Advanced Numerical Modeling of a Large Soil-box for Experiments in Soil-Structure-Interaction

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DOE – PEER workshop

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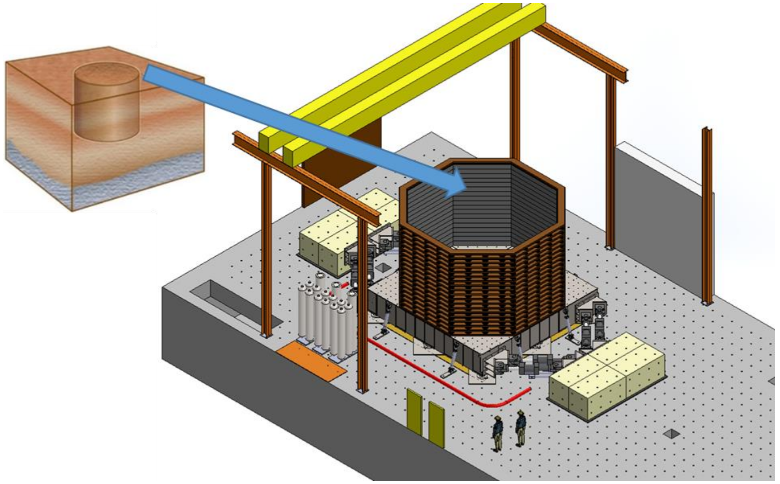
Numerical modeling for the design of LBSB

Conceptual drawing of soil-box and shake table system



3D conceptual drawing of the new shake table and the soil box (credit: Lawrence Berkeley National Lab & P. Laplace)

Performance of system

1. What are the required wall properties (mass, stiffness) in order to make the box "invisible" to the soil?
2. What is the most robust design for the box?
3. How is the box performance affected by the soil nonlinearity/level of shaking?
4. What is the effect of friction and gapping at the soil-wall interface?
5. What are the expected capabilities of the soil-box for SSI experiments?

Demand on components

1. What is base shear on table platen when box is at 2% strain (number and size hydraulic actuators)?
2. What are corresponding demands on actuator stroke and velocity?
3. What is the overturning moment and pressures at the bottom of the box (design of the platen and bearings of shake table)
4. What are forces, stresses, deformations in walls of box?

Overview of Numerical Models in Design Phase

- Conduct extensive numerical analyses and generate information that can be used in order to answer the key questions.

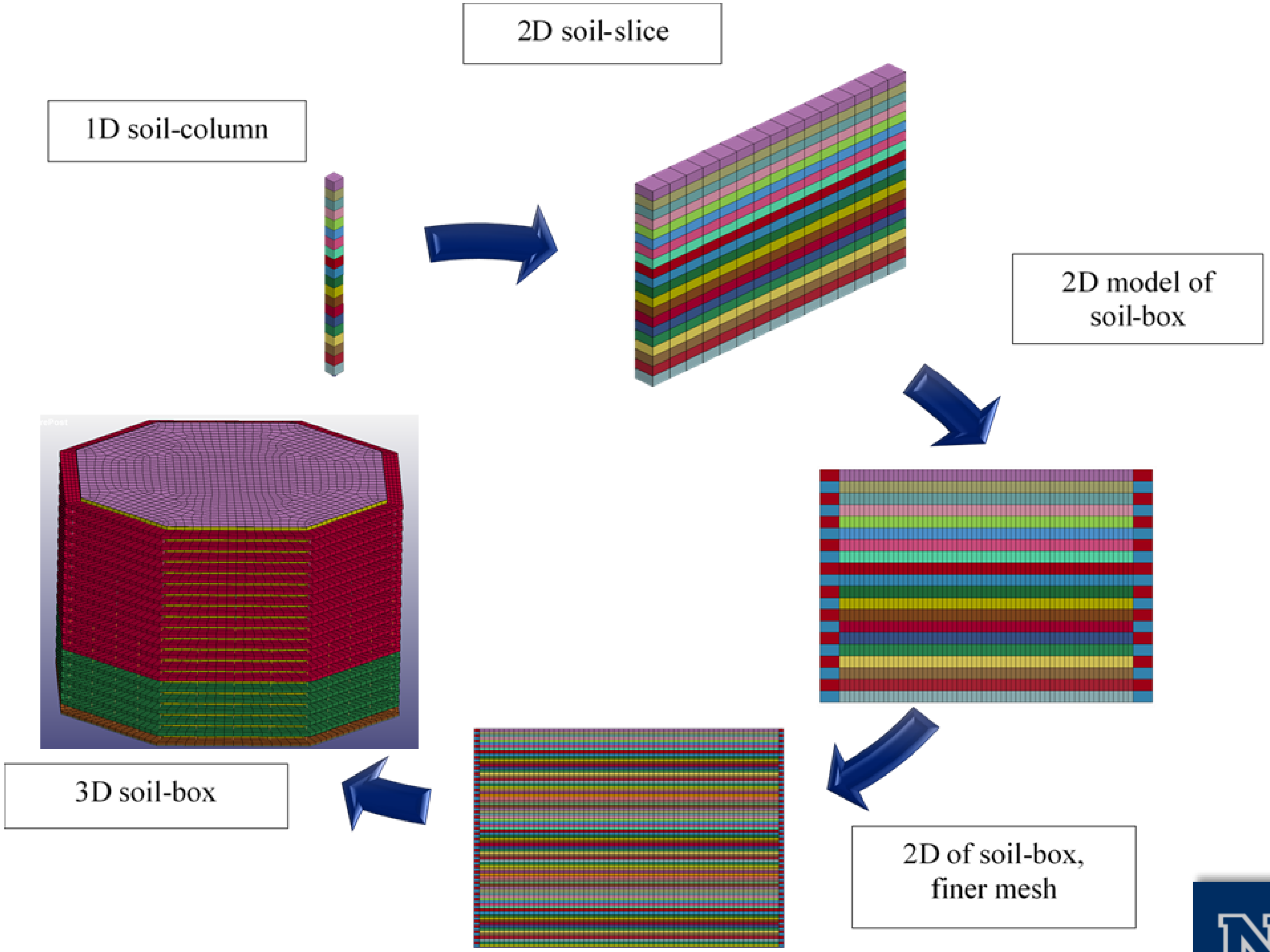
- Several models with increasing complexity were developed including:

  A. 1D soil column

  B. 2D soil-slice

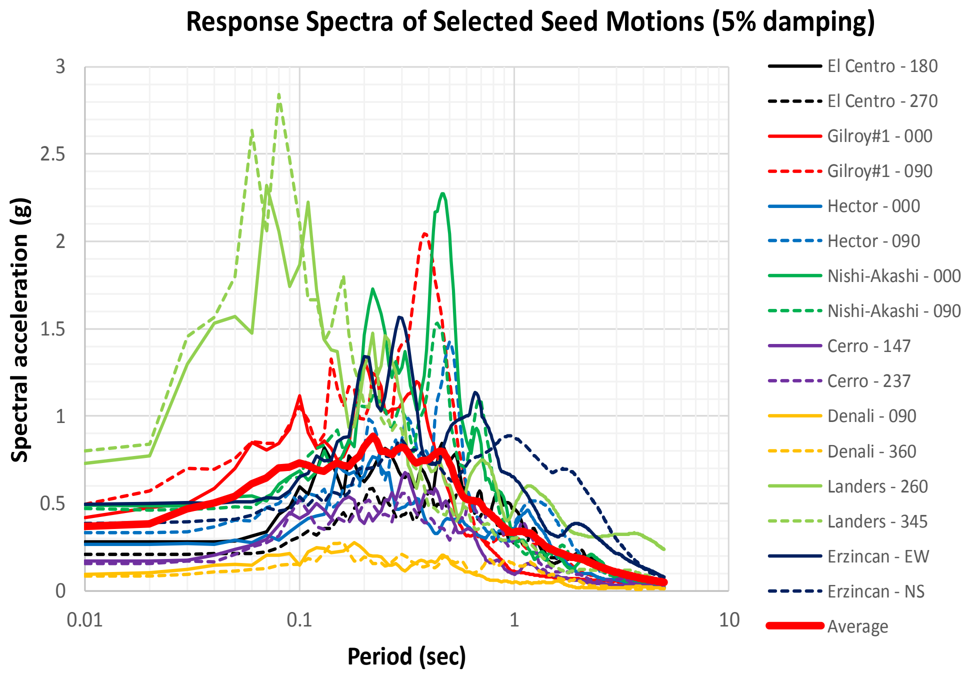
  C. 2D slice of box + soil

  D. 3D model of box + soil



Input motions

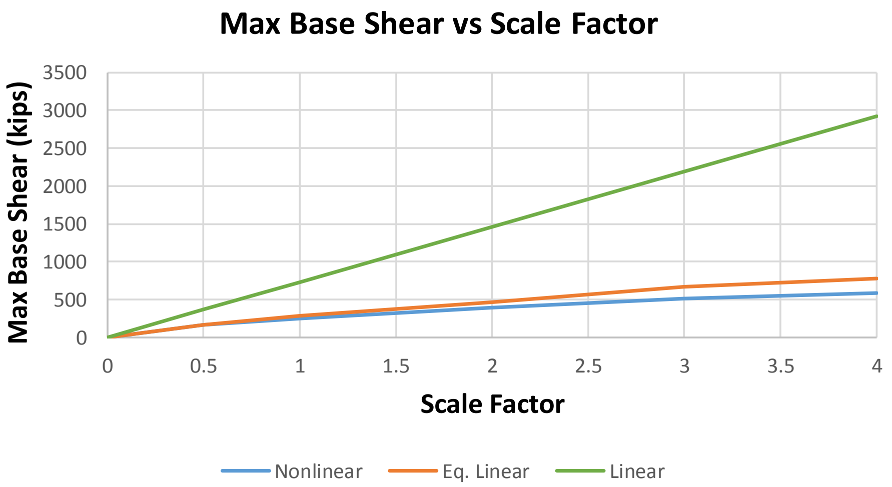
No.	Earthquake	Station	M	Site Vs30 (m/s)	Site Class
1	1940 Imperial Valley-02	El Centro Array #9	6.95	213	D
2	1989 Loma Prieta	Gilroy Array #1	6.9	1428	B
3	1995 Kobe	Nishi-Akashi	6.9	609	C
4	1999 Hector Mine	Hector	7.1	726	C
5	1979 Imperial Valley	Cerro Prieto	6.5	472	C
6	2002 Denali, Alaska	Carlo (temp)	7.9	399	C
7	1992 Landers	Lucerne	7.3	1369	B
8	1992 Erzincan	Erzincan	6.7	352	D

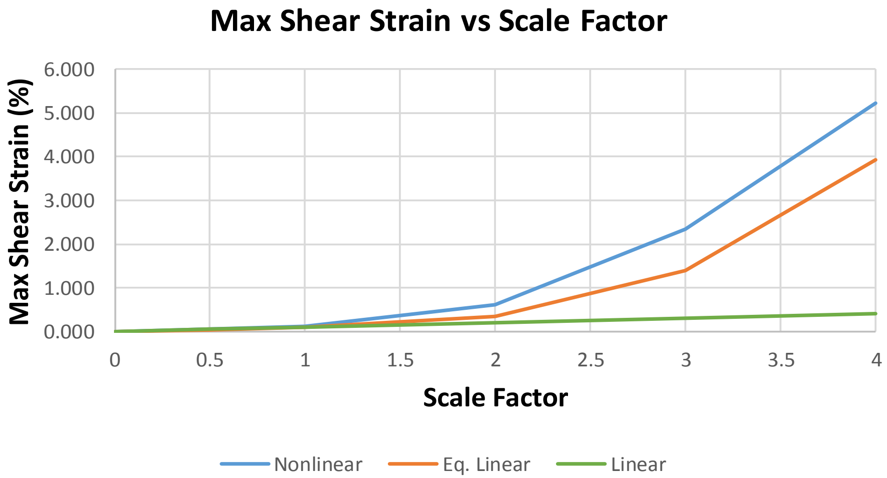


✓ Suite of 8, 2-component ground motions taken from PEER database, for sites with **similar seismogenic and geotechnic features** as found at sites of nuclear facilities, and scaled for PGA as follows:

Scale Factor	1.0	2.0	3.0	4.0
PGA	0.26g	0.52 g	0.78 g	1.04 g

1D models: Linear vs. Eq. linear vs. Nonlinear dynamic analyses

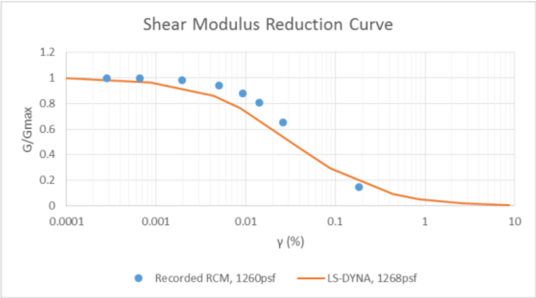


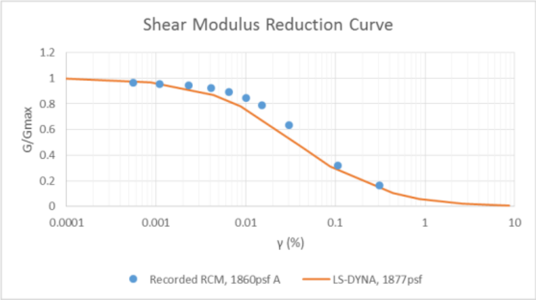


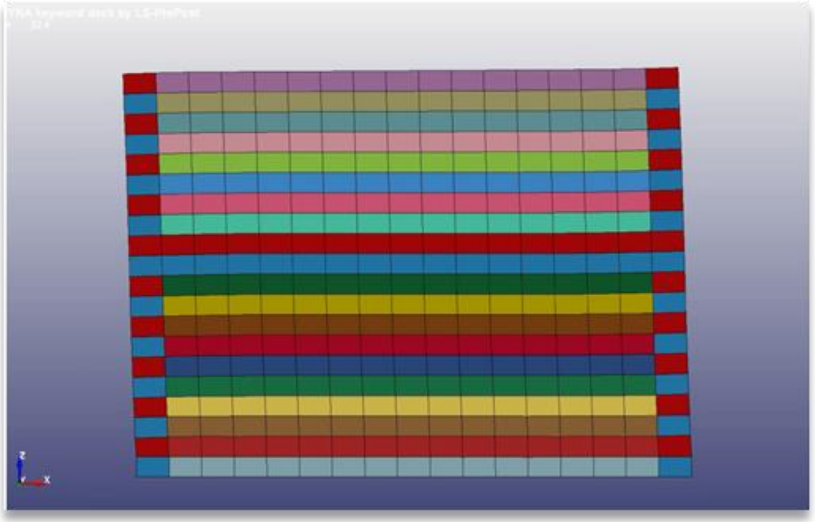
Dense Soil – El Centro 180 – Box 18ftx18ftx20ft						
	Nonlinear		Equivalent Linear		Linear	
Scale Factor	Max Shear Strain (%)	Max Base Shear (kips)	Max Shear Strain (%)	Max Base Shear (kips)	Max Shear Strain (%)	Max Base Shear (kips)
0	0.000	0	0.000	0	0.000	0
0.5	0.047	158	0.039	169	0.051	365
1	0.123	248	0.093	282	0.101	730
2	0.601	395	0.333	468	0.203	1460
3	2.331	513	1.401	671	0.304	2190
4	5.219	585	3.927	776	0.406	2920

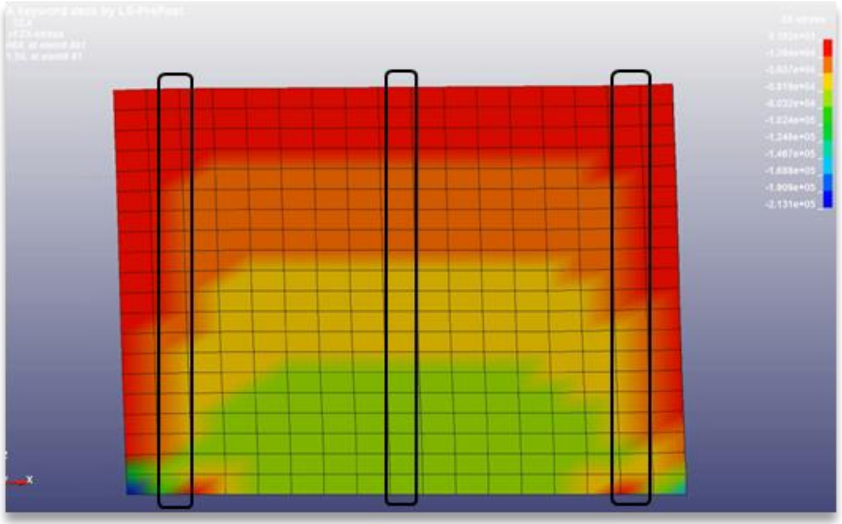
- Linear analyses provide an upper bound for forces and a lower bound for shear strains as expected. The opposite is true for nonlinear analyses.
- Equivalent linear analyses give similar base shears up to SF=2, but still they cannot accurately predict the soil strains. This means that **at large soil strains nonlinear analyses are required**

2D models: Combination of steel and rubber materials

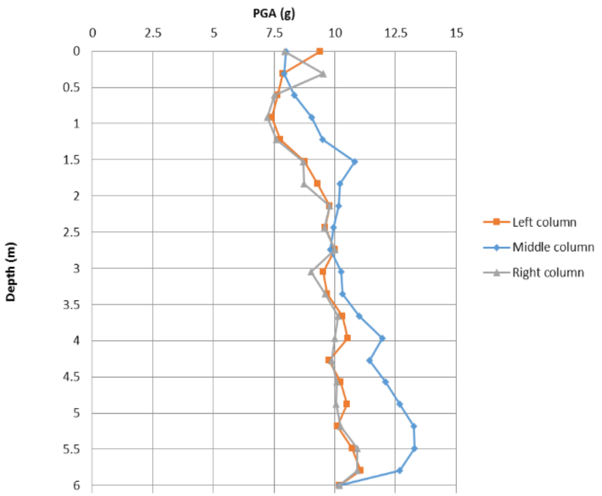


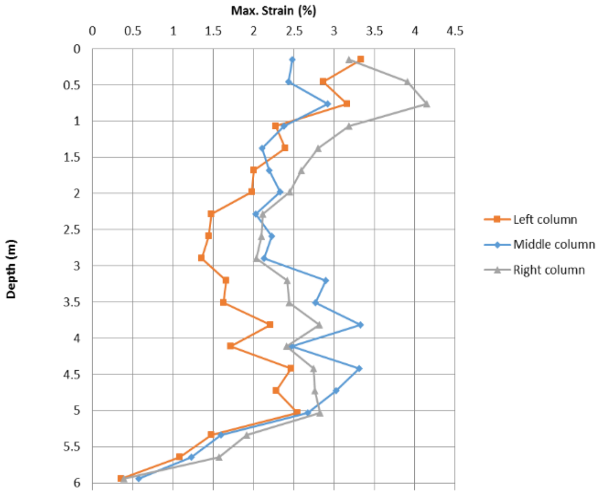






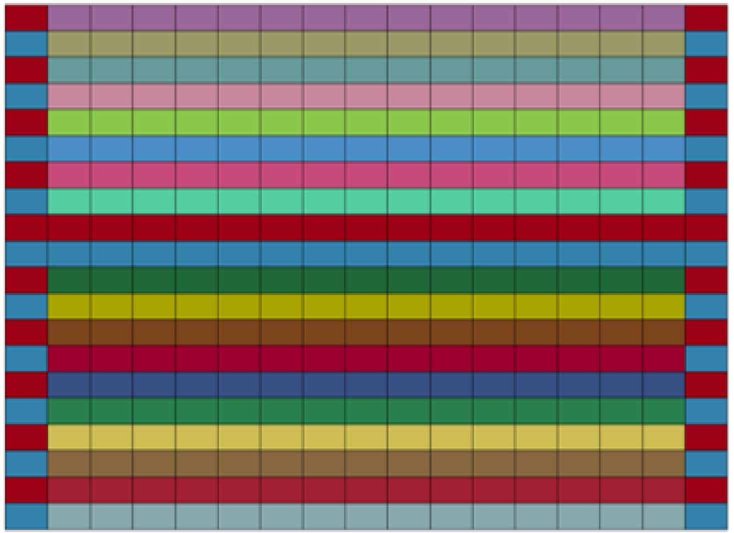
Snapshot of the deformations (left) and the shear stresses (right) of the 2D soil-box model at t=22.4sec

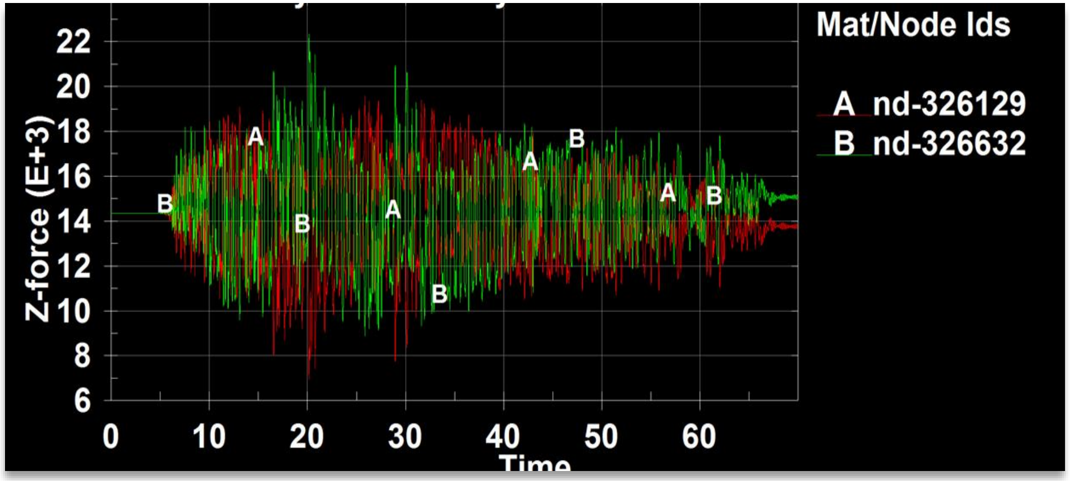


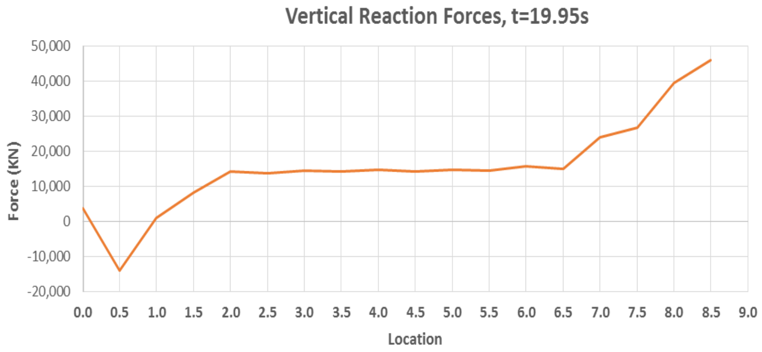


- Soil-columns close to the walls witness different accelerations and strains than the soil-column at the center
- Distorted soil regions close the walls indicates a significant boundary effect

2D models: Combination of steel and rubber materials







- Vertical forces in walls and in soil-columns are out of phase during shaking indicating the generation of overturning moment at the bottom of the box
- Significant complementary shear stresses introduce tension in the walls. Walls need to be designed for that.
- This type of walls **not recommended** because pure shear behavior is limited only to the center half width of the box

2D models: Alternative wall configurations

- ✓ Options to increase the axial and bending stiffness of the walls. Investigate the effect of these stiffnesses.

- ✓ Develop detailed model with nodes at the middle of the walls, where the balls/plugs/bearings will be located

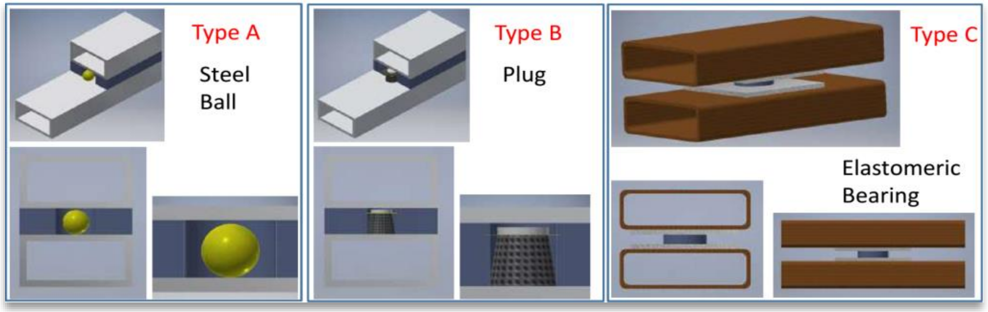
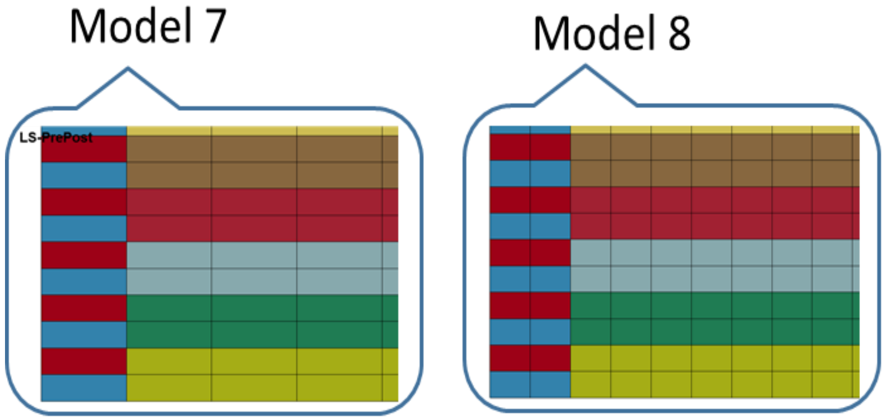
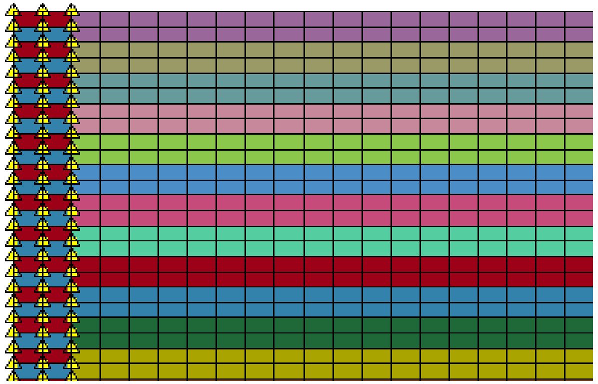


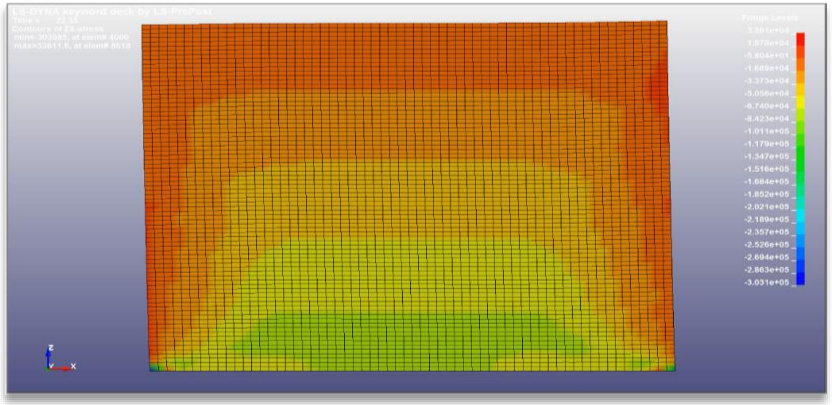
Figure: Three different design alternatives for the walls of the box (credit: S. Elfass)

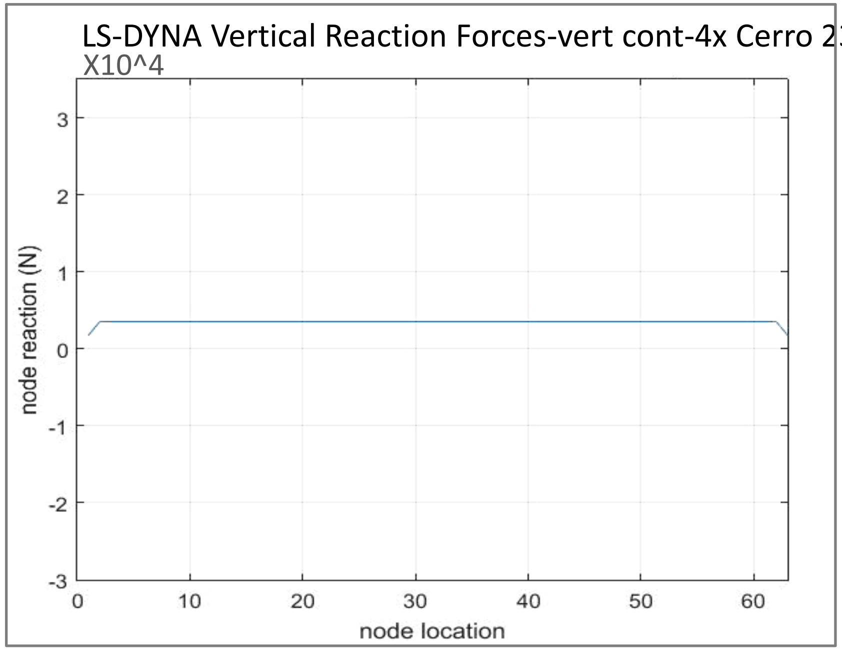


- ✓ Apply vertical constraints or very stiff springs to increase the axial and flexural stiffness



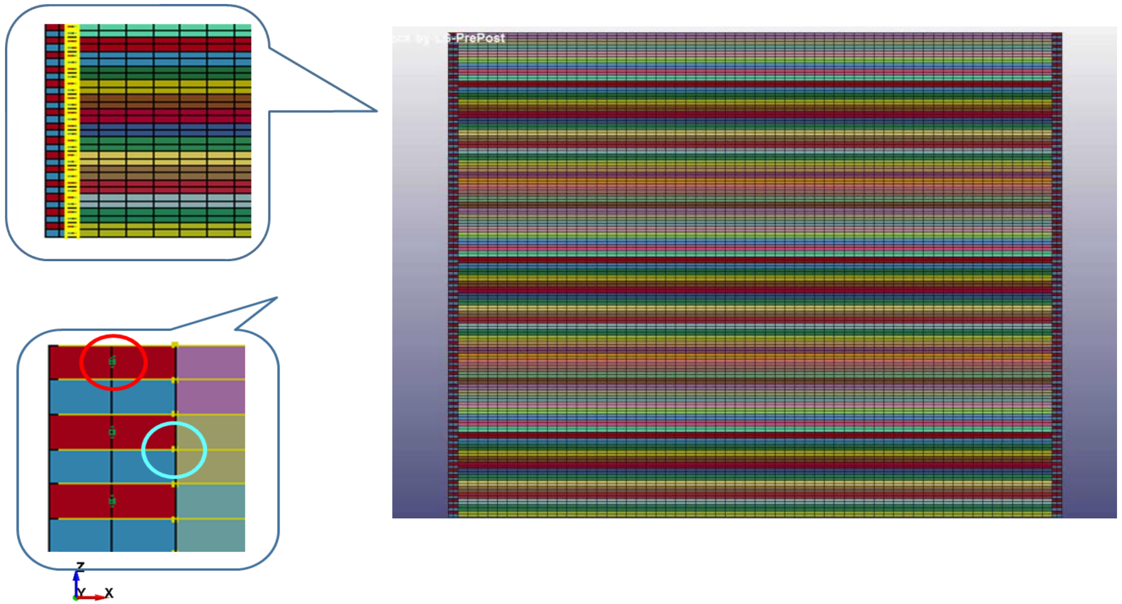
2D models: Comparison of different wall options

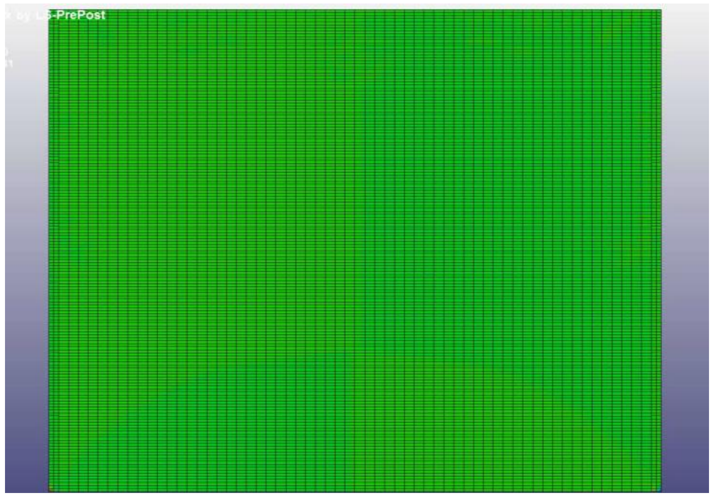


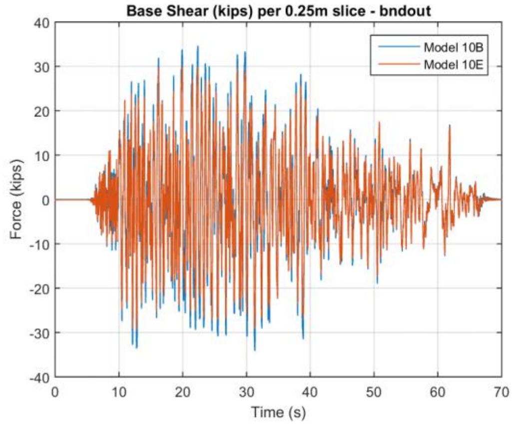


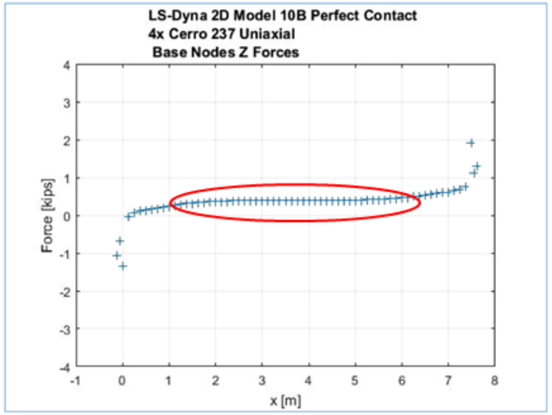
- ✓ Forcing the walls to behave in shear (by zeroing the vertical displacements) has a beneficial effect because it reduces the boundary effect and disturbed soil regions close to the walls leading to more uniform shear stresses along the same soil layer
- ✓ When the axial and flexural stiffness of the walls is very high/infinite, the walls attract/handle the overturning moment, increasing significantly the axial forces (both tension and compression) for which the walls have to be designed.

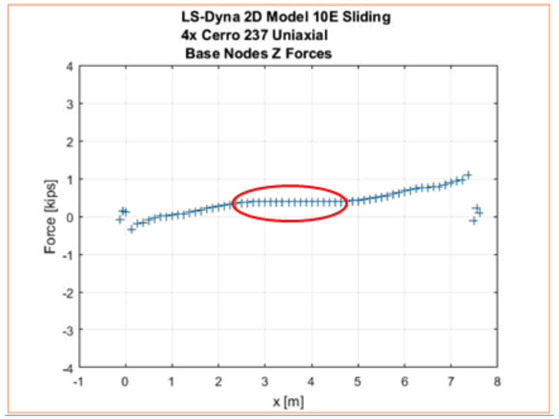
2D models: Role of friction at the soil-wall interface







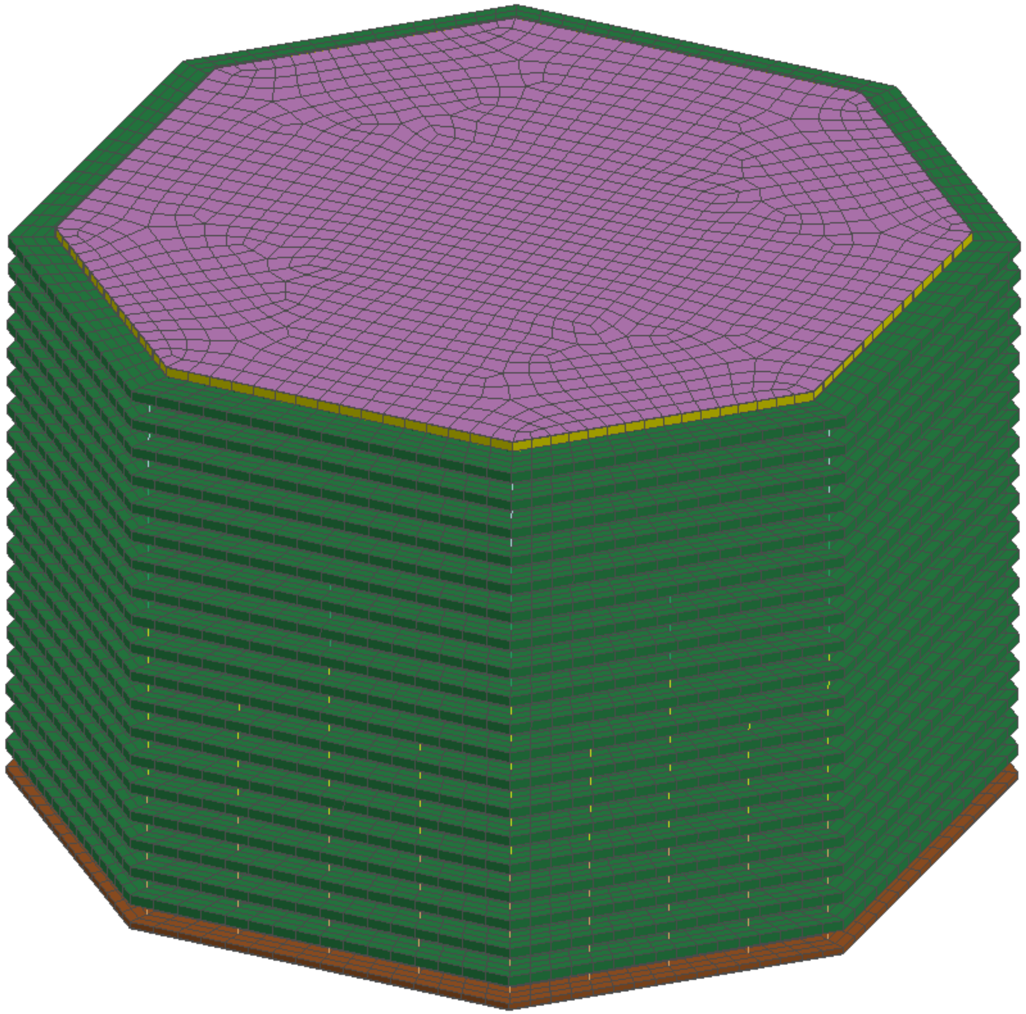




- ✓ When the friction at the soil-wall interface is zero then significant sliding and uplift of the soil is observed close to the soil-wall interface

- ✓ Uplift of soil results in shifting of the center of mass during the shaking and significant boundary effects with distorted soil regions. Soil behavior deviates from pure shear condition.

Description of 3D numerical models



- Exact geometrical shape of the box and bearing location based on semi-automatic/manual mesh

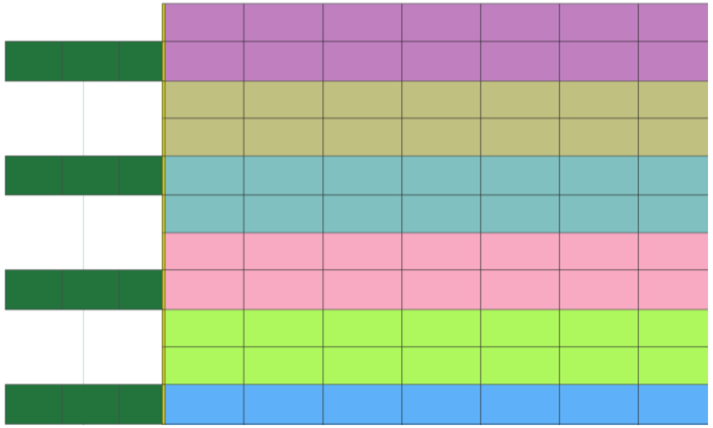
- Uniform mesh at the center of the box, convenient for constructing structural models for SSI analyses

- Complex numerical model consists of:
  - Discrete elements for bearings
  - Shell elements for HSS section
  - Solid elements for steel plate
  - Solid/shell elements for face plates
  - Solid elements for soil

- Several models of empty box and box+soil developed and different types of analyses conducted including: Modal analyses, Linear Static analyses, Nonlinear Dynamic analyses

Description of 3D numerical models (cont)

- Fundamental period in LS-DYNA: **0.10sec**
- Fundamental period from standing wave equation: 0.1016sec



- 30 different soil-layers
- Soil mesh size in vertical direction: 0.27ft, 0.28ft and 0.4ft for bottom layer in order to match the nodes of the walls (face plates)
- Frictional contact at the face plate-soil interface with μ=0.85
- Perfect/Frictional contact (μ=1.0) at the soil-bottom plate interface

3D numerical models of the soil-box

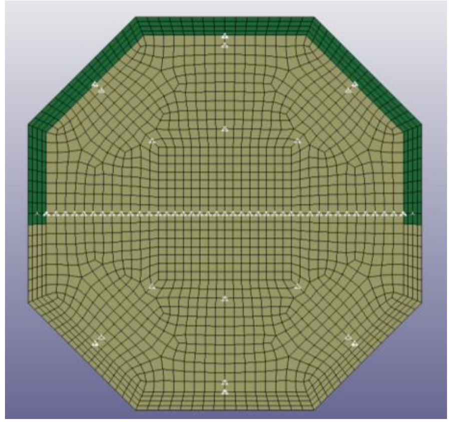
(A) Increase confidence in parameters/values obtained from simplified 1D, 2D and 3D models that were developed during the preliminary design phase

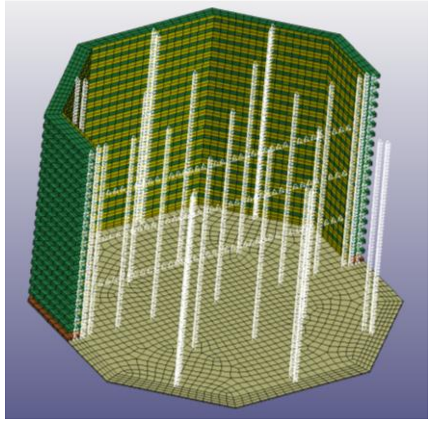
(B) Calculate design parameters that could not be quantified based on previously developed simpler models

(C) Understand the behavior of the box and the expected ground motion at the soil surface to assist the design of SSI experiments

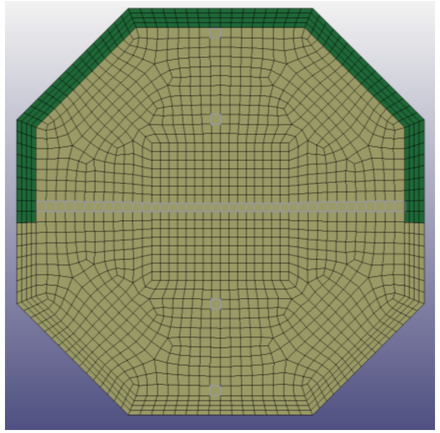
3D numerical models output parameters

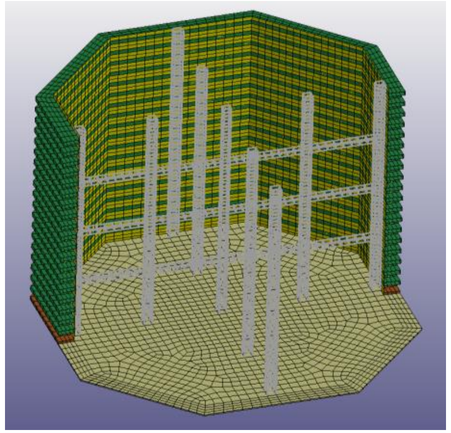
Nodal Displ., Vel., Accel. at selected locations



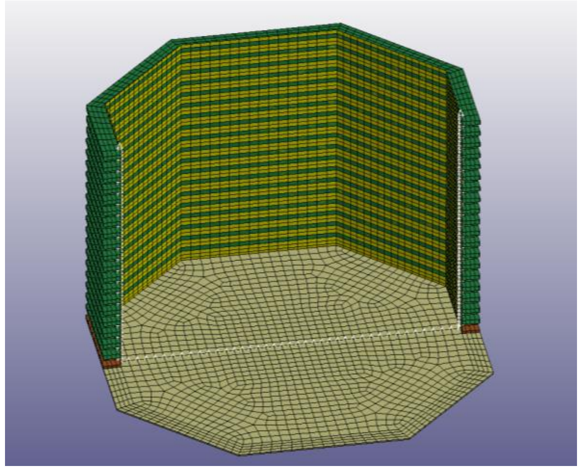


Element Stresses and Strains at selected locations

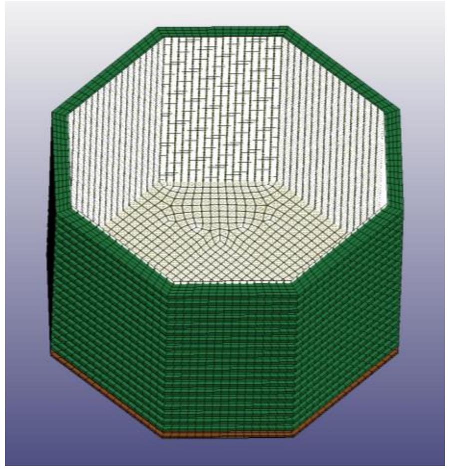




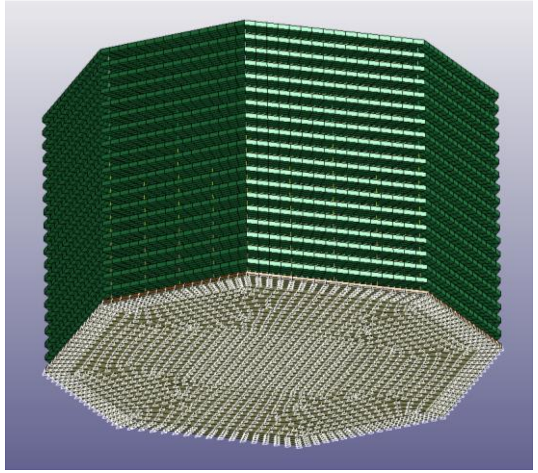
Nodal forces at selected nodes



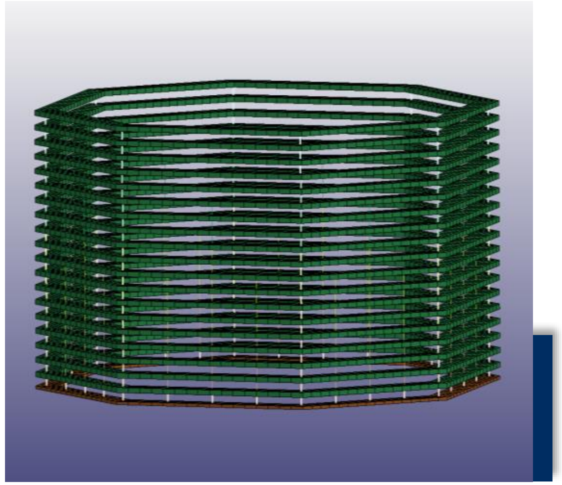
Contact forces at the soil-wall interface



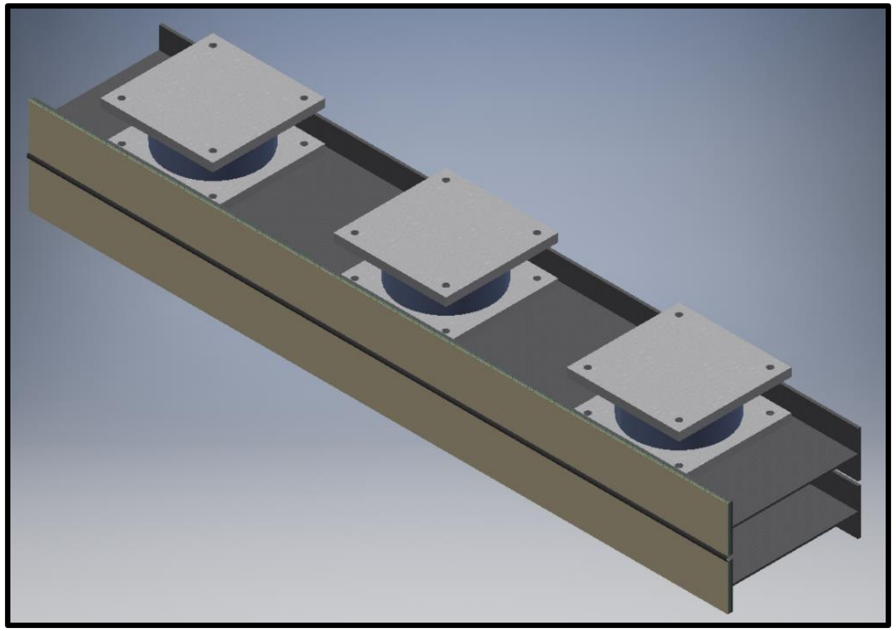
Reaction forces at the bottom of the box

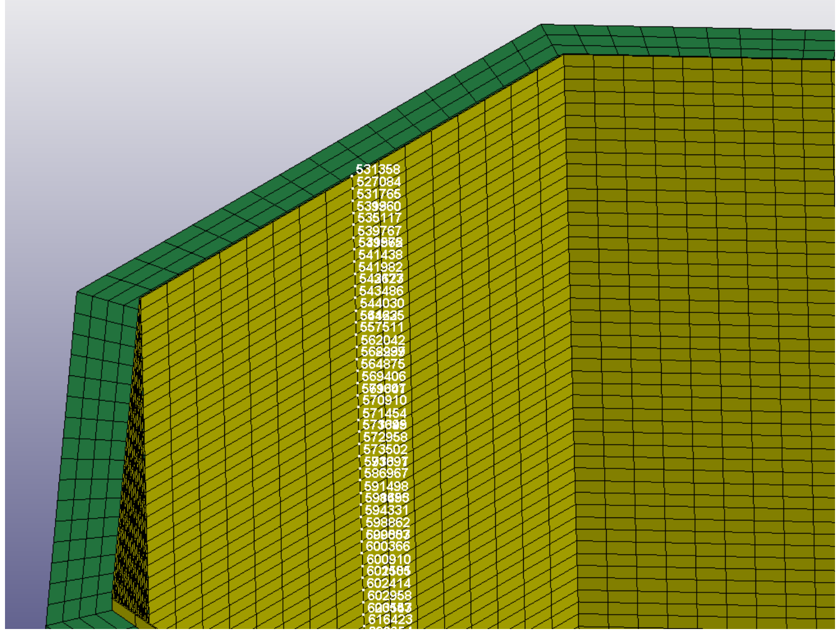


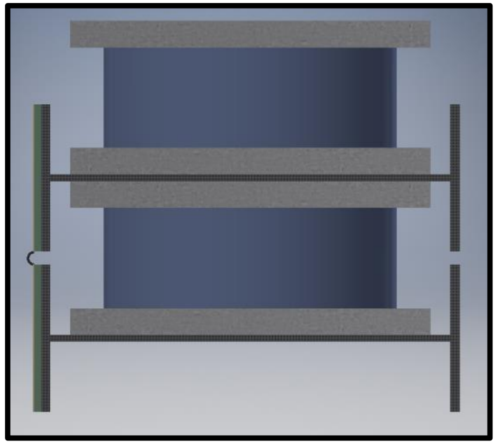
Bearing forces and displacements



Vertical Gap of Face Plates



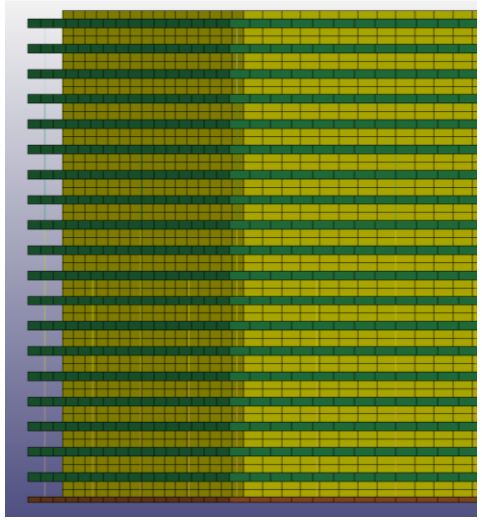


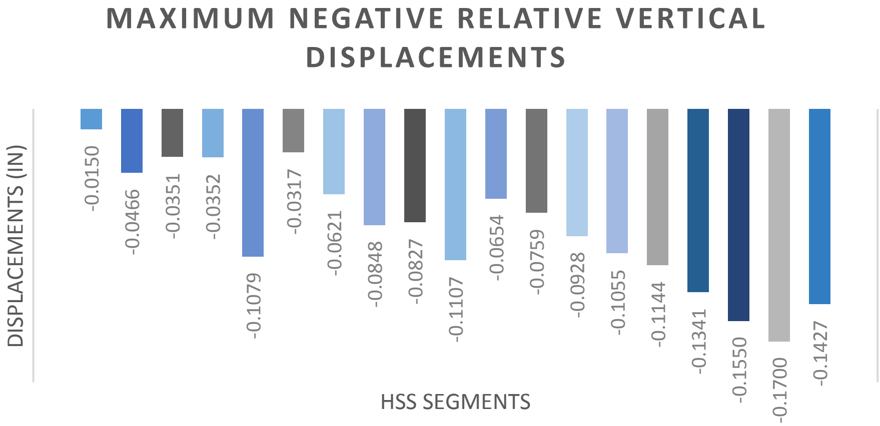


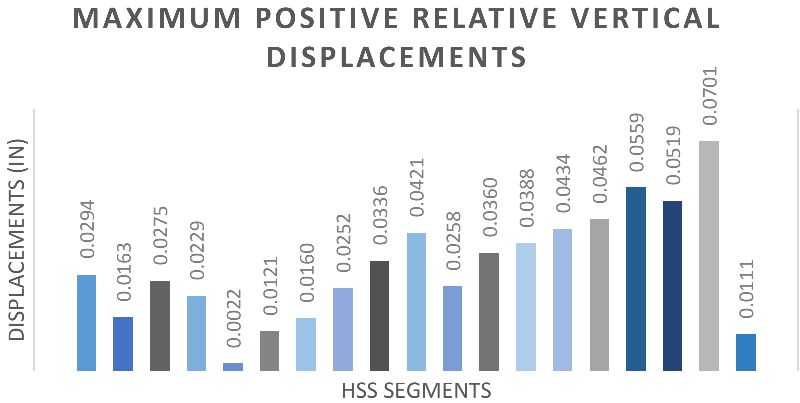
- Given the absolute z-displacements of coinciding nodes and the identification of the nodes it is possible to calculate the opening/closing of the gap. $\Delta z = z_{top,i} - z_{bottom,i}$

- If $\Delta z > 0$, opening of gap occurs (opposite is true for closing of gap)

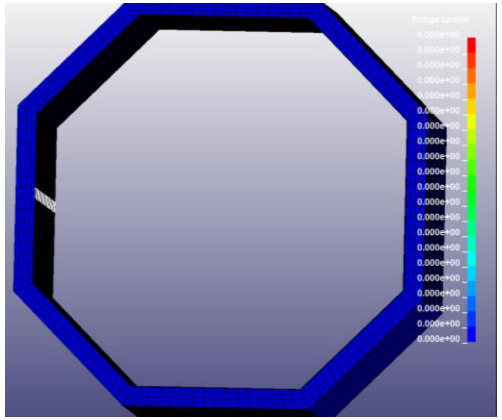
Vertical Gap of Face Plates & Stresses in Walls

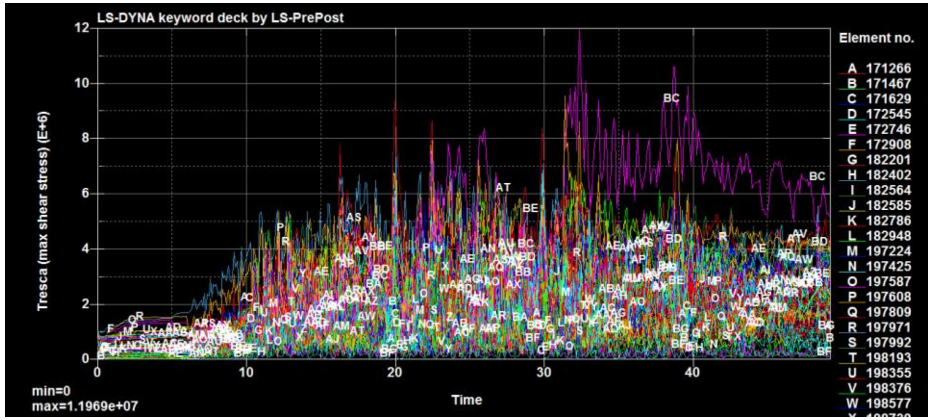






Nonlinear Dynamic
Analyses: Cerro SF4 - biaxial

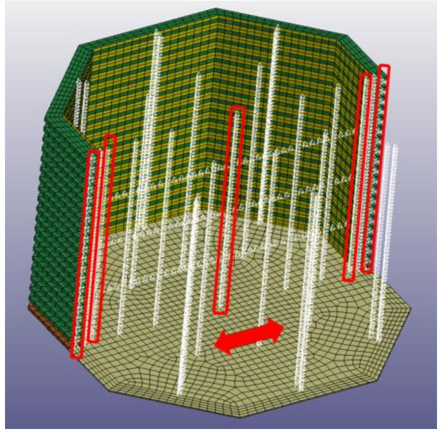


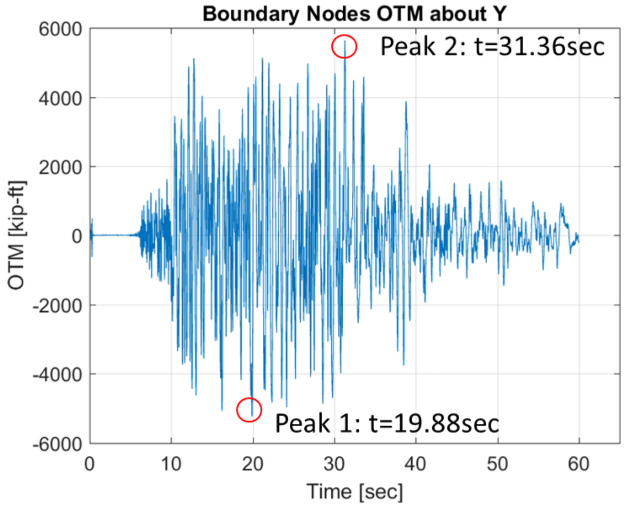


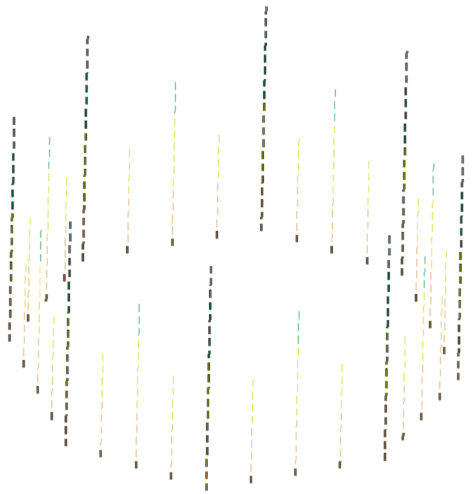
Face plates: A36 ,
f_y=36ksi (tensile)
$f_{xy}=f_y/\sqrt{3}$=20.8ksi (pure shear)

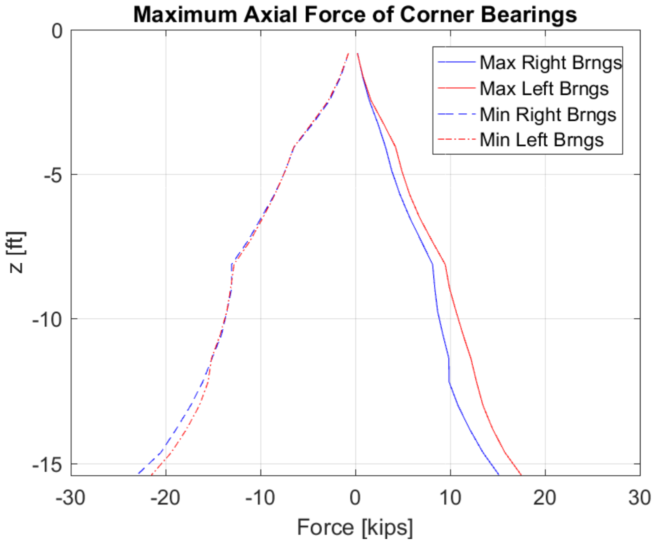
- Max Shear Stress =11969kPa =1.74ksi < f_{xy}=20.8ksi
- The demand on the face plates is approximately 10% of the estimated capacity

Bearing Axial Forces and Lateral Displacements

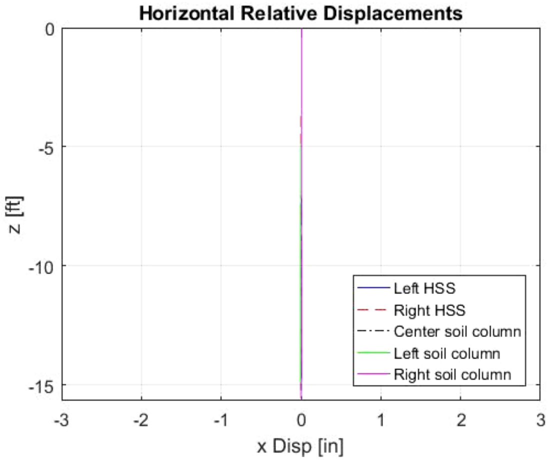




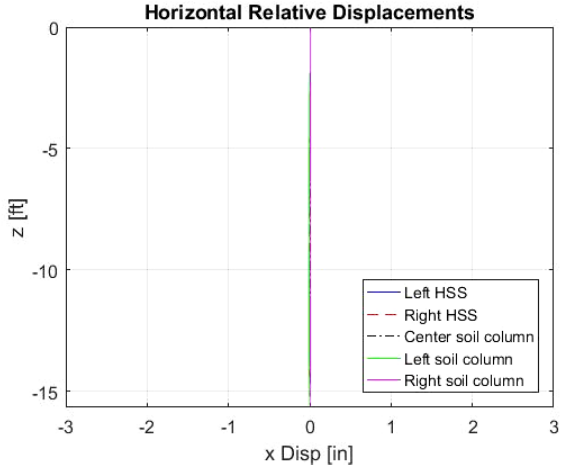


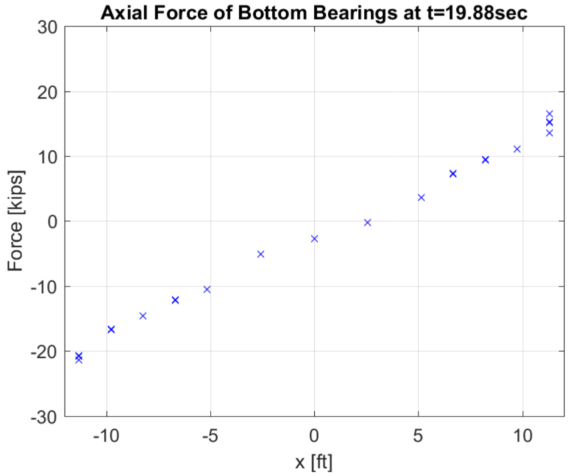


Initial design



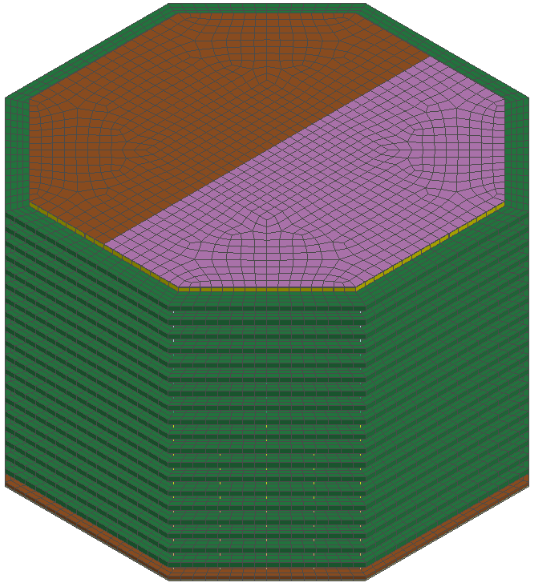
Optimized design

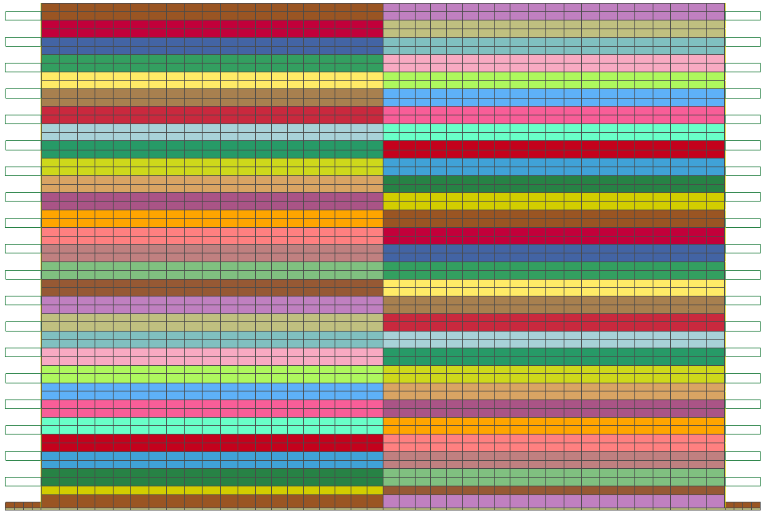




- Maximum axial force occurs in the bearings of the bottom layer as expected.

Accidental eccentricity due to soil variability



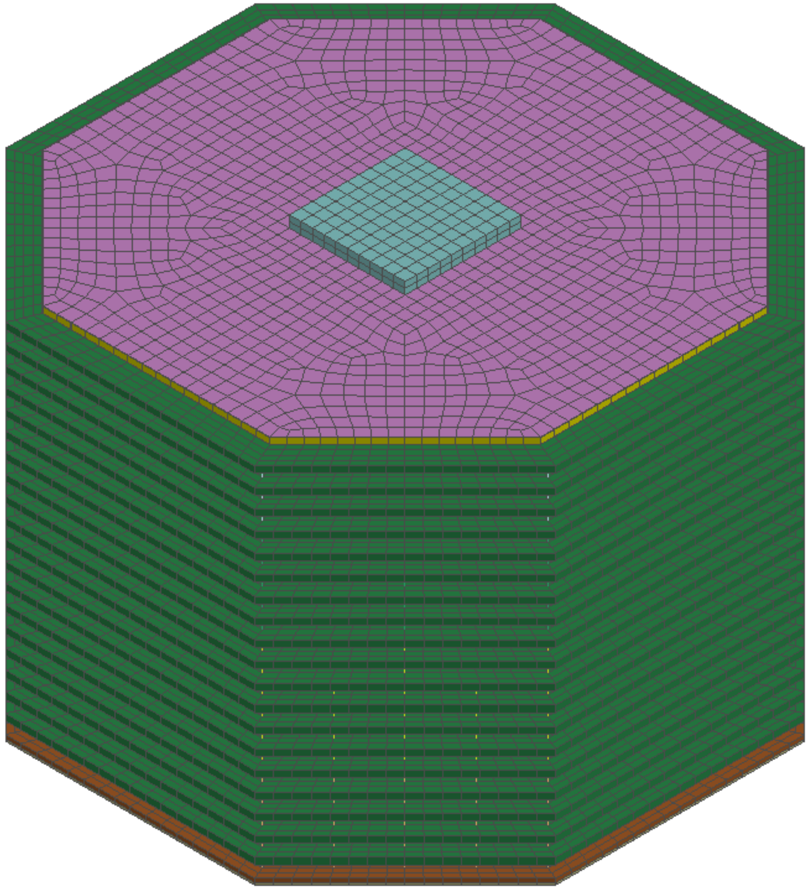


- Uniaxial shaking - Cerro 237 at SF4 (PGA=1.0g)

- Idealized scenario:
  Assume that half of the soil has increased density by 10%. This will cause differences in the shear modulus and shear strength of each soil layer.

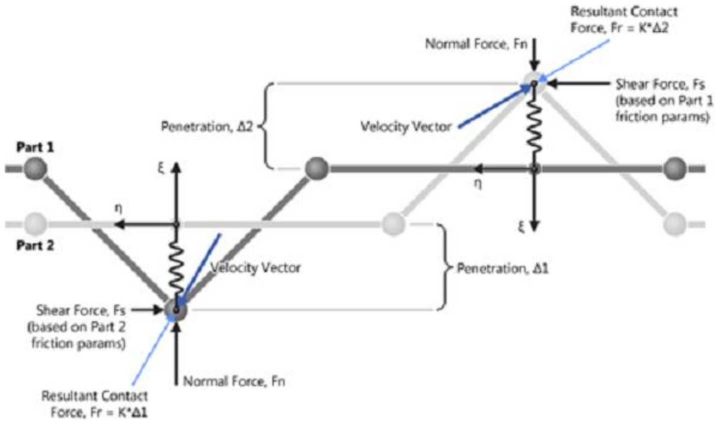
- Conduct both uniaxial and biaxial analyses to check box rotation

SSI analyses of simple structures



Model 15: Concrete Plate on Top surface Dimensions: 5ft x 5ft x 0.5ft

How to simulate the separation?
Contact elements are required for modeling the opening/closing of the gap between the soil and the structure. Use a frictional contact with μ=0.45 at concrete plate-soil interface.

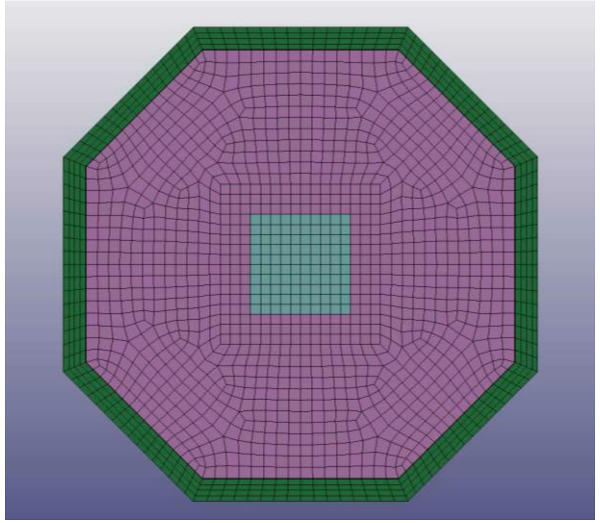


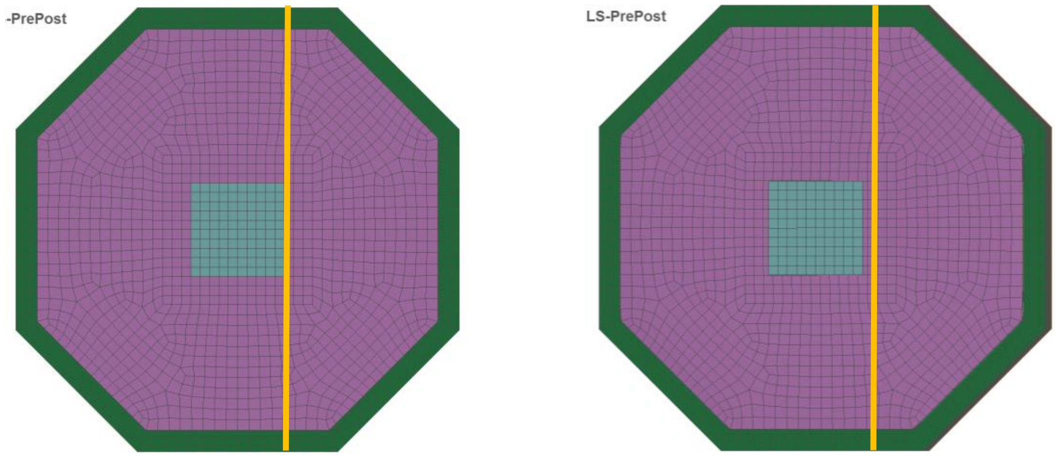
Contact type:
Penalty based contact between segments. Use a 'soft' formulation that adjusts the penalty stiffness to account for the significantly dissimilar material properties between concrete/steel & soil

Numerous numerical parameters can affect the behavior and stability of the contact: sensiti studied are required

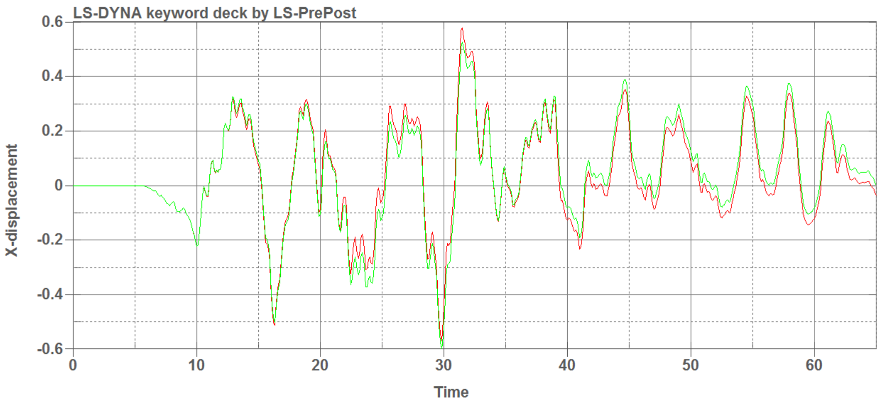
SSI – Concrete slab

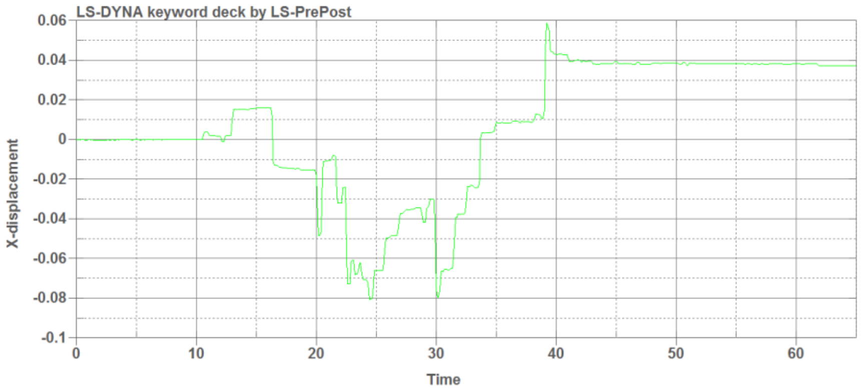
- Simple structure with sliding
- No rocking of structure
- Calibrate contact algorithms





Plan view of model at t=0 (left) and at t=23.8 sec (right)

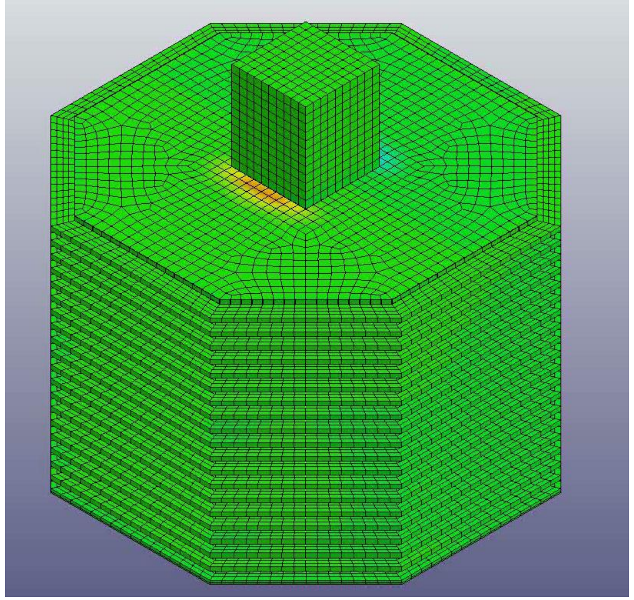




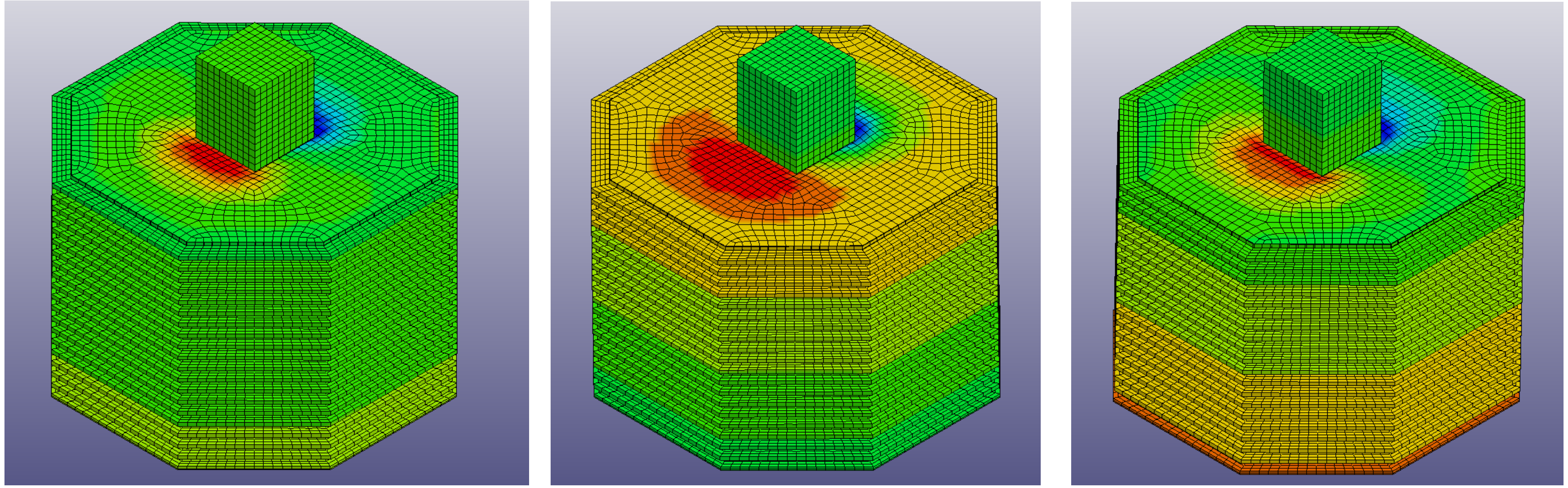
Sliding of the concrete plate seems to occur during uniaxial shaking (PGA=1.0g) and the maximum sliding is approximately 8cm=3.15in

SSI – Concrete block

No embedment in soil



No embedment in soil (at three instants during shaking)



- Simple structure (hollow box) with rocking
- Concentrated nonlinear soil behavior around the structure
- Physics more complicated due (a) soil localized non-linearity, and (b) gap opening between the soil and the structure

Summary: 2D and 3D Models

Investigated in **2D** models:

- Effect of sliding
- Effect of friction and gapping
- Sensitivity of results to the contact type
- Effect of bottom plate
- Sensitivity of results to the numerical approach of transferring shear between the bottom plate and the soil
- Effect of friction between the soil & bottom plate
- Sensitivity of results to the ground motion
- Sensitivity of results to the element formulation

Investigated in **3D** models:

- Effect of friction and gapping – uniaxial and biaxial motion
- Effect of bottom plate – uniaxial motion
- Effect of soil accidental eccentricity
- Soil-structure interaction capabilities
- Sensitivity of results to the in-plane mesh
- Sensitivity of results to the magnitude of ground motion
- Sensitivity of results to the ground motion

Some conclusions

1. Laminar walls that are flexible in every direction are witnessing vertical soil displacements in regions close to the walls, indicating that the soil is not in pure shear and demonstrating the existence of **a significant boundary effect** caused by the walls.

2. Large overturning moment is generated at the bottom of the soil-box during extreme ground shaking. **OTM can introduce significant uplift** in the walls via the complementary shears. Walls should be designed for both shear & tension.

3. To ensure that the soil-box will behave as realistically as possible, it is necessary to have walls **with small lateral stiffness but very high axial and bending stiffness**, together with **a nearly perfect contact (high-coefficient of friction) at the soil-wall interface**, which will transfer the complementary shear of the soils to the walls and minimize the boundary effect.

4. 1D numerical models are efficient and insightful during the preliminary design phase of a soil-box. However, more **advanced 2D and 3D models** are (i) understanding the soil-wall interaction, (ii) providing all the parameters for the final design, (iii) quantifying the soil-structure interaction capabilities.

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Thank you!