sliding can be easily prevented by using shear keys or adhesive (glue) in strategic areas of the embankment, if necessary.

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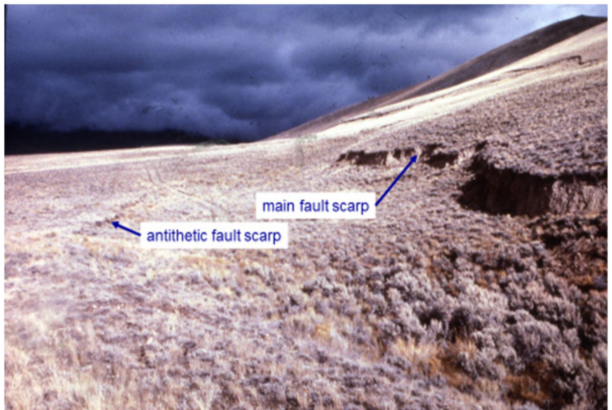
# Seismic Advantages – Lightweight Cover and Backfill for Pipelines

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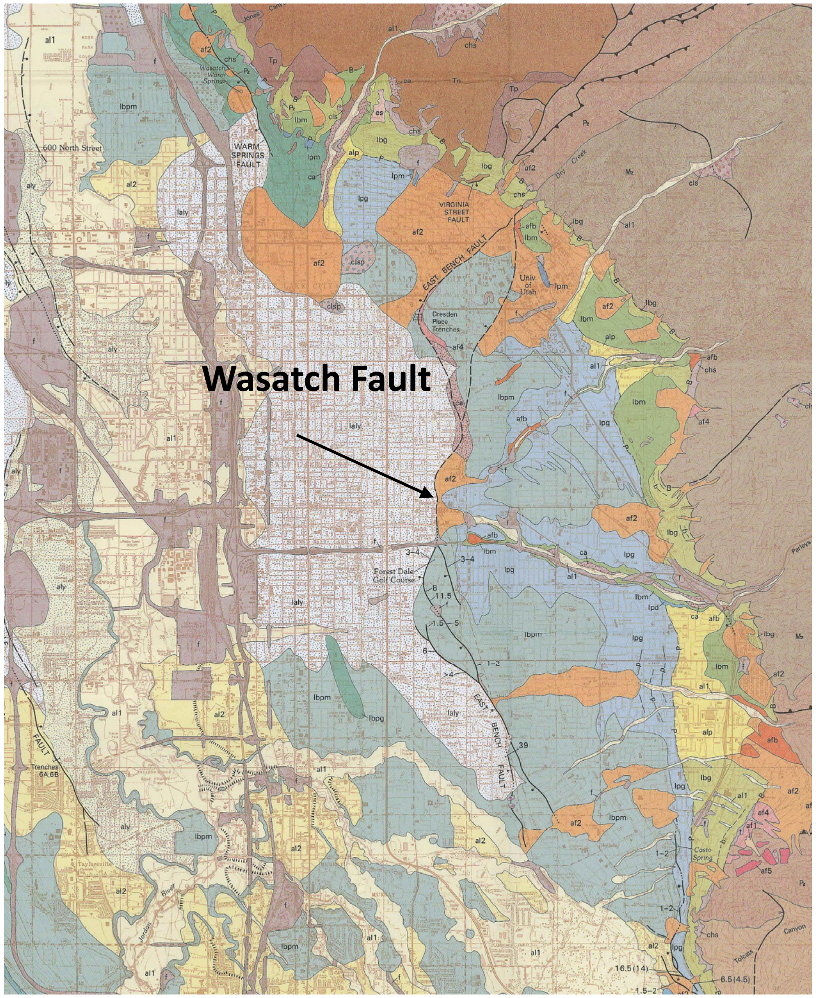
# Wasatch Fault – Salt Lake Valley

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# Pipelines (Light-weight Cover Over Faults)

Shallow Burial – Normal Faulting

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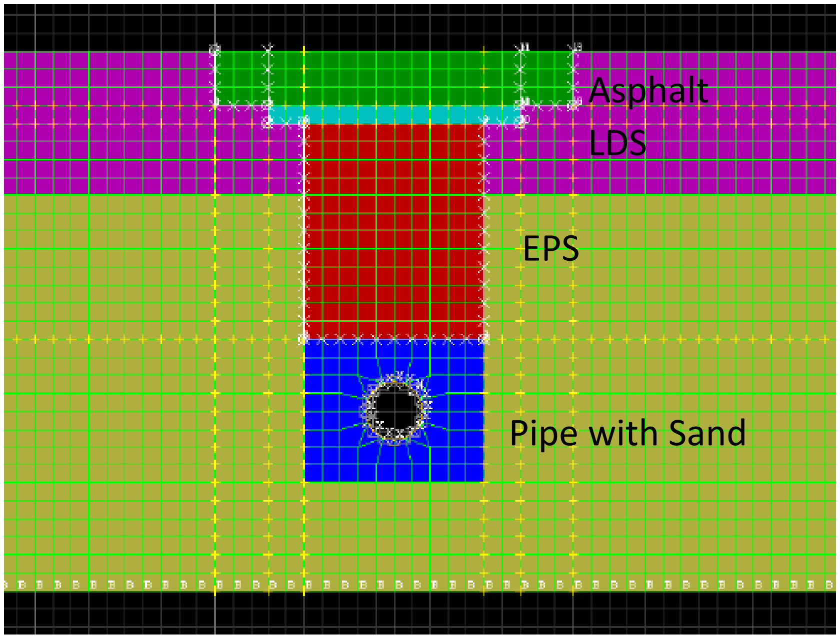
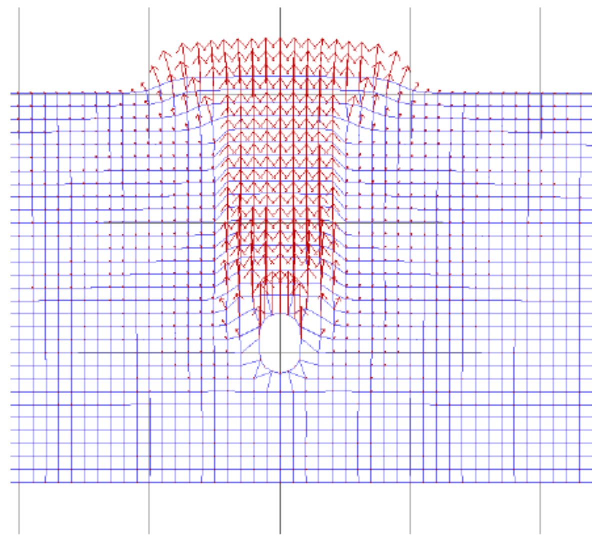
# Pipelines (Light-weight Cover Over Faults)

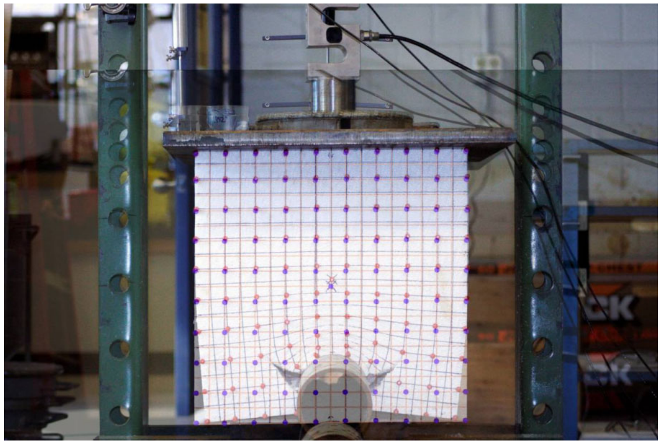



Lightweight-Cover System



Displacement Vectors During Failure

# Uplift Tests



# Seismic Advantages – Lightweight Cover and Backfill for Pipelines Undergoing Vertical Offset

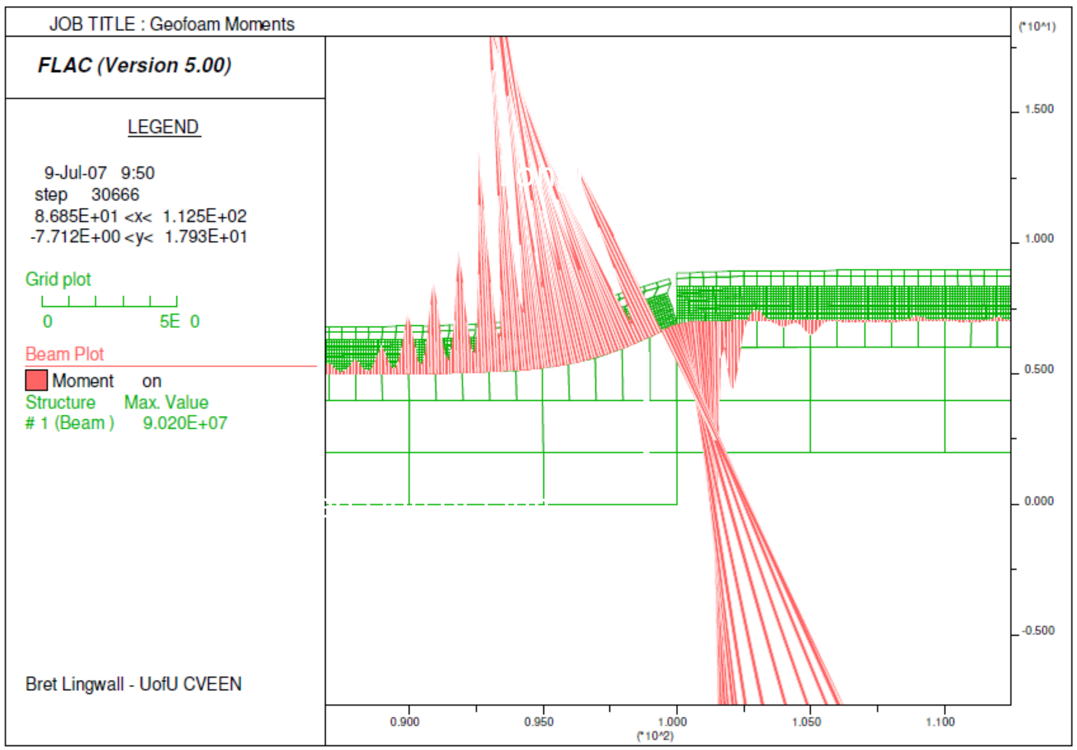
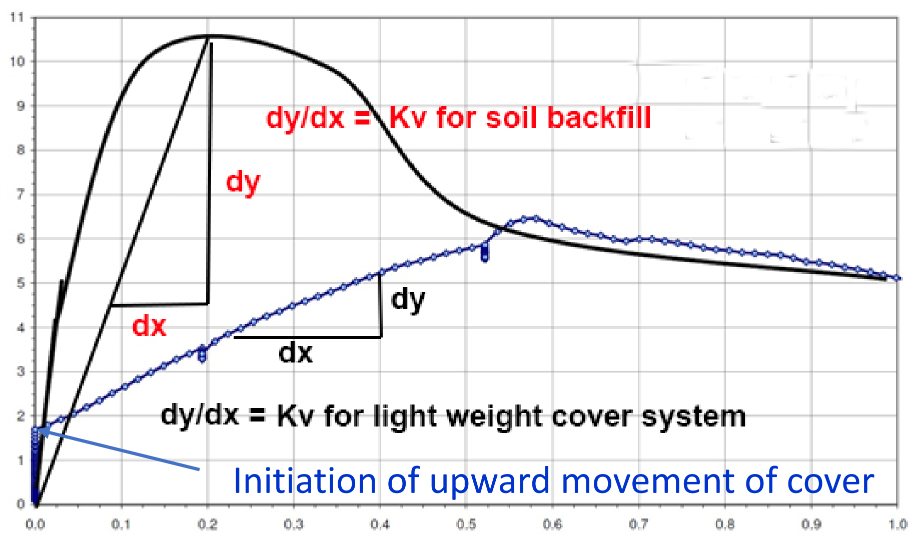



Diagram of Bending Moments in Pipe from 2 m offset

# Seismic Advantages – Lightweight Cover and Backfill for Pipelines – Design Concepts for Vertical Offset




$$K_v = F_v / \delta_v / L$$

where $K_v$ is the vertical spring constant of the LCC cover system per unit length of pipe. $K_v$ is the secant of a vertical force displacement curve at maximum displacement. $\Delta_v$ is the vertical displacement and L is length. Values of $K_v$ are determined from testing, or from numerical modeling.

# Seismic Advantages – Lightweight Cover and Backfill Installation

**Fig. 5.** EPS slot-trench light-weight cover system constructed across the Wasatch fault in Salt Lake City, Utah. Left photo is placement of 0.6-m diameter ductile steel pipe. Middle photo is placement of EPS geofoam and geomembrane cover. Right photo is construction of concrete load distribution slab before placement of roadway section.

# Seismic Advantages – Lightweight Cover for Pipelines – Summary

The consequences of permanent ground deformation and other soil loads and interactions pose a significant threat to buried culverts and pipelines. The potential damage to such systems can be significantly reduced by the construction of a light-weight cover or trench backfill system using EPS geofoam. This can be done in such a fashion so that the buried conveyance system can withstand permanent ground deformation induced from multiple mechanisms. To this end, innovative EPS geofoam cover and trench backfill systems have been described and evaluated in this paper. These systems take advantage of the light-weight and compressible properties of EPS geofoam to reduce the induced vertical and horizontal stresses on buried culvert/pipe line systems from overlying dead and live loads. In most instances, the evaluation of geofoam/soil/culvert/pipe systems involves significant interaction

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Thank you!

## FOR MORE INFORMATION

Steven F. Bartlett, Bartlett@civil.utah.edu
435-841-9837

http://www.civil.utah.edu/~bartlett/pubs/