Finite Element Based LRFD Design of Bottomless Culverts

Western Bridge Engineers' Seminar

Presented By:

Craig Chatelain, P.E., AECOM

Ahilan Selladurai, P.E., AECOM

AECOM

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WBES – 2011 COMMITY

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PART – I

Craig Chatelain, P.E.

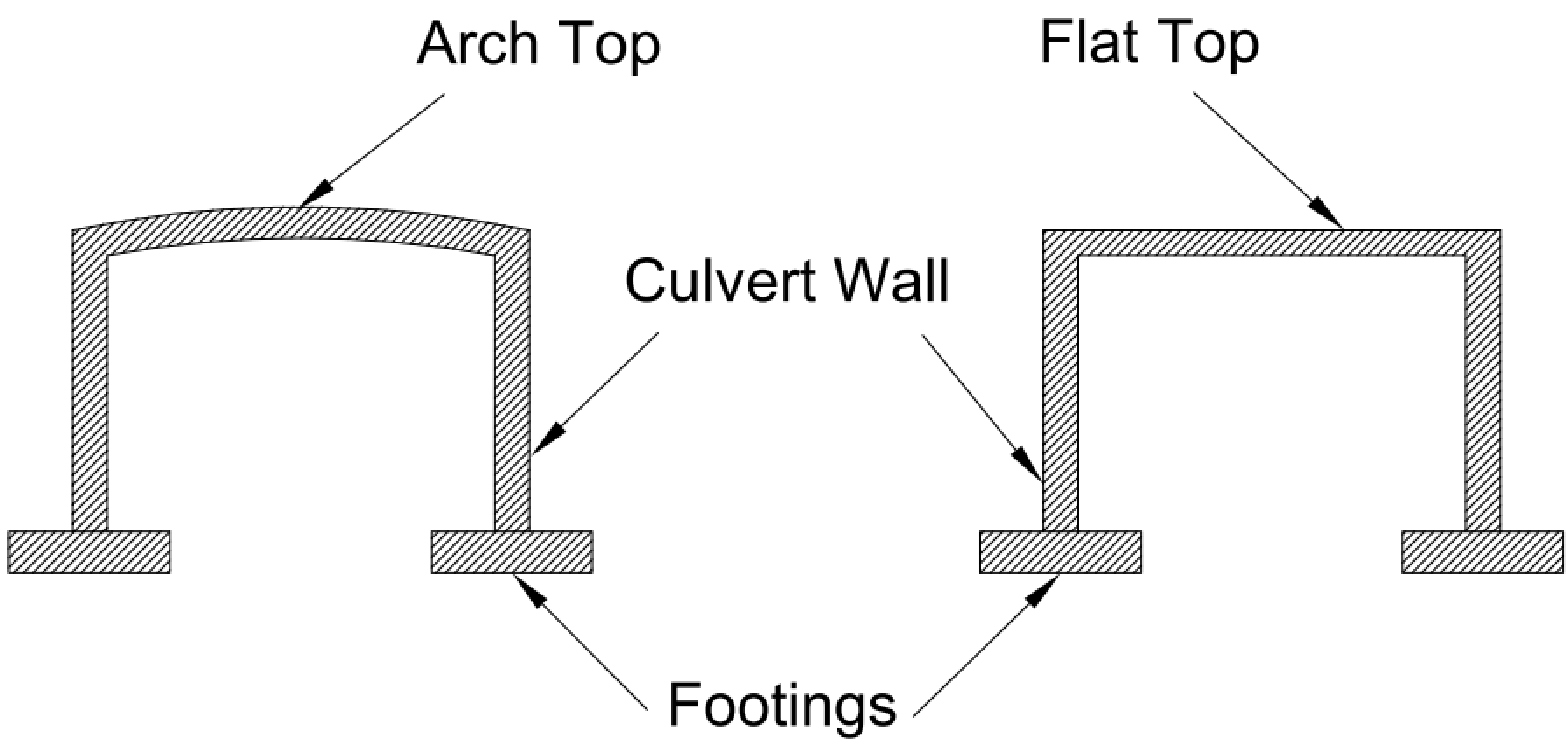
Introduction

A. Description
   - Definition
   - Example Applications

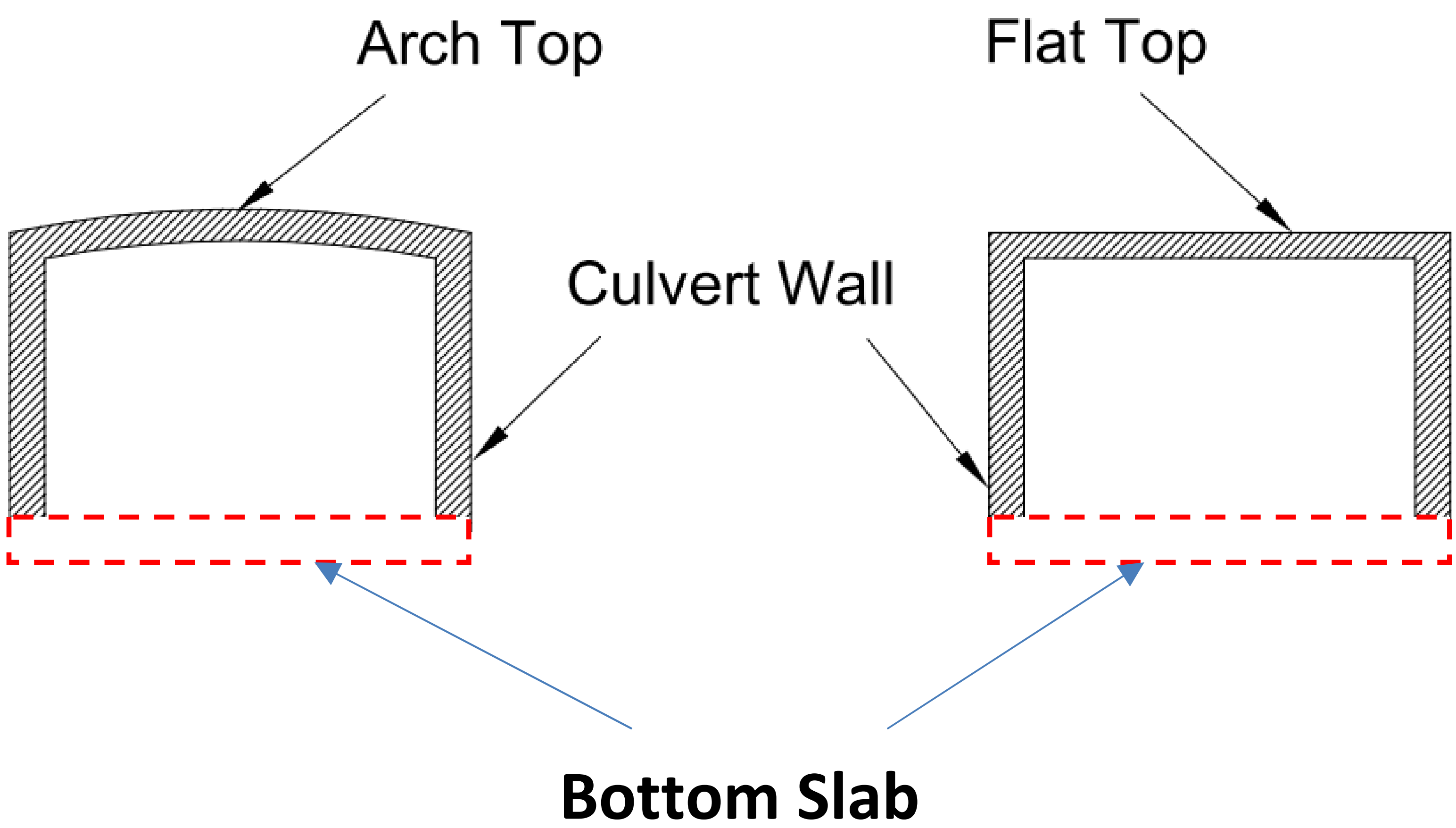
B. Design Methodology

C. Project Objectives

Definition



Definition

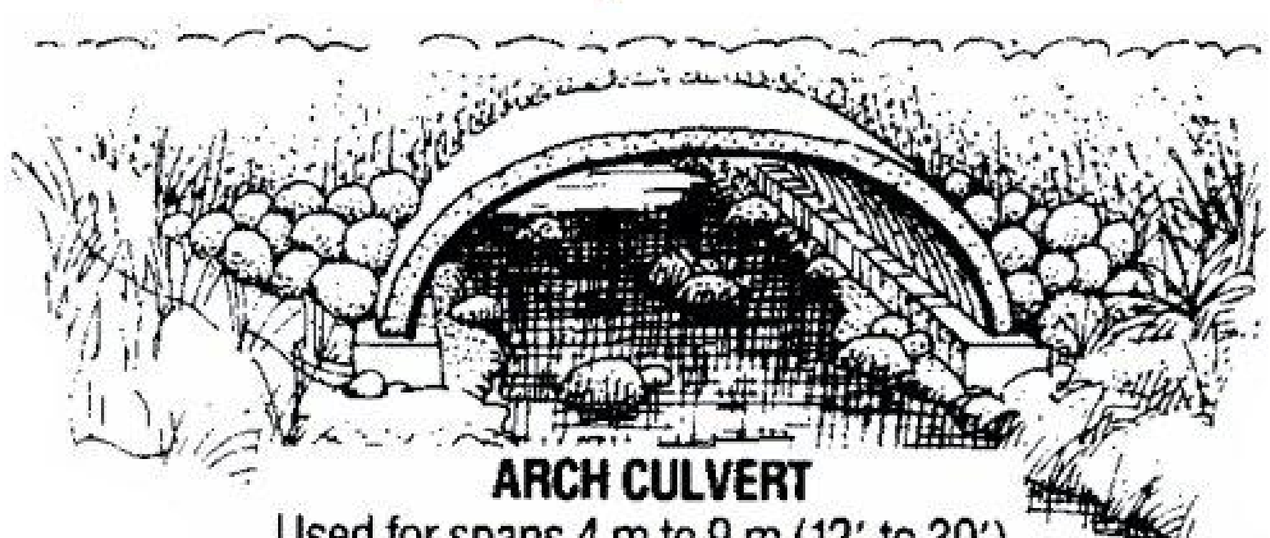


Example Applications

Concrete

Metal (Aluminum / Steel)

Green Applications



(OMNR 1988)

Green Applications – Fish Passages

Green Applications – Fish Passages

Green Applications – Fish Passages

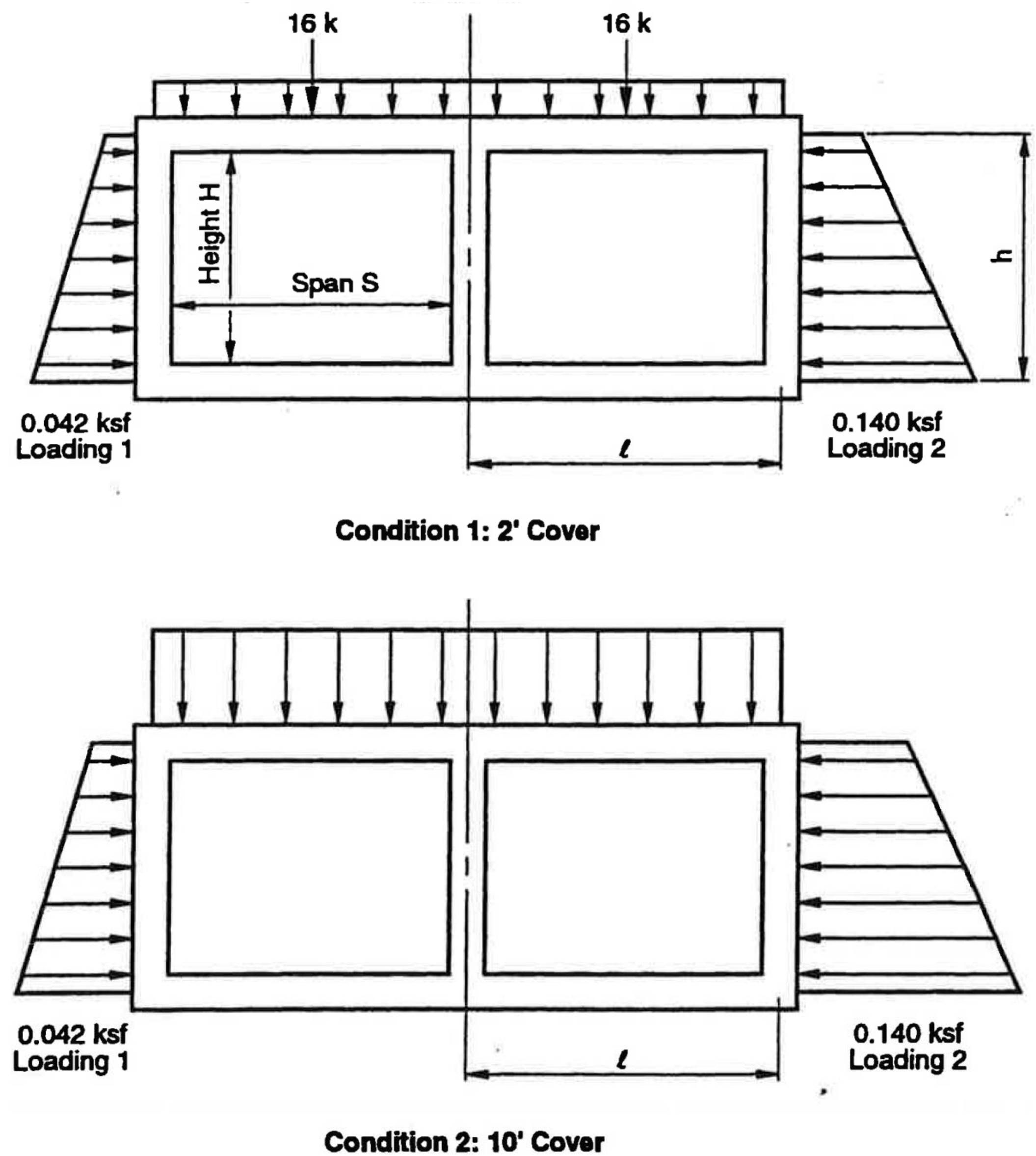
Green Applications – Animal Crossings

B. Design Methodology

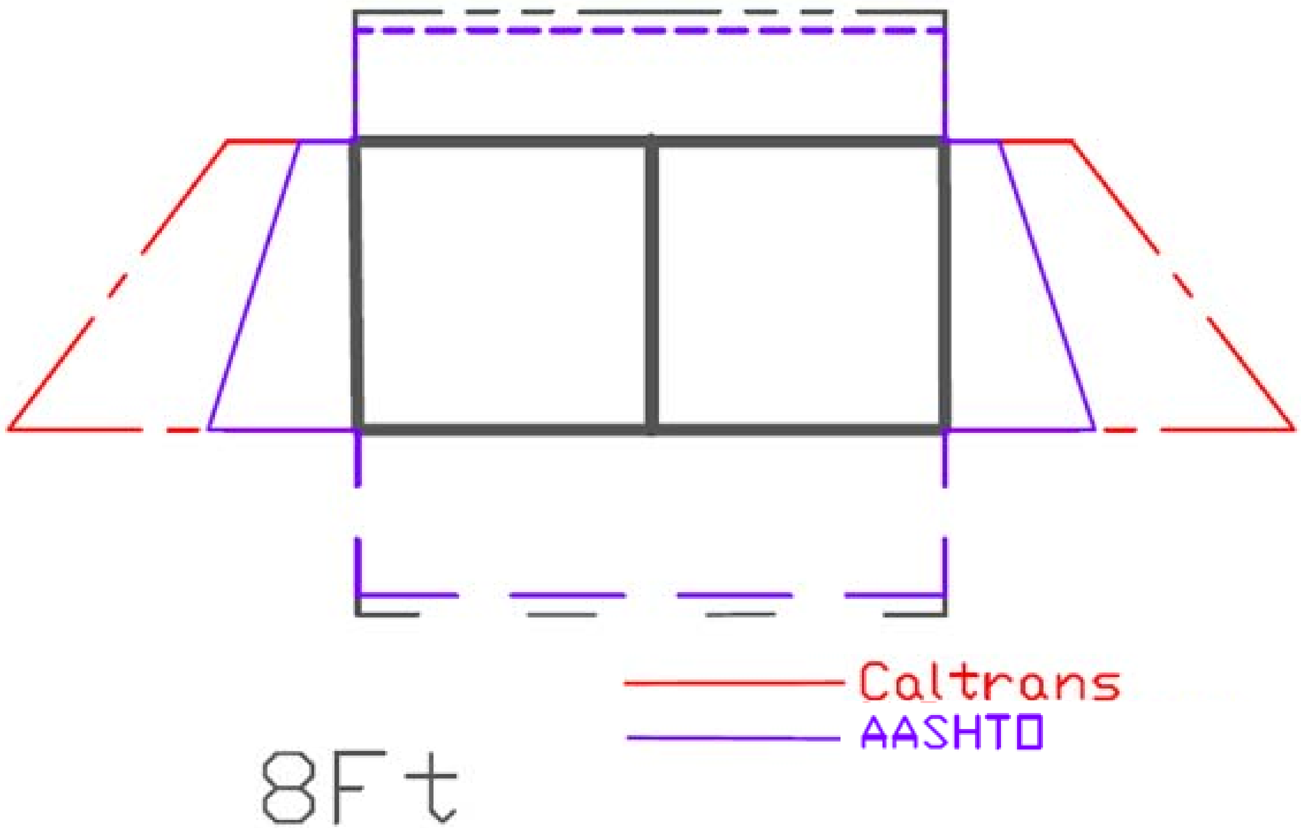
- Traditional
- Detailed (FEM)
- Transition to LRFD

Traditional Methods-

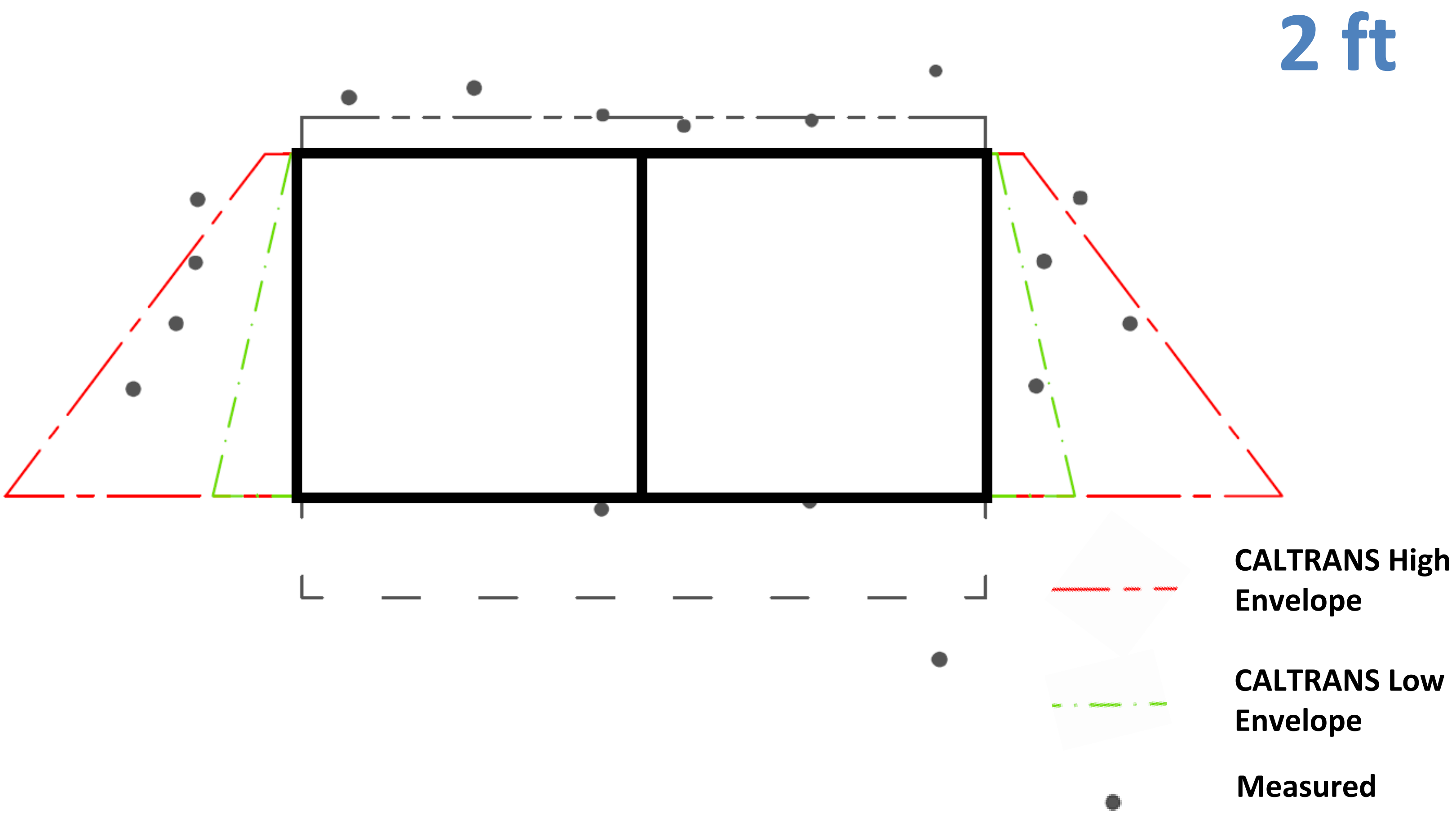
Caltrans Pressure Envelopes



Caltrans vs AASHTO



1989 Full-Scale Testing
(University of Nebraska)



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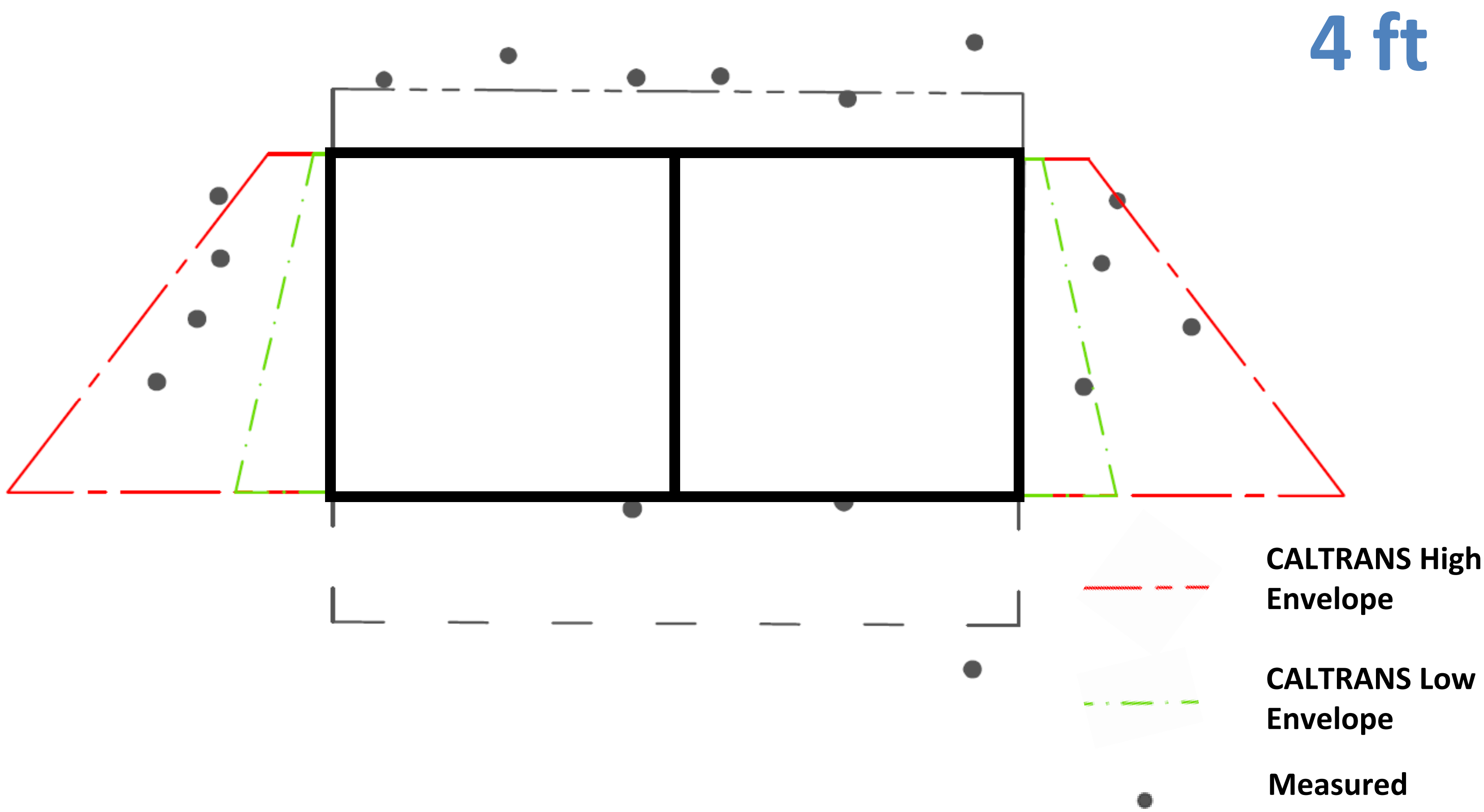

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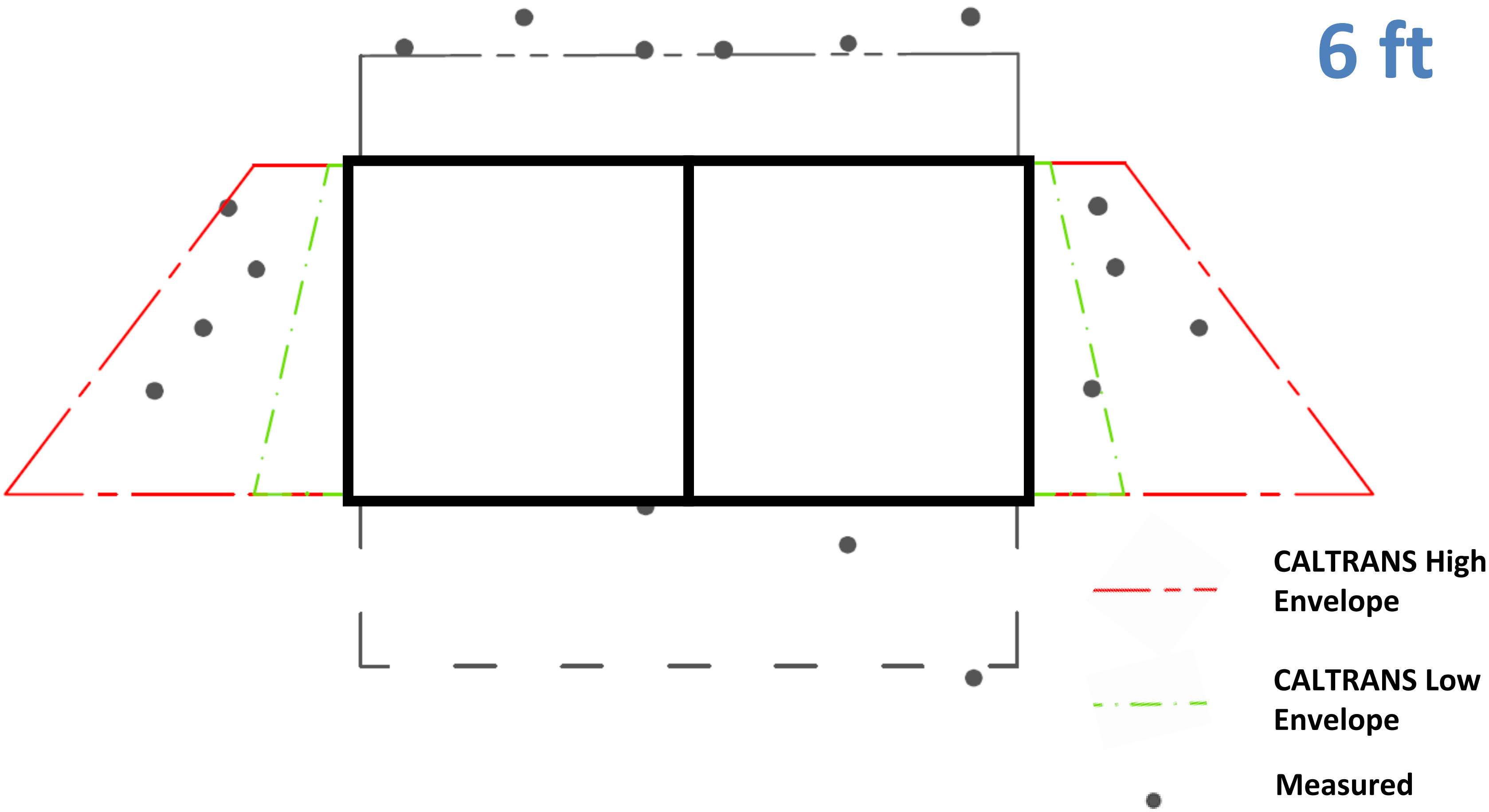

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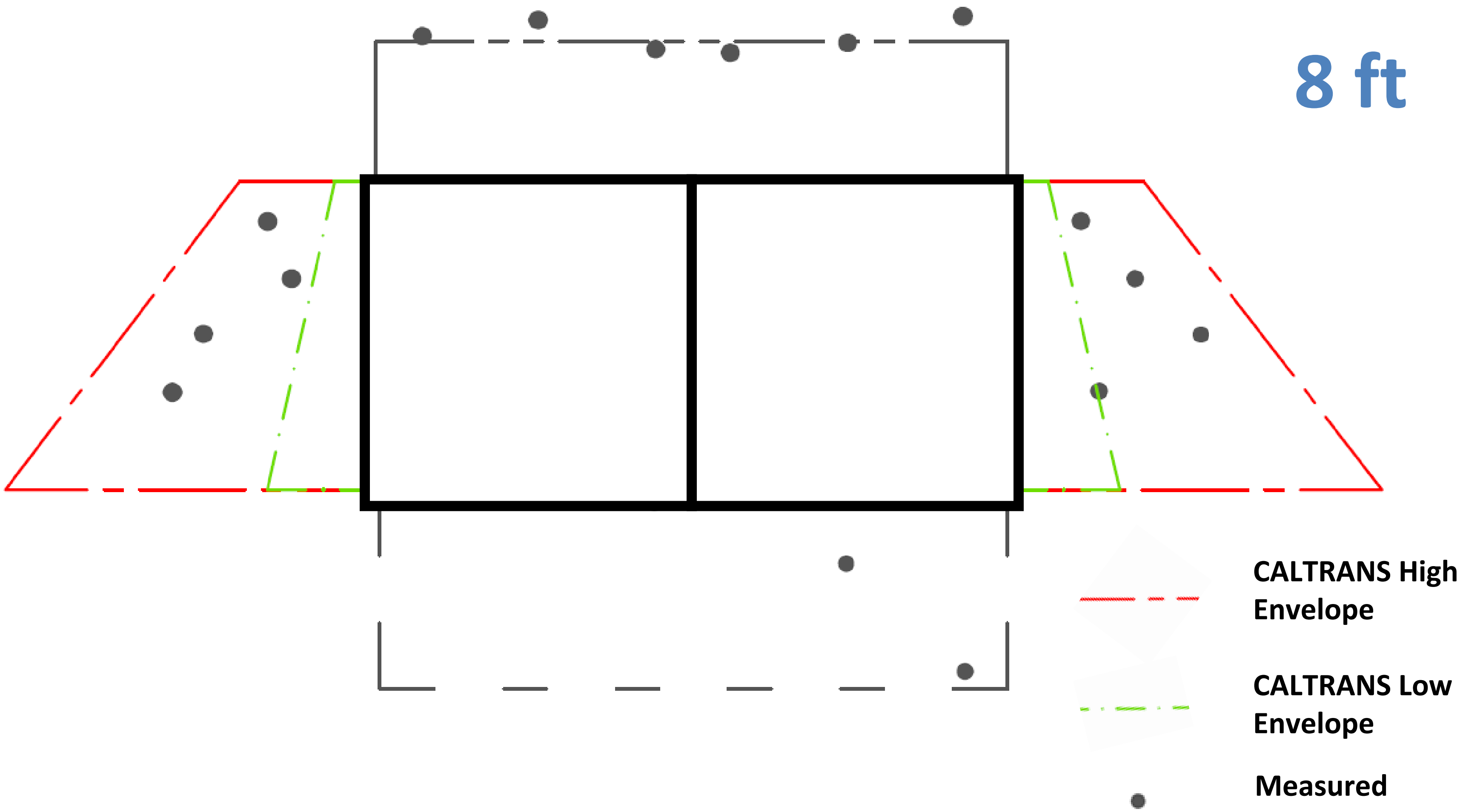

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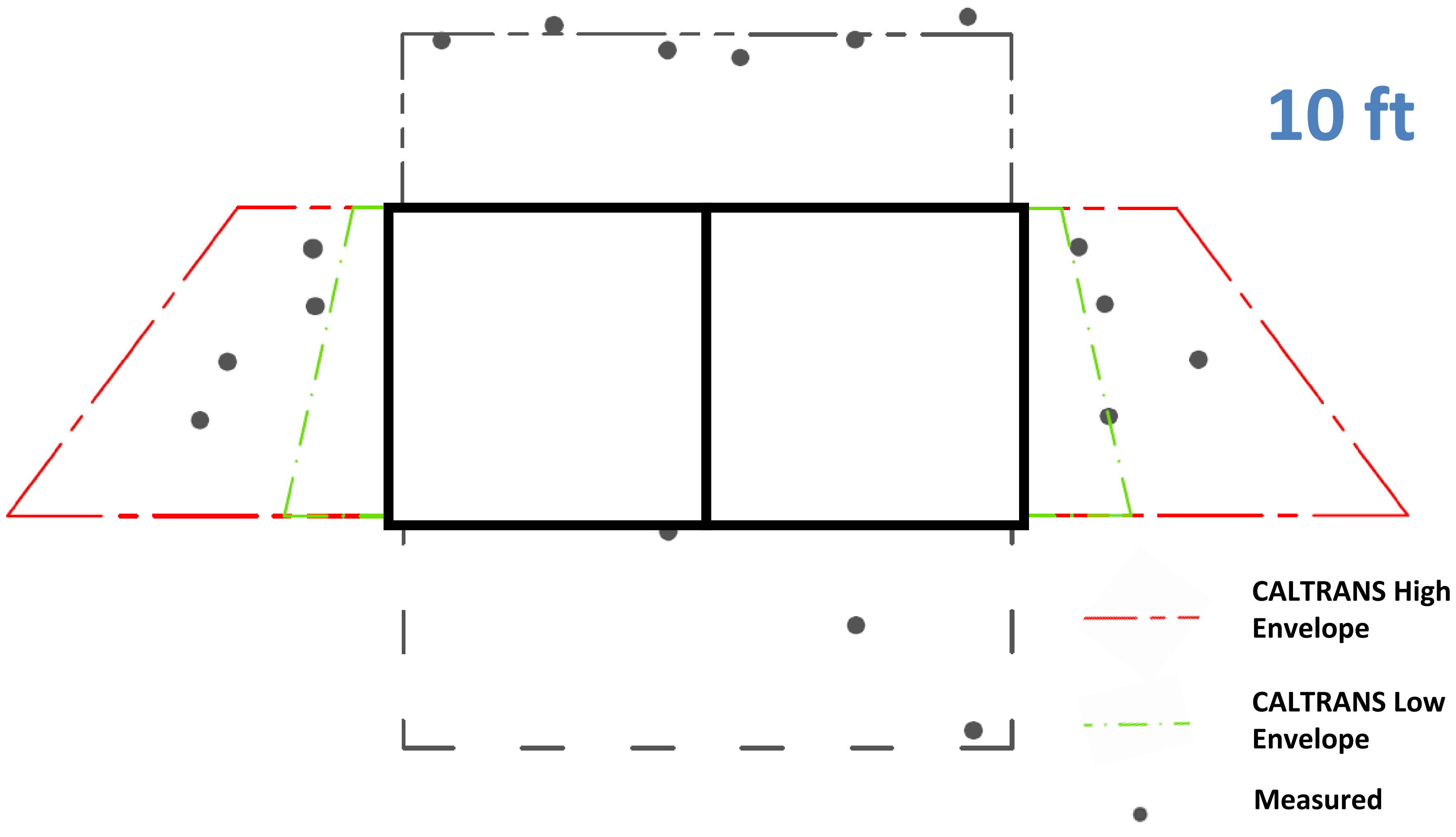

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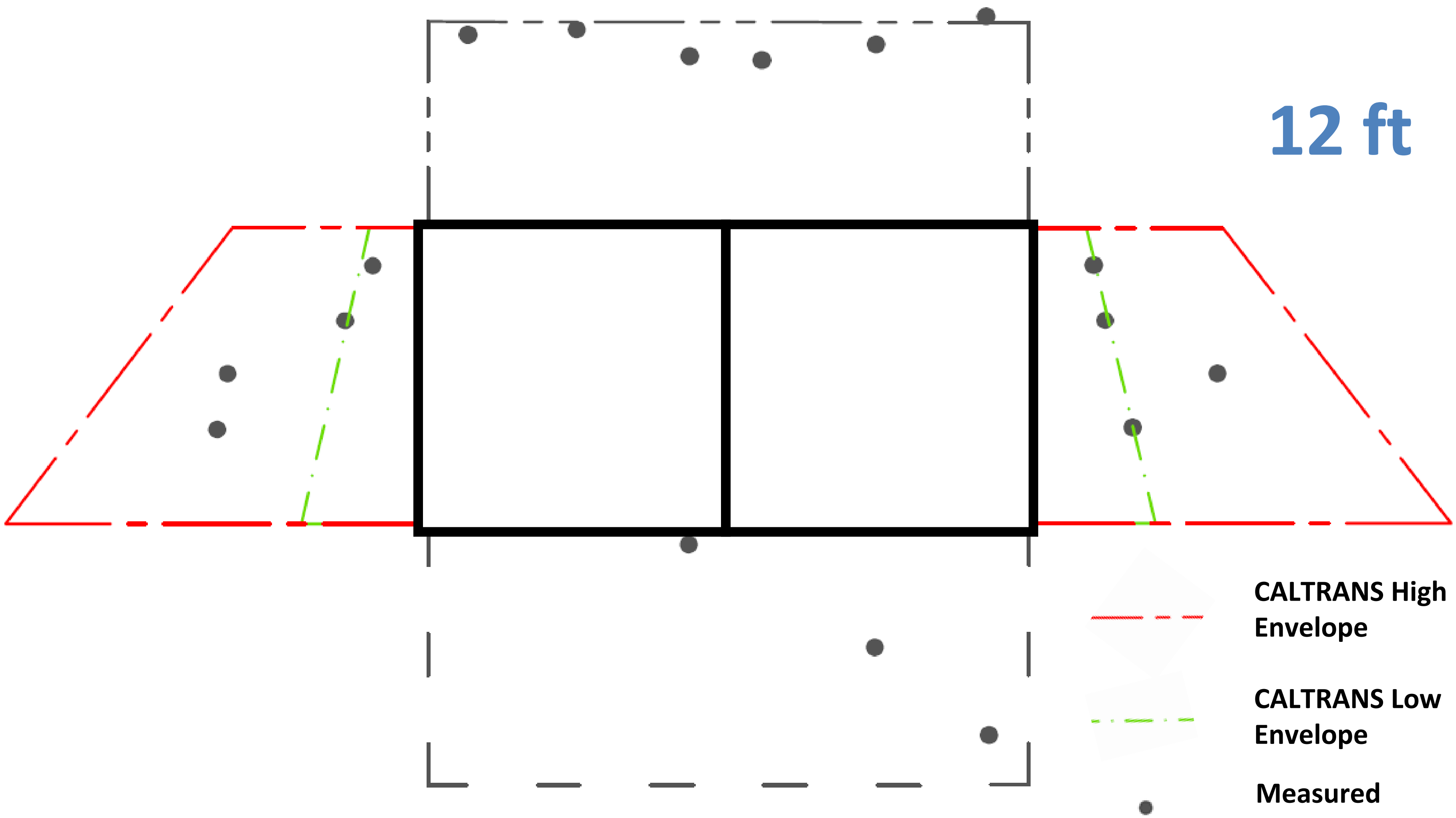
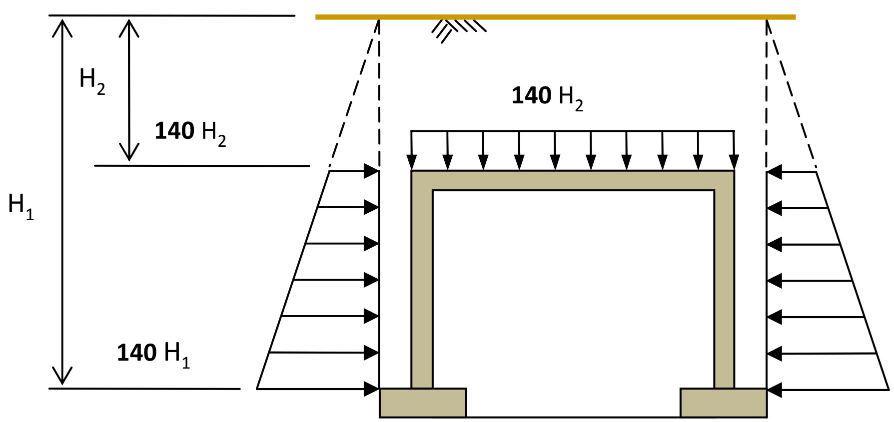


Caltrans Earth Pressure Envelopes

CALTRANS MAXIMUM ENVELOPE



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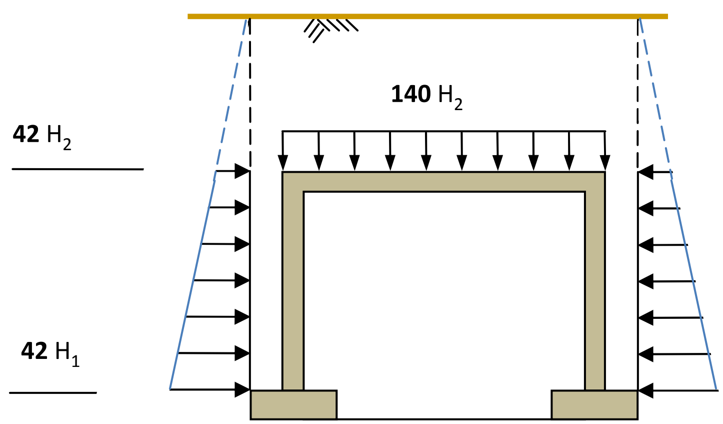
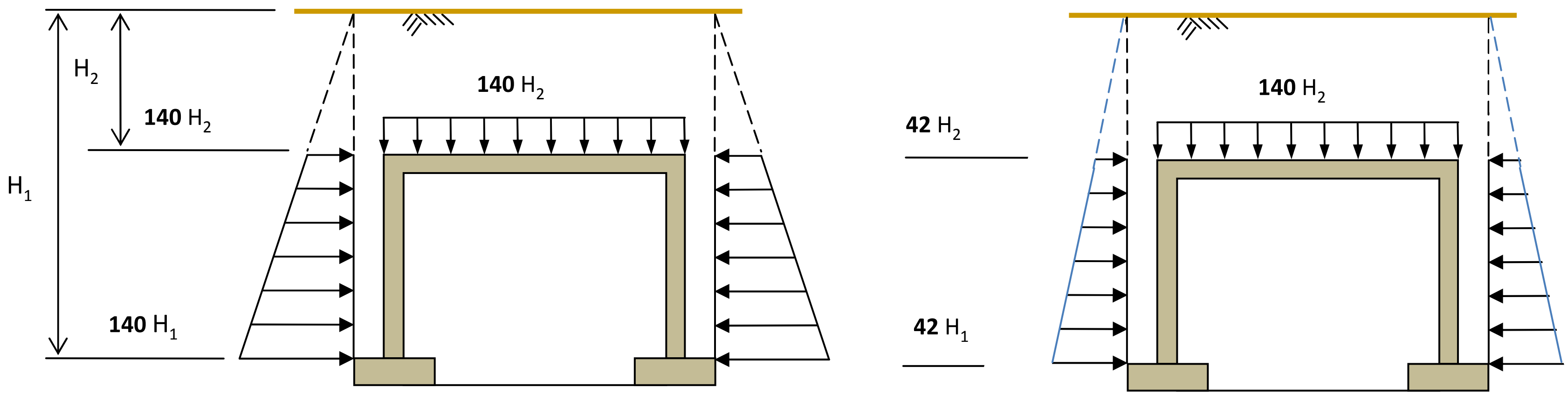


Caltrans Earth Pressure Envelopes

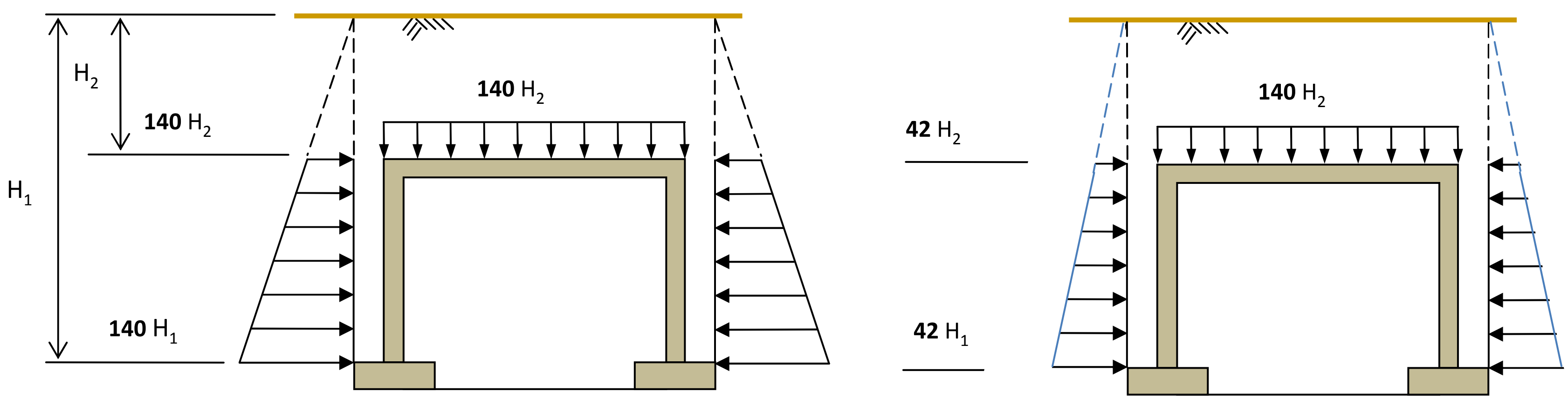
CALTRANS MAXIMUM ENVELOPE **CALTRANS MINIMUM ENVELOPE**



- Have been successfully used for nearly 30 years!

Caltrans Earth Pressure Envelopes

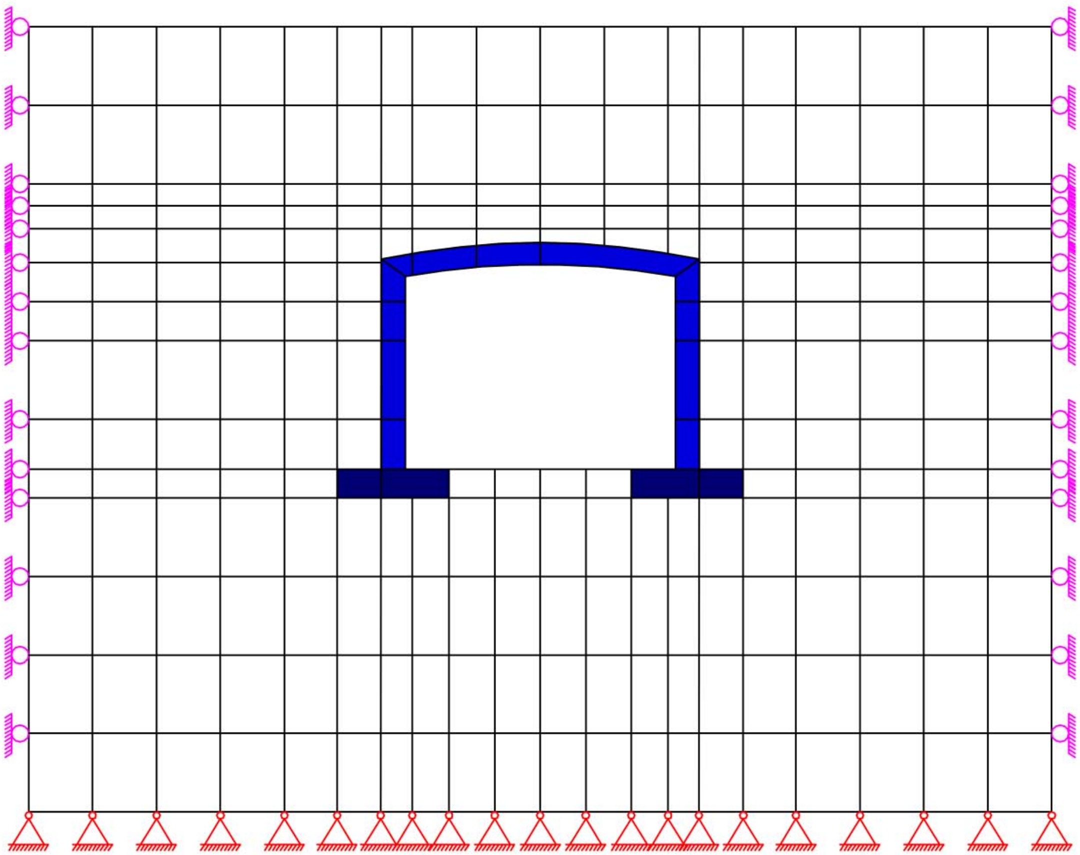
CALTRANS MAXIMUM ENVELOPE | **CALTRANS MINIMUM ENVELOPE**



- Have been successfully used for nearly 30 years!
- Have a great deal of credibility

Detailed Methods-

Finite Element Method (FEM)



FE Mesh

Detailed Methods-

Finite Element Method (FEM)

Advantages of FEM:

- Accounts for Soil-Structure Interaction
- Accounts for Variability of Materials
- Takes into Account Material Non-linearity
- Detailed modeling of Live Load Effects
- Fast!

Departure from Traditional- Considerations:

- Precedence
- Designer's Confidence
- Other (Seismic Design)

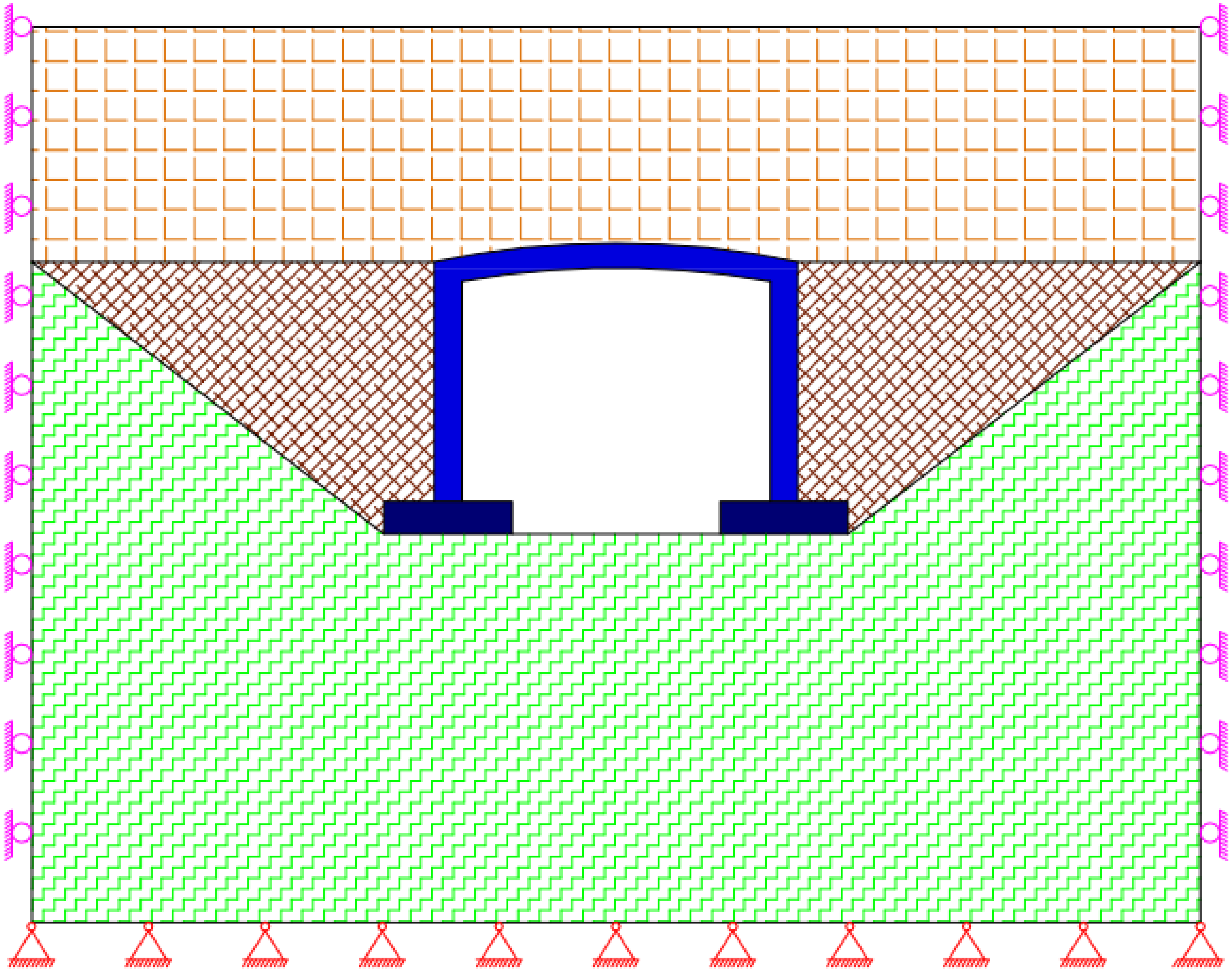
LRFD Adaptation- *A Calibration Process:*

- Obtain similar level of confidence to the Traditional Method
- Fine-tune the modeling parameters & methodology to meet LRFD requirements

C. Project Objectives

- Review Submittals for specific Culverts
- Verify Design Methodology & Conclusions
- Develop Recommendations for Streamlining the Review Process to Expedite Approval

SUBMITTAL REVIEW



General:

- 20' Max Span
- No Seismic

Review Problem:

- 16 ft Span
- 10 ft Rise
- 20 ft Max Fill

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Presented By:

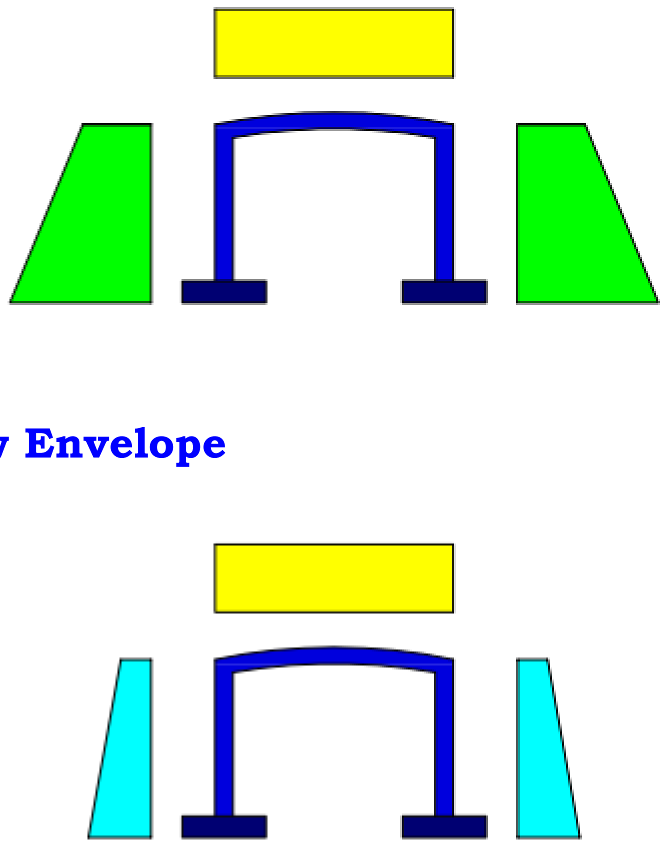
PART – II

Ahilan Selladurai, P.E.

CONVENTIONAL → DETAIL FEM

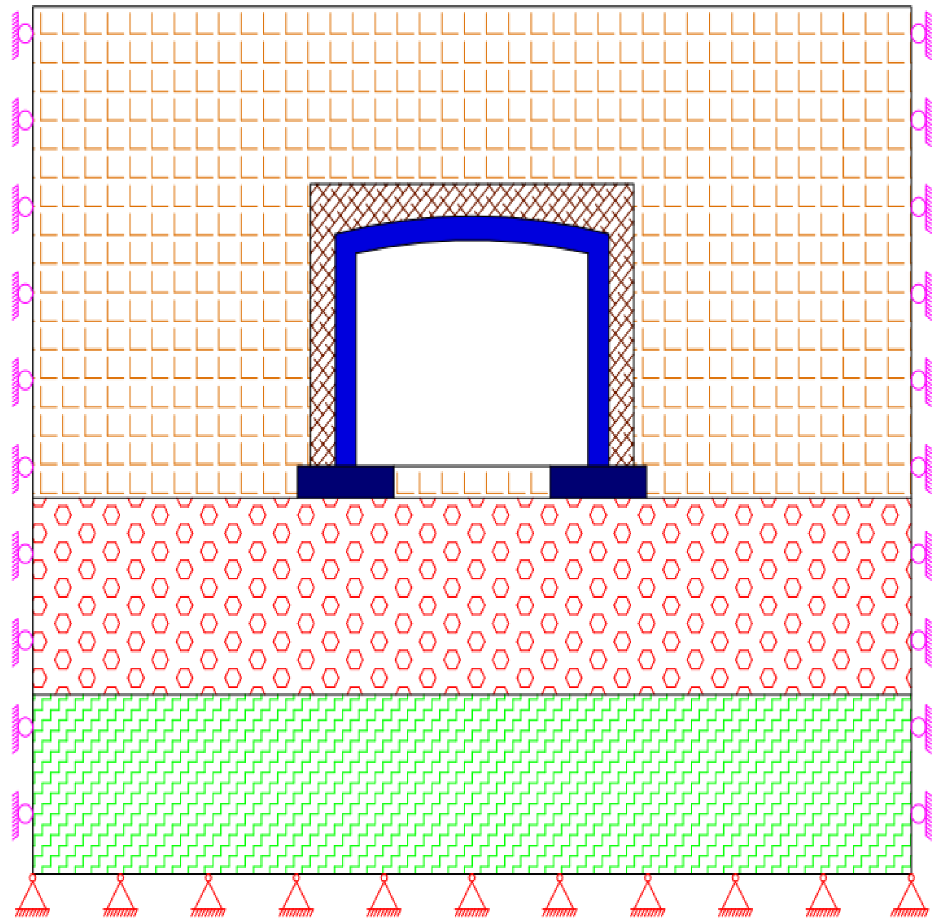
High Envelope

Low Envelope



CALTRANS CONVENTIONAL

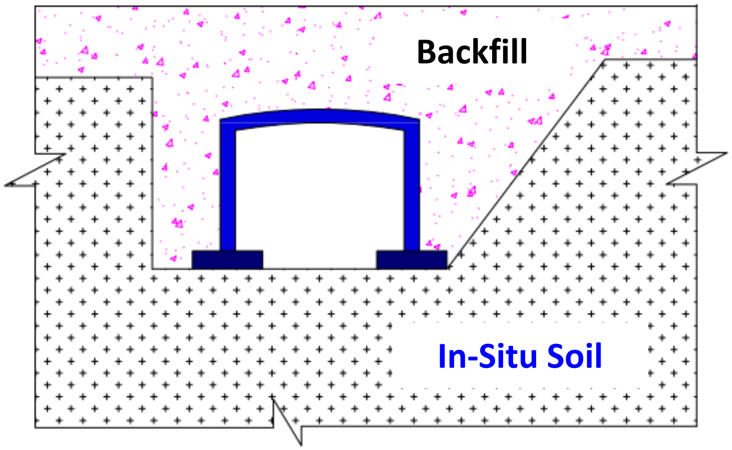
Embankment Condition



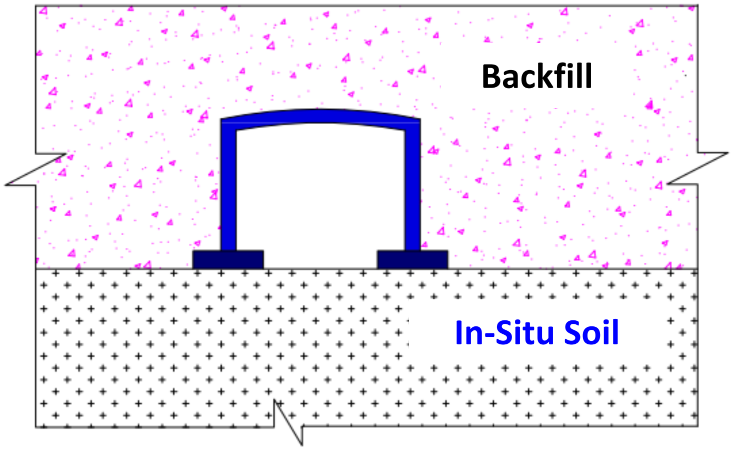
DETAIL FINITE ELEMENT MODEL

REVIEW PROCESS

- **Installation condition**
- Finite Element Model
- Soil Types & Limits
- Soil Properties
- Interface Elements
- Live Load Analysis
- Load Factors & Combinations
- Design Recommendations



TRENCH



EMBANKMENT

REVIEW PROCESS

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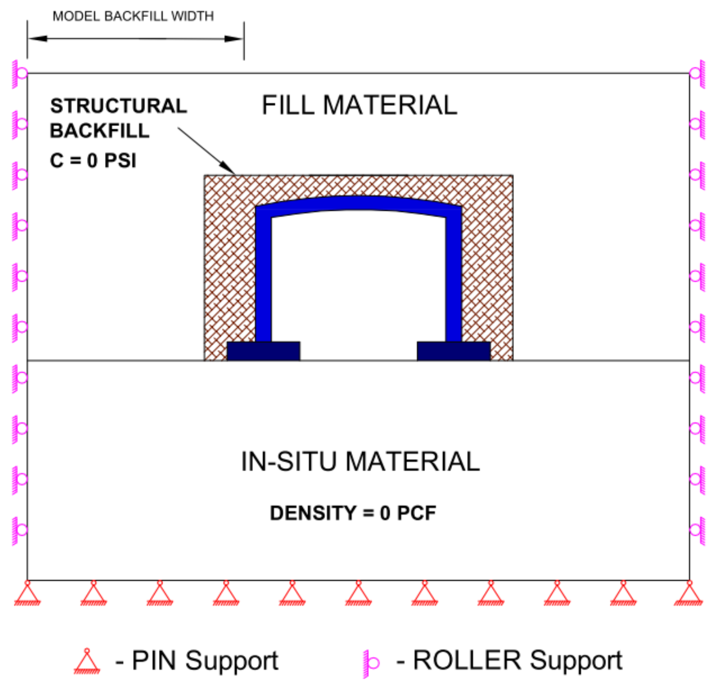

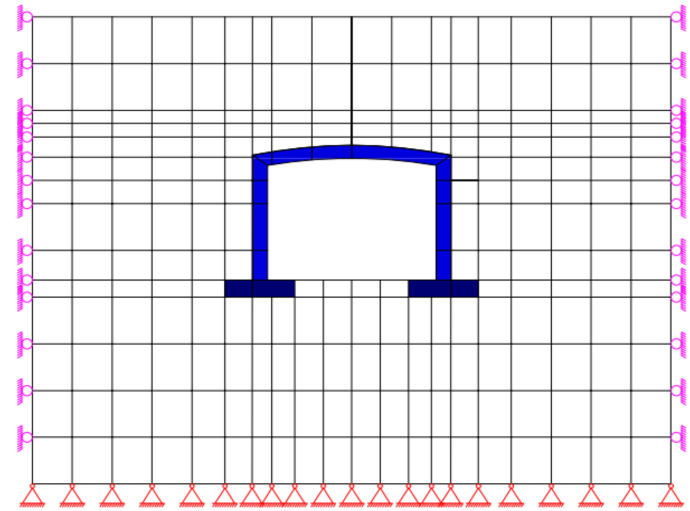

REVIEW PROCESS

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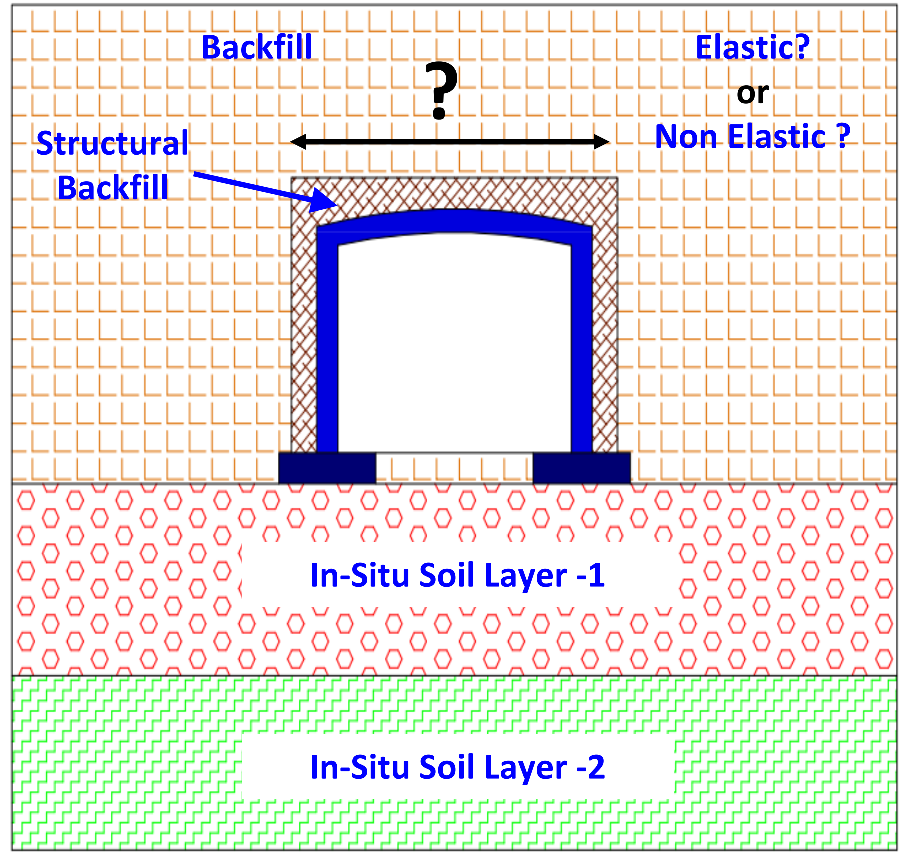

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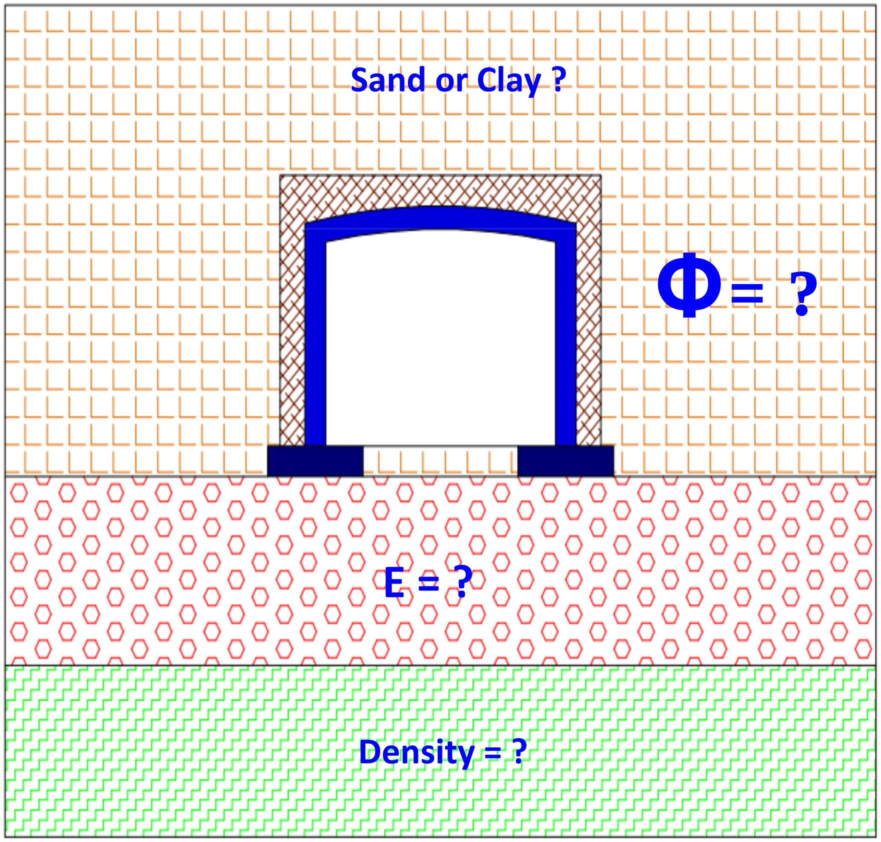

REVIEW PROCESS

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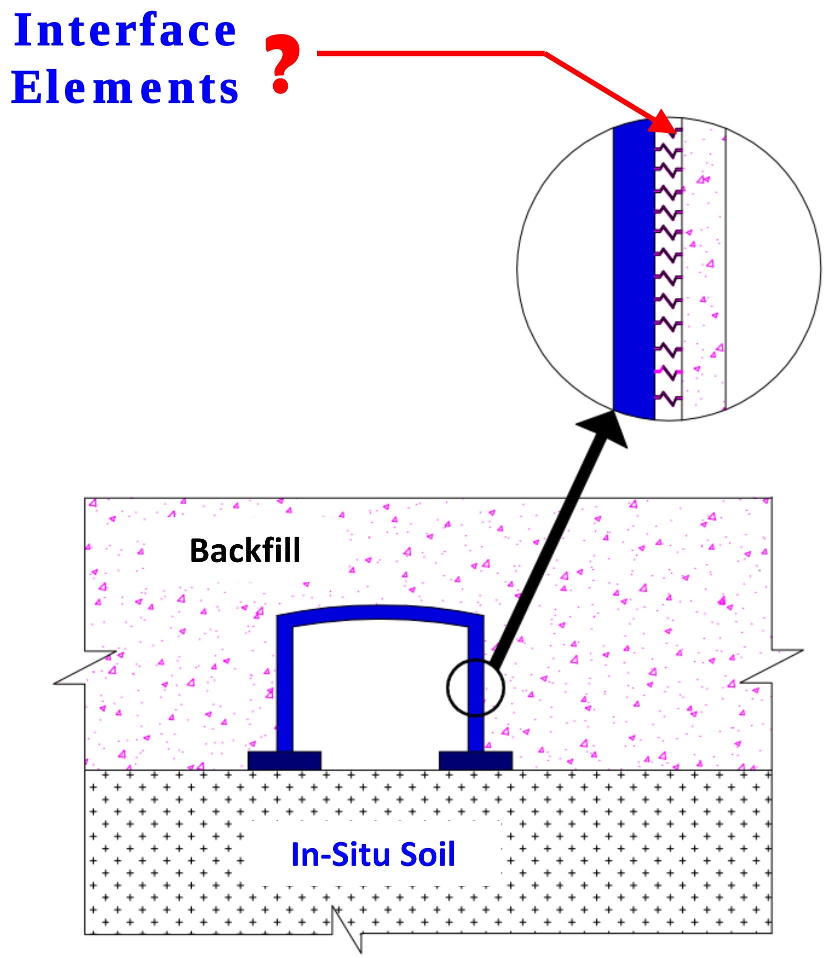

REVIEW PROCESS

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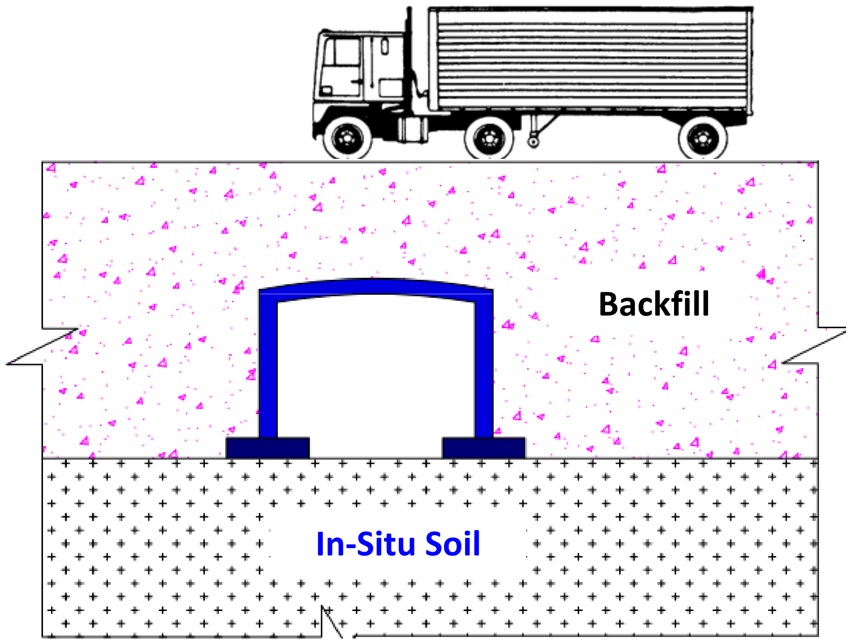

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REVIEW PROCESS

AECOM

- Installation condition
- Finite Element Model
- Soil Types & Limits
- Soil Properties
- Interface Elements
- Live Load Analysis
- **Load Factors & Combinations**
- Design Recommendations

Table 3.4.1-1—Load Combinations and Load Factors

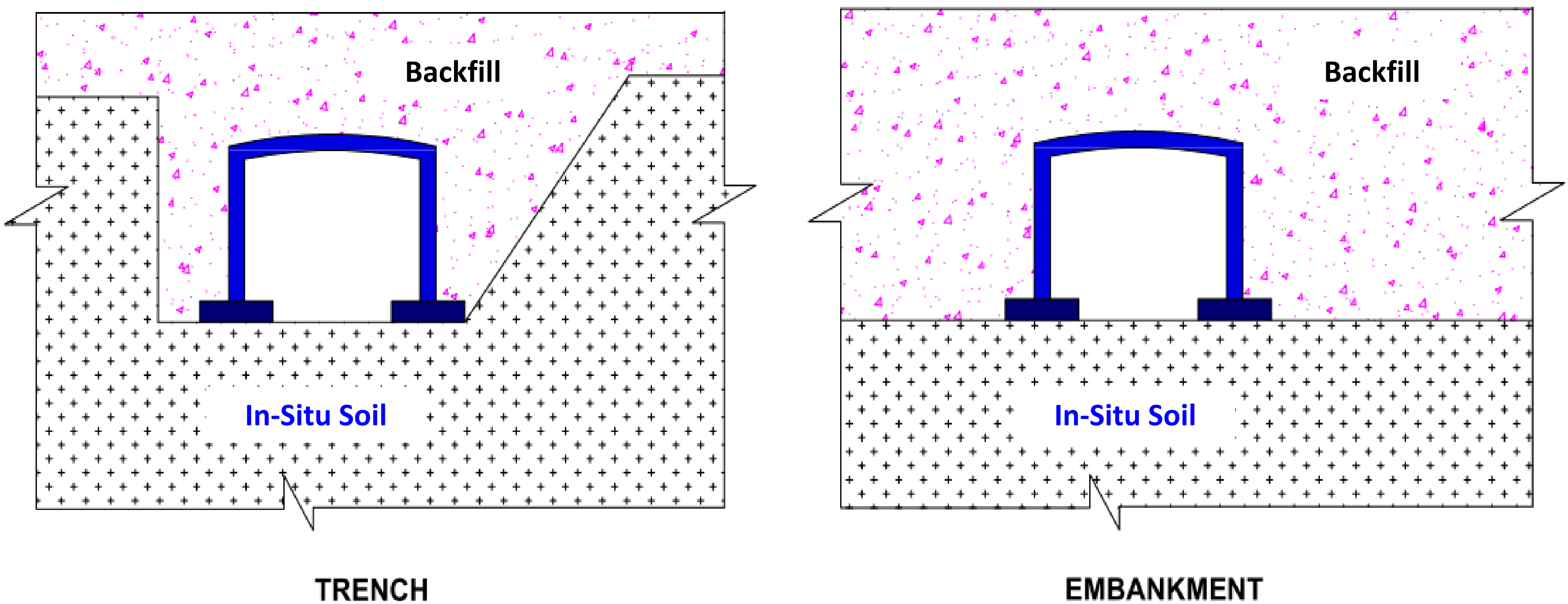
Load Combination Limit State	*DC* *DD* *DW* *EH* *EV* *ES* *EL* *PS* *CR* *SH*	*LL* *IM* *CE* *BR* *PL* *LS*	*WA*	*WS*	*WL*
Strength I (unless noted)	γ_p	1.75	1.00	—	—
Strength II	γ_p	1.35	1.00	—	—
Strength III	γ_p	—	1.00	1.40	—
Strength IV	γ_p	—	1.00	—	—
Strength V	γ_p	1.35	1.00	0.40	1.0
Extreme Event I	γ_p	γEQ	1.00	—	—
Extreme	γ_p	0.50	1.00	—	—

REVIEW PROCESS

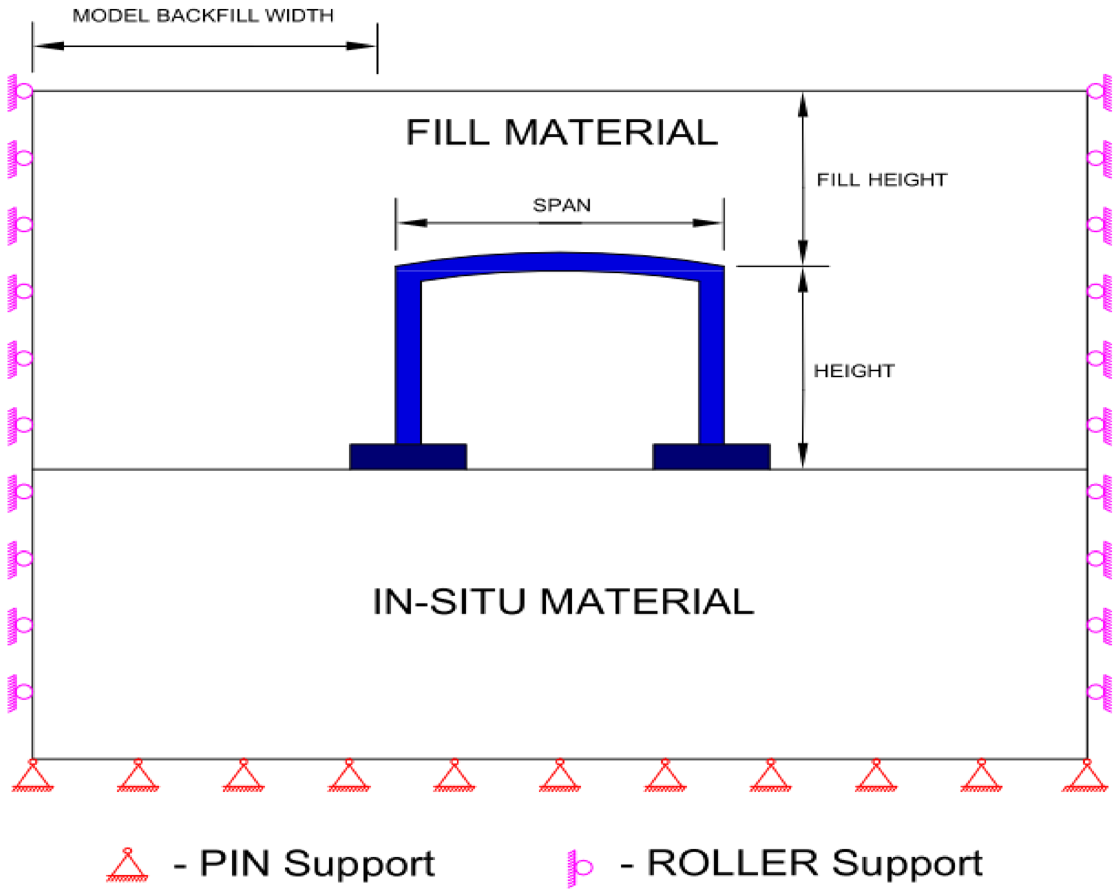
- Installation condition
- Finite Element Model
- Soil Types & Limits
- Soil Properties
- Interface Elements
- Live Load Analysis
- Load Factors & Combinations
- **Design Recommendations**

INSTALLATION CONDITION

- **Two types of Installation Conditions: Trench & Embankment Conditions**
- **Embankment Installation is Critical compared to Trench Installation.**

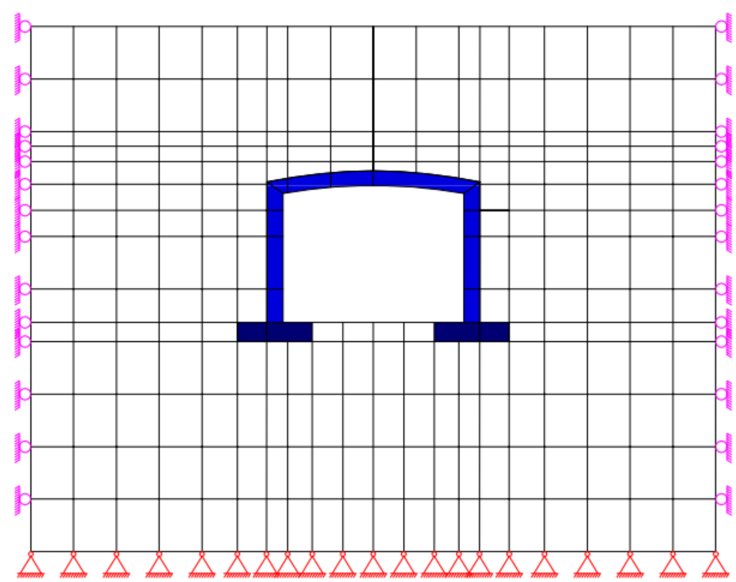


FINITE ELEMENT MODEL



SUPPOTS CONDITION

FE MESH



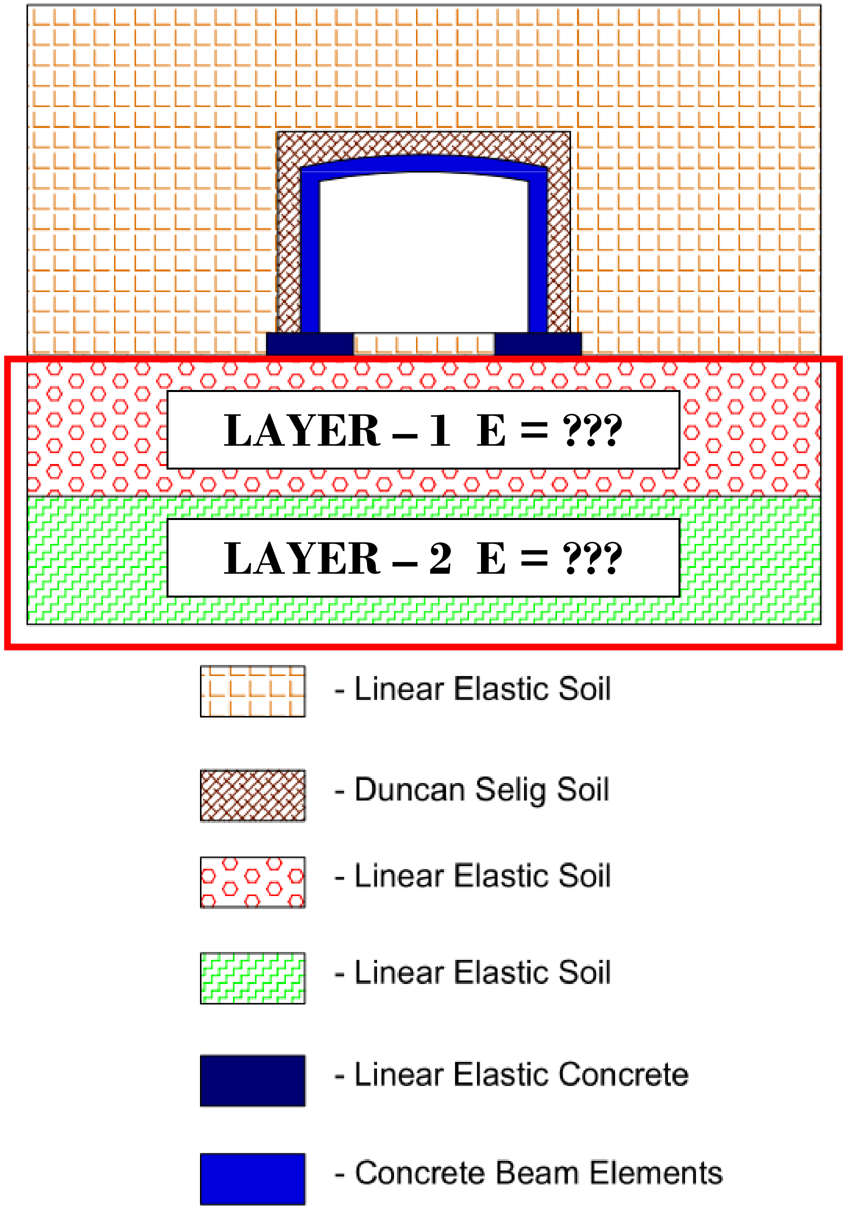
SOIL TYPES AND LIMITS

- Bottom in-situ soil is typically divided one or two layers based on soil properties.

- Layer -1: Non linear if compacted soil layer.

- Width and fill height of structural backfill around the culvert significantly affect results.

- Other fill Soil may be assumed as linear elastic soil if there is no site specific soil information.



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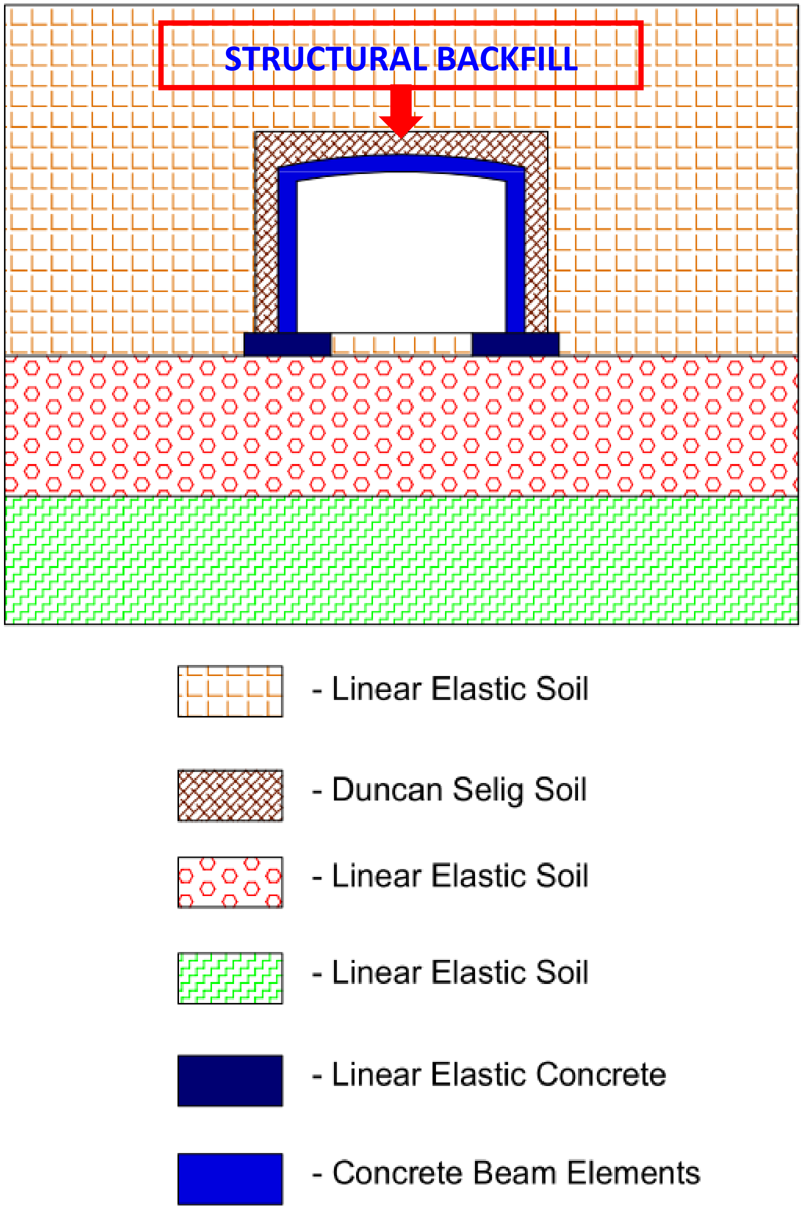

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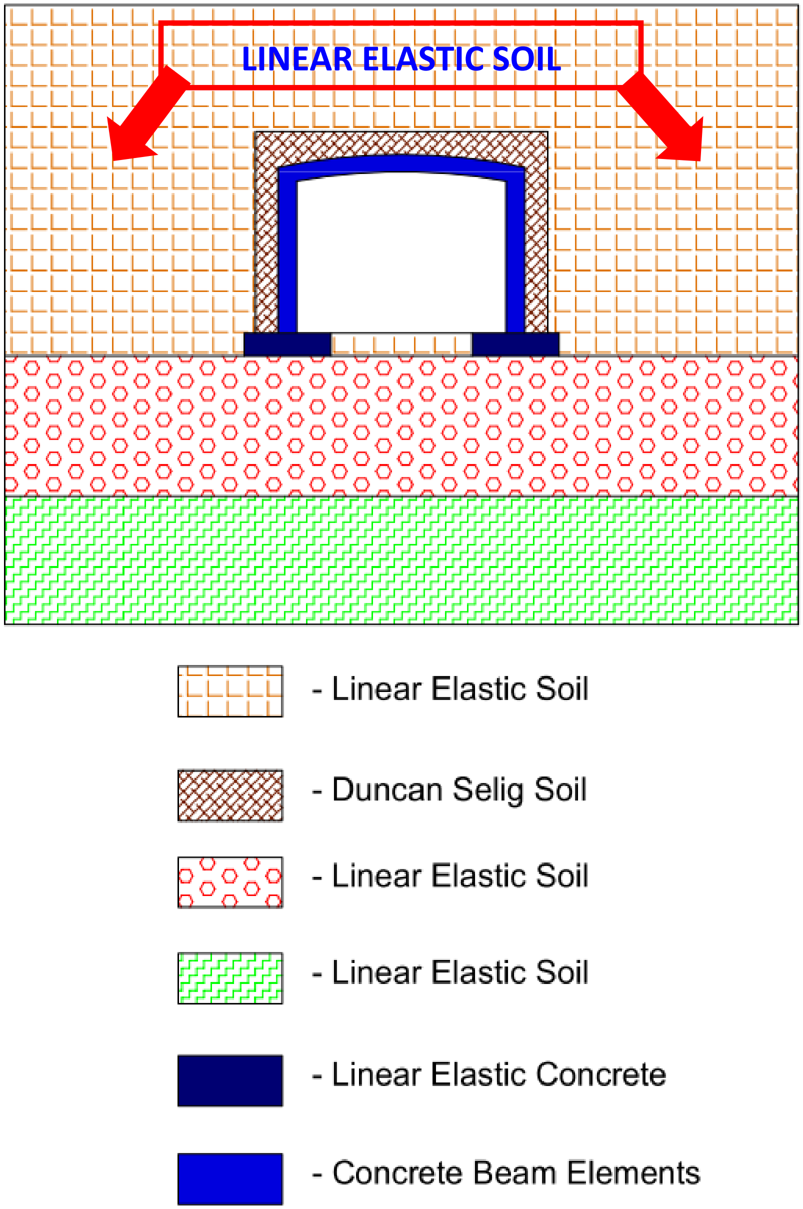

SOIL PROPERTIES

TABLE 4.4.7.2.2A Elastic Constants of Various Soils
Modified after U.S. Department of the Navy (1982) and Bowles (1982)

Typical Range of Values

Soil Type	Young's Modulus, E_s (ksf)	Poisson's Ratio, ν (dim)
Clay:		
Soft sensitive	50-300	0.4-0.5
Medium stiff	300-1,000	(undrained)
to stiff	1,000-2,000	
Very stiff		
Loess	300-1,200	0.1-0.3
Silt	40-400	0.3-0.35
Fine sand:		
Loose	160-240	
Medium dense	240-400	0.25
Dense	400-600	
Sand:		
Loose	200-600	0.2-0.35
Medium dense	600-1,000	
Dense	1,000-1,600	0.3-0.4
Gravel:		
Loose	600-1,600	0.2-0.35
Medium dense	1,600-2,000	
Dense	2,000-4,000	0.3-0.4

Estimating Es From E_s From N[1]

Soil Type	E_s (ksf)
Silts, sandy silts, slightly cohesive mixtures	$8N_1$[2]
Clean fine to medium sands and slightly silty sands	$14N_1$
Coarse sands and sands with little gravel	$20N_1$
Sandy gravel and gravels	$24N_1$

Estimating E_s From s_u[3]

Soil Type	E_s (ksf)
Soft sensitive clay	$400s_u$-$1,000s_u$
Medium stiff to stiff clay	$1,500s_u$-$2,400s_u$
Very stiff clay	$3,000s_u$-$4,000s_u$

Estimating E_s From q_c[4]

Soil Type	E_s (ksf)
Sandy soils	$4q_c$

(1)N = Standard Penetration Test (SPT) resistance.
(2)N_1 = SPT corrected for depth.
(3)s_u = Undrained shear strength (ksf).
(4)q_c = Cone penetration resistance (ksf).

Ref: Caltrans Bridge Design Specifications, Nov 2003

SOIL TYPES & PROPERTIES

TABLE 4.4.7.2.2A Elastic Constants of Various Soils
Modified after U.S. Department of the Navy (1982) and Bowles (1982)

Sand:

Loose: E= 200 – 600 ksf
Medium Dense: E= 600 – 1000 ksf
Dense: E= 1000 – 1600 ksf

Typical Range of Values

Soil Type	Young's Modulus, E_s (ksf)	Poisson's Ratio, ν (dim)
Clay:		
Soft sensitive		
Medium stiff to stiff	1	
Very stiff		
Loess		
Silt	40-400	0.3-0.35
Fine sand:		
Loose	160-240	
Medium dense	240-400	0.25
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Sand:		
Loose	200-600	0.2-0.35
Medium dense	600-1,000	
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Gravel:		
Loose	600-1,600	0.2-0.35
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Estimating Es From E_s From N[(1)]

Soil Type	E_s (ksf)
ly silts, slightly ve mixtures	$8N_1$[(2)]
to medium sands ghtly silty sands	$14N_1$
nds and sands with avel	$20N_1$
vel and gravels	$24N_1$

Estimating E_s From s_u[(3)]

Soft sensitive clay	$400s_u$-$1,000s_u$
Medium stiff to stiff clay	$1,500s_u$-$2,400s_u$
Very stiff clay	$3,000s_u$-$4,000s_u$

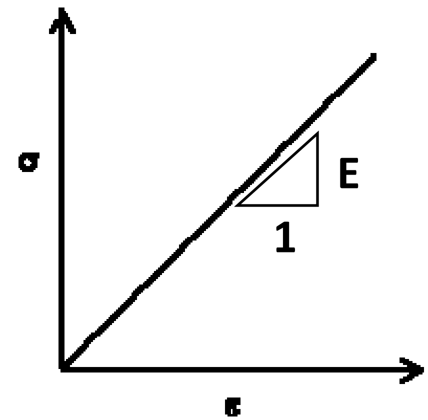
Estimating E_s From q_c[(4)]

Sandy soils	$4q_c$

(1)N = Standard Penetration Test (SPT) resistance.
(2)N_1 = SPT corrected for depth.
(3)s_u = Undrained shear strength (ksf).
(4)q_c = Cone penetration resistance (ksf).

Ref: Caltrans Bridge Design Specifications, Nov 2003

- **Soil Model**
  - **Simple**
    - **Linear Elastic Soil**
  - **Intermediate**
    - **Overburden Dependent**
  - **Complex**
    - **Duncan / Duncan - Selig Soil**
    - **Extended Harden**

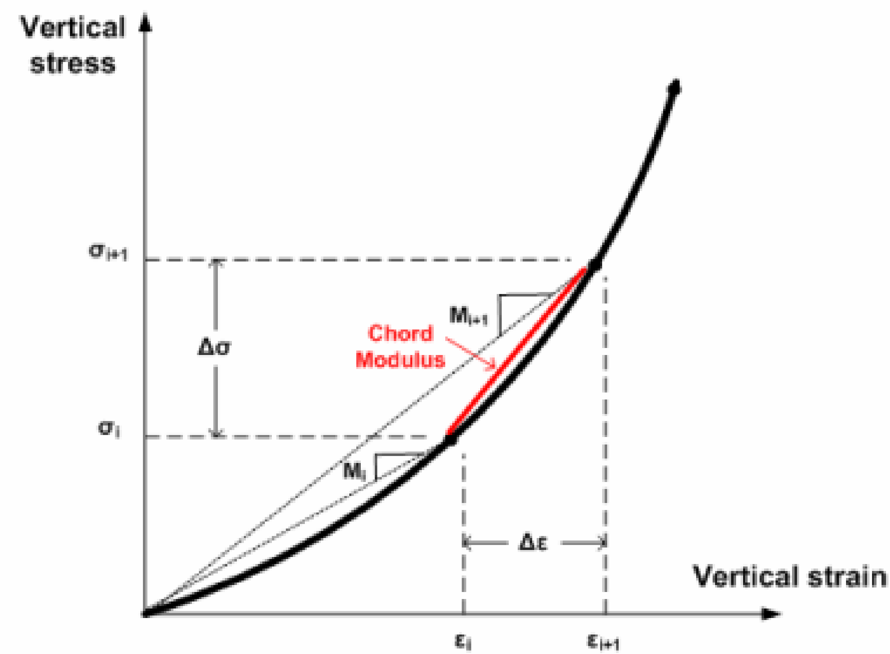


(3 Input Parameter)

- **Structural Backfill Limits**
  - **Width on both side of culvert walls**
  - **Height above the top slab**

CRITICAL PARAMETERS FOR ENVELOPING RESULTS

- **Soil Model**
  - Simple
    - Linear Elastic Soil
  - **Intermediate**
    - **Overburden Dependent**
  - Complex
    - Duncan / Duncan - Selig Soil
    - Extended Harden



(4 Input Parameter)

- Structural Backfill Limits
  - Width on both side of culvert walls
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CRITICAL PARAMETERS FOR ENVELOPING RESULTS

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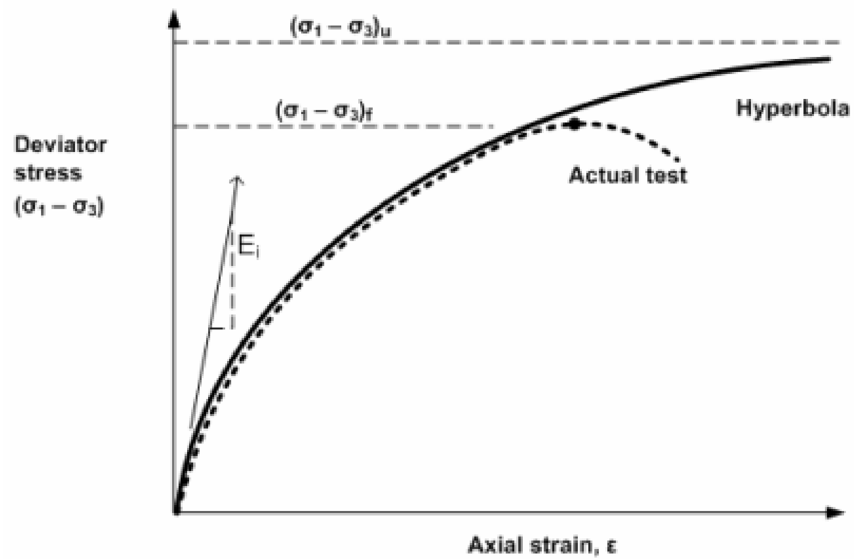

(12 Input Parameter)

- **Structural Backfill Limits**
  - **Width on both side of culvert walls**
  - **Height above the top slab**

CRITICAL PARAMETERS FOR ENVELOPING RESULTS

- Soil Model
  - Simple
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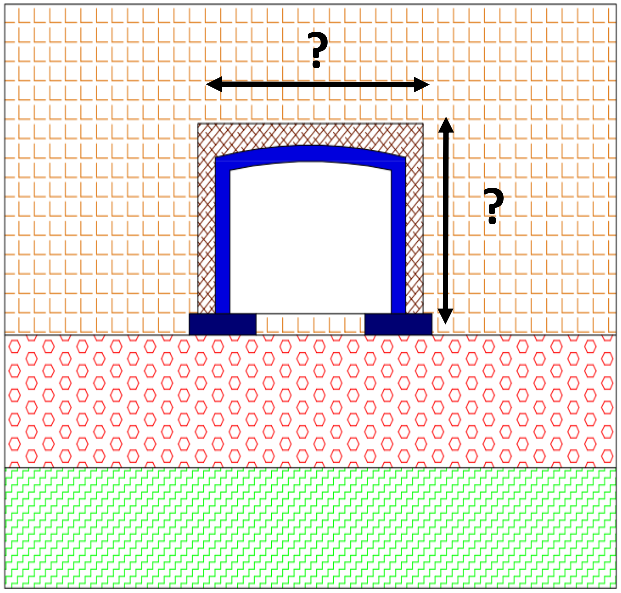
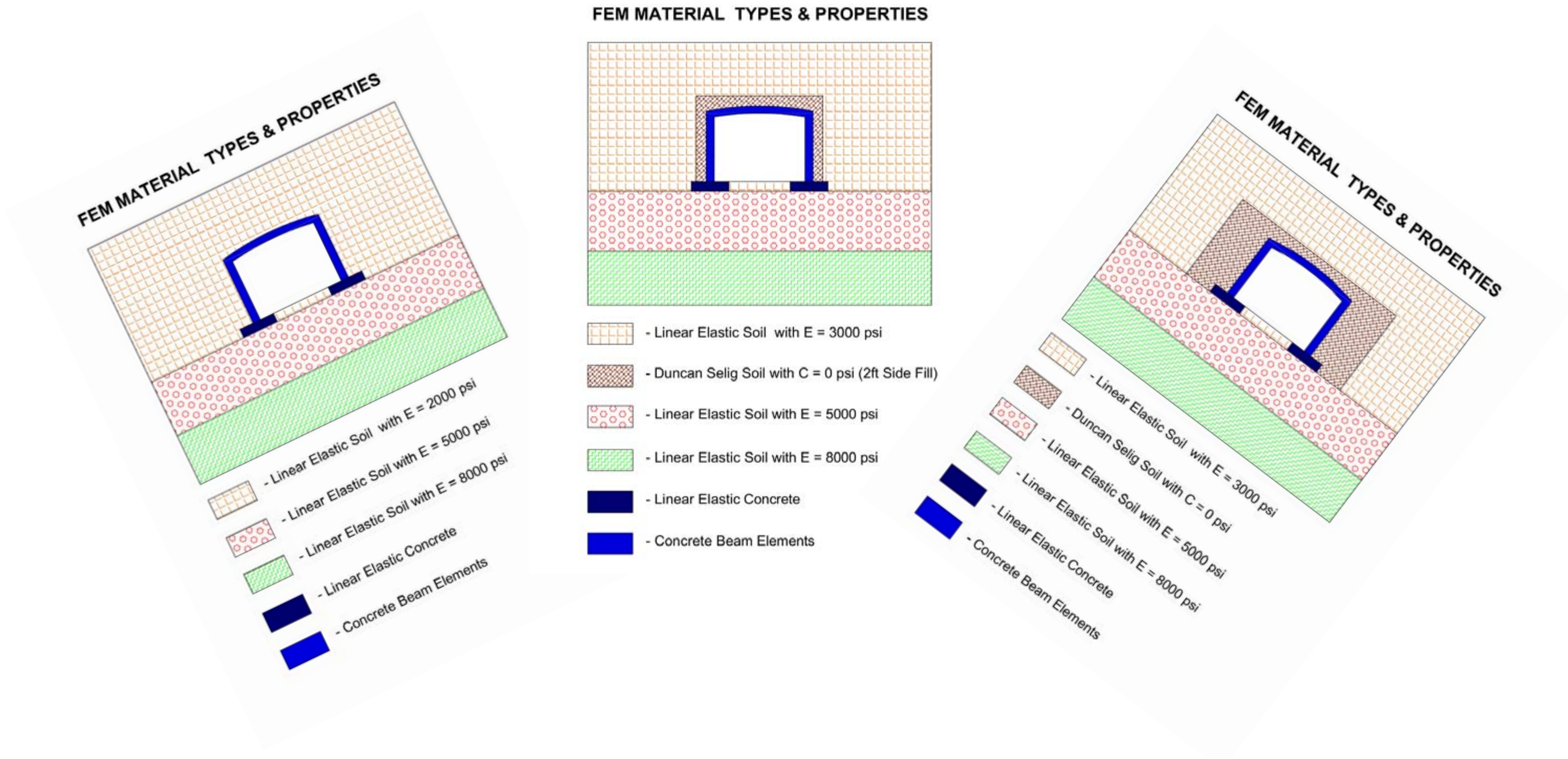
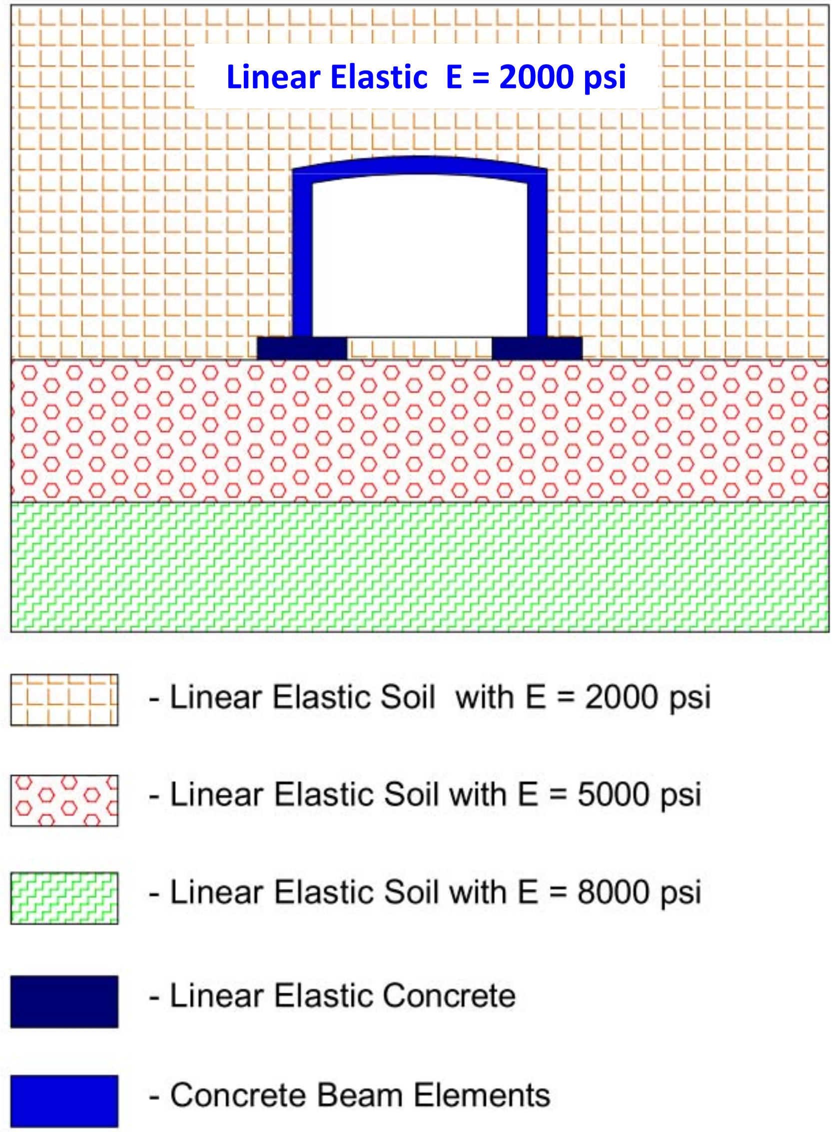


PARAMETRIC STUDY

10 Different finite element models are considered to identify critical soil parameters



FEM MATERIAL TYPES & PROPERTIES



FINITE ELEMENT MODEL - 1

- **In-Situ Soil assigned with zero density (Affects trench condition analysis)**
- **Structural Backfill assigned with zero cohesion to meet Caltrans backfill specifications**
- **Final Model shall not be overly conservative, but design should include possible uncertainties**

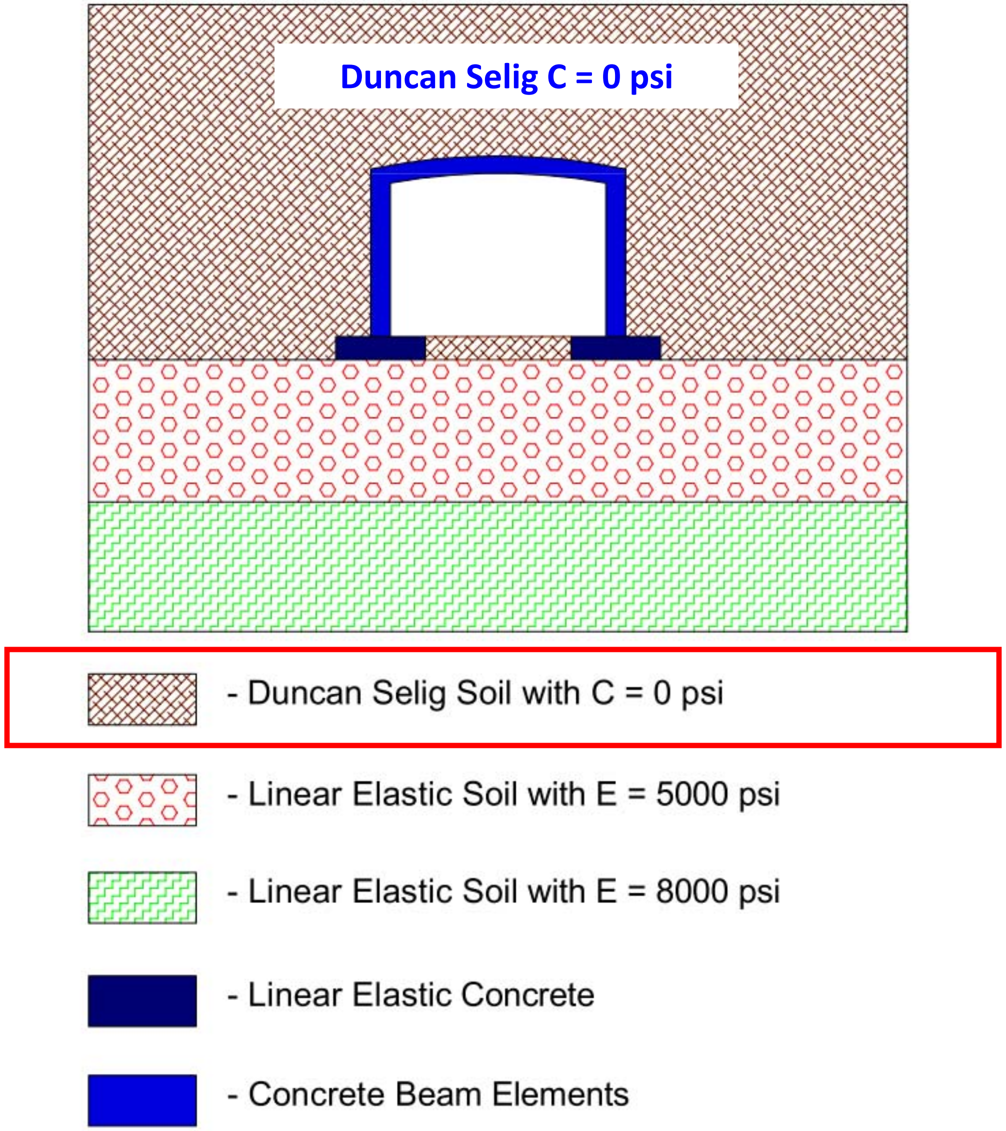
FINITE ELEMENT MODEL - 2

- **In-Situ Soil assigned with zero density (Affects trench condition analysis)**

- **Structural Backfill assigned with zero cohesion to meet Caltrans backfill specifications**

- **Final Model shall not be overly conservative, but design should include possible uncertainties**

FEM MATERIAL TYPES & PROPERTIES



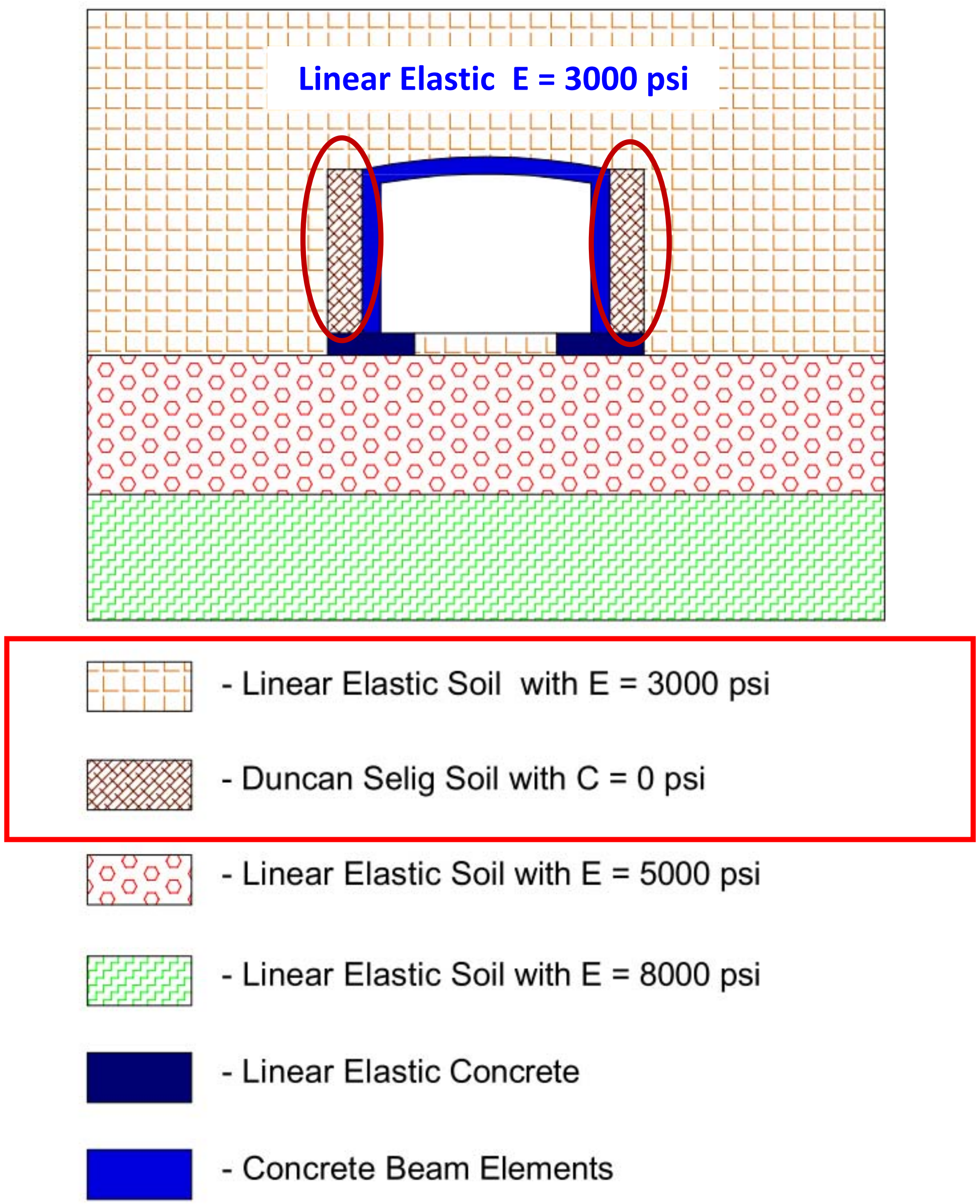
FINITE ELEMENT MODEL - 3

- **In-Situ Soil assigned with zero density (Affects trench condition analysis)**

- **Structural Backfill assigned with zero cohesion to meet Caltrans backfill specifications**

- **Final Model shall not be overly conservative, but design should include possible uncertainties**

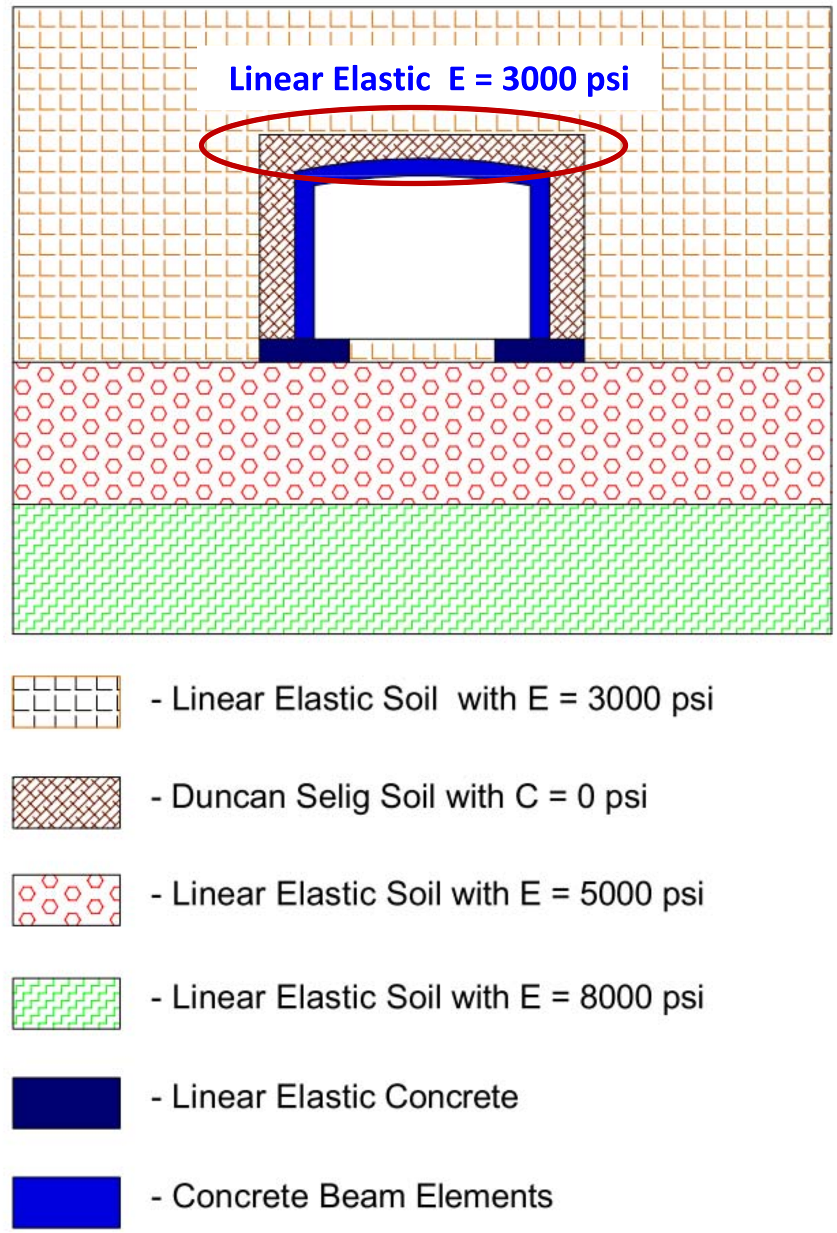
FEM MATERIAL TYPES & PROPERTIES



FINITE ELEMENT MODEL - 4

- **In-Situ Soil assigned with zero density (Affects trench condition analysis)**
- **Structural Backfill assigned with zero cohesion to meet Caltrans backfill specifications**
- **Final Model shall not be overly conservative, but design should include possible uncertainties**

FEM MATERIAL TYPES & PROPERTIES



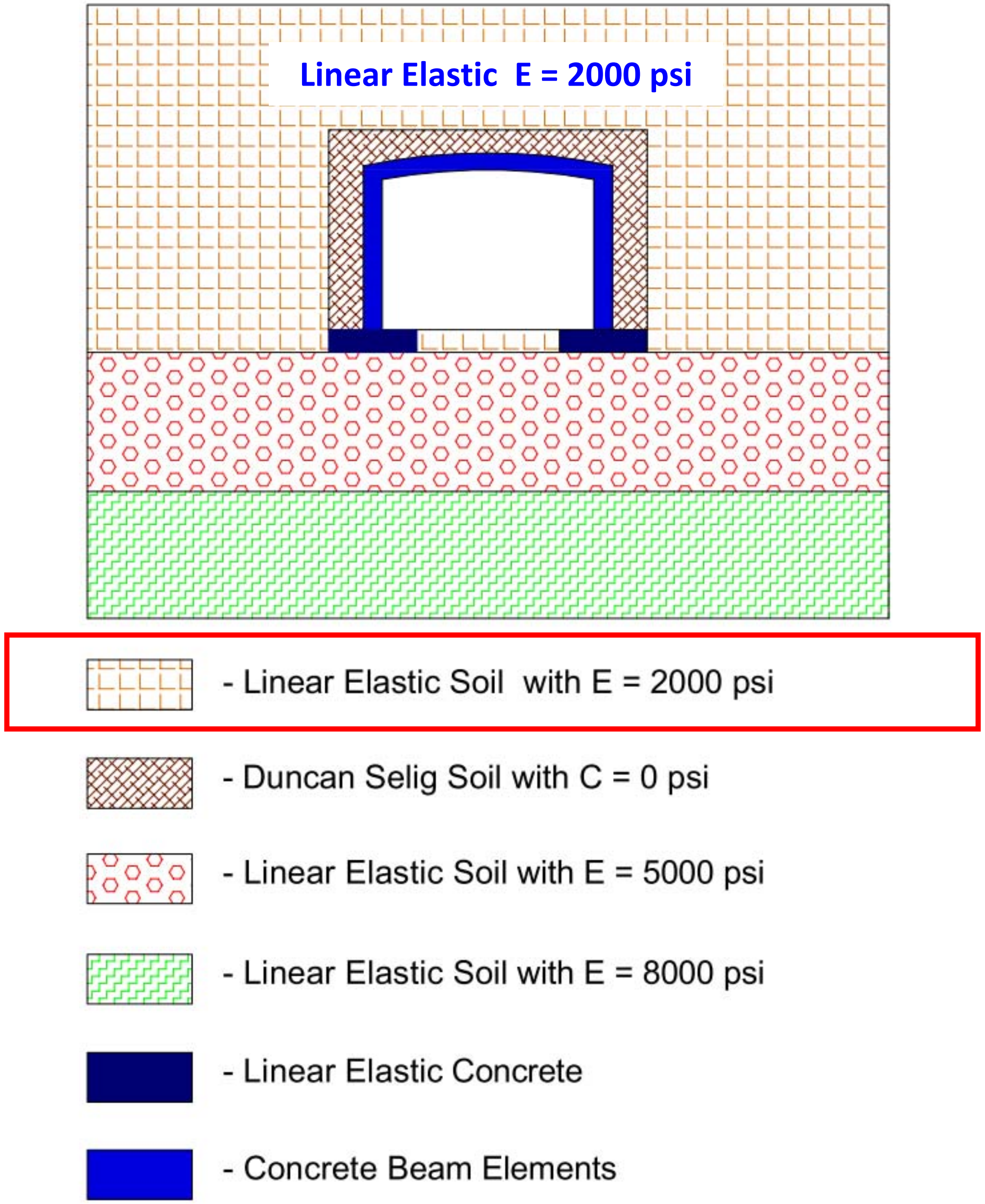
FINITE ELEMENT MODEL - 5

- **In-Situ Soil assigned with zero density (Affects trench condition analysis)**

- **Structural Backfill assigned with zero cohesion to meet Caltrans backfill specifications**

- **Final Model shall not be overly conservative, but design should include possible uncertainties**

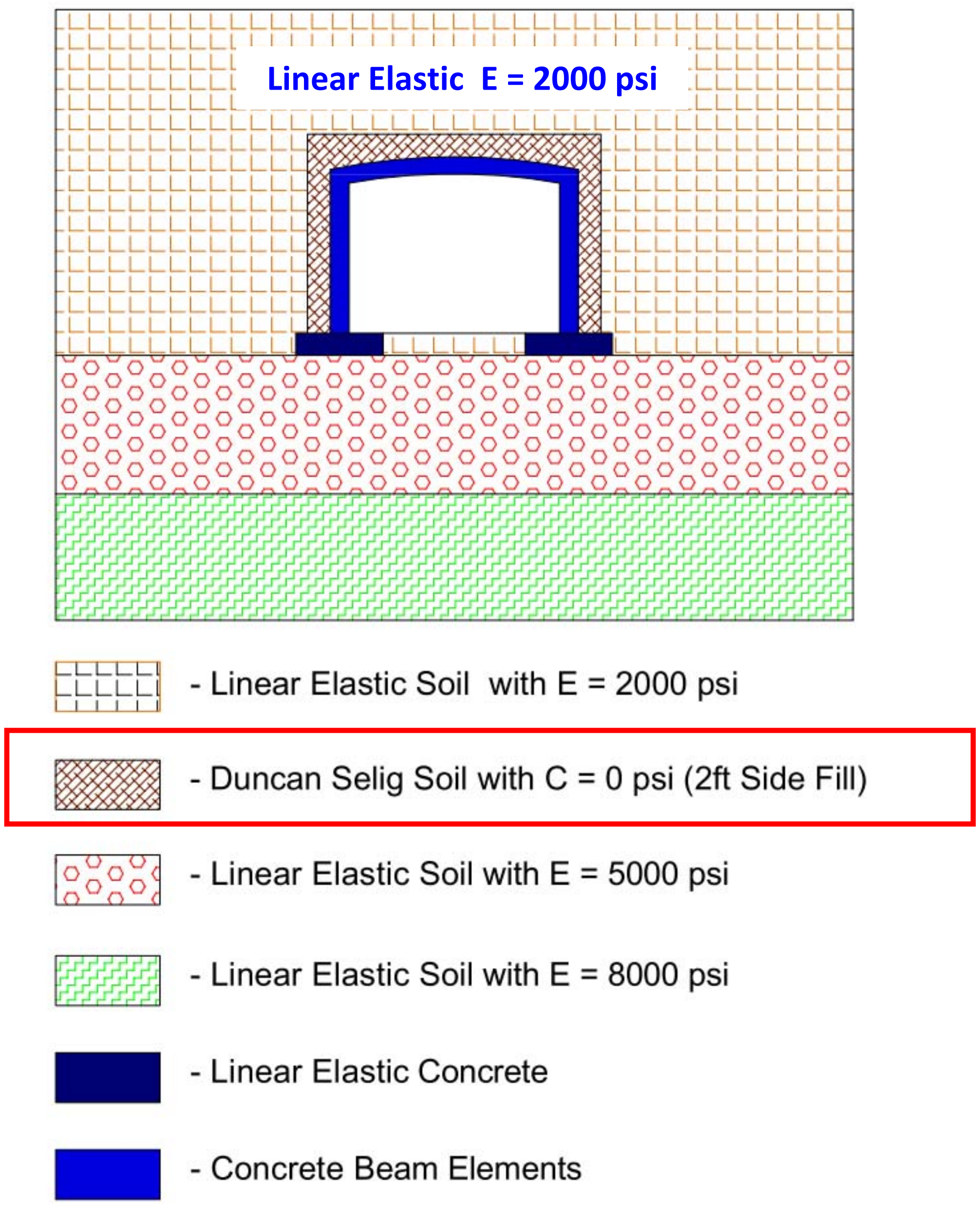
FEM MATERIAL TYPES & PROPERTIES



FINITE ELEMENT MODEL - 6

- In-Situ Soil assigned with zero density (Affects trench condition analysis)
- Structural Backfill assigned with zero cohesion to meet Caltrans backfill specifications
- Final Model shall not be overly conservative, but design should include possible uncertainties

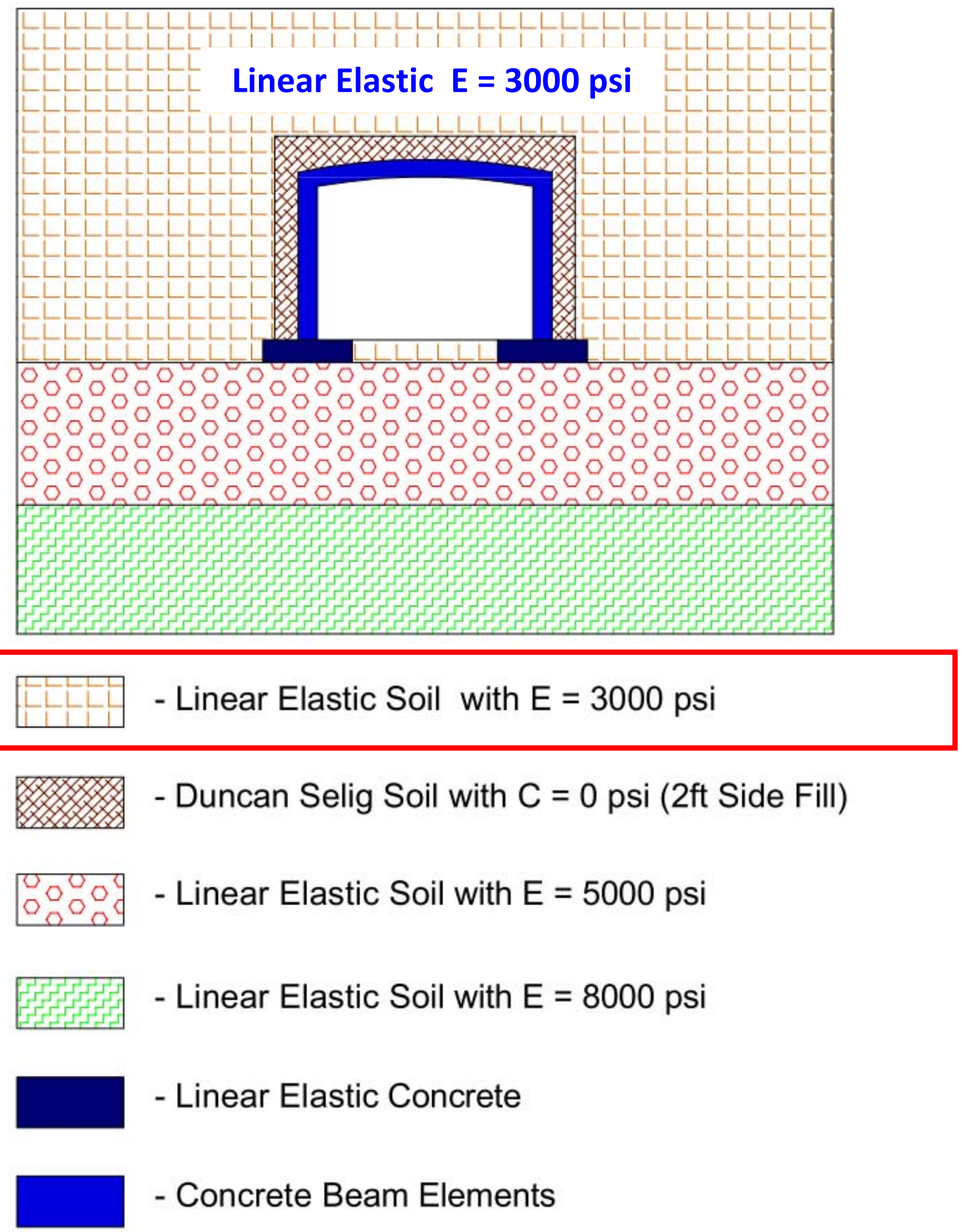
FEM MATERIAL TYPES & PROPERTIES



FINITE ELEMENT MODEL - 7

- **In-Situ Soil assigned with zero density (Affects trench condition analysis)**
- **Structural Backfill assigned with zero cohesion to meet Caltrans backfill specifications**
- **Final Model shall not be overly conservative, but design should include possible uncertainties**

FEM MATERIAL TYPES & PROPERTIES



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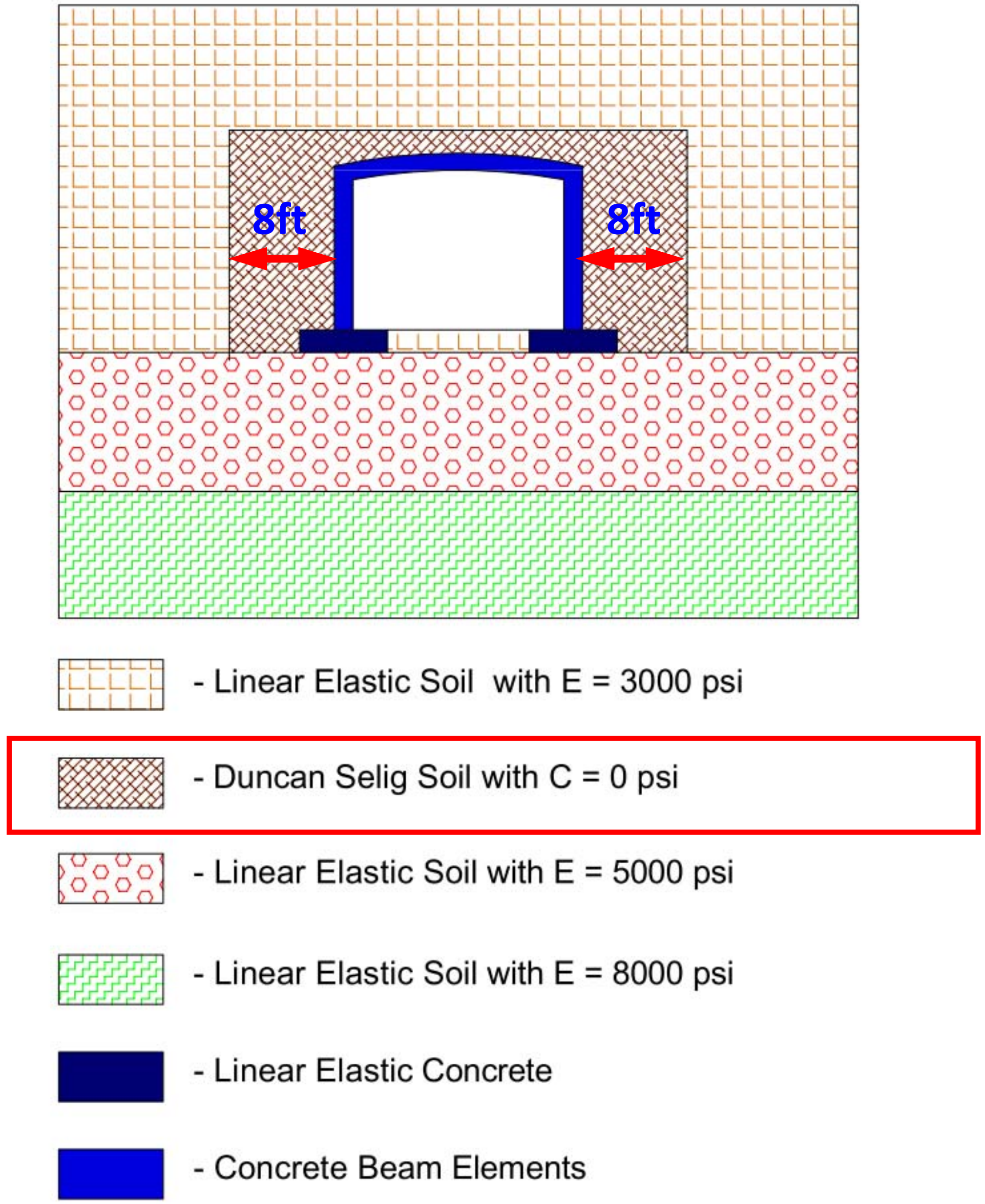
FINITE ELEMENT MODEL - 8

- **In-Situ Soil assigned with zero density (Affects trench condition analysis)**

- **Structural Backfill assigned with zero cohesion to meet Caltrans backfill specifications**

- **Final Model shall not be overly conservative, but design should include possible uncertainties**

FEM MATERIAL TYPES & PROPERTIES



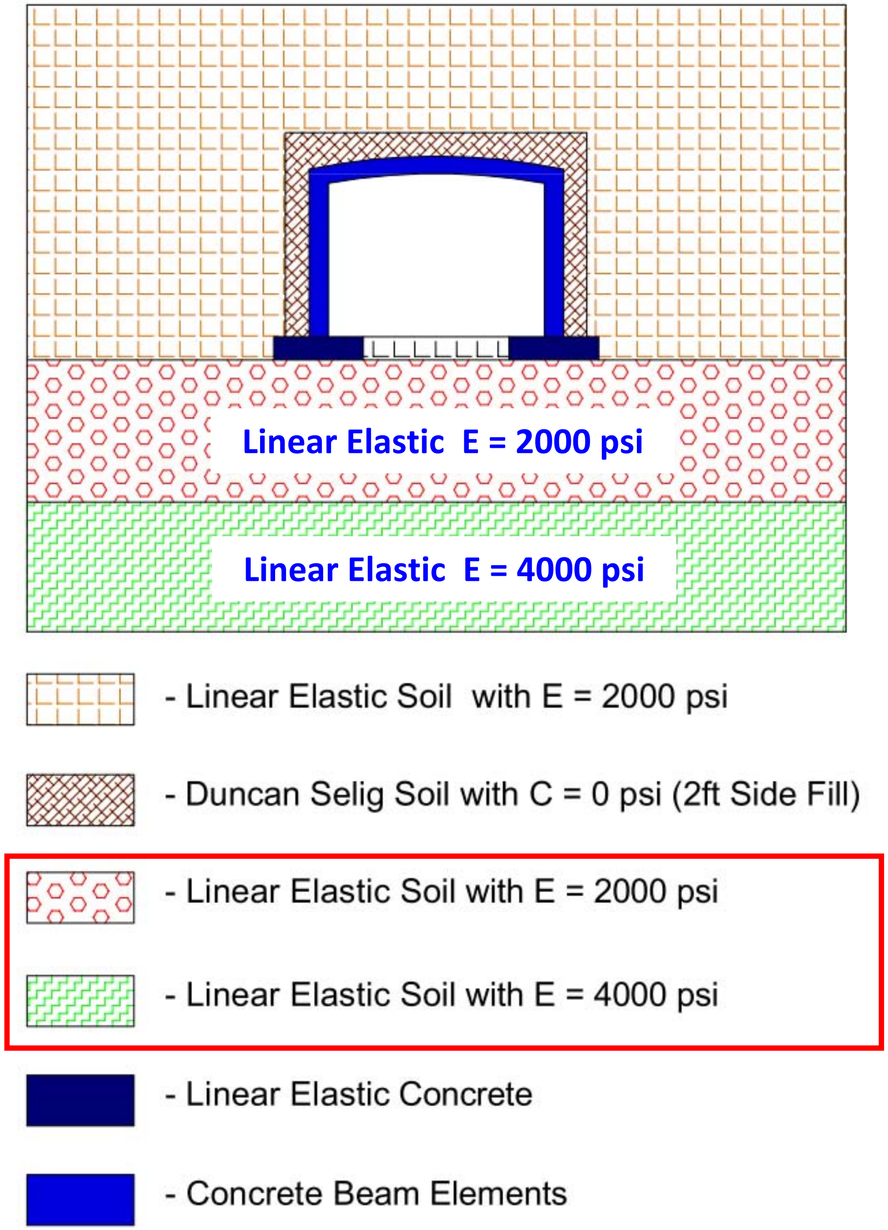
FINITE ELEMENT MODEL - 9

- **In-Situ Soil assigned with zero density (Affects trench condition analysis)**

- **Structural Backfill assigned with zero cohesion to meet Caltrans backfill specifications**

- **Final Model shall not be overly conservative, but design should include possible uncertainties**

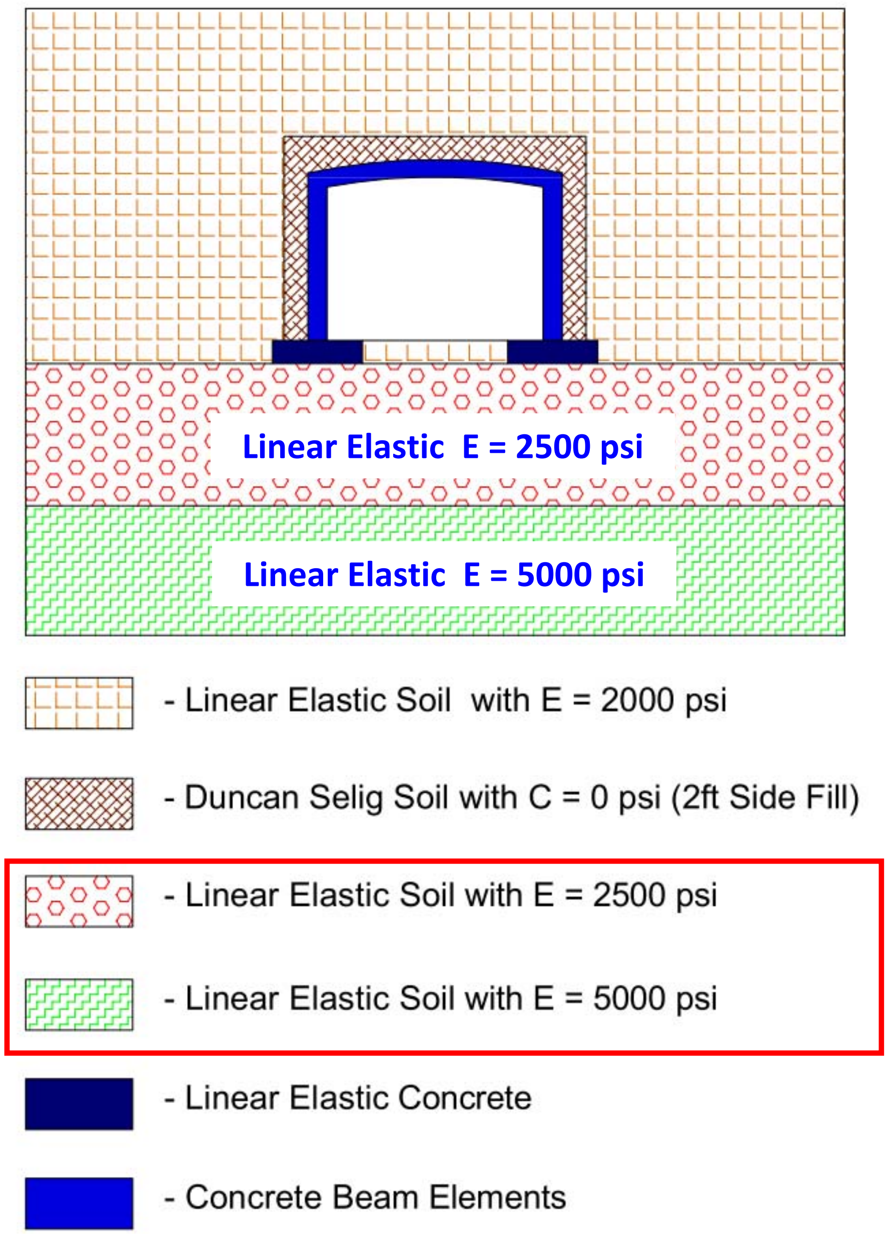
FEM MATERIAL TYPES & PROPERTIES



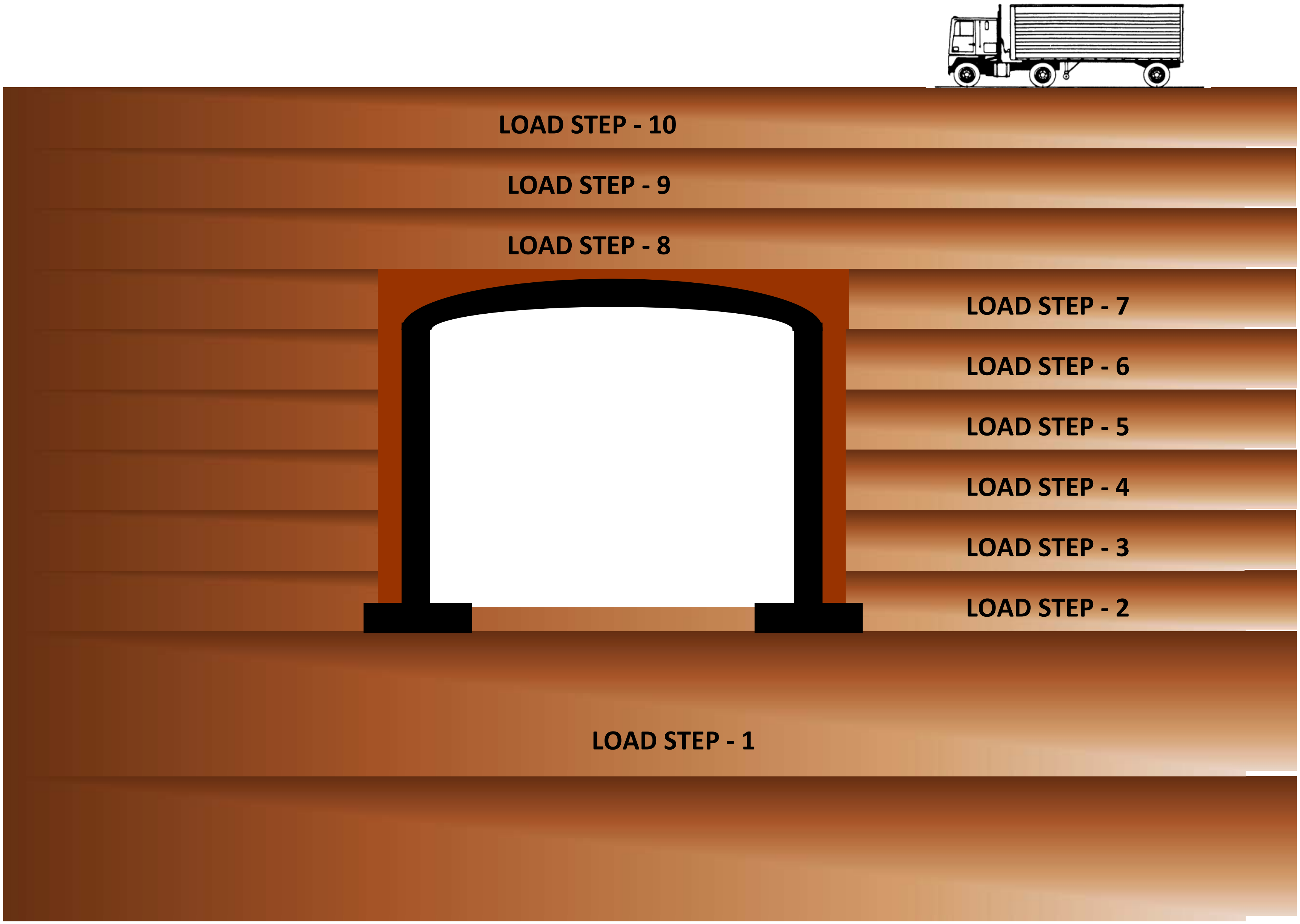
FINITE ELEMENT MODEL - 10

- **In-Situ Soil assigned with zero density (Affects trench condition analysis)**
- **Structural Backfill assigned with zero cohesion to meet Caltrans backfill specifications**
- **Final Model shall not be overly conservative, but design should include possible uncertainties**

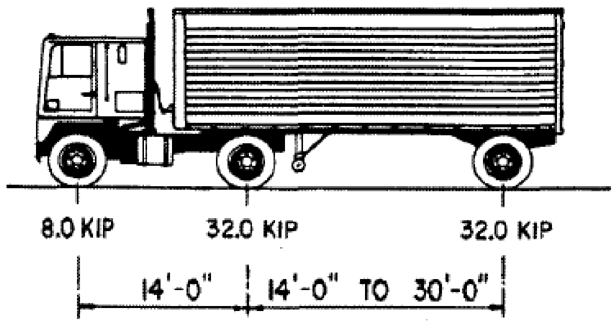
FEM MATERIAL TYPES & PROPERTIES



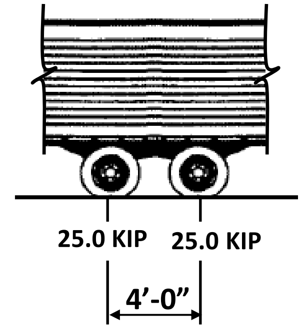
BACKFILL SEQUENCE/LOAD STEPS



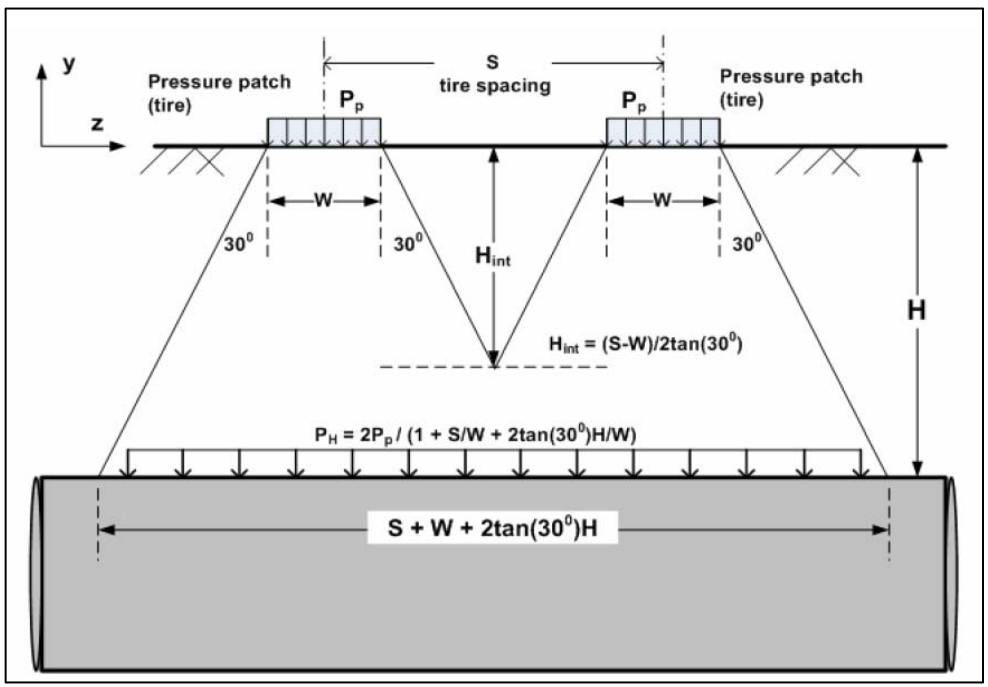
LIVE LOAD ON CULVERTS



Design Truck



Design Tandem



AASHTO LRFD two-wheel load distribution along axis of culvert. CANDE 2007 Solution Method Figure 8.1.3-1

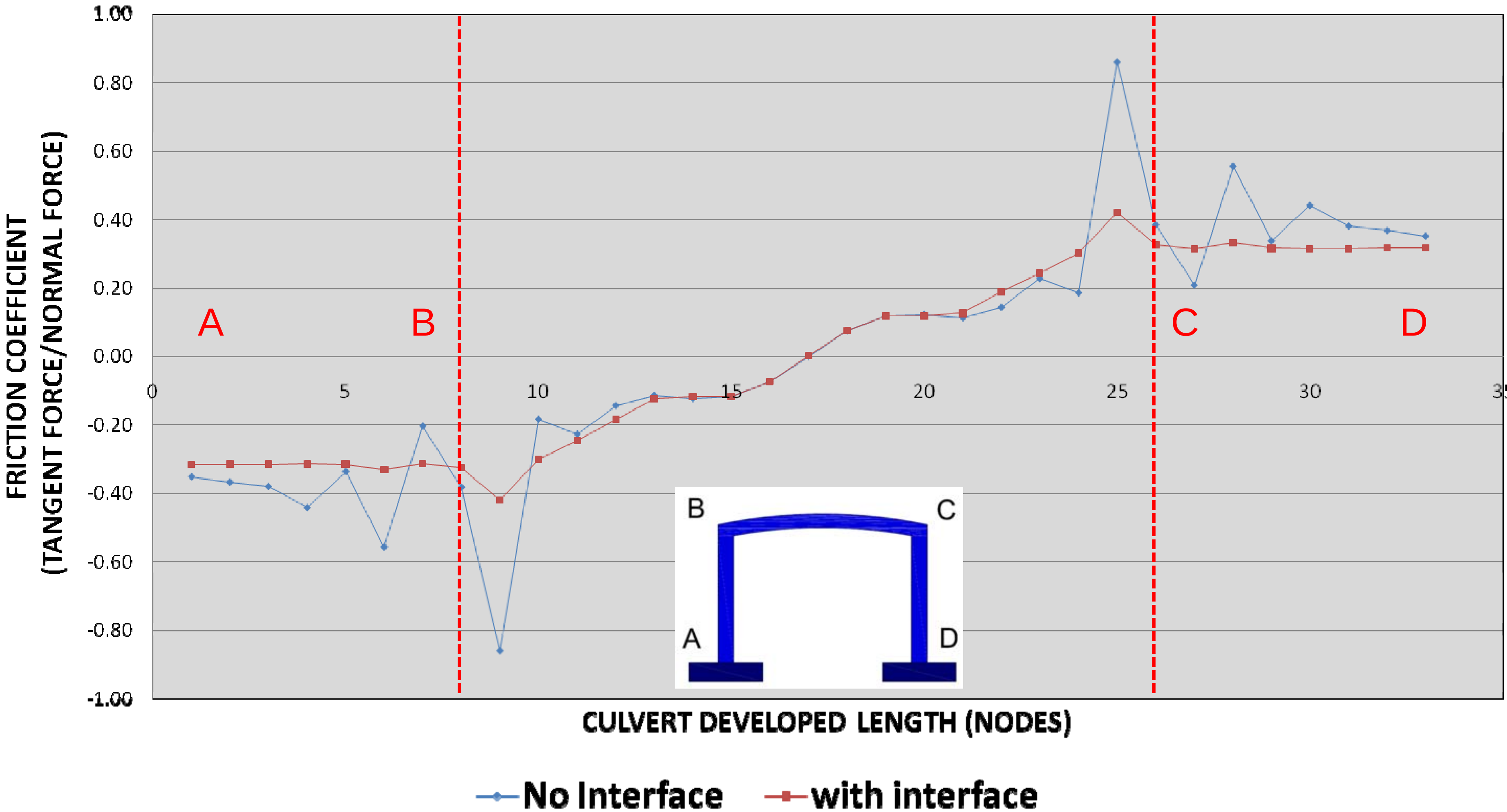
LOAD FACTORS & COMBINATIONS

- **COMBINATION-1: Critical for culvert corner (EH-Max + EV-Max)**
- **COMBINATION-2: Critical for wall span moment (EH-Max + EV-Min)**
- **COMBINATION-3: Critical for culvert top slab (EH-Min + EV-Max)**
- **COMBINATION-4: Service load Combination for Crack Control**

LOAD STEPS	COMB-1	COMB-2	COMB-3	COMB-4
Load Step – 1 (For In-Situ Soil)	0	0	0	0
Load Step – 2 - 5 (For Side Soil) - EH	1.5	1.5	0.9	1.0
Load Step – 5 (For Soil over top slab) - EV	1.3	1.0	1.3	1.0
Load Step- 12-XX (Live Load) - LL	1.75	0	1.75	1.0

INTERFACE ELEMENTS

- **Types: Fully Bonded/ Partially Bonded/ Frictionless**
- **Transfer normal & shear forces based on friction coefficient value of element**



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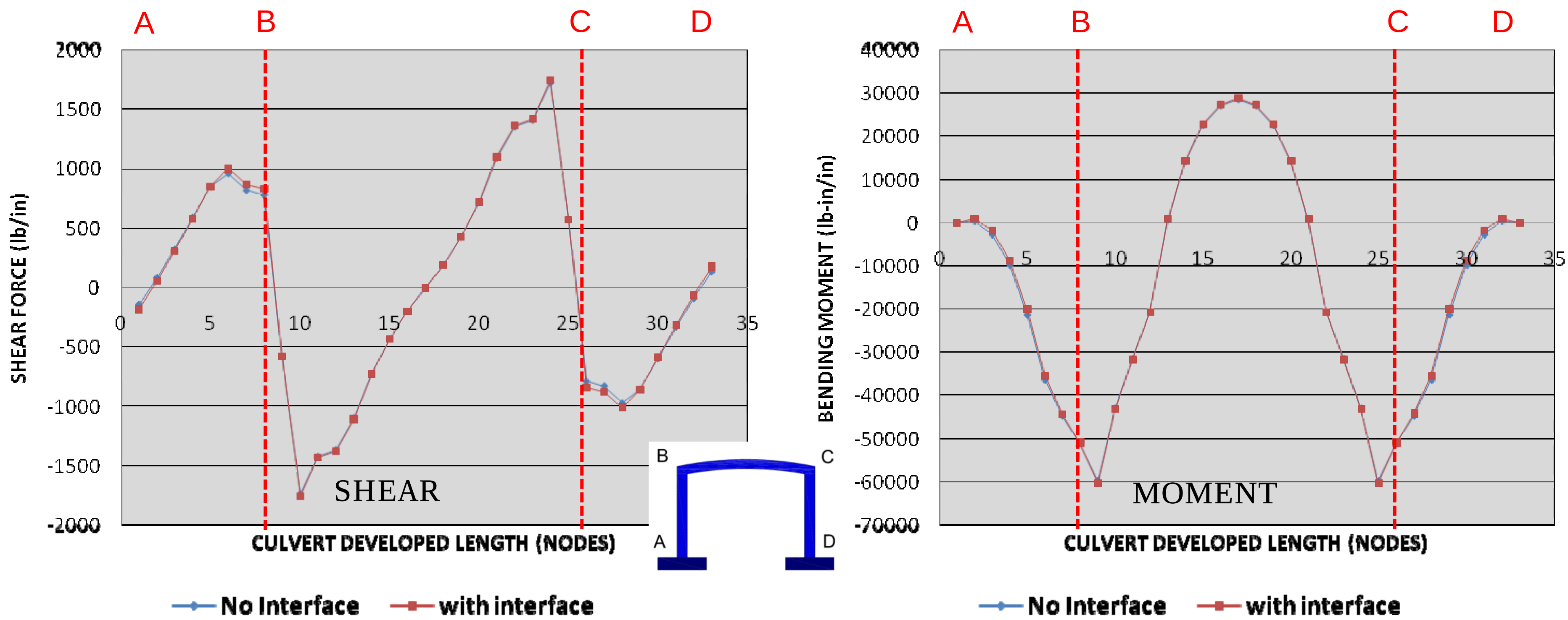
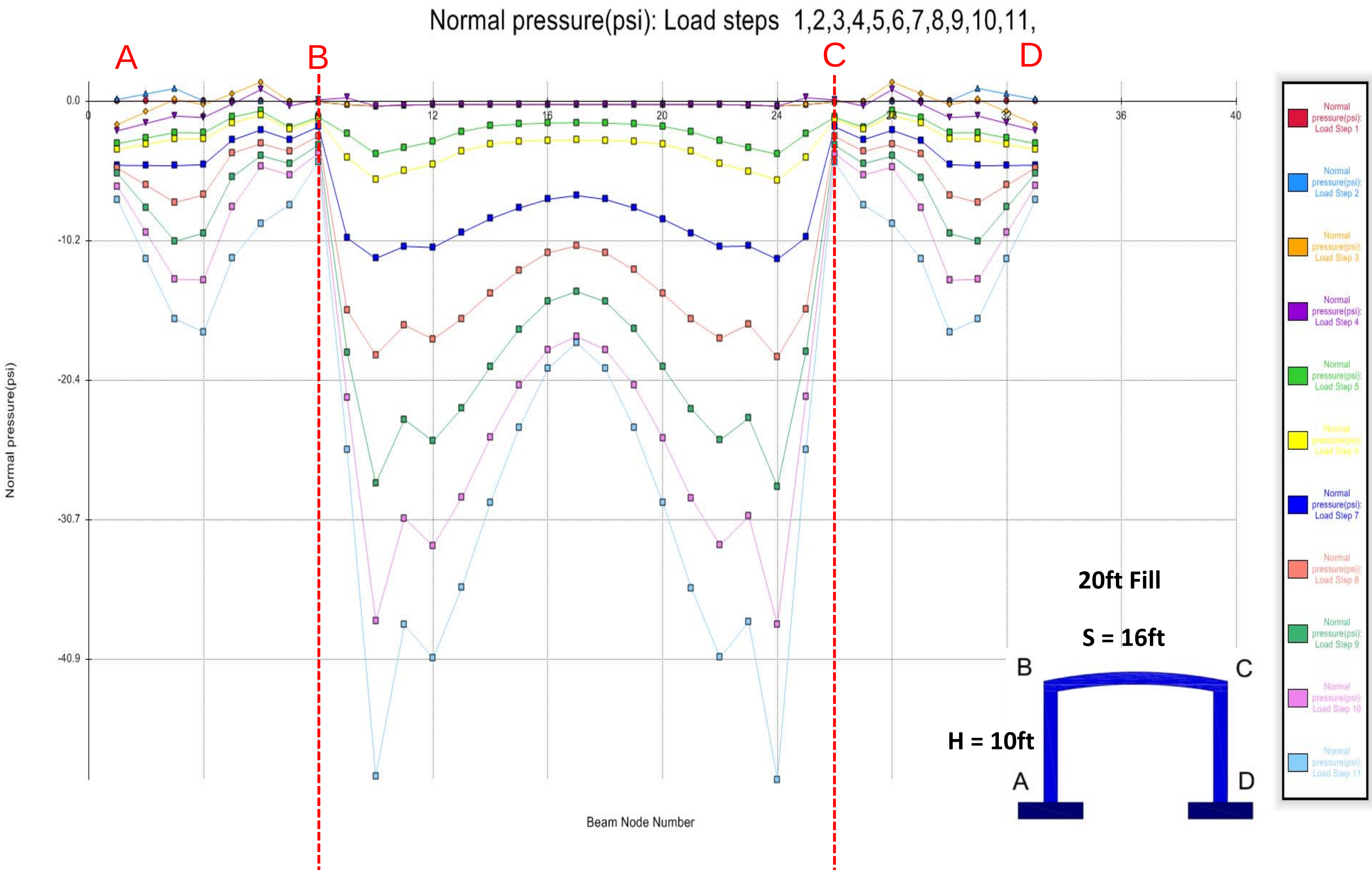
AECOM

INTERFACE VS NO INTERFACE

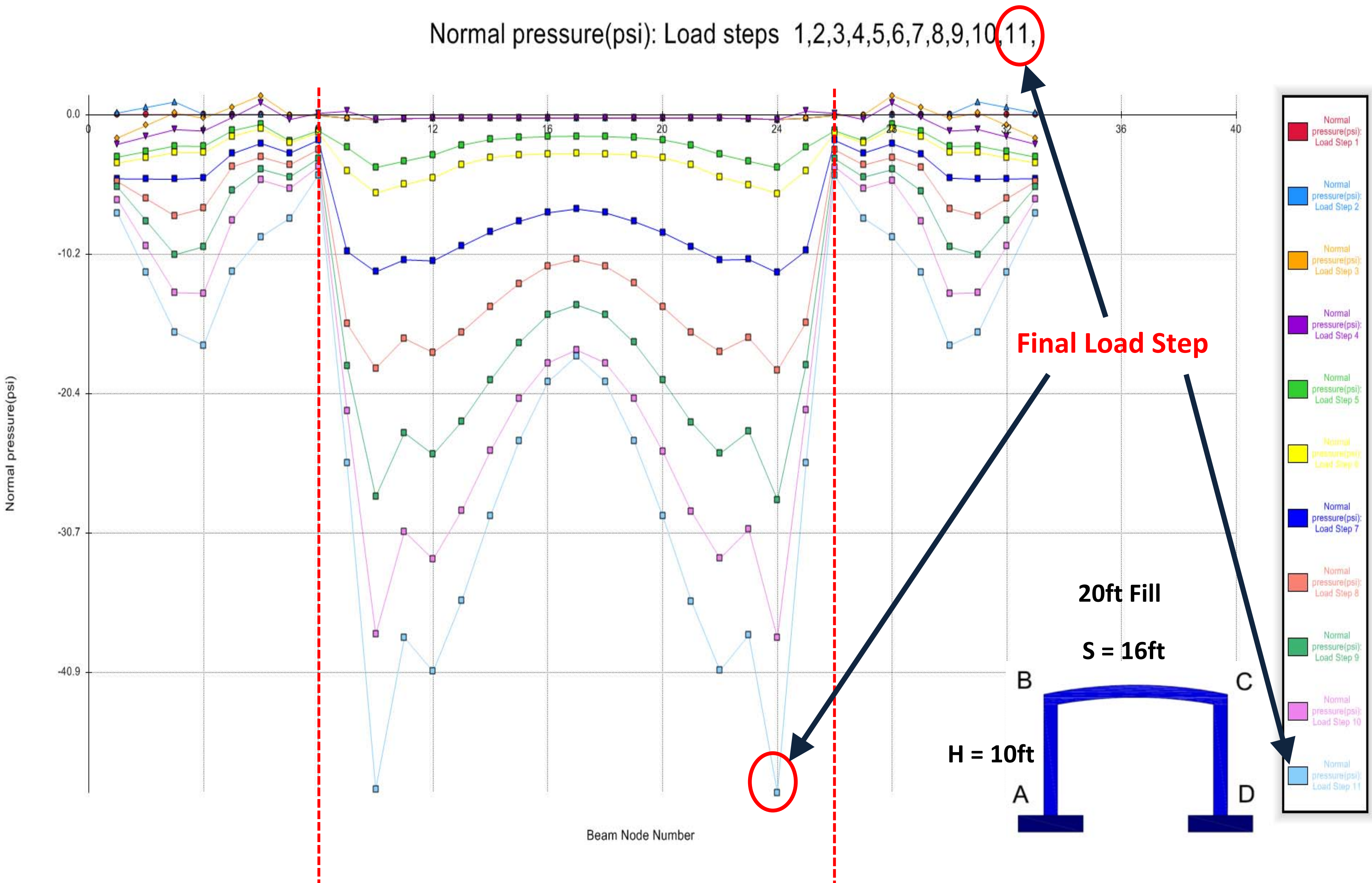


- ➢ **Model with interface elements produces more realistic results**
- ➢ **Accuracy gained appears to be very minor and does not justify the additional effort required**

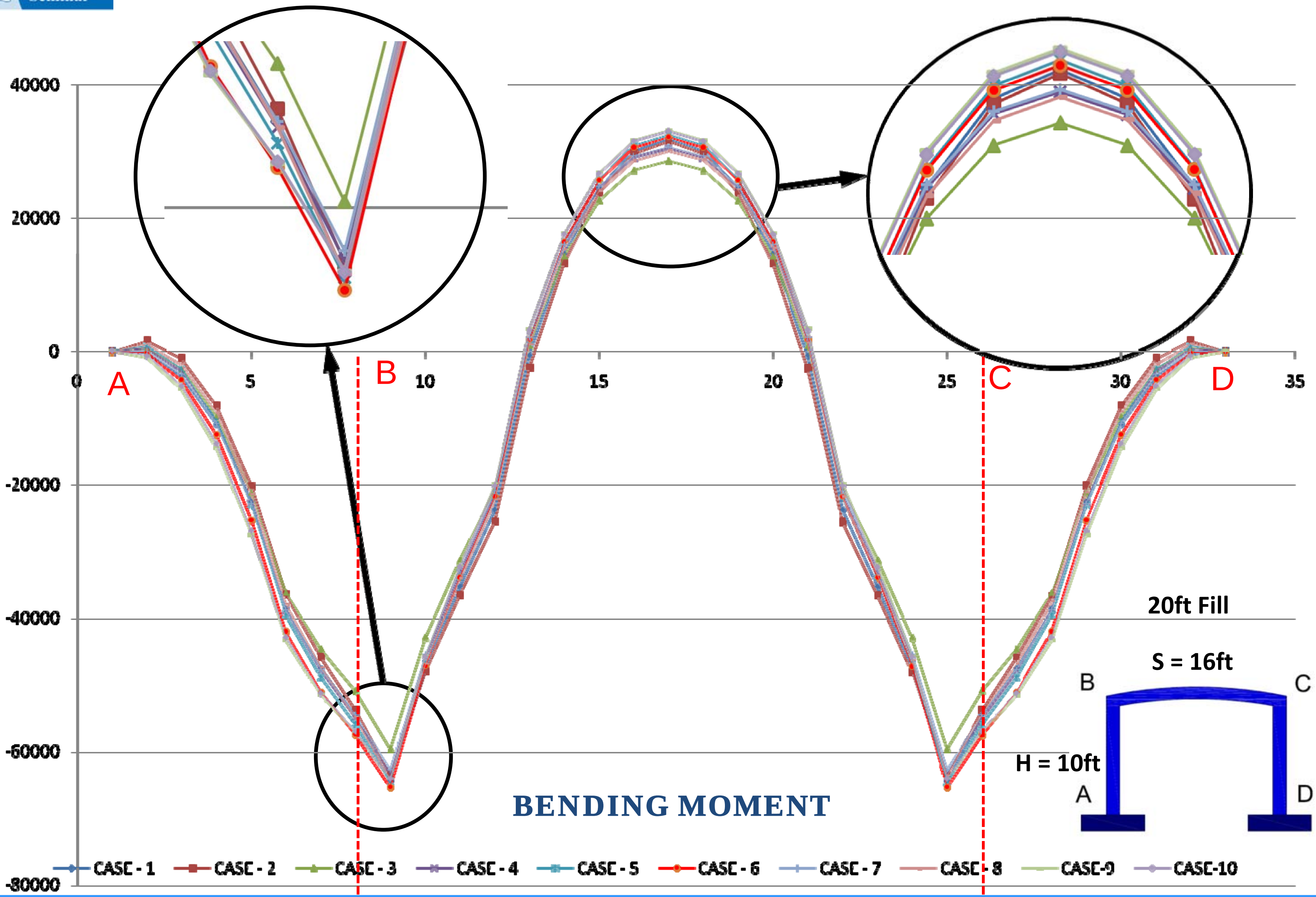
SAMPLE RESULT OUTPUT



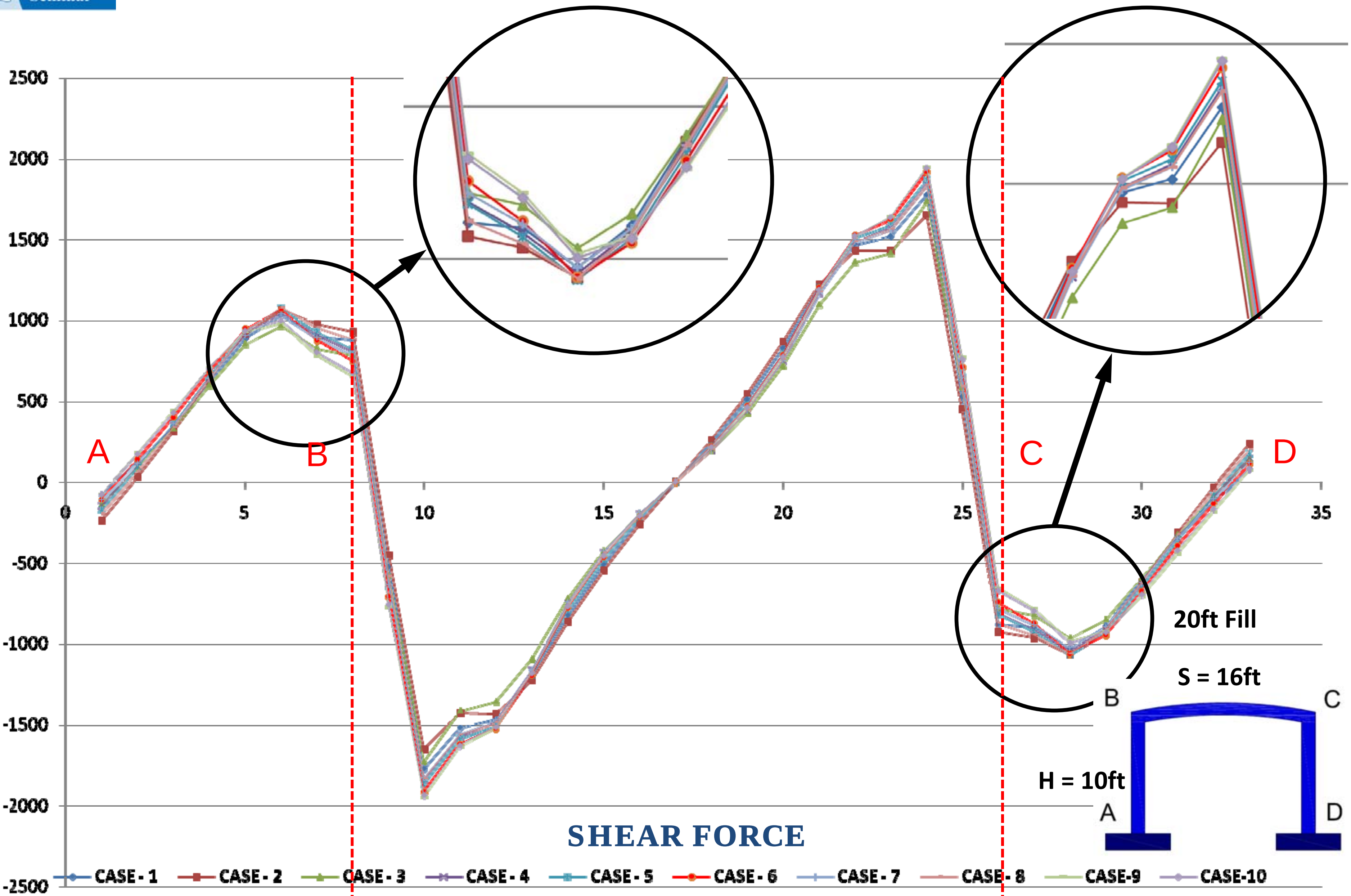
SAMPLE RESULT OUTPUT



FINITE ELEMENT MODEL 1-10 RESULTS

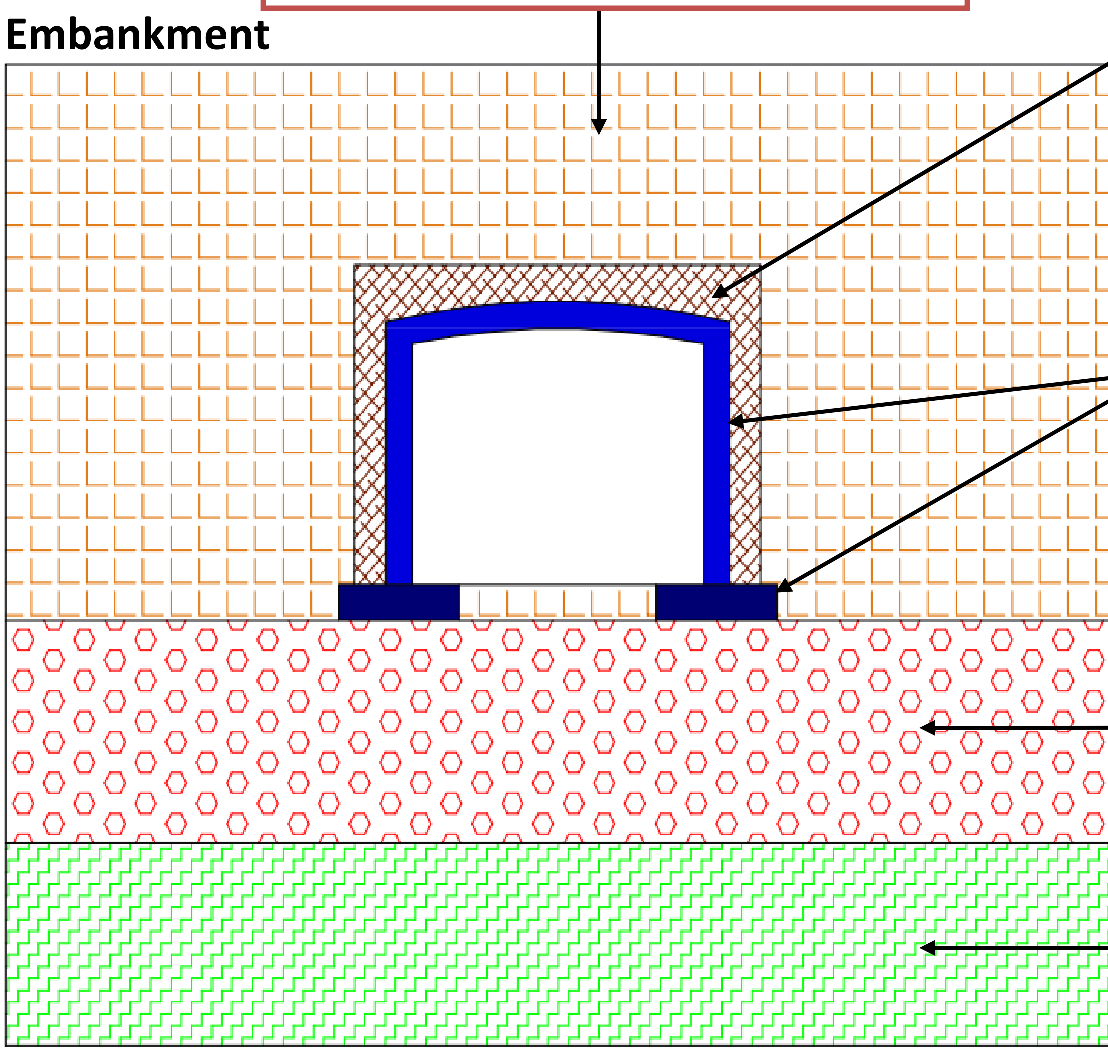


FINITE ELEMENT MODEL 1-10 RESULTS



RECOMMENDED MODEL

Linear Elastic , Density = 140 pcf,
E = 2000 psi, Poisson's Ratio = 0.3



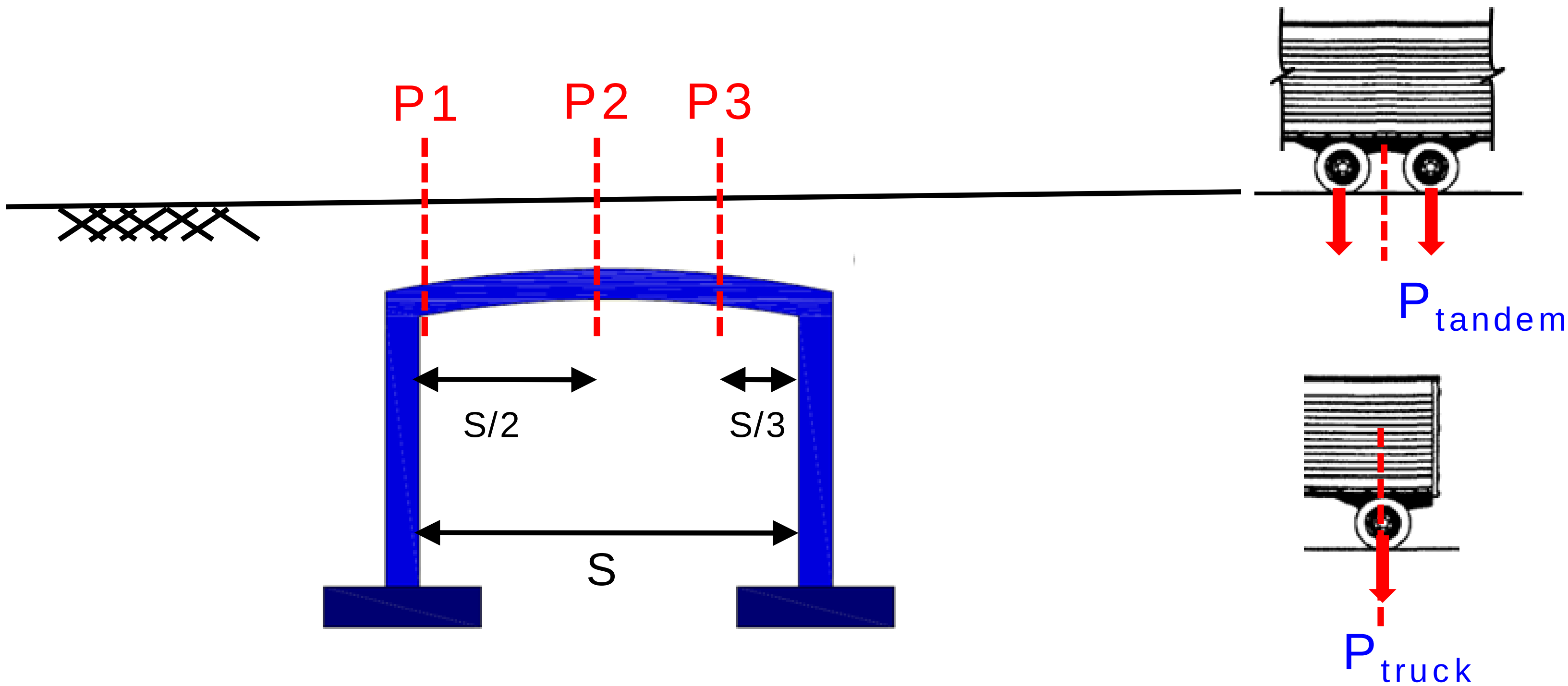
Duncan Selig, Cohesion = 0 psi, Density = 140 pcf, Initial Friction Angle = 34 deg, Magnitude of Initial Tangent Modulus = 400
Magnitude of Tangent Bulk Modulus = 42.8
(For 95% Compaction Level)

Linear Elastic, Density = 150 pcf, Poisson's Ratio = 0.17, (Concrete)
E = 33 x $W_c^{1.5}$ x sqrt (f'c)

Linear Elastic , Density = 0 pcf,
E = 2500 psi, Poisson's Ratio = 0.3
(E Can be higher for prepared bed soil)

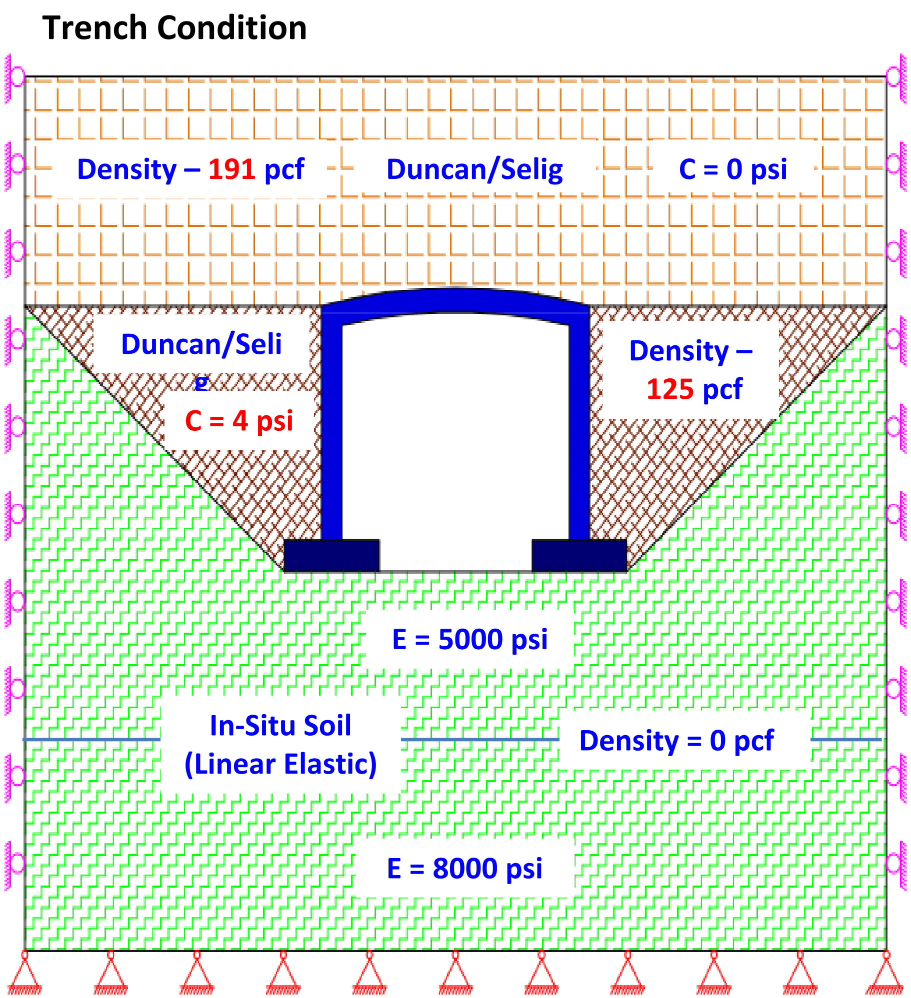
Linear Elastic , Density = 0 pcf,
E = 5000 psi, Poisson's Ratio = 0.3
(E Can be higher for prepared bed soil)

RECOMENDED MINIMUM LIVE LOAD APPLICATION

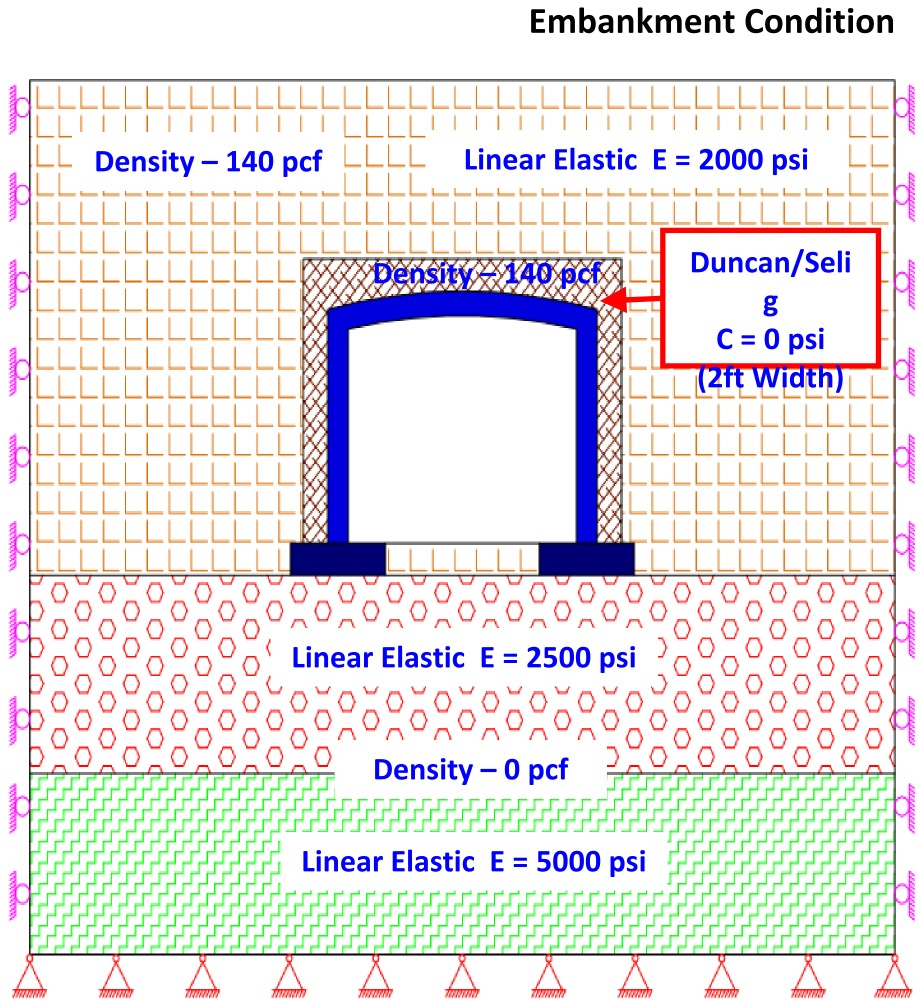


LOCATION	CRITICAL EFFECTS
P1	**Shear in Top Slab**
P2	**Maximum Top Slab Span Moment**
P3	**Maximum Culvert Corner Moment**

ORIGINAL MODEL VS RECOMENDED MODEL

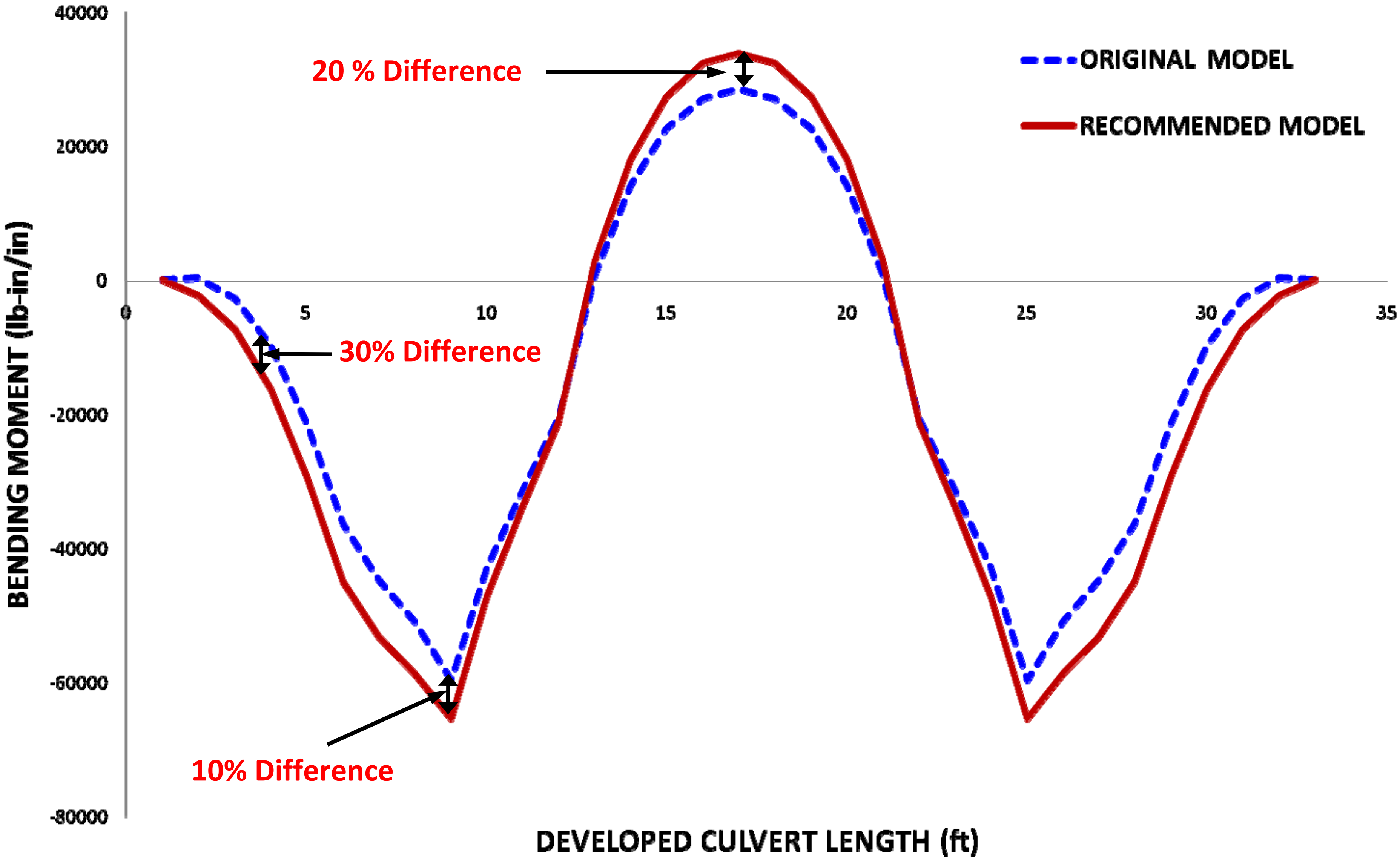


ORIGINAL MODEL (REVIEW PROBBLEM)



RECOMMENDED MODEL

ORIGINAL MODEL VS RECOMENDED MODEL



FOR LOAD COMBINATION -1

Thank You

Q & A

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