Dynamic Earth pressure - Myths, Realities and Practical Ways for Design

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Presentation Outline

Introduction and Background

Standard Practice

- Simplified Determination of Lateral Earth Pressures
- Hydrodynamic Fluid Pressures
- Review of Lateral Soil Pressure Theories
- Recent Experimental Results

Detailed Seismic Fluid Soil Structure Interaction

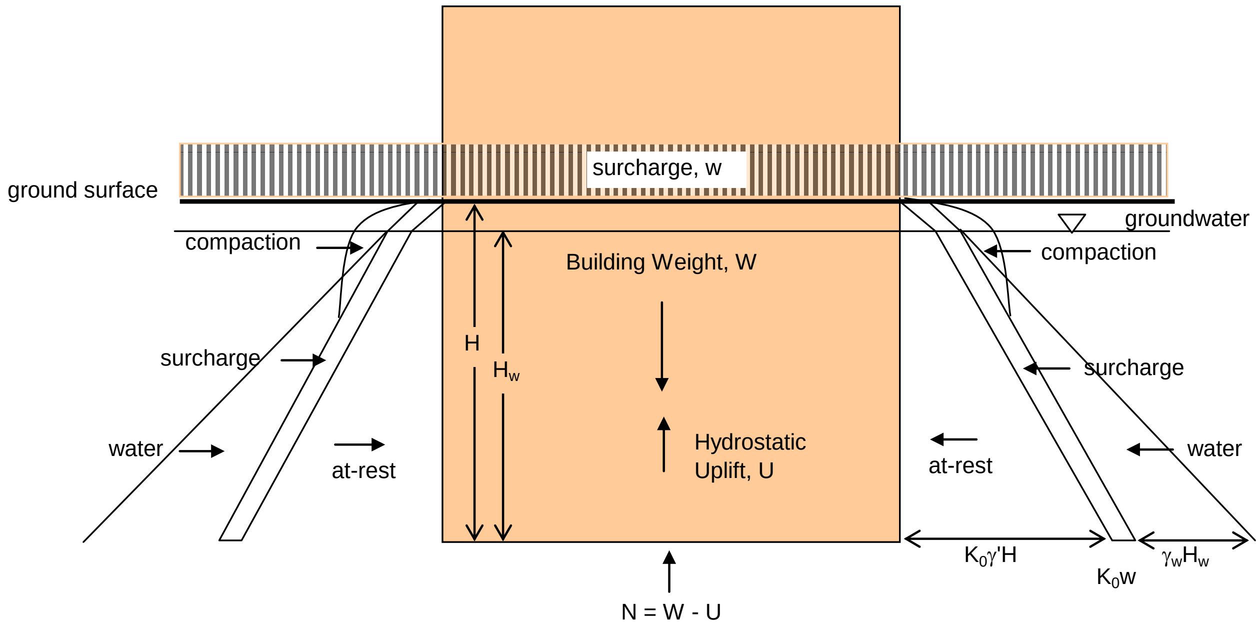
- Detailed fluid-structure interaction
- Simplified fluid modeling
- Seismic soil structure interaction

Case Study Intake Pump Station

Introduction and Background

Force Diagram of Subsurface Walls - Static Conditions

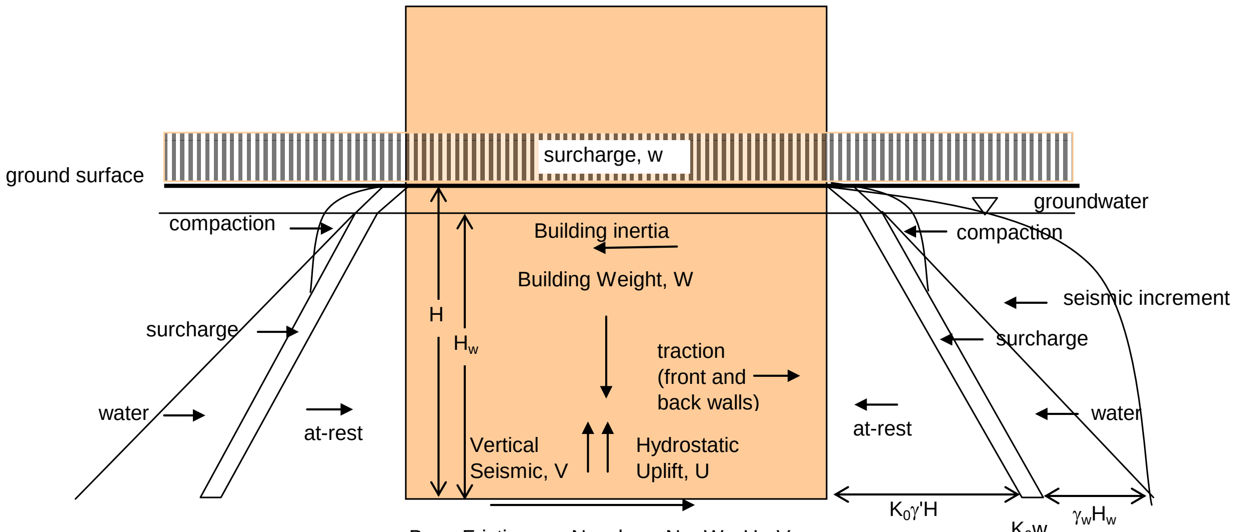
STATIC



<u>Applicable loads</u>
at-rest earth pressure
surcharge stress from surface loading
compaction stresses from Duncan's method (1991 and 1993)
U = buoyancy due to water table
N = normal stress along basemat

Force Diagram of Subsurface Walls – Seismic Without Movement

SEISMIC - NO MOVEMENT



Base Friction = μ N , where N = W - U - V
+ Base adhesion

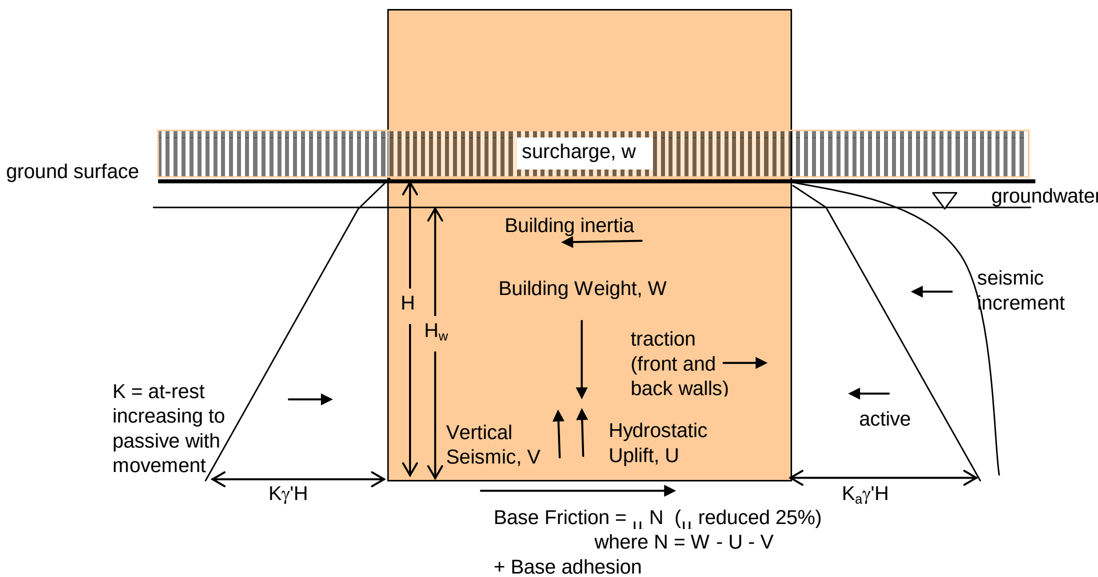
Applicable loads
at-rest earth pressure
surcharge stress from surface loading
compaction stresses from Duncan's method (1991 and 1993)
U = buoyancy due to water table
V = vertical seismic force
N = normal stress along basemat
base friction using interface coefficient, μ
traction = friction along building sides = at-rest pressure x μ_{sides}
μ_{sides} = friction coefficient along sidewalls of structure
seismic increment = horizontal base forces from SASSI output include all driving forces, composed of those from seismic, at-rest, and building inertia

Sliding check

Compare SASSI basemat horizontal forces (Demand = D)
against basemat frictional/adhesional resistance (Capacity = C).
If FS = C/D $\geq$ 1.1, then building is stable against sliding

Force Diagram of Subsurface Walls – Seismic With Movement

SEISMIC - WITH MOVEMENT



Applicable loads

resisting earth pressure is dependent on amount of movement
surcharge stress from surface loading

U = buoyancy due to water table

V = vertical seismic force

N = normal stress along basemat
reduced base friction using interface coefficient, μ_{red}

reduced traction = friction along building sides = at-rest pressure x μ_{sides_red}

μ_{sides_red} = reduced friction coefficient along sidewalls of structure

seismic increment = horizontal base forces from SASSI output include all driving forces, composed of those from seismic, at-rest, and building inertia

Sliding check

Compare SASSI basemat horizontal driving forces (Demand = D)
against basemat friction/adhesion + side friction + passive resistance (Capacity = C)
using reduced resistance coefficients for frictional/adhesional components
If FS = C/D $\geq$ 1.1, then building is stable against further sliding

Standard Practice for Partially or Fully Buried Liquid-containing Structures

Total Base Shear and Wall Pressures

STANDARD

8.1—General

Dynamic earth pressures shall be taken into account when computing the base shear of a partially or fully buried liquid-containing structure and when designing the walls.

The effects of groundwater table, if present, shall be included in the calculation of these pressures.

The coefficient of lateral earth pressure at rest K_o shall be used in estimating the earth pressures unless it is demonstrated by calculation that the structure deflects sufficiently to lower the coefficient to some value between K_o and the active coefficient of lateral earth pressure K_a.

In a pseudostatic analysis, the resultant of the seismic component of the earth pressure shall be assumed to act at a point 0.6 of the earth height above the base, and when part or all of the structure is below the water table, the resultant of the incremental increase in groundwater pressure shall be assumed to act at a point 1/3 of the water depth above the base.

COMMENTARY

R8.1—General

The lateral forces due to the dynamic earth and groundwater pressures are combined algebraically with the impulsive forces on the tank as in Eq. (4-5).

P_i = total lateral impulsive force associated with W_i, lb (kN)

P_w = lateral inertia force of the accelerating wall W_w, lb (kN)

P_r = lateral inertia force of the accelerating roof W_r, lb (kN)

P_c = total lateral convective force associated with W_c, lb (kN)

P_{eg} = lateral force on the buried portion of a tank wall due to the dynamic earth and groundwater pressures, lb (kN)

$$V = \sqrt{(P_i + P_w + P_r)^2 + P_c^2 + P_{eg}^2} \quad (4\text{-}5)$$

$$M_b = \sqrt{(M_i + M_w + M_r)^2 + M_c^2} \quad (4\text{-}10)$$

Practical Earth Pressure Analysis

Select all potential critical interface combinations at the base and sides of the structure on which to determine the minimum base frictional resistance.

Compare base and side frictional resistance to seismic at-rest demand. If C/D > 1.0, then use seismic at-rest demand to design walls.

If the C/D < FS, then sliding will occur. Then reduce base and side friction coefficients by 25%. loading side of the structure will be subject to the active earth pressure, the seismic lateral active earth pressure increment, and the building inertia. Increase resisting load on the passive side, until C/D ≥ 1.0.

$$V = \sqrt{(P_i + P_w + P_r)^2 + P_c^2 + P_{eg}^2} \qquad (4\text{-}5)$$

Sliding or wall rotation must occur for K < K_0

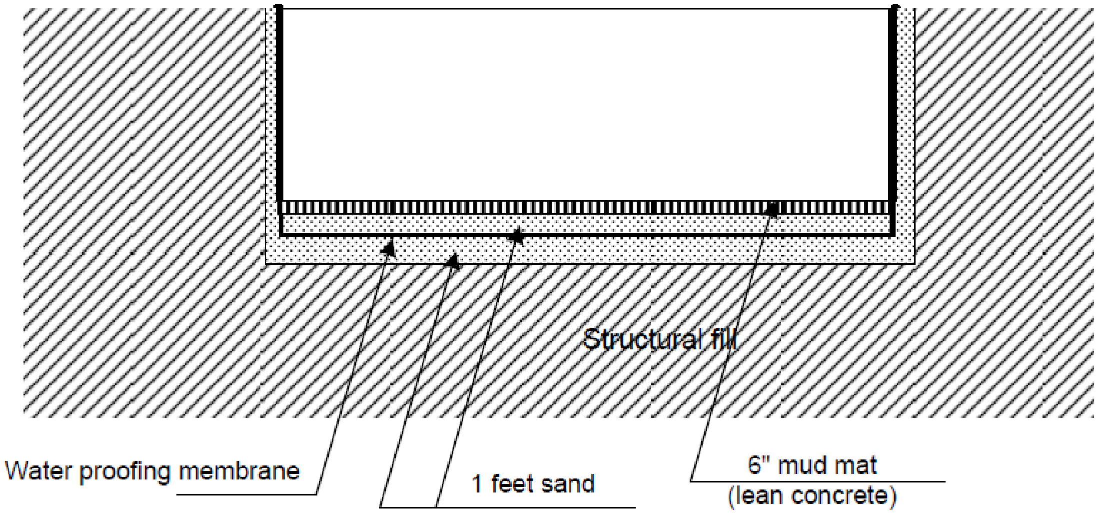
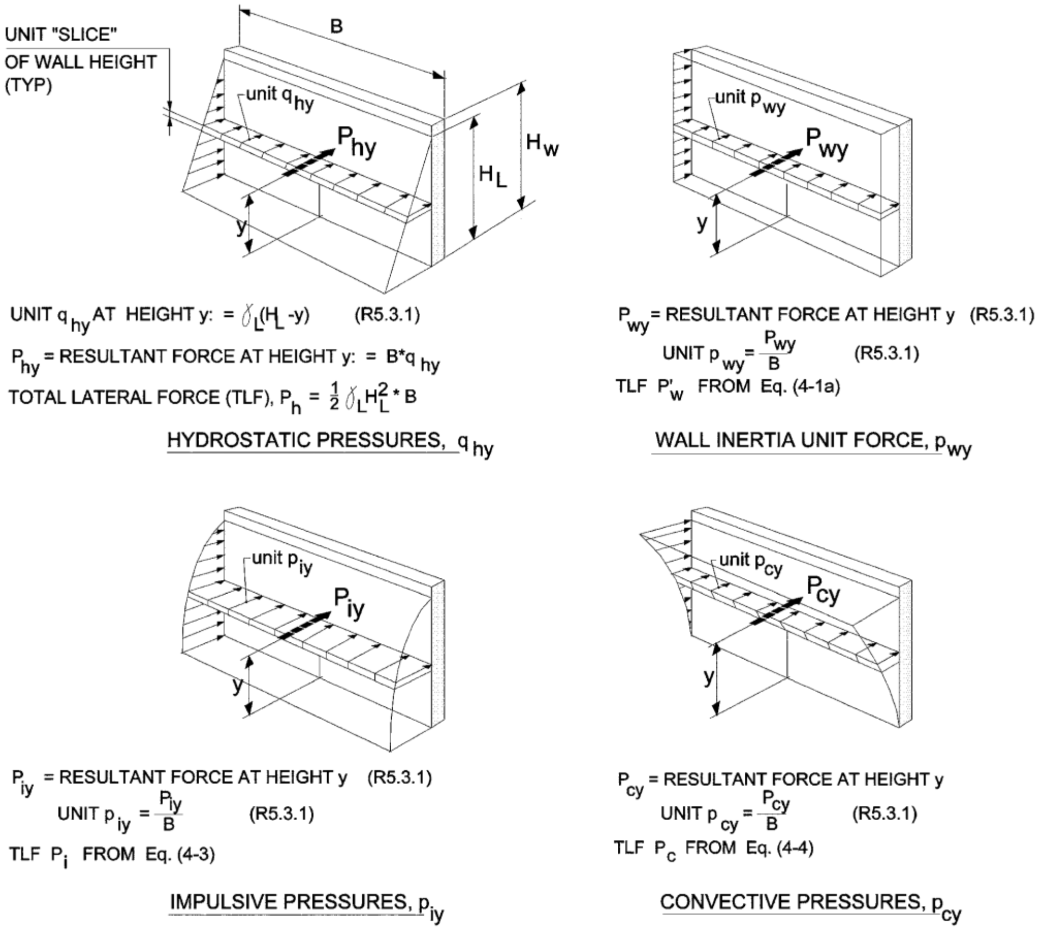


Table 3 – Summary of Recommended Interface Friction Parameters[1]

Interface	*Coefficient, μ*	*Adhesion, c_a (ksf)*
Concrete - Mudmat	0.6	0
Mudmat – C33 sand	0.58	0
C33 sand – Structural fill	0.58	0
Mudmat – Soil Type IIC	0.21	1.2
HDPE - C33 sand	0.52	0

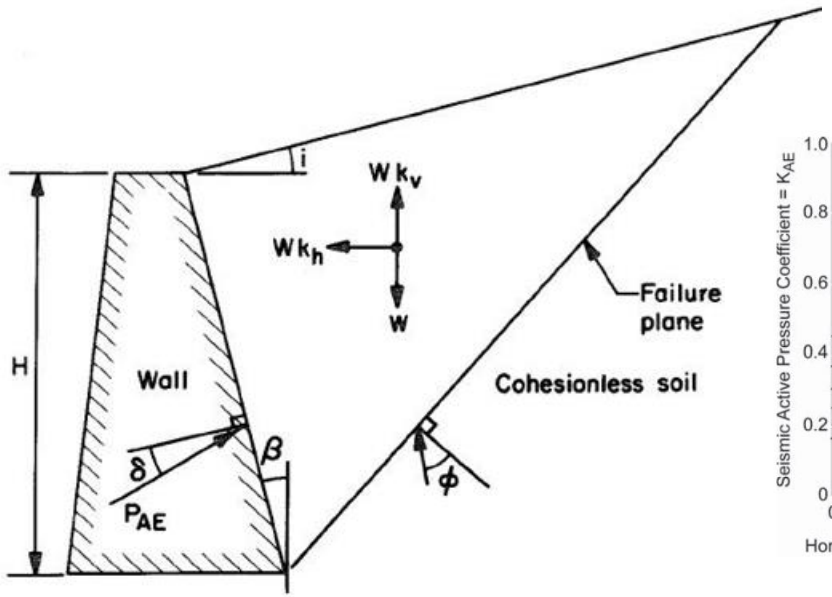
Note: 1 Sliding resistance = Vertical load * μ + c_a * area of contact

Hydrodynamic Pressures (ACI 350)

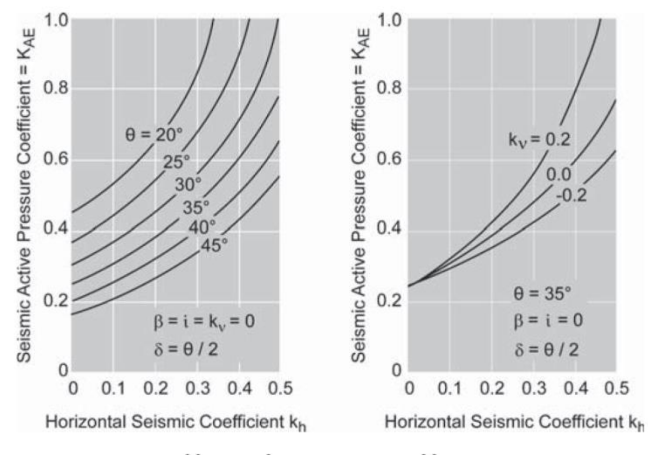


$$V = \sqrt{(P_i + P_w + P_r)^2 + P_c^2 + P_{eg}^2} \qquad (4\text{-}5)$$

Seismic Active and At-Rest Lateral Earth Pressure



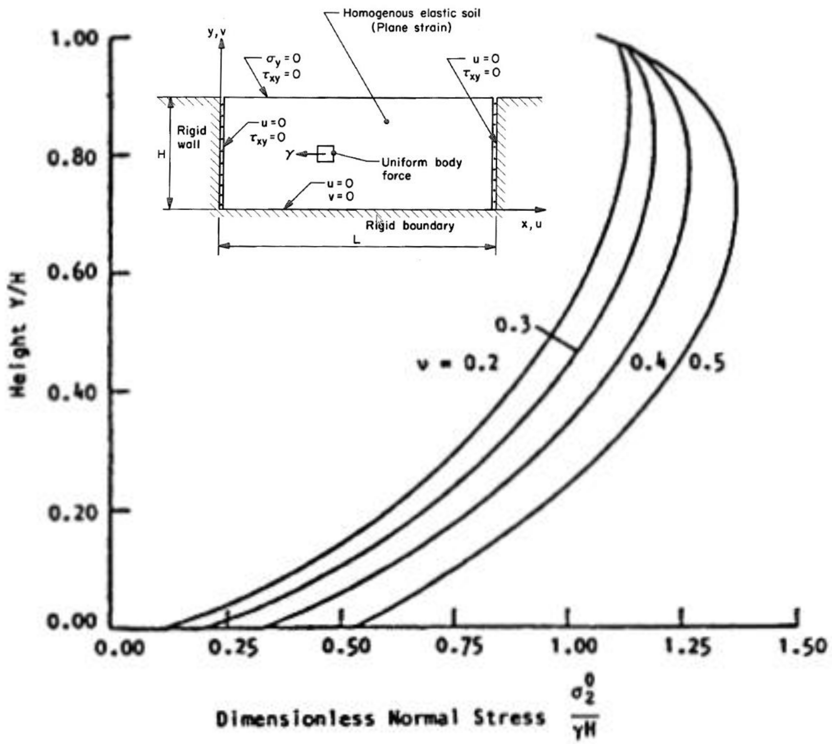
NCHRP 611



$$K_{AE} = \frac{cos^2(\phi - \theta - \beta)}{\cos\theta \cos^2\boldsymbol{\beta} \cos(\beta + \theta + \delta)\left[1 + \sqrt{\frac{\sin(\phi + \delta)\sin(\phi - \theta - i)}{\cos(\beta + \theta + \delta) * \cos(i - \beta)}}\right]^{\mathbf{2}}} \qquad \boldsymbol{\theta} = \tan^{-1}\frac{k_h}{1 - k_v}$$

$P_{AE} = 0.5 \cdot \gamma \cdot H^2 \cdot (K_A + \Delta K_{AE})$ $p_{AD} = \Delta K_{AE} \cdot \gamma \cdot (H\text{-}z)$ $\Delta K_{AE} \sim 0.75 k_h$ $p_{0D} = 2 \cdot \Delta K_{AE} \cdot \gamma \cdot (H\text{-}z)$

Dynamic Soil Pressures ASCE 4-98 (Wood 1973)

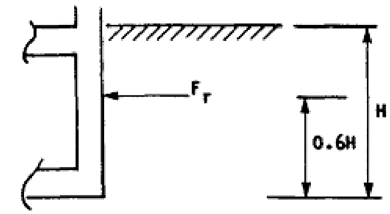


Explanation

H	=	embedment height
Y	=	distance from base of retaining structure
γ	=	soil unit weight
υ	=	Poisson's ratio
σ_2^o	=	lateral dynamic soil pressure against the retaining structure for 1.0g horizontal earthquake acceleration

$F_r = \alpha_h C_\upsilon \gamma H^2$

$M_r = \alpha_h D_\upsilon \gamma H^3$



F_r	=	resultant force associated with dynamic soil pressure distribution shown in Fig. 3.5-1
M_r	=	resultant overturning moment about base of retaining structure for pressure distribution in Fig. 3.5-1
α_h	=	horizontal earthquake acceleration (g)
γ	=	soil unit weight
H	=	embedment height
υ	=	Poisson's ratio
C_υ, D_υ	=	coefficients as a function of Poisson's ratio

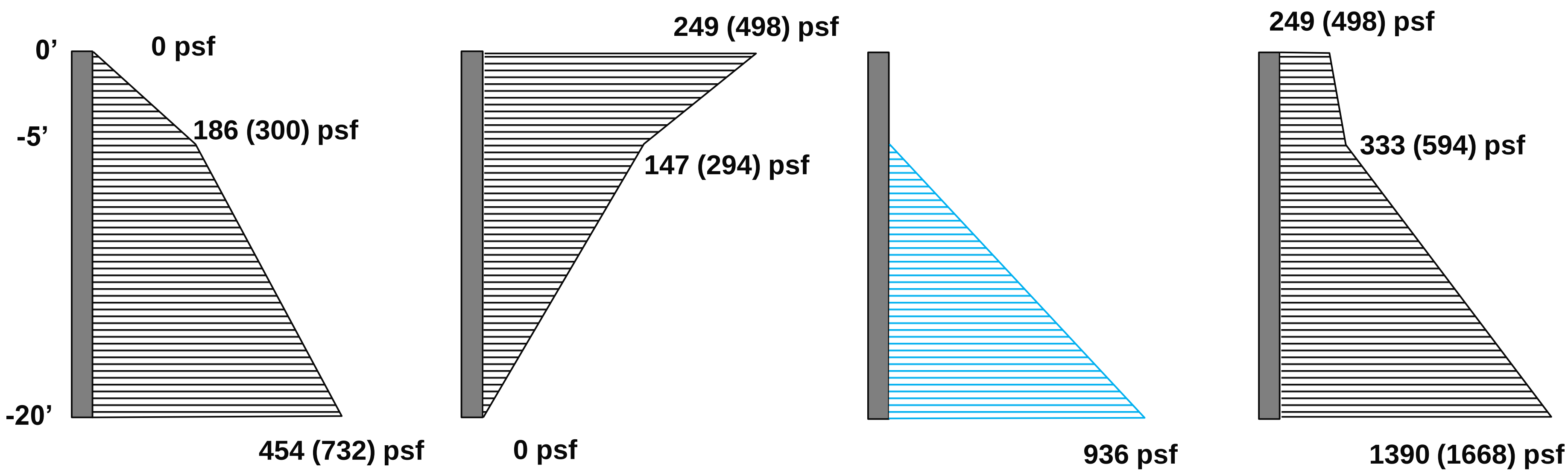
υ	C_υ	D_υ
0.5	1.13	0.67
0.4	1.04	0.63
0.3	0.94	0.56
0.2	0.87	0.52

Soil Pressures Sample Calculation

H = 20 ft.
$\theta = \tan^{-1}(0.25) = 14^o$
K_{AE} = = 0.48
$K_A = 0.31$
$\Delta K_{AE} = 0.48 - 0.31 = 0.17$
$\Delta K_{AE} \sim 3/4 \cdot 0.25 = 0.1875$, use 0.17
$\gamma_{moist} = 120$ pcf
$\gamma_{sub} = 120 - 62.4 = 57.6$ pcf

$K_{0S} = 1 - \sin(32^o) = 0.47$, use $K_{0S} = 0.5$
$\Delta K_{0E} = 2\Delta K_{AE} = 2 \cdot 0.17 = 0.34$

$\phi = 32^0$
$\gamma = 120$ pcf
$K_h = 0.25$



Static Earth Pressure | Seismic Earth Pressure | Hydrostatic Pressure | Total Pressure

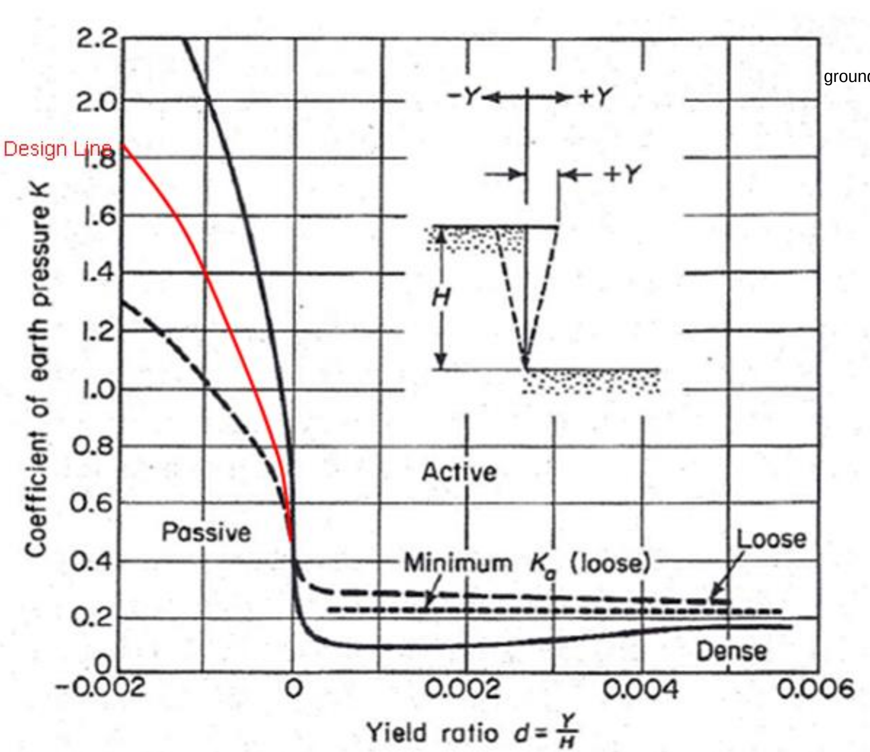
Ground Water Considerations

if the backfill is well drained, seismic ground water pressures need not be considered. In this case, only hydrostatic pressures are taken into consideration:

$$p_W = \gamma_W \cdot z$$

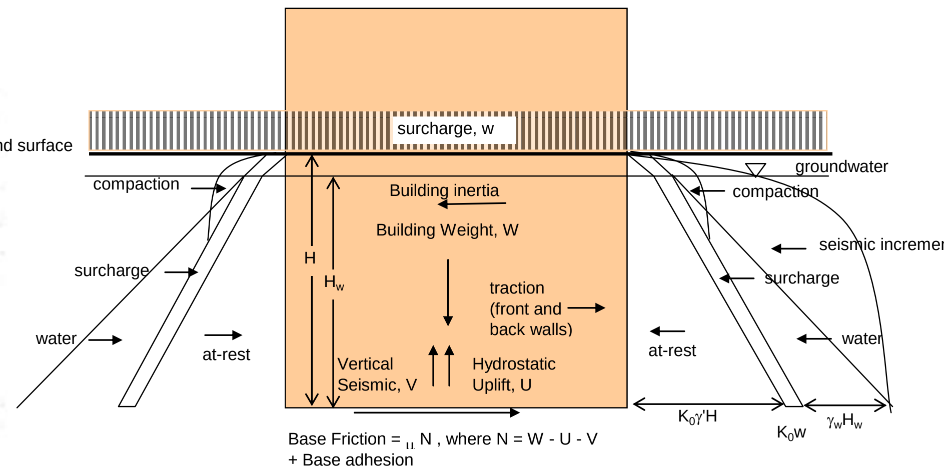
Whitman, RV (1990) suggests that the seismic ground water thrust exceeds 35% of the hydrostatic thrust for k_h>0.3g.

Influence of Wall Movement on Intensity of Earth Pressures in Cohesionless Materials

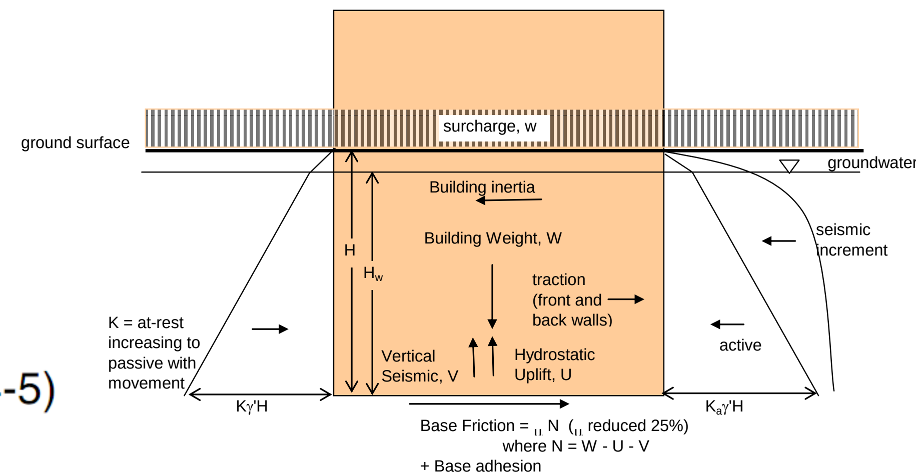


$$V = \sqrt{(P_i + P_w + P_r)^2 + P_c^2 + P_{eg}^2} \qquad (4\text{-}5)$$

SEISMIC - NO MOVEMENT

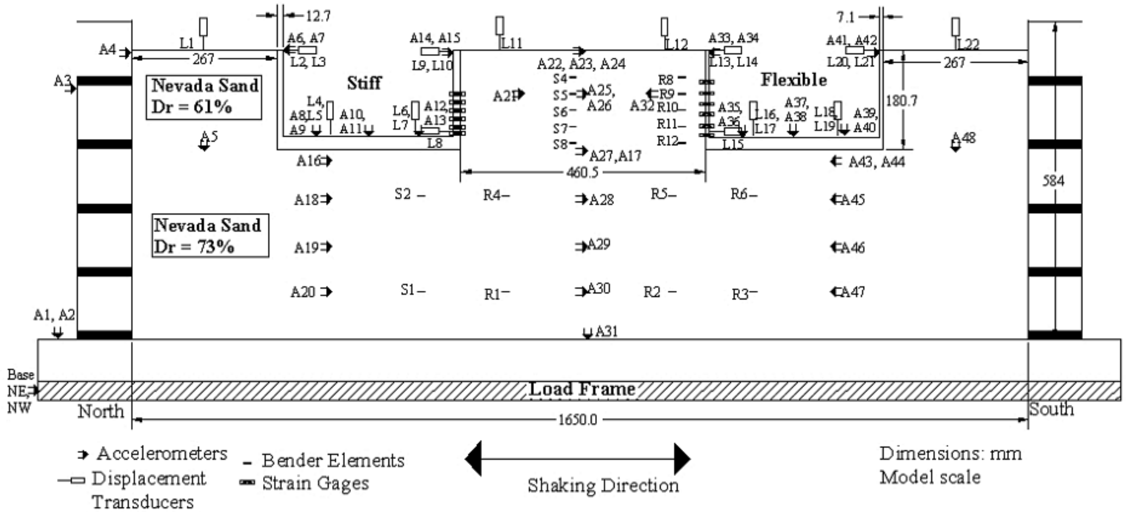


SEISMIC - WITH MOVEMENT

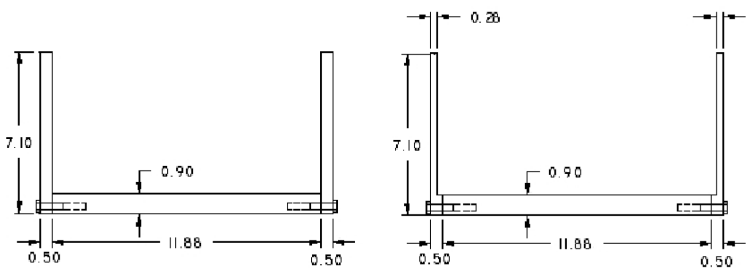


Experimental Results

Recent Experimental Studies (PEER 2007/06)



Centrifuge model configuration

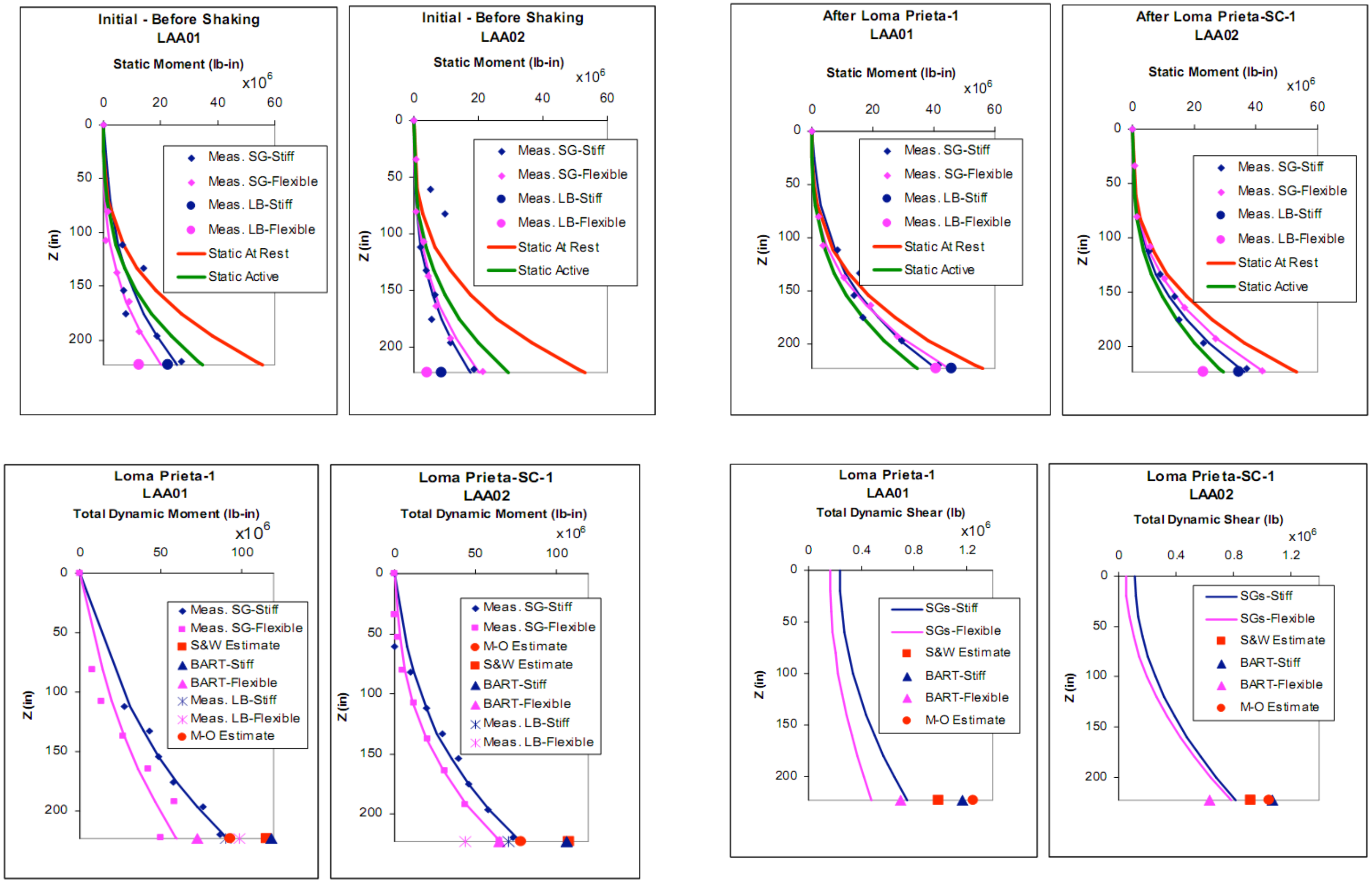


Stiff and flexible model structures configuration

	Stiff	Flexible
Stem Height (ft)	18.6	18.6
Stem Thickness (ft)	1.5	0.84
Stem Stiffness (lb-in.^{2} per ft width)	5.83E+10	1.02E+10
Base Width (ft)	35.64	36.96
Base Thickness (ft)	2.7	2.7
Base Stiffness (lb-in.^{2} per ft width)	3.40E+11	3.40E+11
Estimated Natural Period (sec)	0.23	0.49

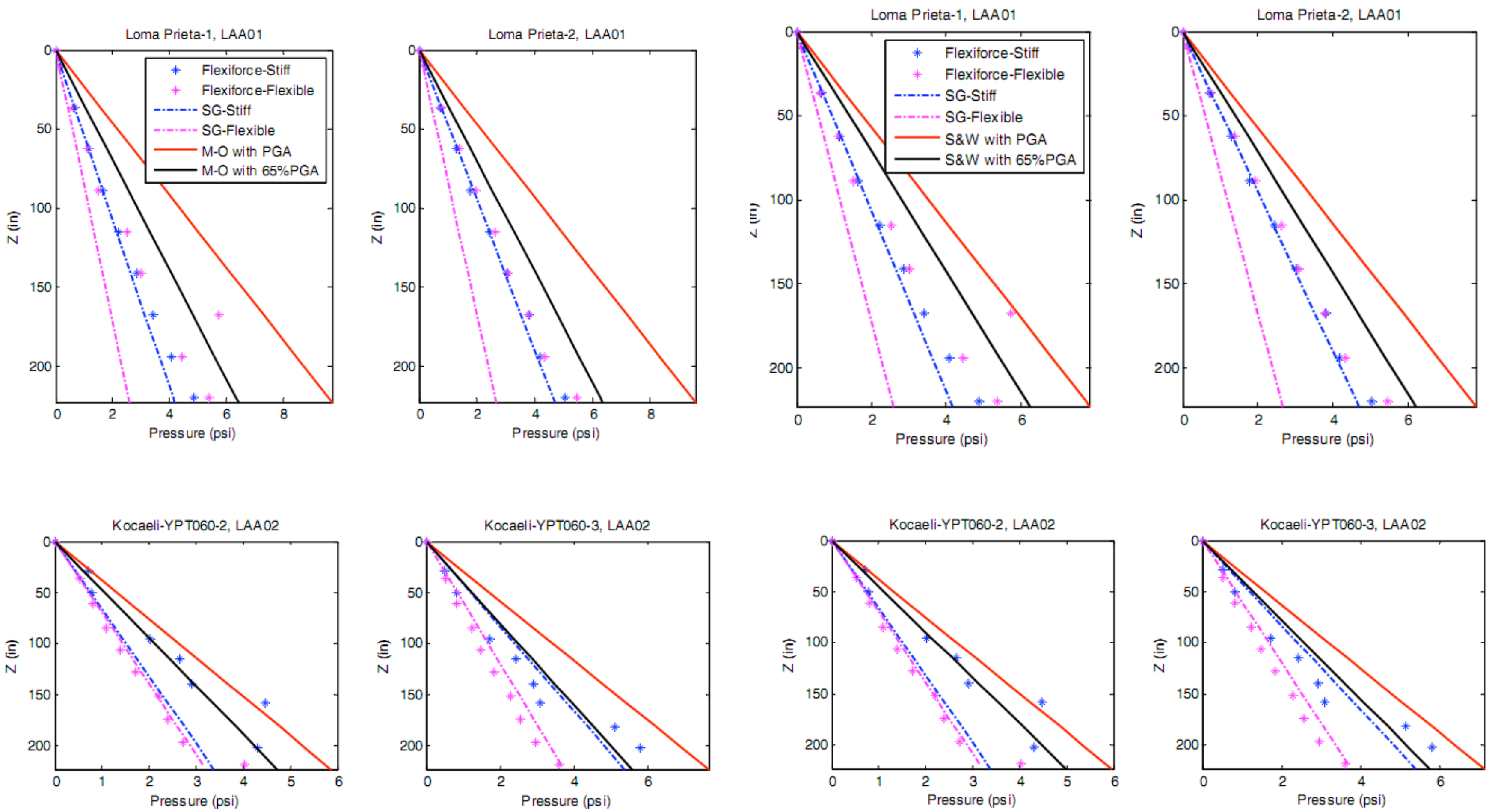
L. Atik and N. Sitar (2007)

Representative Experimental Results



L. Atik and N. Sitar (2007)

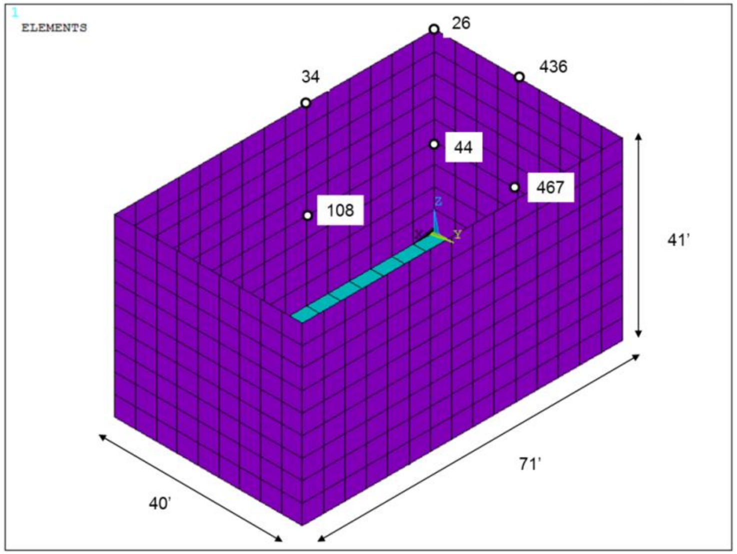
Maximum total dynamic pressure distributions measured and estimated

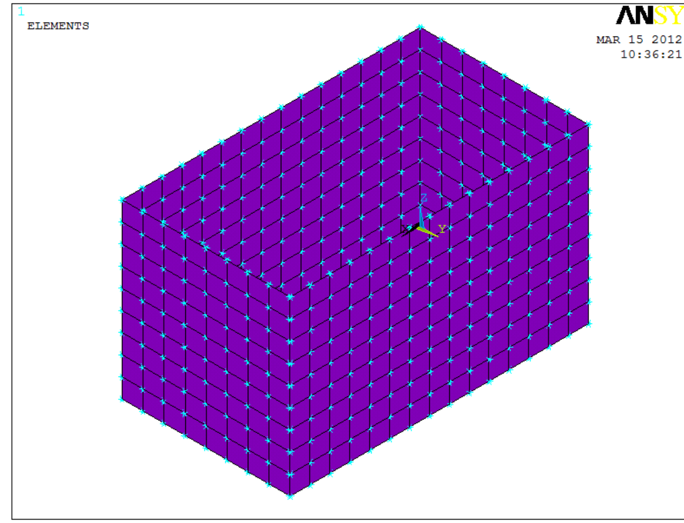


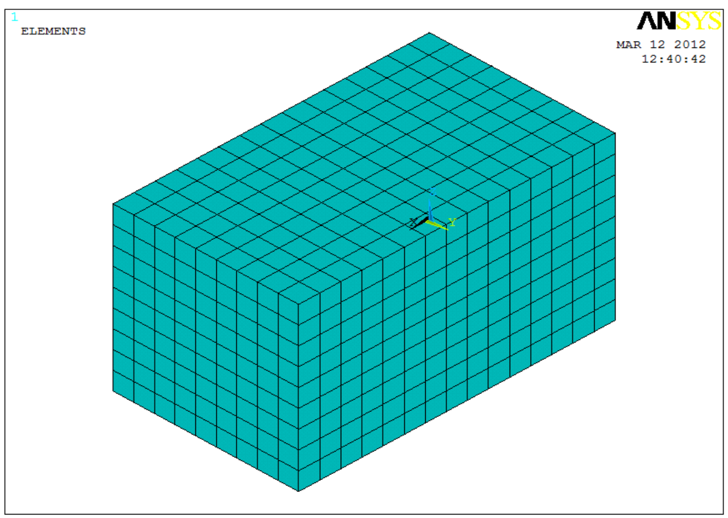
L. Atik and N. Sitar (2007)

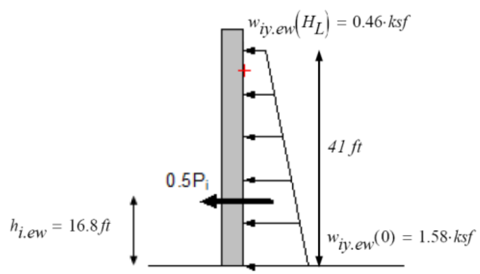
Detailed Seismic Fluid Soil Structure Interaction

Fluid Structure Interaction

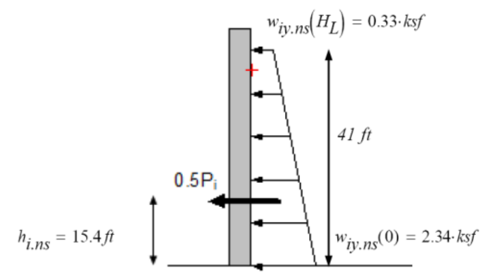








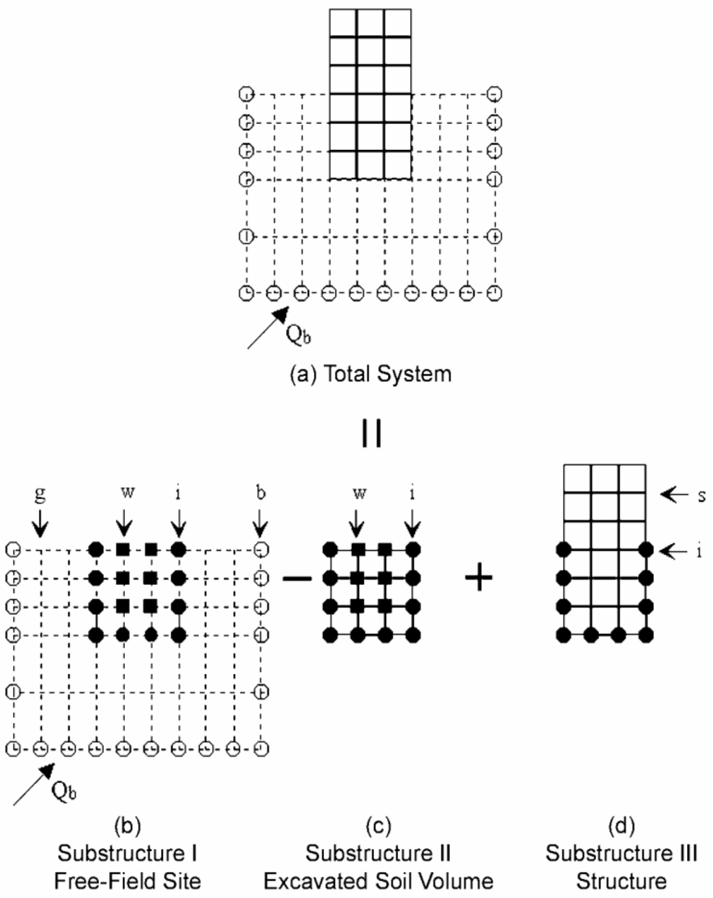
(a) Impulsive weight acting on NS walls



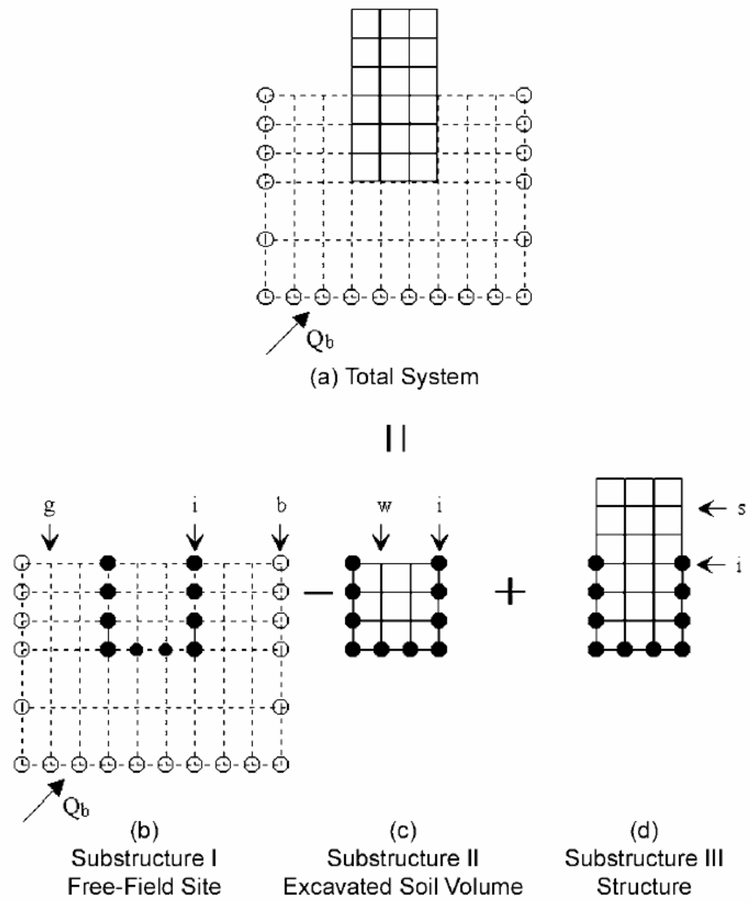
(b) Impulsive weight acting on EW walls

Seismic Soil Structure Interaction

Substructuring in the Flexible Volume Method



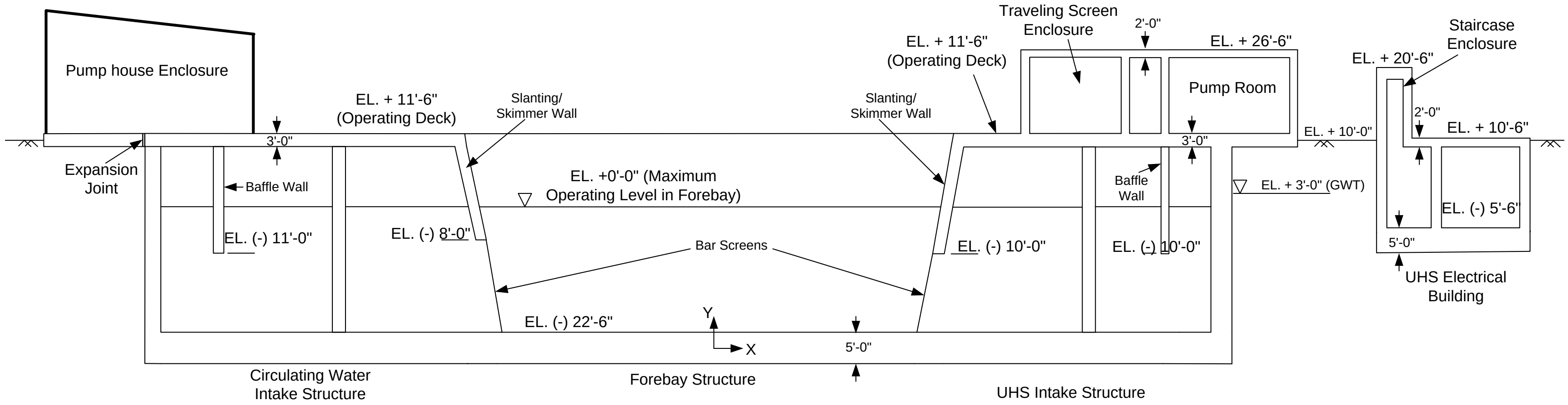
Substructuring in the Substructure Subtraction Method

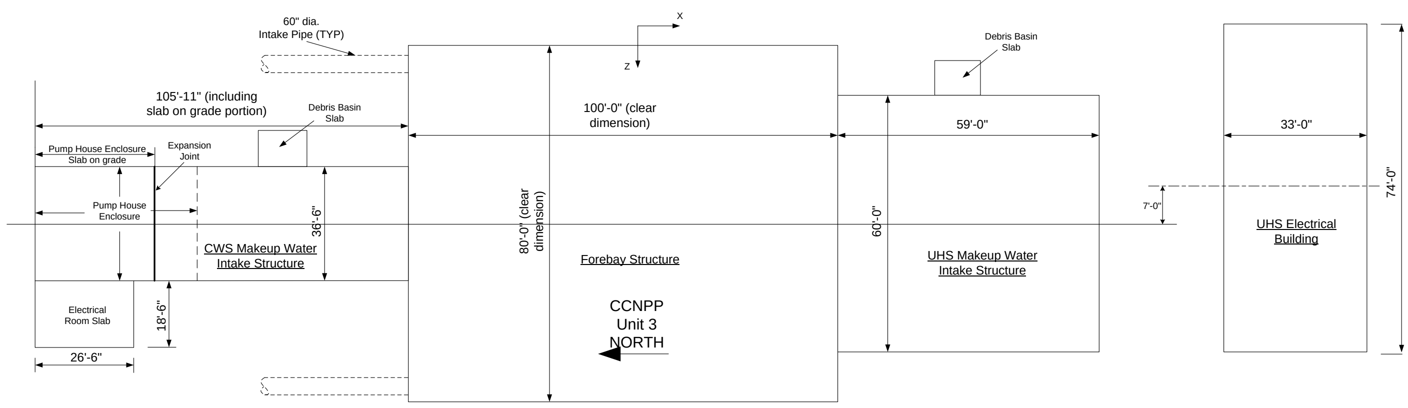


(SASSI2010 Theory Manual)

Case Study: Intake Pump Station

Structure Geometry





Overall Analysis/Design Approach

- The finite element model of the structures is developed using GT STRUDL Version 29.1.
- Lumped Mass is used to model the Hydrodynamic Load.
- The SSI analysis is performed using Site-Specific Input Ground Motion and three soil cases (UB, BE and LB).
- The FE model used for the SSI analysis is modified to obtain the static response of the structure, using GT STRUDL.
- Only **critical** panels are designed. Microsoft Excel Workbook is used to combine element forces and moments from static and SSI analyses, for these critical panels.

Finite Element Model, Showing Critical Panels

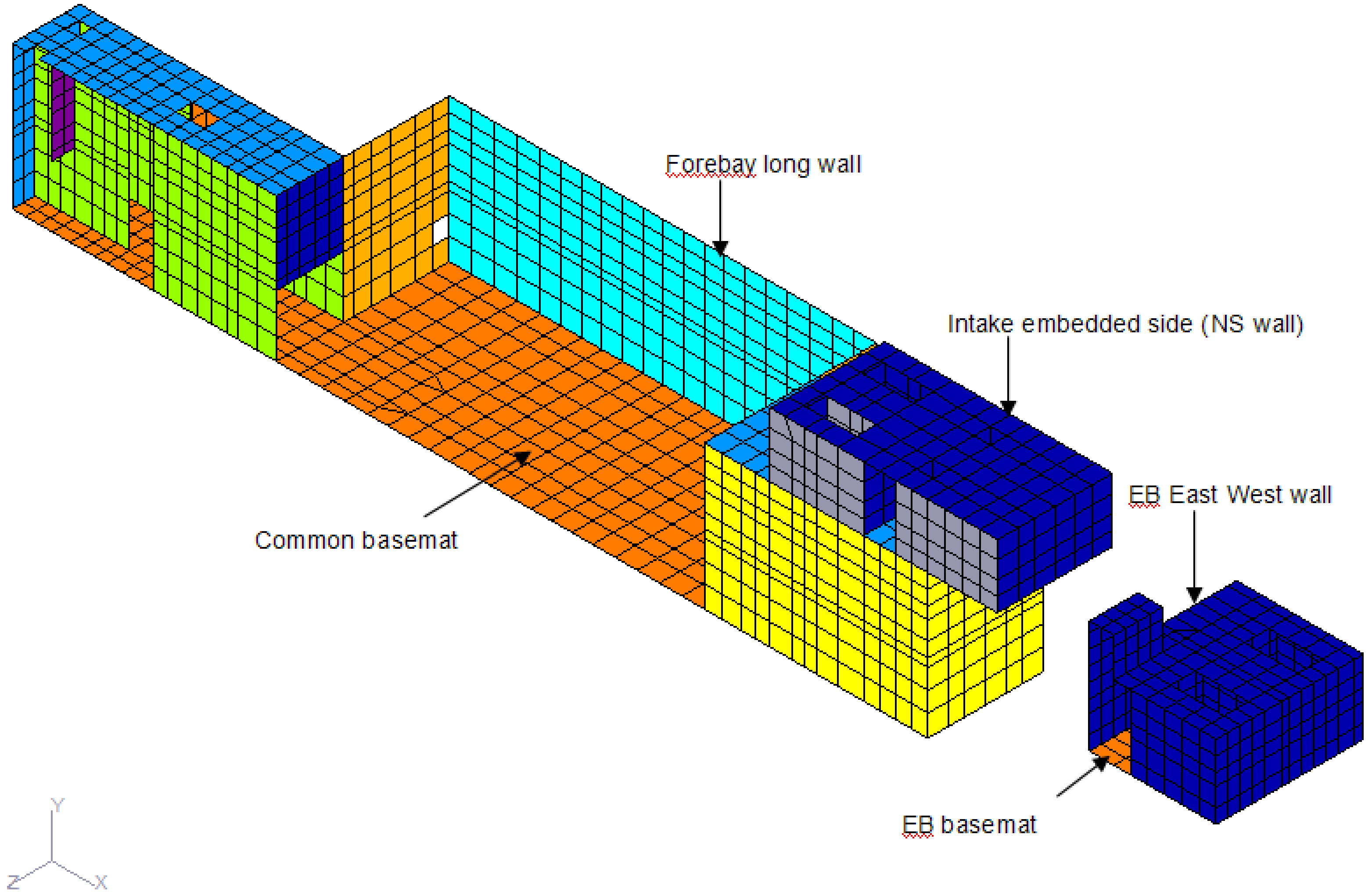
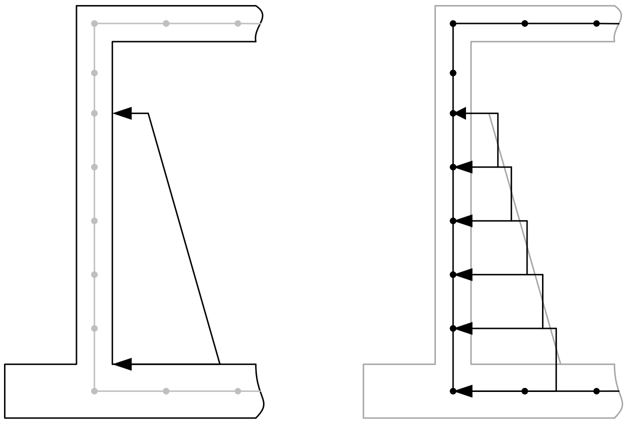


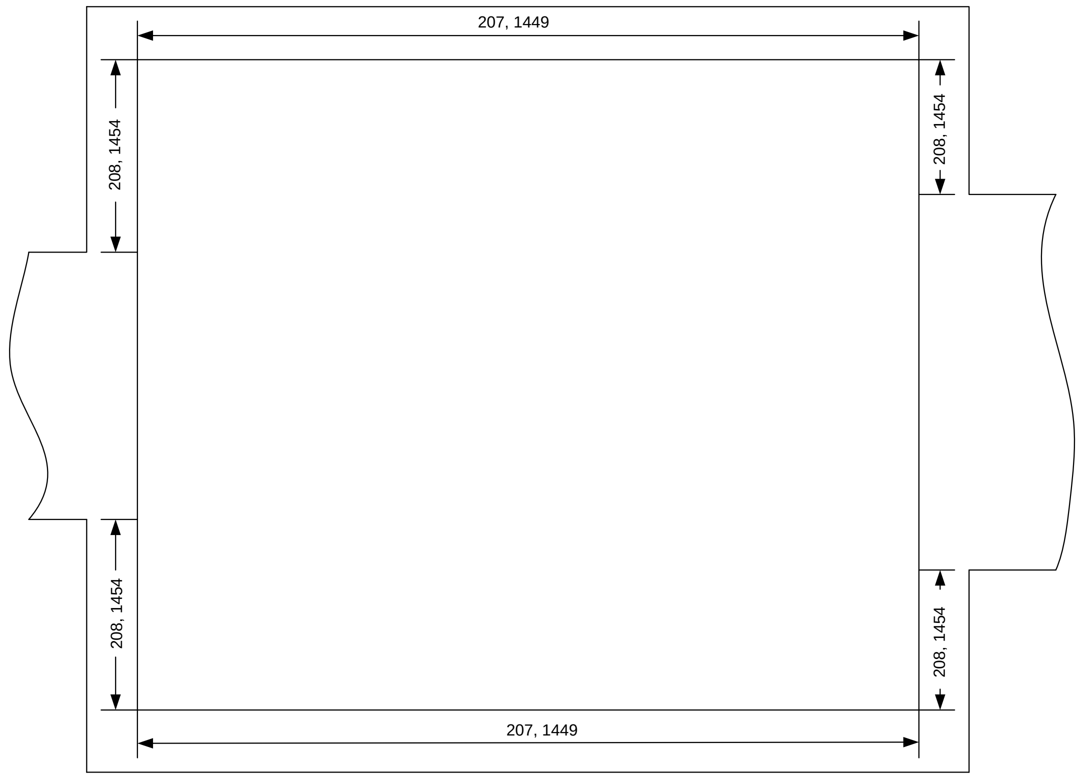
Figure 3: Critical walls and slab selected for design in this calculation.

Hydrodynamic loads



(a) Actual distribution

(b) Idealized distribution



Equivalent weights of accelerating liquid

$$W_{i.ew} := \left(\frac{\tanh\left(0.866 \cdot \frac{L_{ew}}{H_L}\right)}{0.866 \cdot \frac{L_{ew}}{H_L}} \right) \cdot W_L$$

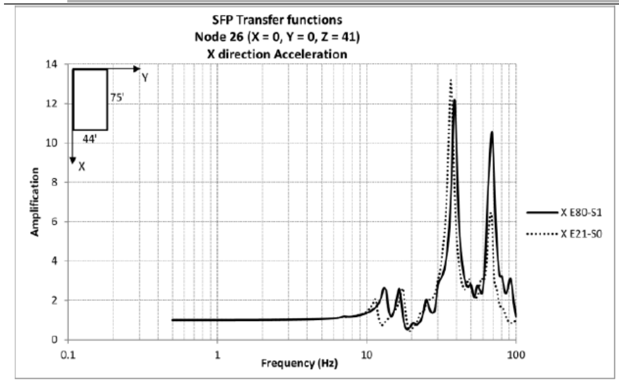
Impulsive Weight Distributions

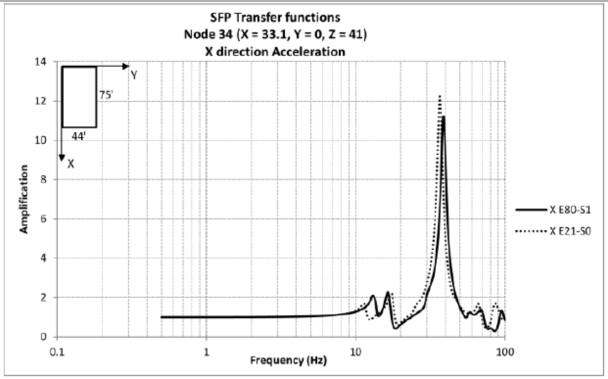
$$W_{iy.ew}(y) := \frac{W_{i.ew}}{2} \cdot \frac{\left(4H_L - 6 \cdot h_{i.ew}\right) - \left(6 \cdot H_L - 12 \cdot h_{i.ew}\right) \cdot \left(\frac{y}{H_L}\right)}{H_L^{\ 2}}$$

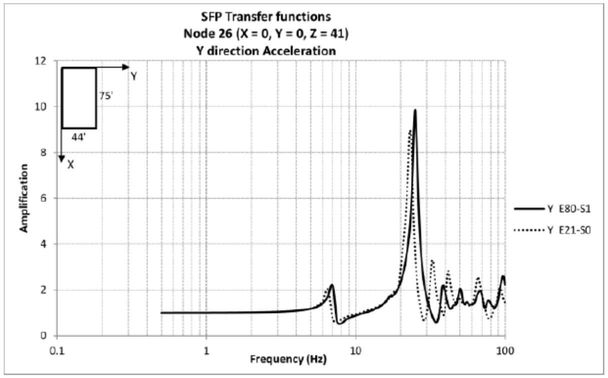
Height to centers of gravity EBP

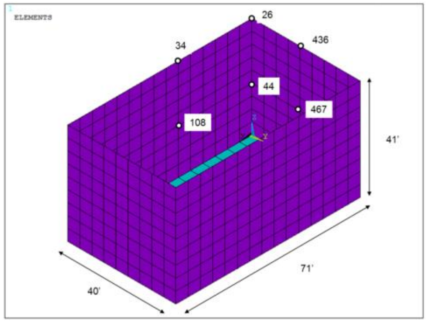
$$h_{i.ew} := \begin{cases} \left(0.5 - 0.09375 \cdot \frac{L_{ew}}{H_L}\right) \cdot H_L & \text{if } \frac{L_{ew}}{H_L} < 1.333 \\ \left[(0.375) \cdot H_L\right] & \text{otherwise} \end{cases}$$

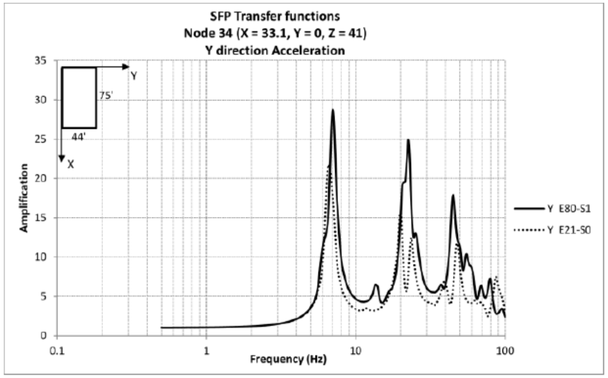
Comparison of Acceleration Transfer Functions

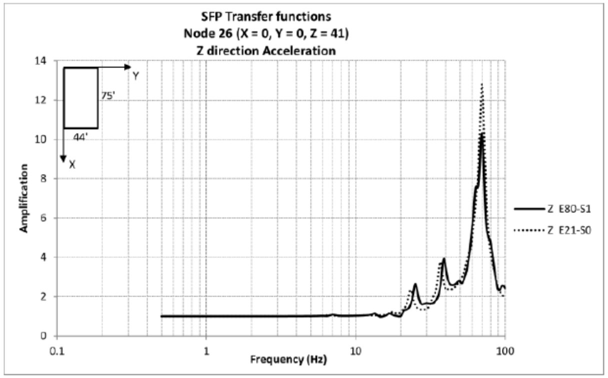


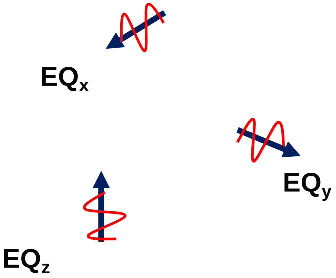


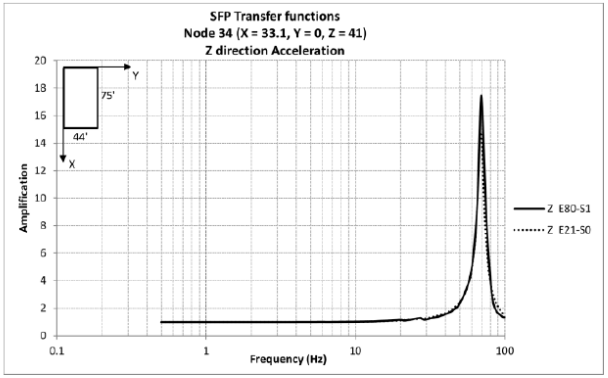




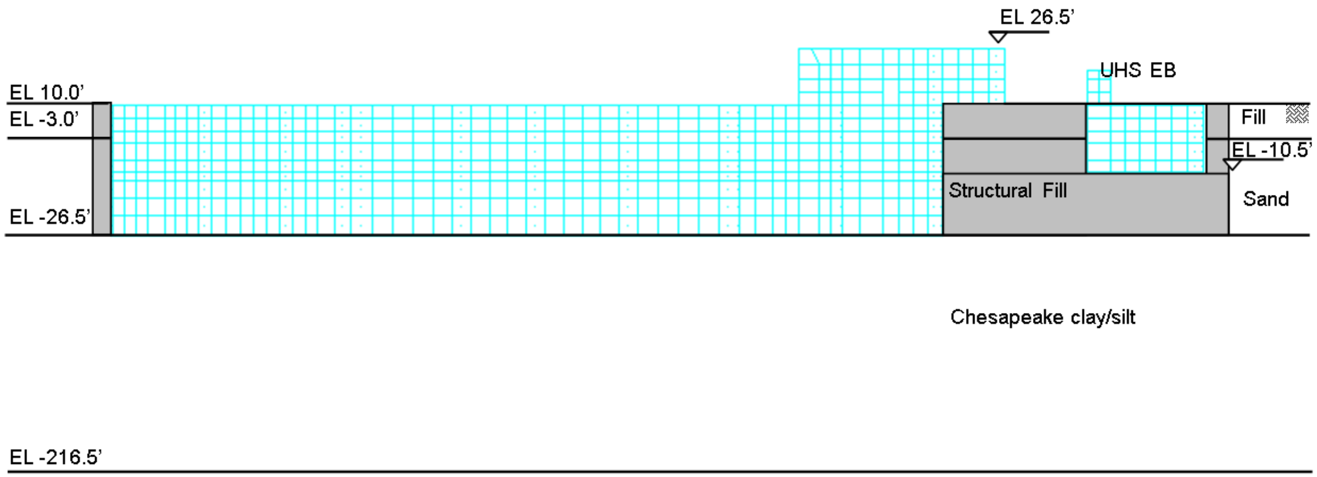


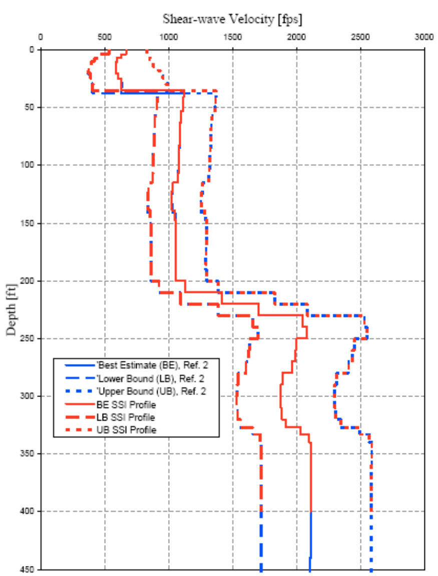


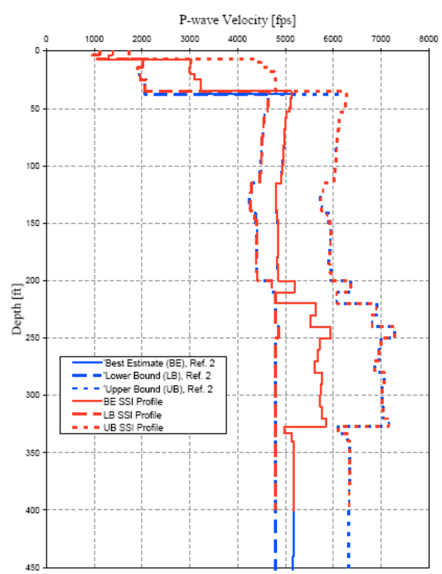


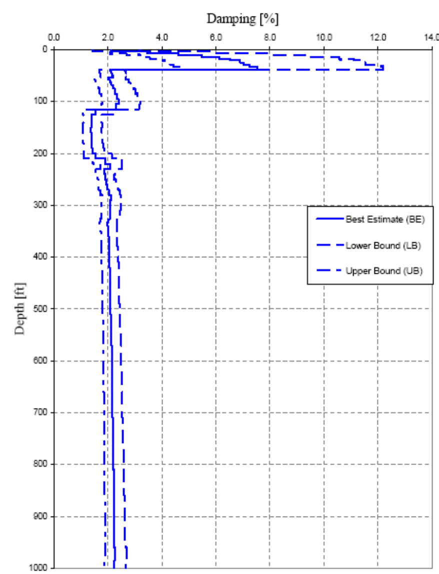


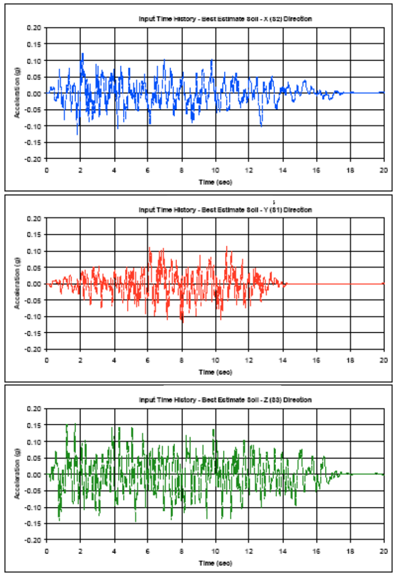
SSI Model


EL 26.5'
UHS EB
EL 10.0'
EL -3.0'
Fill
EL -10.5'
Structural Fill
Sand
EL -26.5'
Chesapeake clay/silt
EL -216.5'

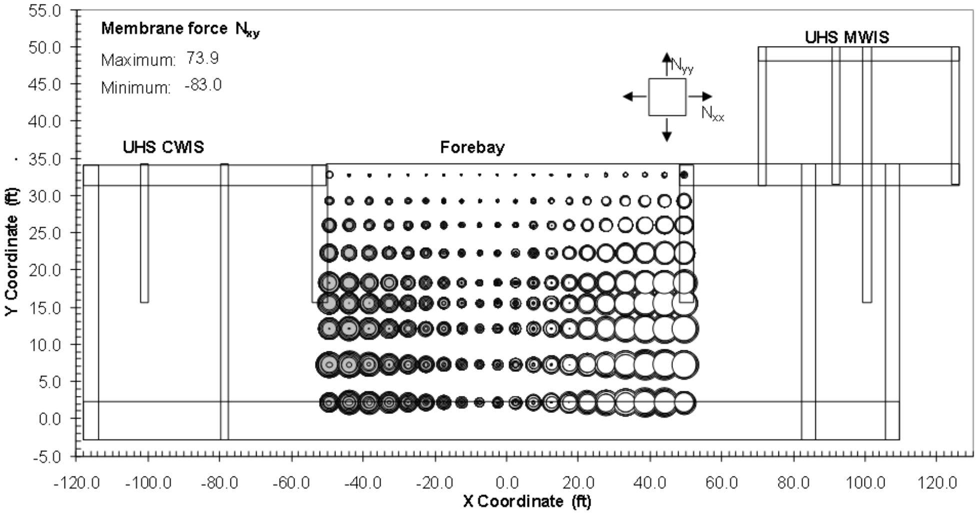

Shear-wave Velocity [fps]
Depth [ft]
Best Estimate (BE), Ref. 2
Lower Bound (LB), Ref. 2
Upper Bound (UB), Ref. 2
BE SSI Profile
LB SSI Profile
UB SSI Profile

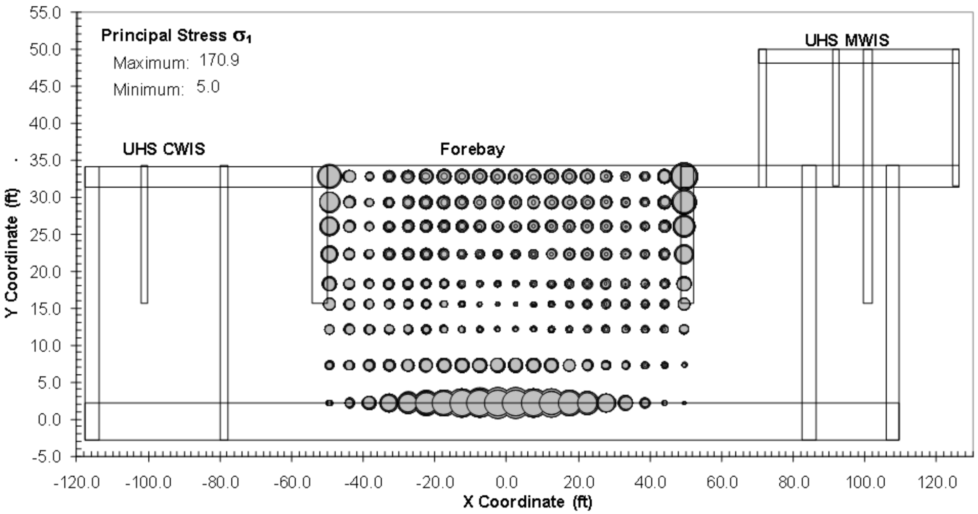

P-wave Velocity [fps]
Depth [ft]
Best Estimate (BE), Ref. 2
Lower Bound (LB), Ref. 2
Upper Bound (UB), Ref. 2
BE SSI Profile
LB SSI Profile
UB SSI Profile


Damping [%]
Depth [ft]
Best Estimate (BE)
Lower Bound (LB)
Upper Bound (UB)



Sample Results





Design of Walls and Slabs

Forces and moments computed after combination of seismic and static results are used for the design of each critical panel, using a Microsoft Excel Workbook, as outlined next and described in detail later.

a. Design for In-plane shear using full section cuts.

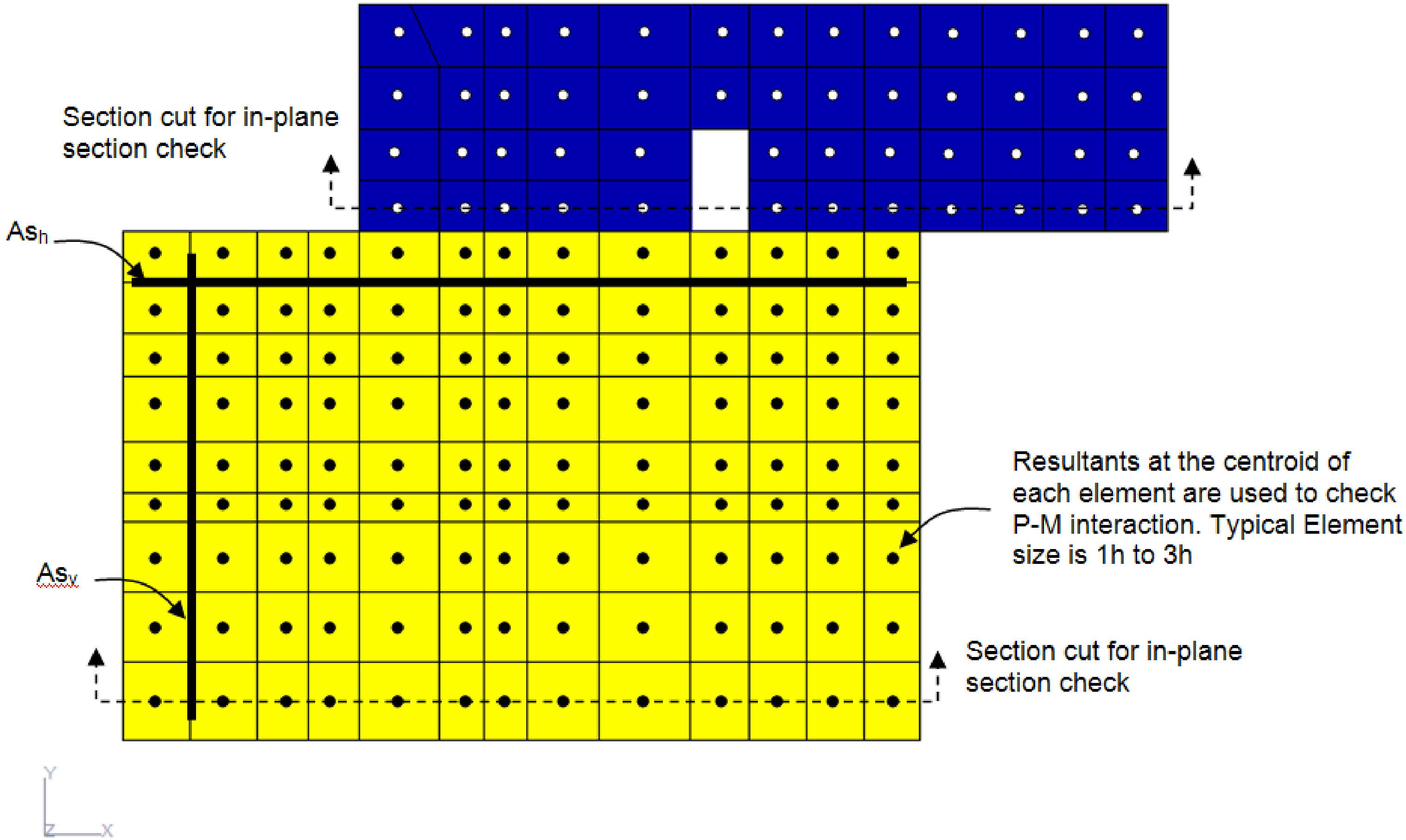
b. Design vertical and horizontal sections for out-of-plane moments and axial forces using a P-M interaction analysis.

c. Conservatively add the reinforcement from steps a and b

d. Check out-of-plane shear for the whole wall, or whole segments on either side of openings, based on average shear.

e. Check for punching shear where required.

Design of Walls and Slabs



Conclusions

Simplified and detailed approached for the dynamic analysis of embedded liquid containing structures where presented. Conclusions and recommendations are as follows:

Additional guidelines are required for the calculations of dynamic earth pressures. In particular regarding the use of active or at rest dynamic soil pressures.

Detailed soil structure interaction analyses can provide additional inside regarding the behavior of embedded liquid containing structures. However they are only warranted for critical structures.

Thank You!