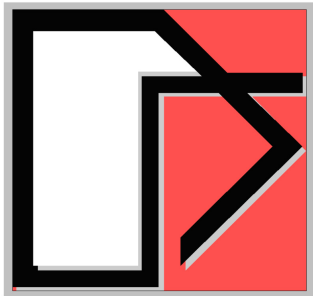# Validation of Modified Subtraction Method (MSM) for Seismic SSI Analysis of Large-Size Embedded Nuclear Islands
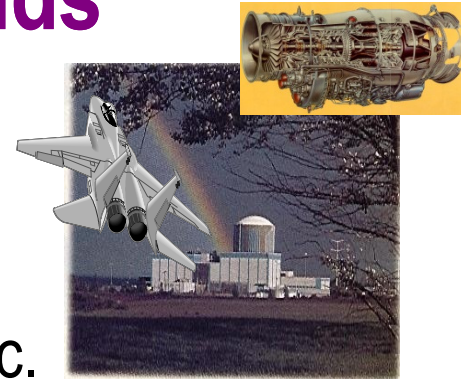
Dr. Dan M. Ghiocel

Email: dan.ghiocel@ghiocel-tech.com

Ghiocel Predictive Technologies Inc.

Dongyi Yue and Michael McKenna

Email: dongyi.yue@urs.com

URS Energy and Construction Corporation

Hiro Fuyama and Tomoyuki Kitani

Mitsubishi Heavy Industries, Ltd.

SMiRT22 Conference, San Francisco, CA
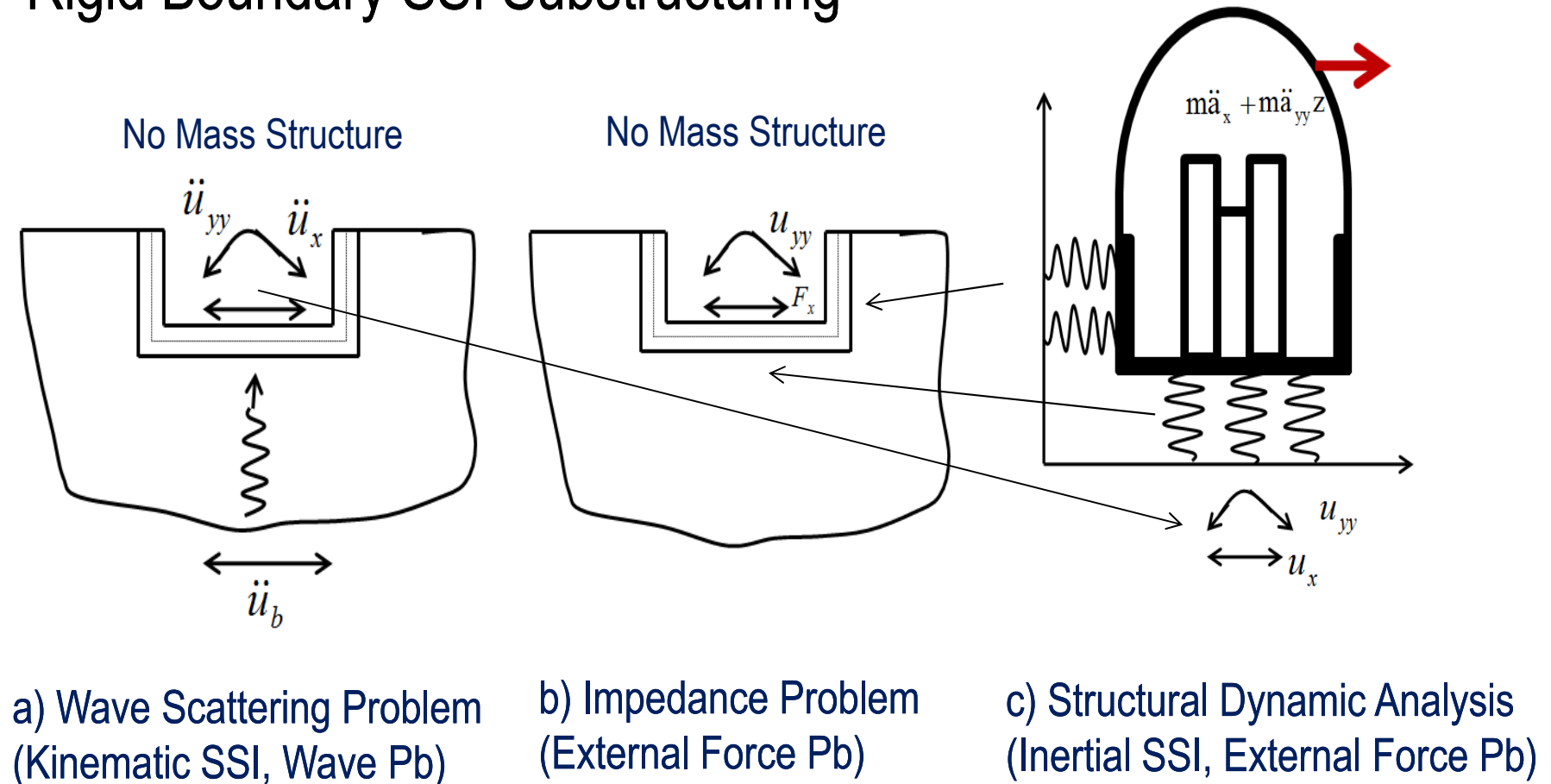## August 18-22, 2013

1

Purpose of This Presentation:

To present selected results of a series of validation studies for Modified Subtraction Method (MSM) and Fast Flexible Volume (FFV). The validation of MSM is focused on application to large-size embedded SSI models, specific to NI complexes, while the validation of FFV is focused on application to deeply embedded SSI models, specific to SMRs.

The validation of these methods, as required by ASCE 04-2013 and SRP 3.7.2-2013 drafts, is performed against the SASSI Flexible Volume (FV) method that is considered to be the reference method for embedded SSI analysis problems.
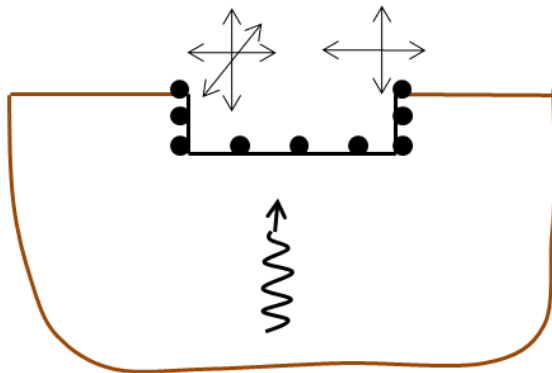
Linearized SSI Analysis Using Complex Frequency Substructuring (3 Steps SSI Approach)
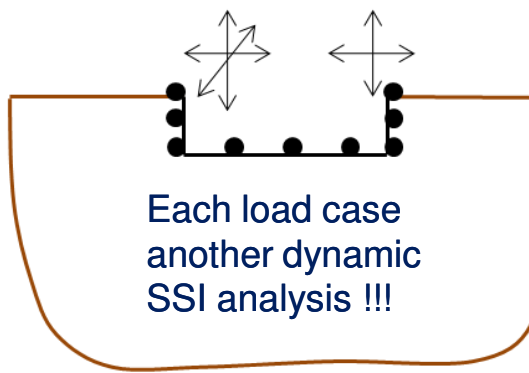
Rigid Boundary SSI Substructuring

No Mass Structure

$\ddot{u}_{yy}$ $\ddot{u}_x$

$\ddot{u}_b$

No Mass Structure

u_{yy}

F_x

$m\ddot{a}_x + m\ddot{a}_{yy}z$

u_{yy}

u_x

a) Wave Scattering Problem
(Kinematic SSI, Wave Pb)

b) Impedance Problem
(External Force Pb)

c) Structural Dynamic Analysis
(Inertial SSI, External Force Pb)

Flexible Boundary SSI Substructuring
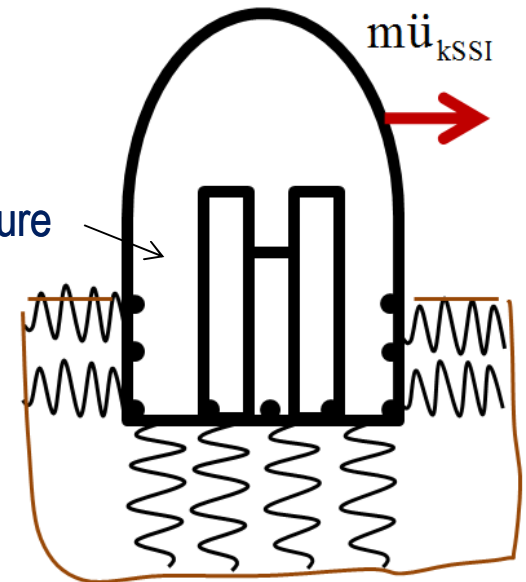
No Mass Structure

No Mass Structure

Each load case another dynamic SSI analysis !!!

$m\ddot{u}_{kSSI}$

Structure

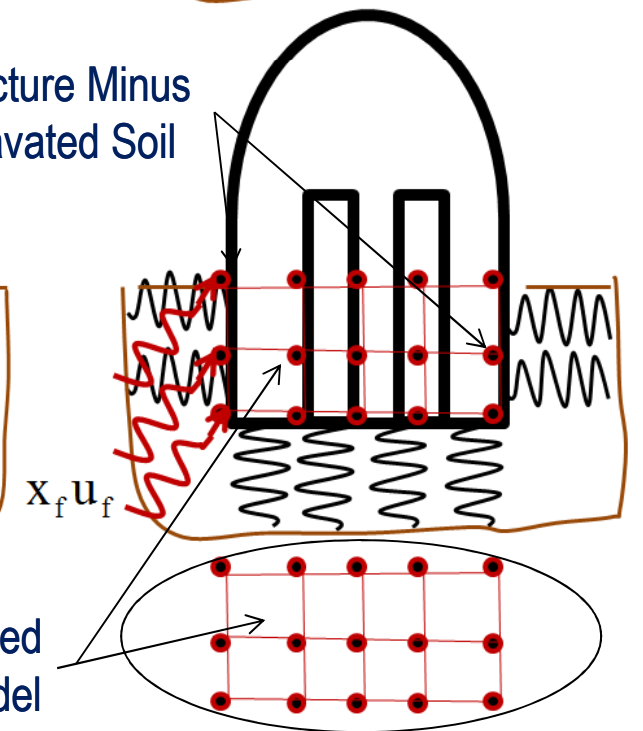# Flexible Volume SSI Substructuring

- No wave scattering analysis.
- Free-Field Soil Impedance Problem is trivial; reduced to a simple axisymmetric problem.
- Structural SSI dynamic problem slightly more complex since includes a coupled excavated soil
- Multiple SSSI effects could be analyzed without including any surrounding soil layering elements!
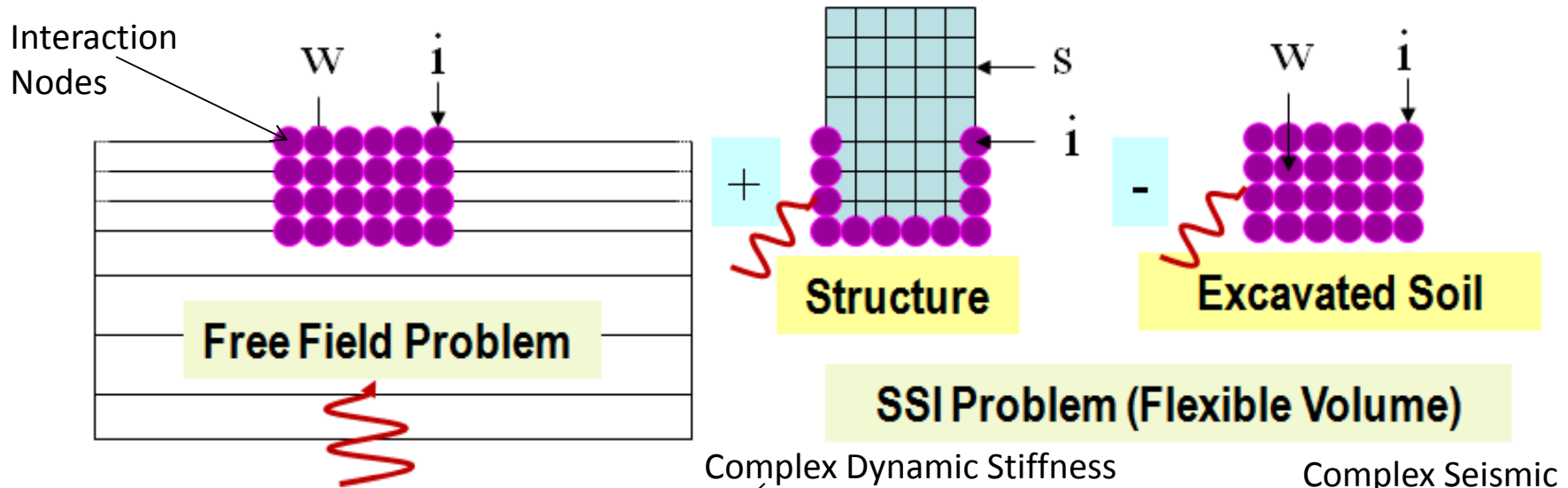
Structure Minus Excavated Soil

No Mass Structure
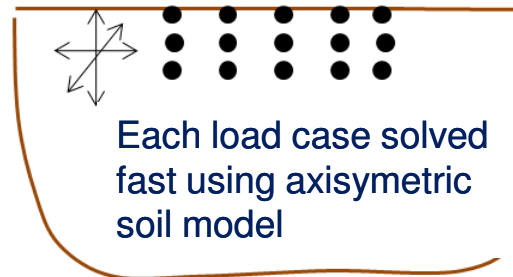
Each load case solved fast using axisymetric soil model

$x_f u_f$

Excavated Soil Model

4

SASSI Flexible Volume (FV) Substructuring Method

Interaction Nodes

W   i

Free Field Problem

+   **Structure**   s   i

-    **Excavated Soil**   W   i

SSI Problem (Flexible Volume)

Complex Dynamic Stiffness

Complex Seismic Load Vector

Complex Frequency Domain Formulation:

$$C(\omega)U(\omega) = Q(\omega)$$

Complex Absolute Displacements

Complex Soil Impedance Terms

$$
\begin{bmatrix}
C_{ii}^{s} - C_{ii}^{e} + X_{ii} & -C_{iw}^{e} + X_{iw} & C_{is}^{s} \\
-C_{wi}^{e} + X_{wi} & -C_{ww}^{e} + X_{ww} & 0 \\
C_{si}^{s} & 0 & C_{ss}^{s}
\end{bmatrix}
\begin{Bmatrix}
U_{i} \\
U_{w} \\
U_{s}
\end{Bmatrix}
=
\begin{Bmatrix}
X_{ii}U'_{i} + X_{iw}U'_{w} \\
X_{wi}U'_{i} + X_{ww}U'_{w} \\
0
\end{Bmatrix}
$$

REMARK: All Excavated Soil nodes are interaction nodes (include exact equations of motion)

5

# SASSI Flexible Volume Methods for Embedded Structures
Flexible Volume Substructuring Approaches

FV

Free Field Problem · Structure · Excavated Soil · SSI Problem (Flexible Volume)

SM (FI-FSIN)

Free Field Problem · Structure · Excavated Soil · SSI Problem (Subtraction)

MSM (FI-EVBN)

Free Field Problem · Structure · Excavated Soil · SSI Problem (Modified Subtraction)
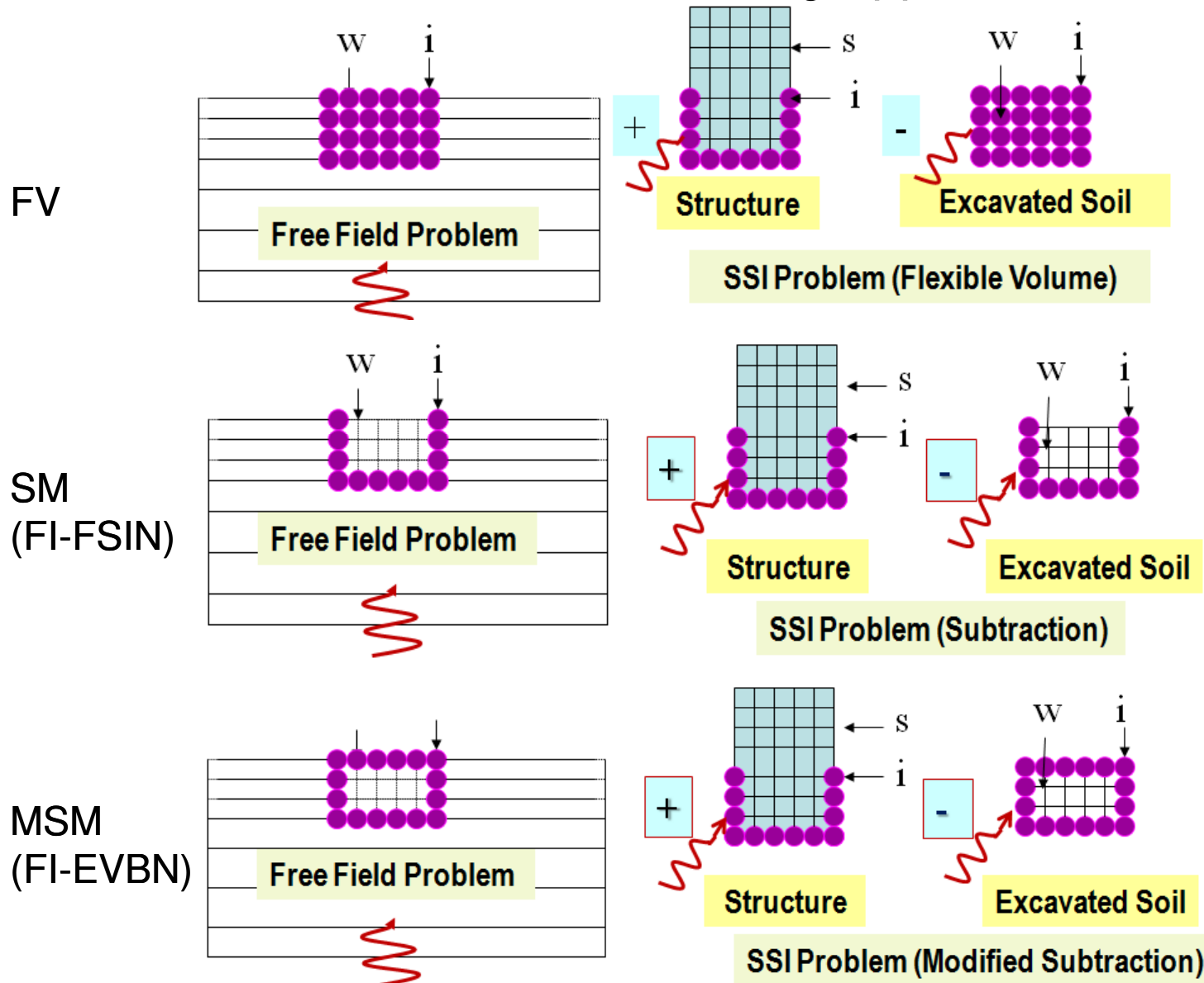
Excavated Soil Vibration Using FVM, SM and MSM

Effects of Ground Surface Constraints on Scattered Surface Wave Solution

DM or FV
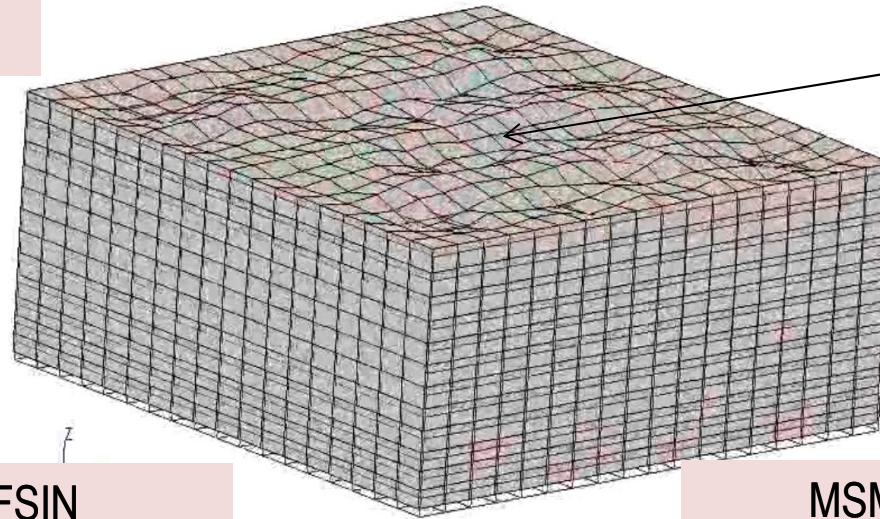
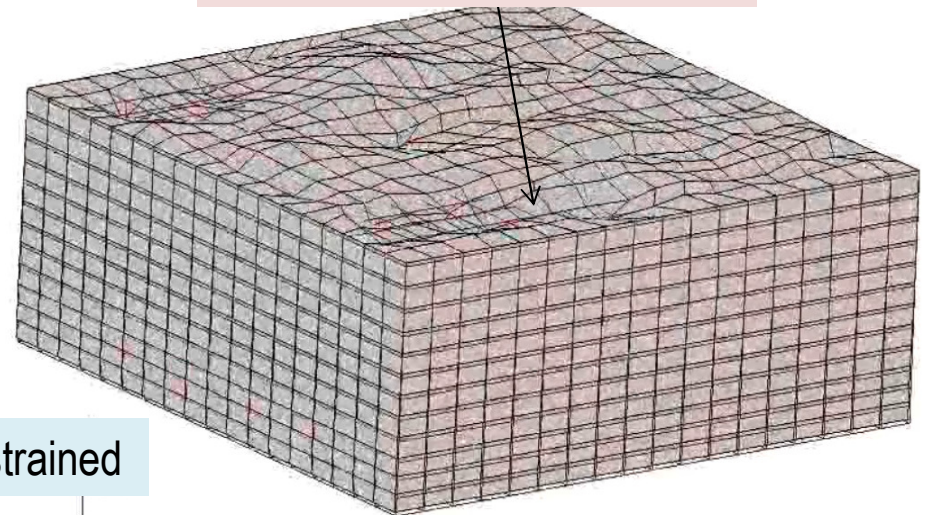Surface is moving constrained by free-field
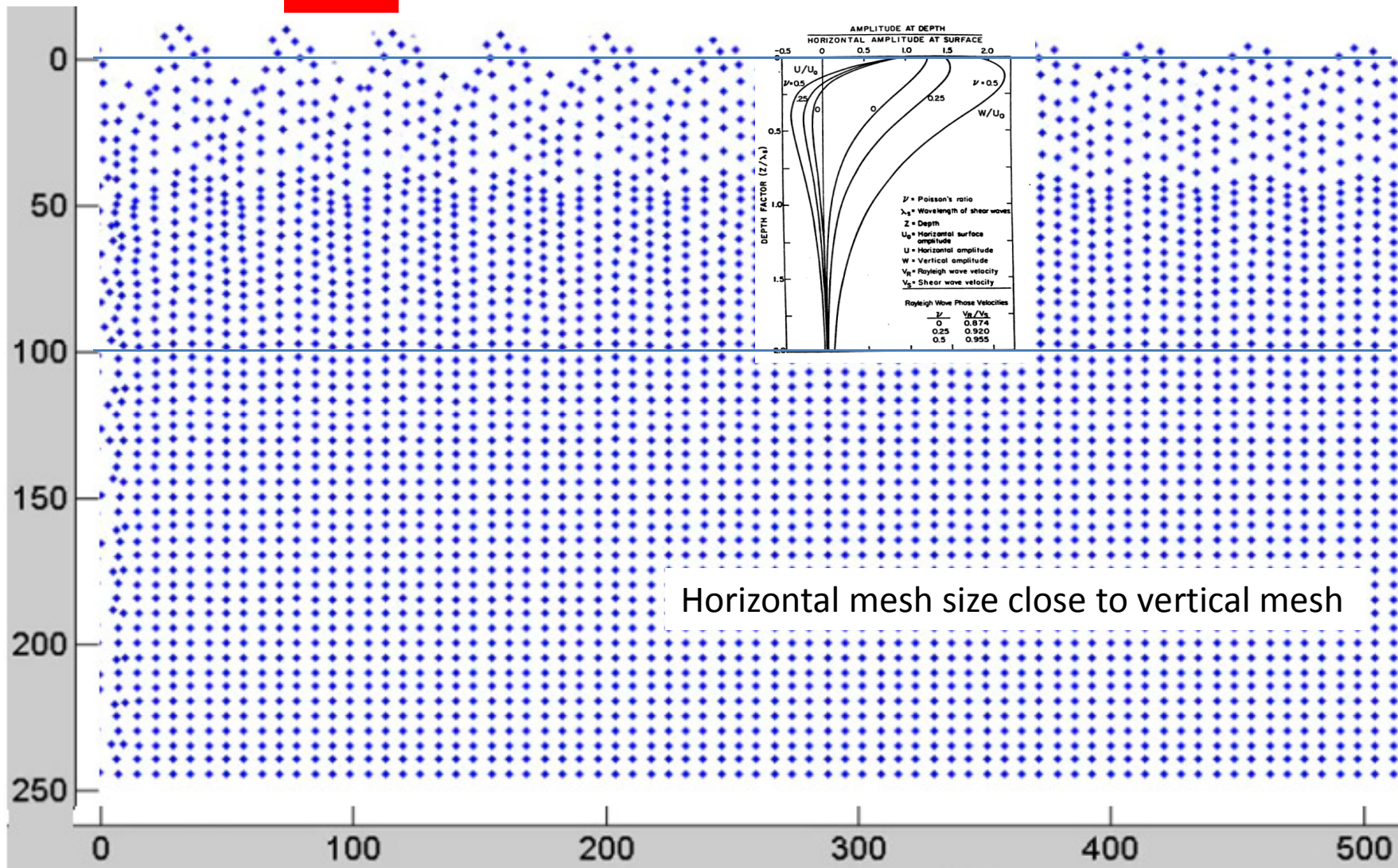
Show excavated soil animations

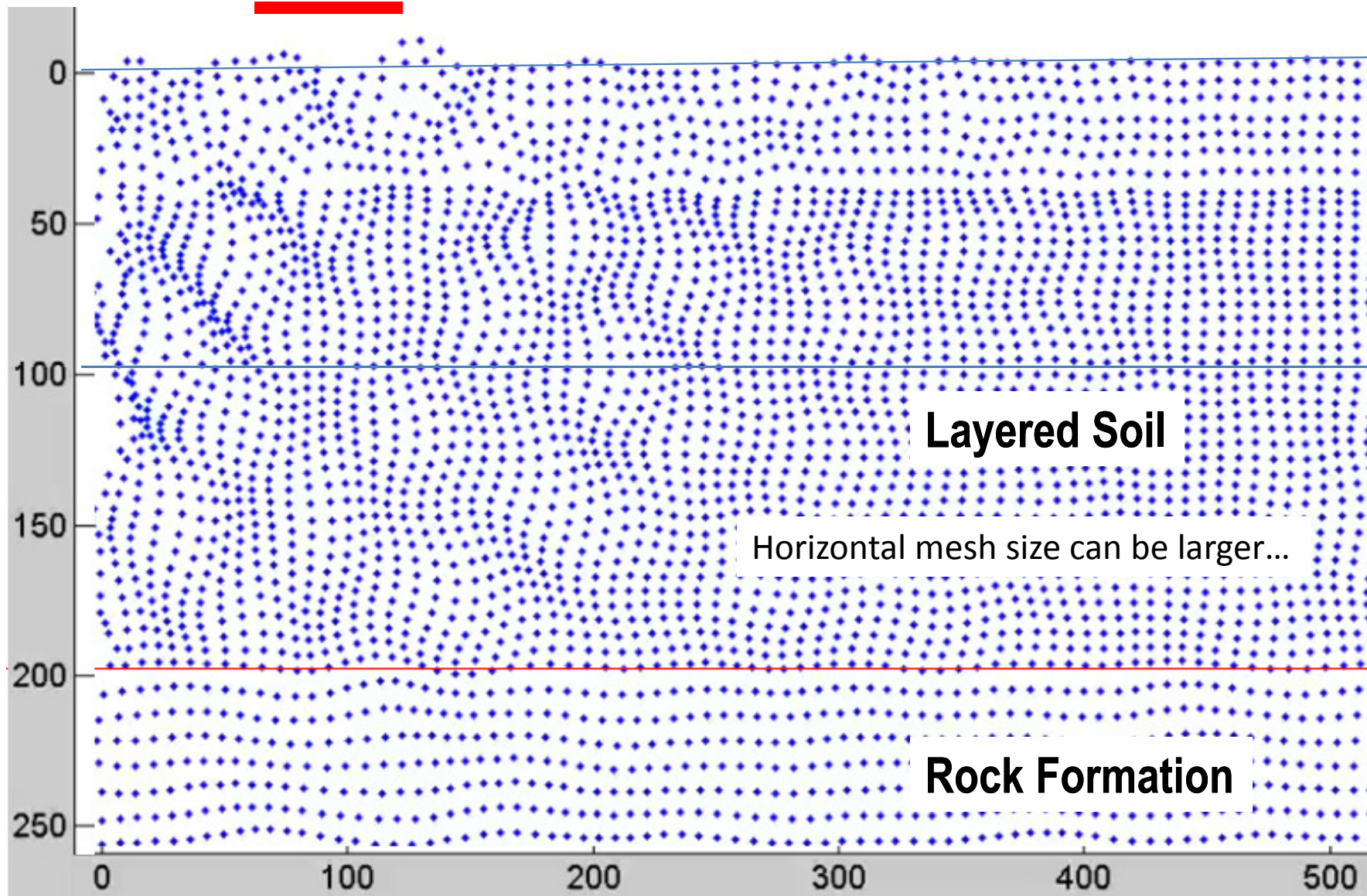SM or FI-FSIN
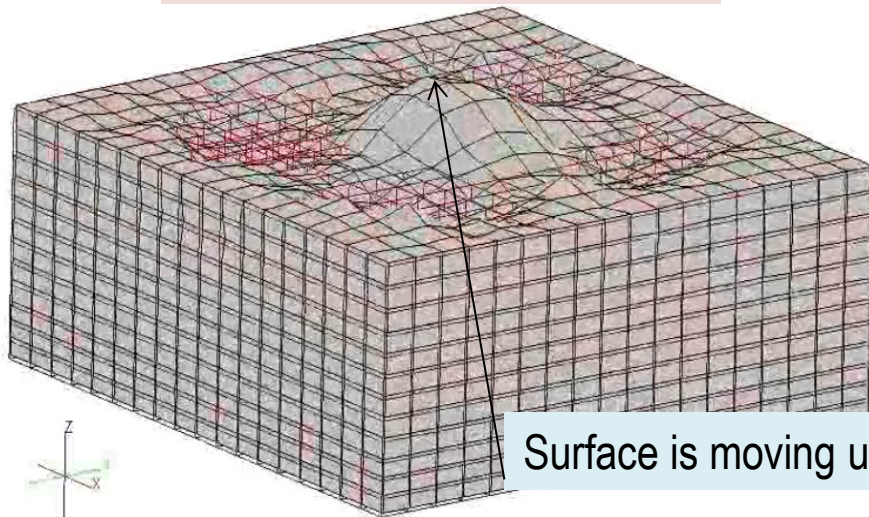
MSM or FI-EVBN

Surface is moving unconstrained

7

Rayleigh Wave Propagation in Half-Space (30 Hz)

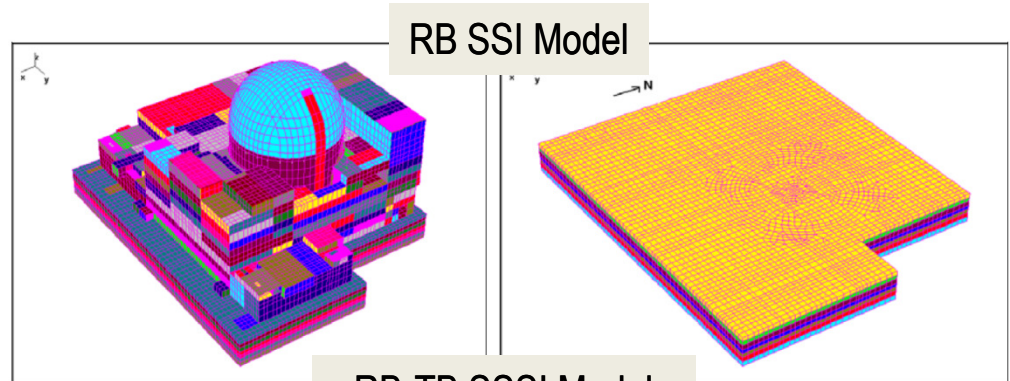Horizontal mesh size close to vertical mesh

Rayleigh Waves in Soil Layering Over Rock (30 Hz)

Layered Soil

Horizontal mesh size can be larger…

Rock Formation

NI RB Complex SSI Model Case Studies
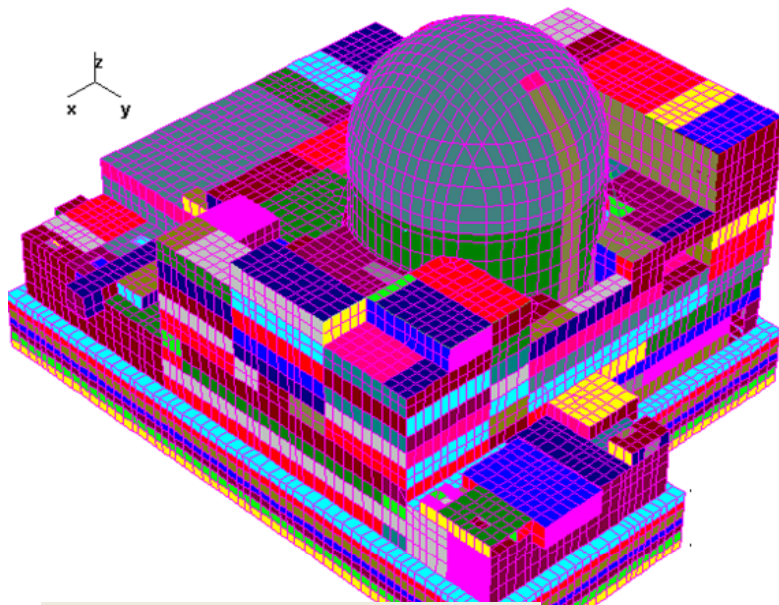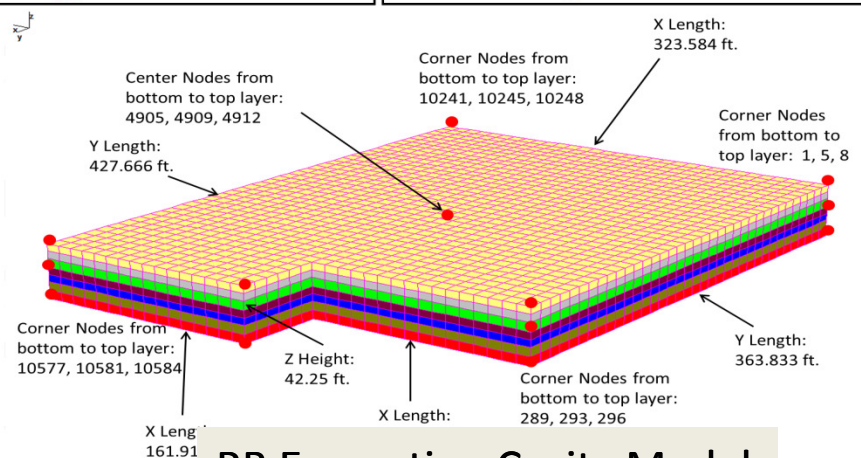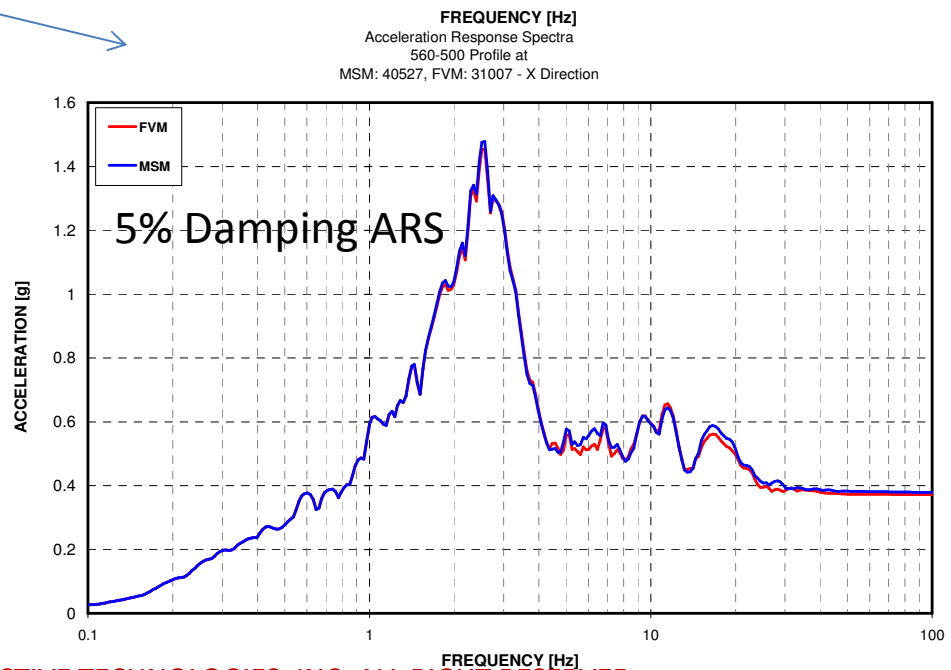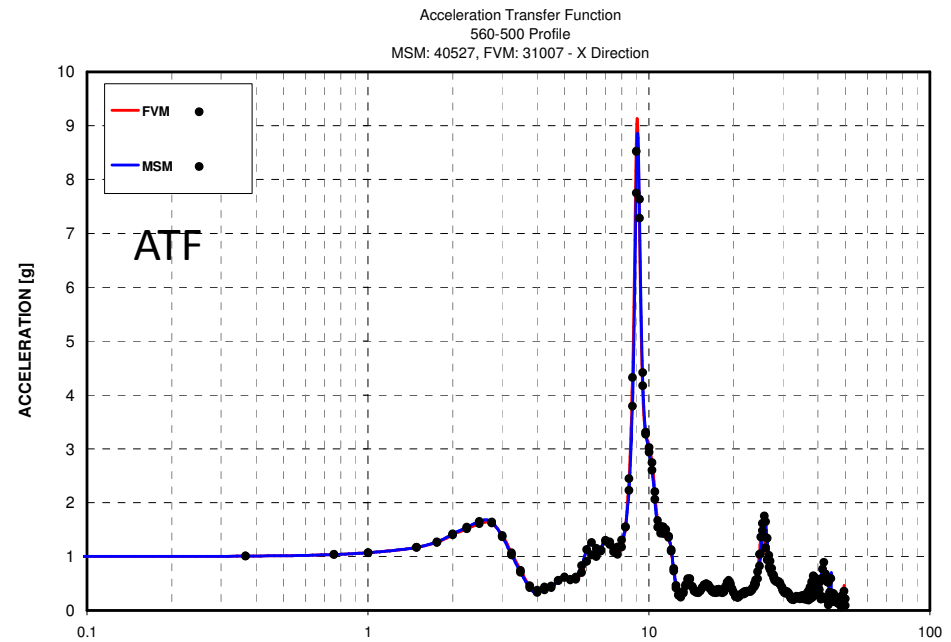

RB SSI Model

RB-TB SSSI Model
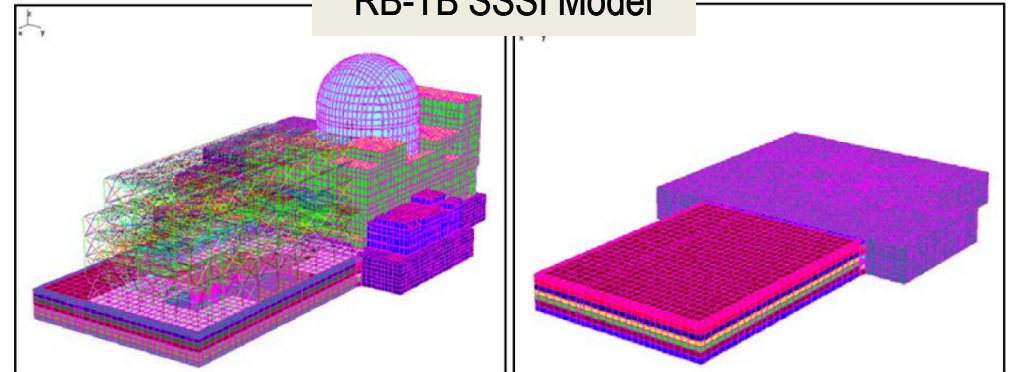
RB Complete SSI Model
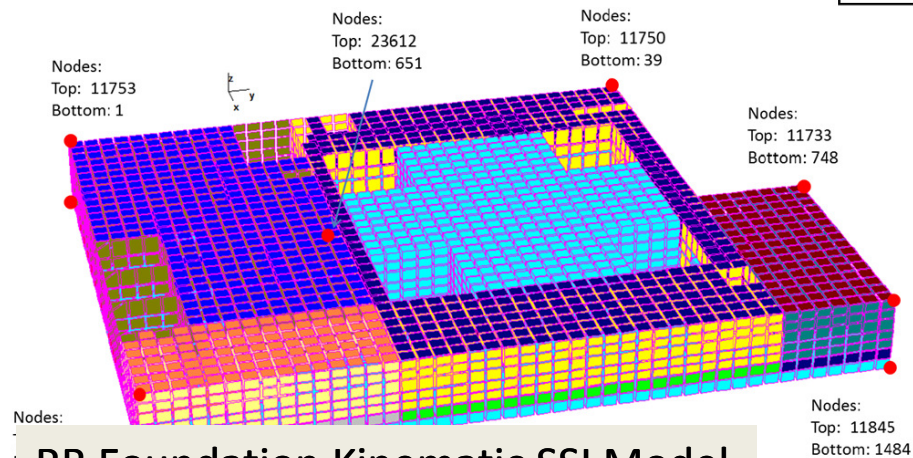
RB Foundation Kinematic SSI Model

RB Excavation Cavity Model

Nodes:
Top: 11753
Bottom: 1

Nodes:
Top: 23612
Bottom: 651

Nodes:
Top: 11750
Bottom: 39

Nodes:
Top: 11733
Bottom: 748

Nodes:
Top: 11845
Bottom: 1484

Center Nodes from bottom to top layer: 4905, 4909, 4912

Corner Nodes from bottom to top layer: 10241, 10245, 10248

X Length: 323.584 ft.

Corner Nodes from bottom to top layer: 1, 5, 8

Y Length: 427.666 ft.

Corner Nodes from bottom to top layer: 10577, 10581, 10584

Z Height: 42.25 ft.

X Length: 161.91

Corner Nodes from bottom to top layer: 289, 293, 296
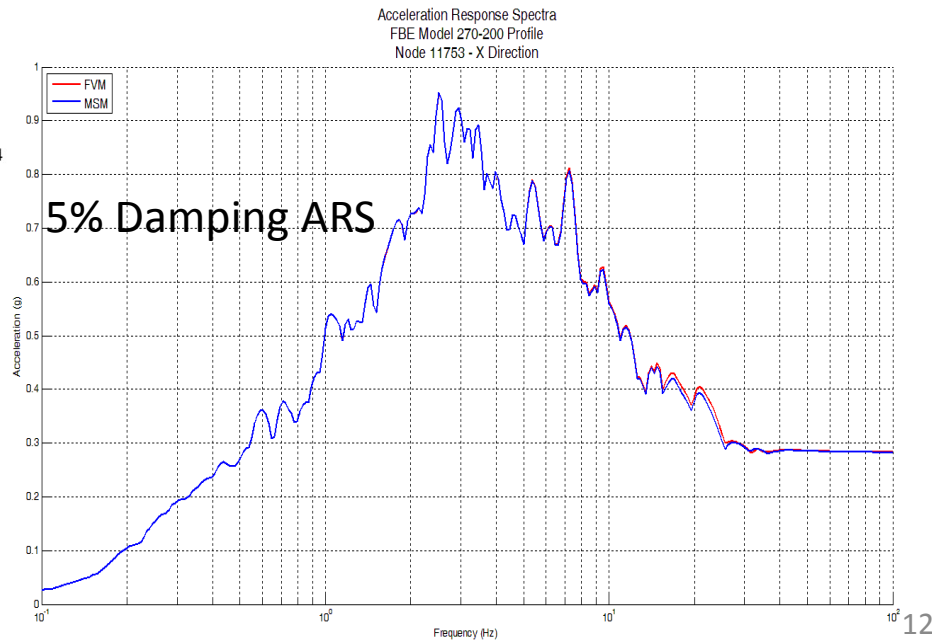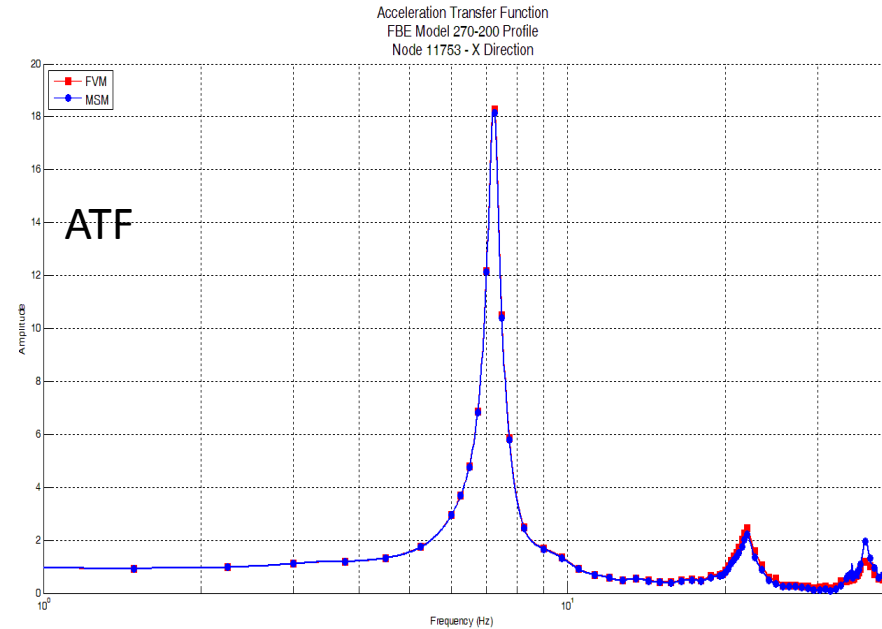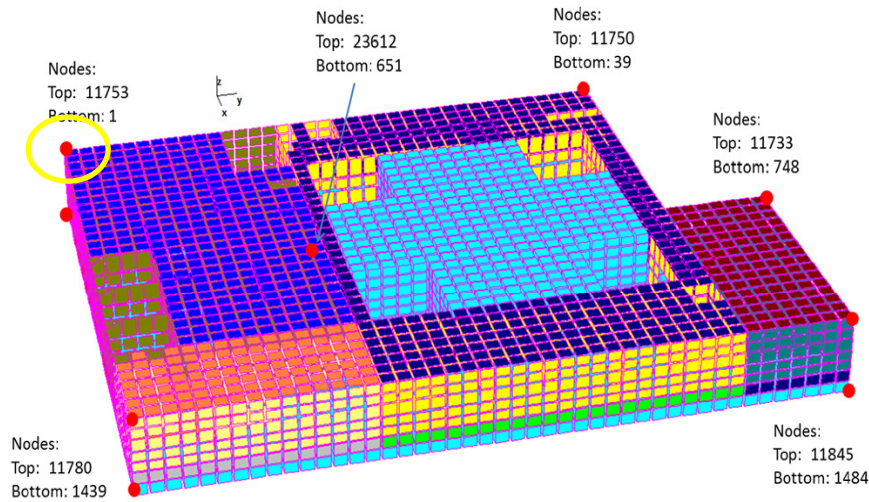
Y Length: 363.833 ft.

Complete SSI Analysis Using RB Complex SSI Model

RB Complex SSI Model

Acceleration Transfer Function
560-500 Profile
MSM: 40527, FVM: 31007 - X Direction

ATF

Acceleration Response Spectra
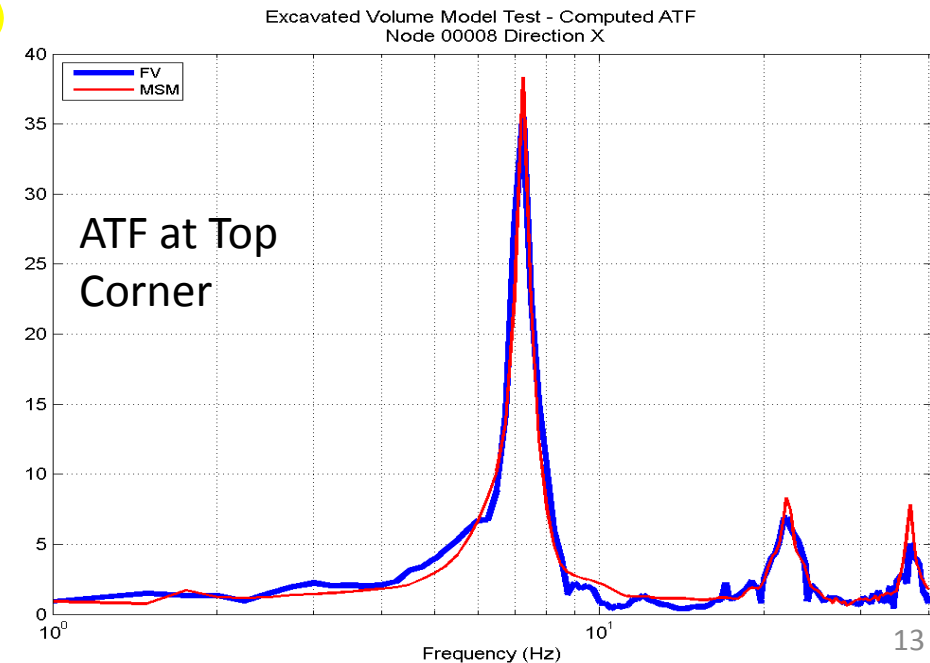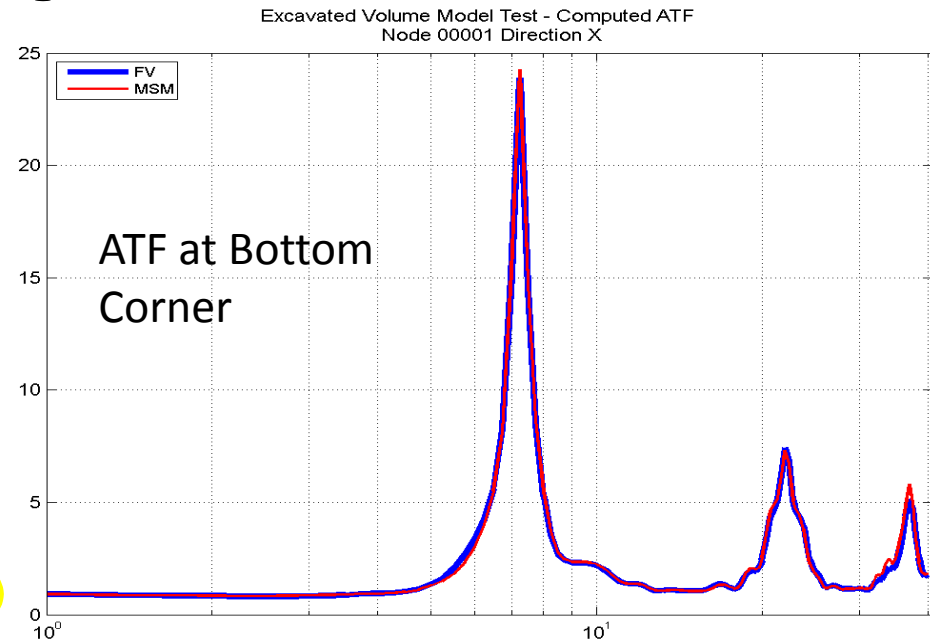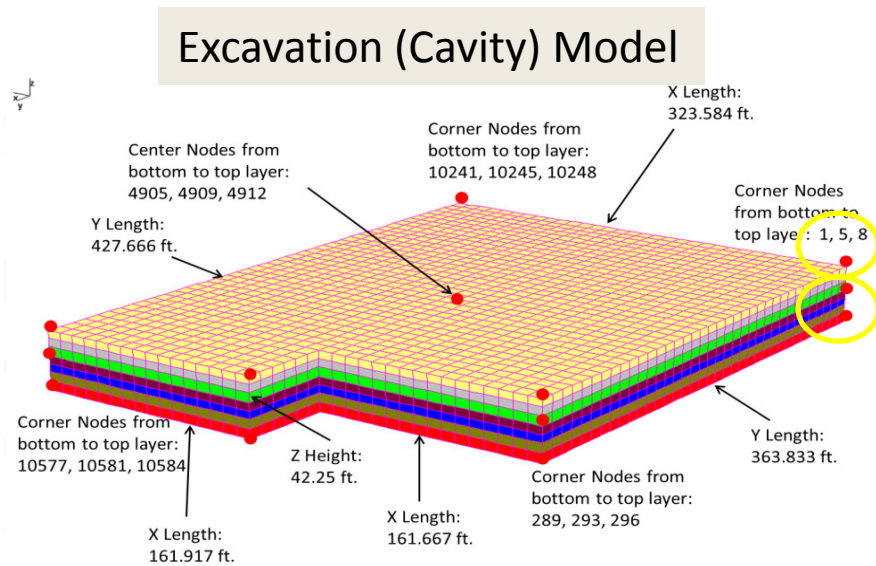560-500 Profile at
MSM: 40527, FVM: 31007 - X Direction

5% Damping ARS
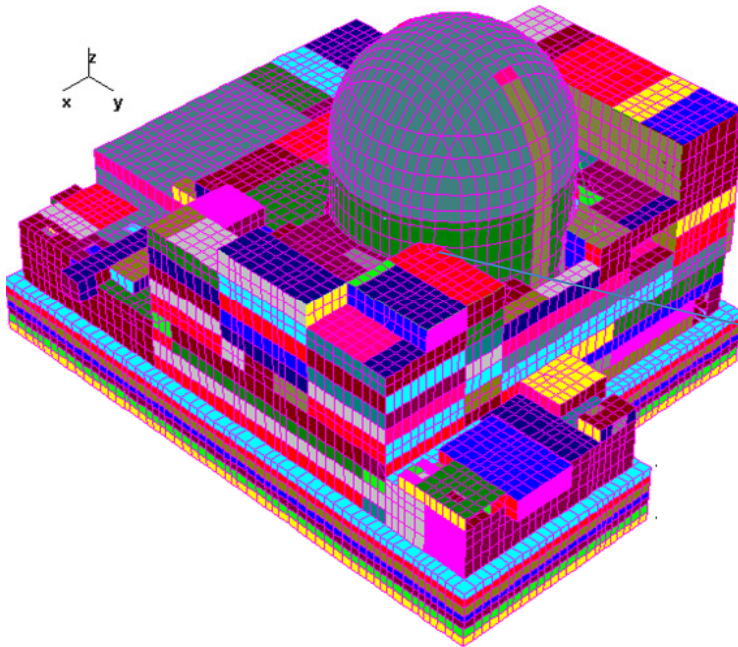
Kinematic SSI Analysis Using RB Foundation Model

Massless Foundation SSI Model

ATF

5% Damping ARS

12

Wave Analysis Using RB Excavation Model

Excavation (Cavity) Model

ATF at Bottom Corner

ATF at Top Corner

Fast FV (FFV) Methods for Embedded Structures

**Excavated Soil Interaction Nodes
Configuration for MSM**
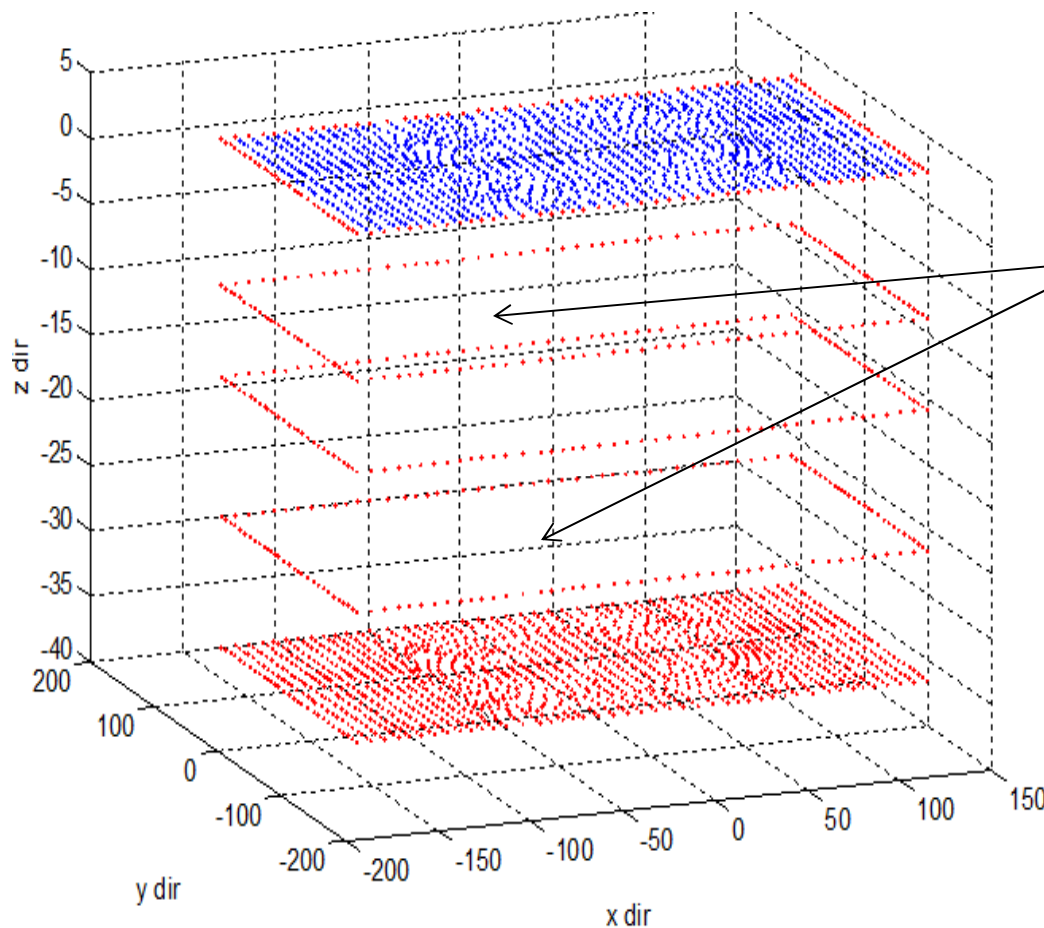
Internal Nodes

Fast FV methods include additional interaction nodes selected from the excavated soil internal nodes

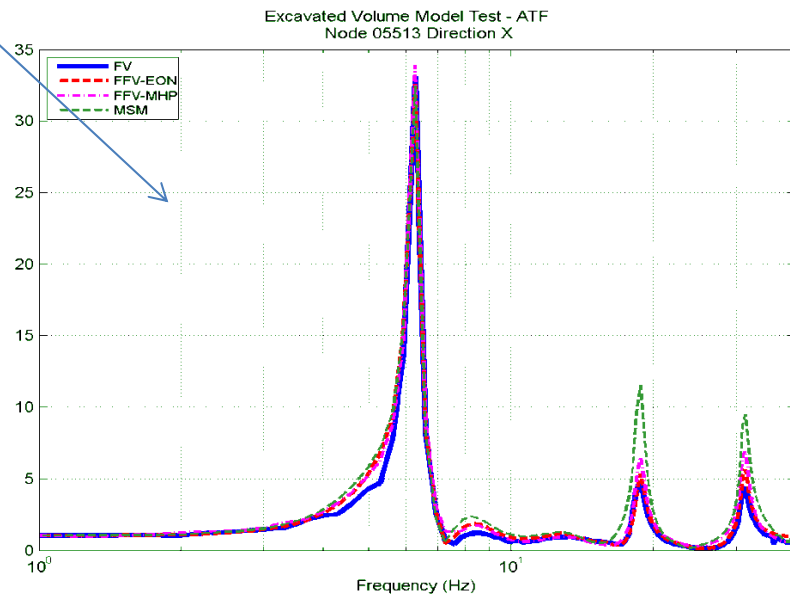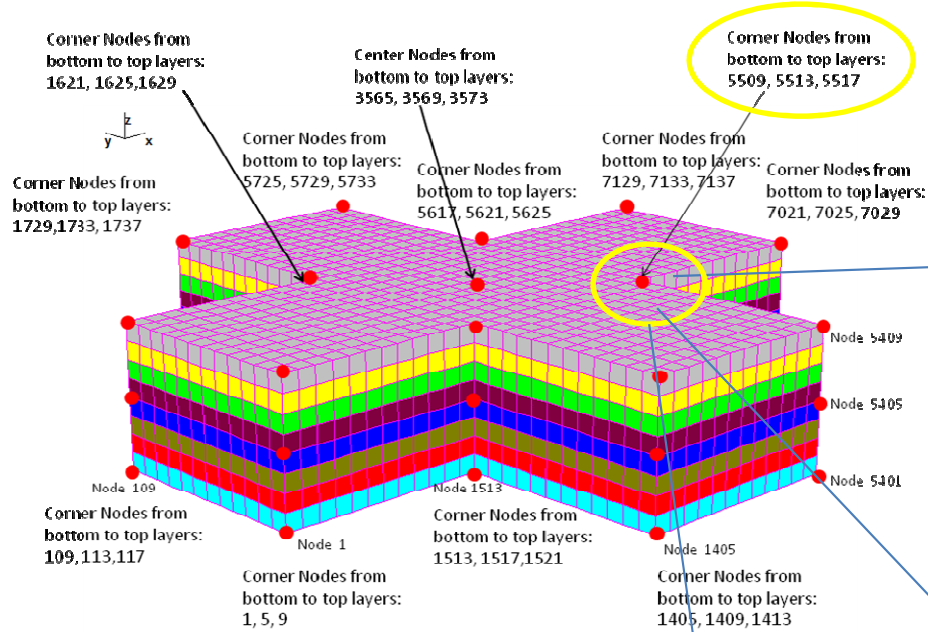# Cross-Shaped Excavation Cavity Study (180 ft x 180 ft x 50ft)
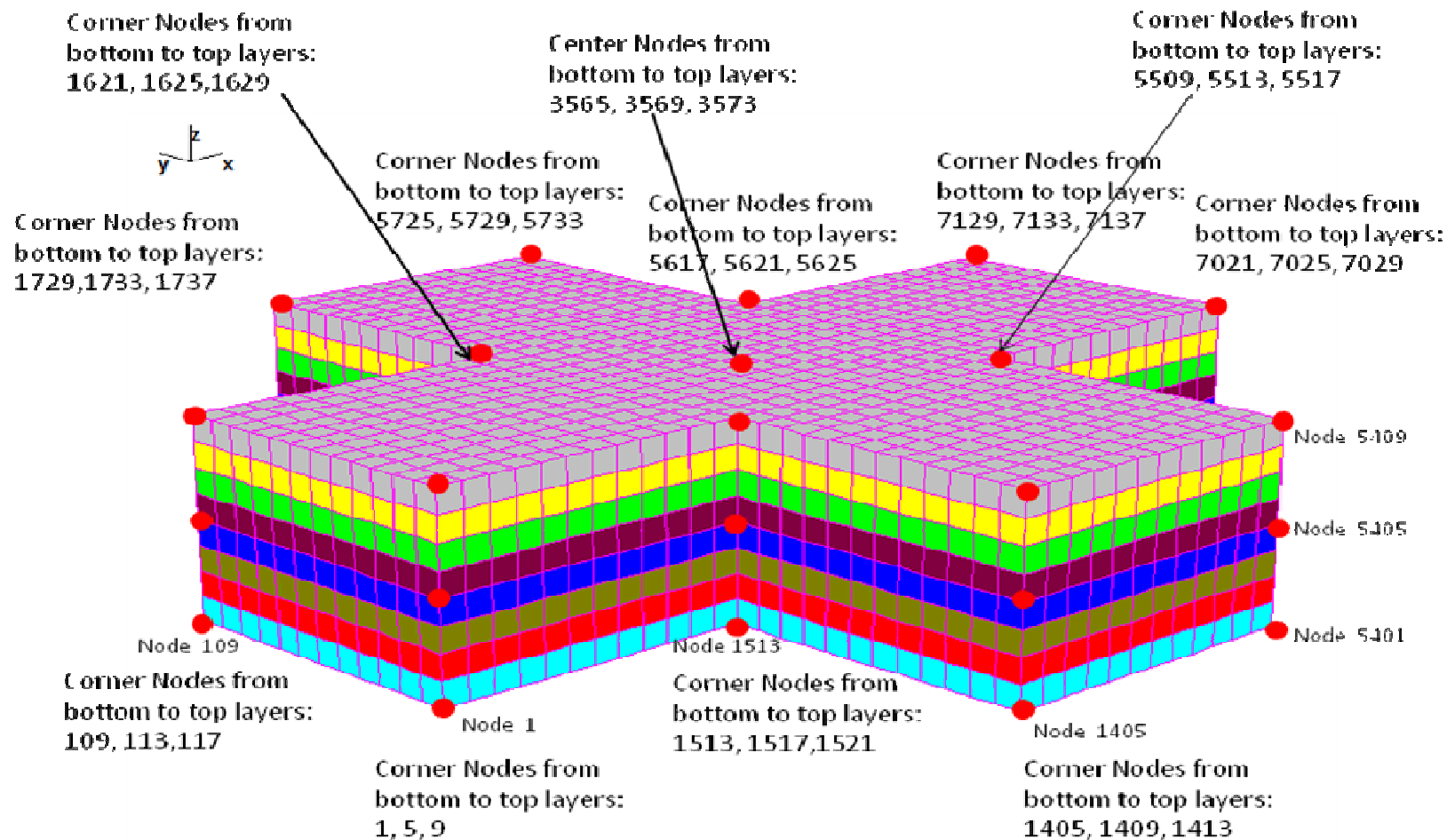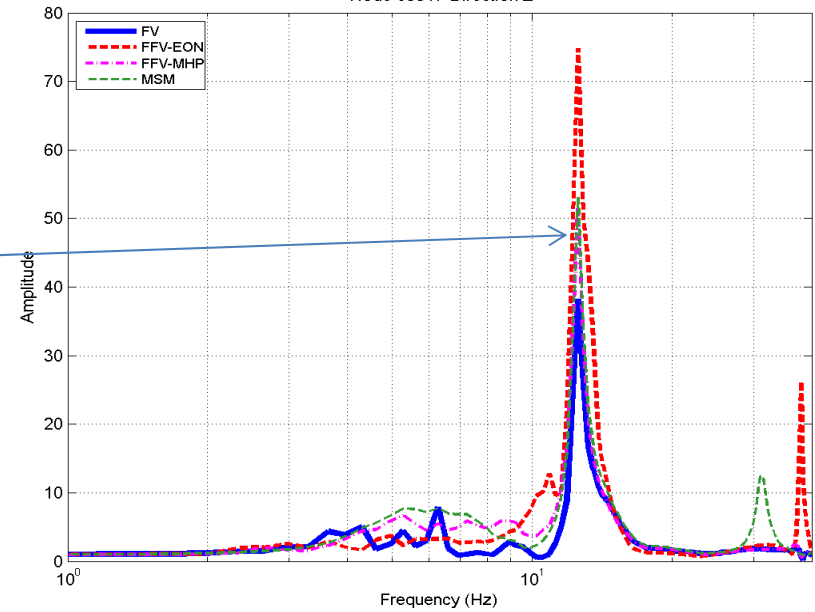
MSM vs. FFV vs. FV Methods: Horizontal ATF
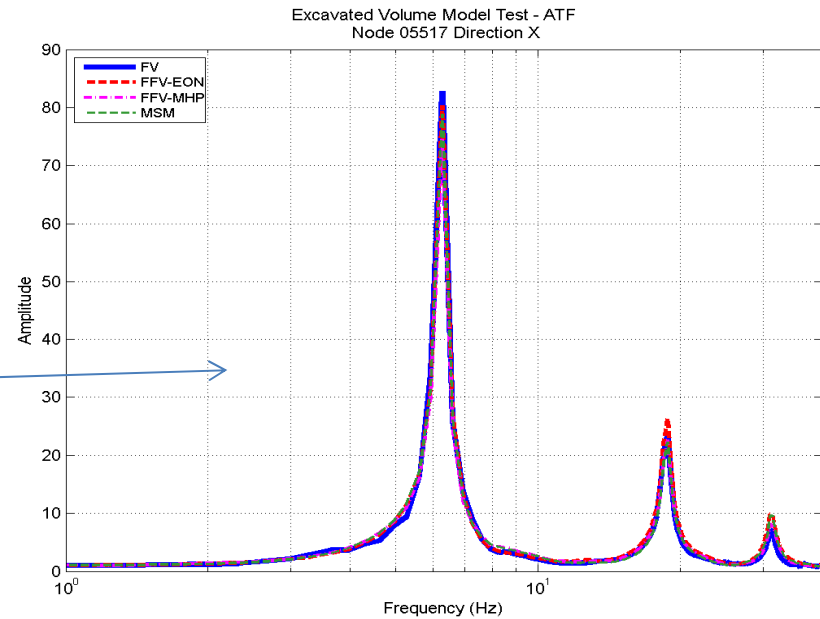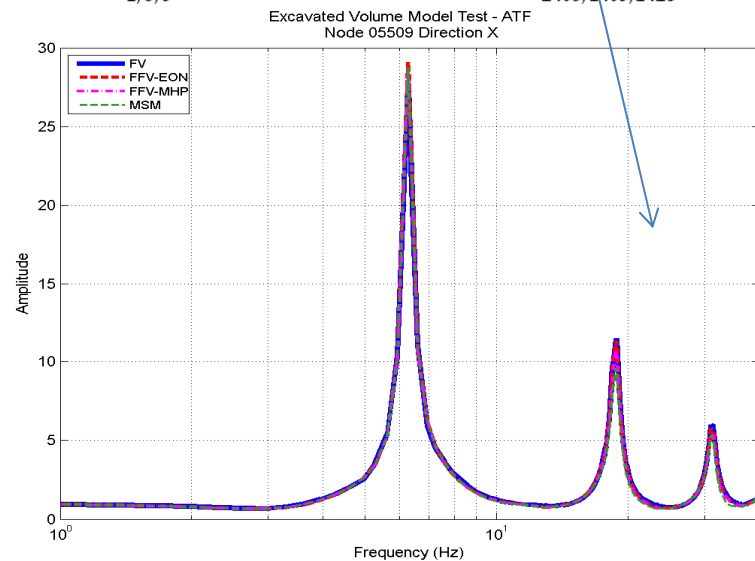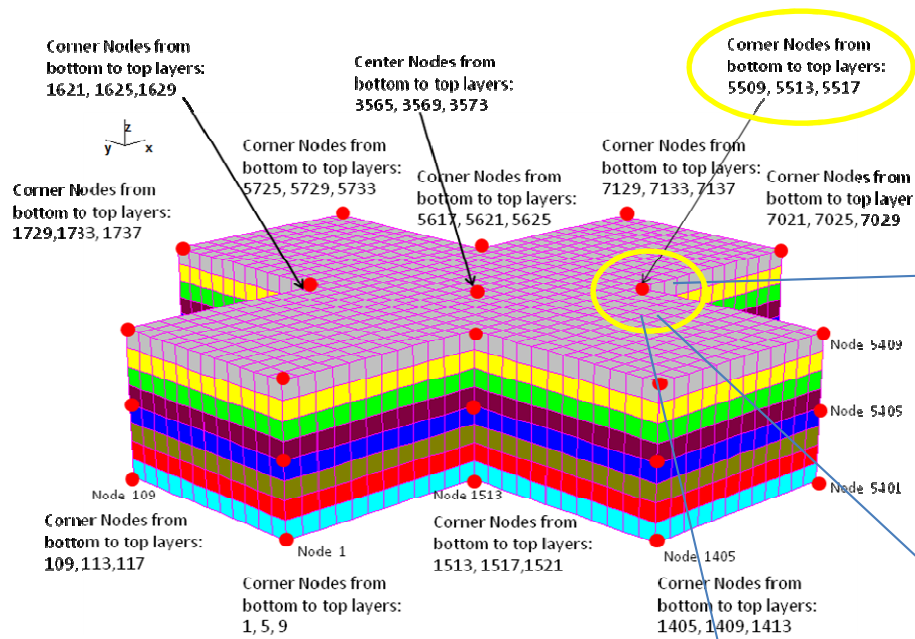
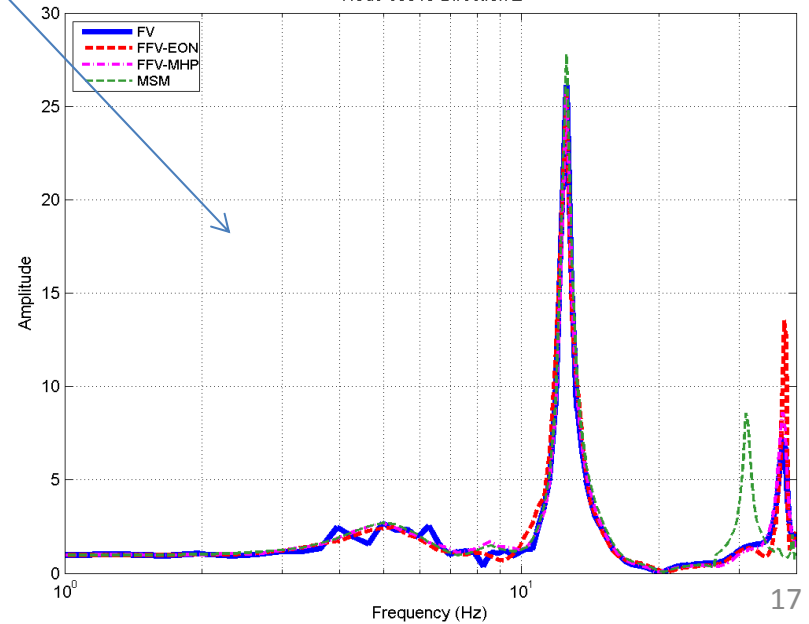# MSM vs. FFV vs. FV Methods: Vertocal ATF
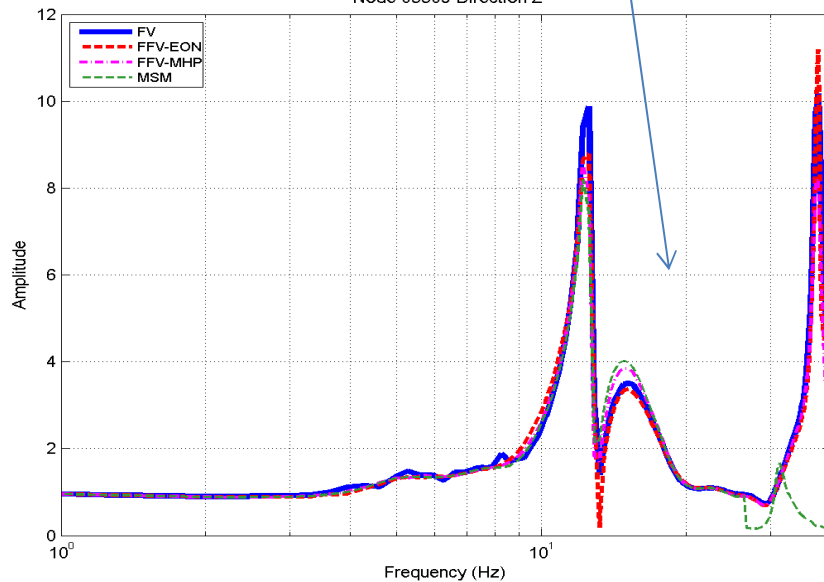
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Deeply Embedded Excavation Models

Excavated Soil

Massless Foundation

Uniform Soil

A

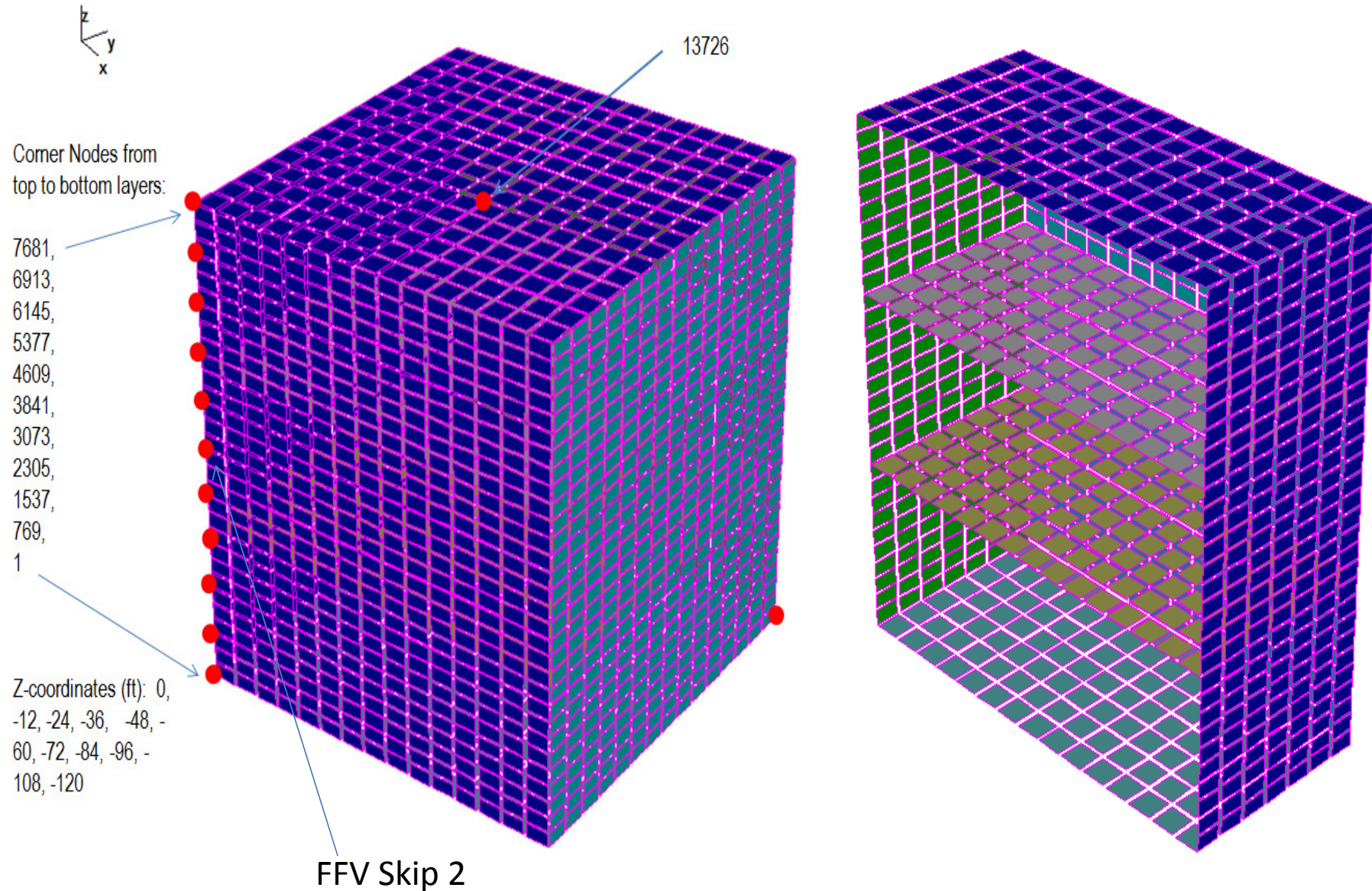| Layer	Thickness	Depth	Unit Weight	P-Wave Velocity	S-Wave Velocity	P-Wave Damping Ratio	S-Wave Damping Ratio
1	4	4	0.1	2000	1000	0.02	0.02
2	4	8	0.1	2000	1000	0.02	0.02
3	4	12	0.1	2000	1000	0.02	0.02
4	4	16	0.1	2000	1000	0.02	0.02
5	4	20	0.1	2000	1000	0.02	0.02
6	4	24	0.1	2000	1000	0.02	0.02
7	4	28	0.1	2000	1000	0.02	0.02
8	4	32	0.1	2000	1000	0.02	0.02
9	4	36	0.1	2000	1000	0.02	0.02
10	4	40	0.1	2000	1000	0.02	0.02
11	4	44	0.1	2000	1000	0.02	0.02
12	4	48	0.1	2000	1000	0.02	0.02
13	4	52	0.1	2000	1000	0.02	0.02
14	4	56	0.1	2000	1000	0.02	0.02
15	4	60	0.1	2000	1000	0.02	0.02
16	4	64	0.1	2000	1000	0.02	0.02
17	4	68	0.1	2000	1000	0.02	0.02
18	4	72	0.1	2000	1000	0.02	0.02
19	4	76	0.1	2000	1000	0.02	0.02
20	4	80	0.1	2000	1000	0.02	0.02
21	4	84	0.1	2000	1000	0.02	0.02
22	4	88	0.1	2000	1000	0.02	0.02
23	4	92	0.1	2000	1000	0.02	0.02
24	4	96	0.1	2000	1000	0.02	0.02
25	4	100	0.1	2000	1000	0.02	0.02
26	4	104	0.1	2000	1000	0.02	0.02
27	4	108	0.1	2000	1000	0.02	0.02
28	4	112	0.1	2000	1000	0.02	0.02
29	4	116	0.1	2000	1000	0.02	0.02
30	4	120	0.1	2000	1000	0.02	0.02
Halfspace							
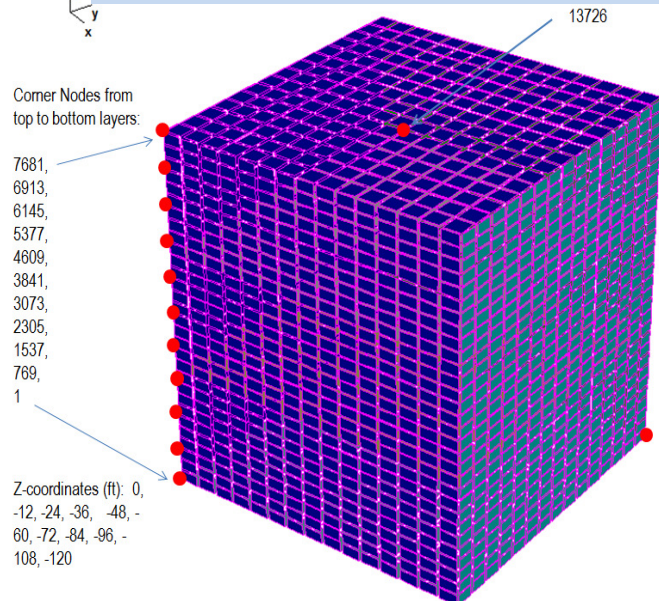
B Non-Uniform Soil

Layer	Thickness	Depth	Unit Weight	P-Wave Velocity	S-Wave Velocity	P-Wave Damping Ratio	S-Wave Damping Ratio
1	4	4	0.1	2000	1000	0.02	0.02
2	4	8	0.1	2000	1000	0.02	0.02
3	4	12	0.1	2000	1000	0.02	0.02
4	4	16	0.1	2000	1000	0.02	0.02
5	4	20	0.1	2000	1000	0.02	0.02
6	4	24	0.1	2000	1000	0.02	0.02
7	4	28	0.1	2000	1000	0.02	0.02
8	4	32	0.1	2000	1000	0.02	0.02
9	4	36	0.1	2000	1000	0.02	0.02
10	4	40	0.1	2000	1000	0.02	0.02
11	4	44	0.1	2000	1000	0.02	0.02
12	4	48	0.1	2000	1000	0.02	0.02
13	4	52	0.1	5000	10000	0.02	0.02
14	4	56	0.1	5000	10000	0.02	0.02
15	4	60	0.1	5000	10000	0.02	0.02
16	4	64	0.1	5000	10000	0.02	0.02
17	4	68	0.1	5000	10000	0.02	0.02
18	4	72	0.1	5000	10000	0.02	0.02
19	4	76	0.1	5000	10000	0.02	0.02
20	4	80	0.1	5000	10000	0.02	0.02
21	4	84	0.1	5000	10000	0.02	0.02
22	4	88	0.1	5000	10000	0.02	0.02
23	4	92	0.1	5000	10000	0.02	0.02
24	4	96	0.1	5000	10000	0.02	0.02
25	4	100	0.1	5000	10000	0.02	0.02
26	4	104	0.1	5000	10000	0.02	0.02
27	4	108	0.1	5000	10000	0.02	0.02
28	4	112	0.1	5000	10000	0.02	0.02
29	4	116	0.1	5000	10000	0.02	0.02
30	4	120	0.1	5000	10000	0.02	0.02
Halfspace							

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Masless Foundation Deeply Embedded Model

13726

Corner Nodes from
top to bottom layers:

7681,
6913,
6145,
5377,
4609,
3841,
3073,
2305,
1537,
769,
1

Z-coordinates (ft): 0,
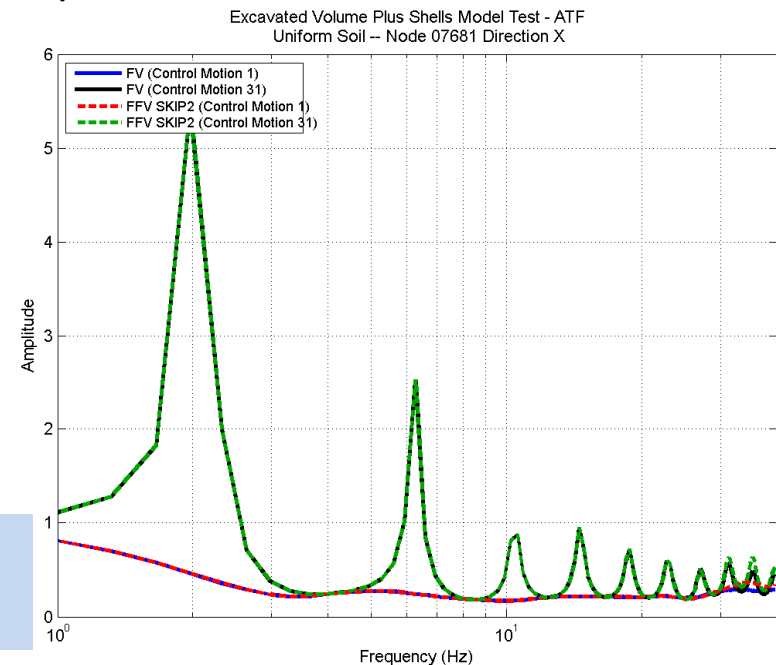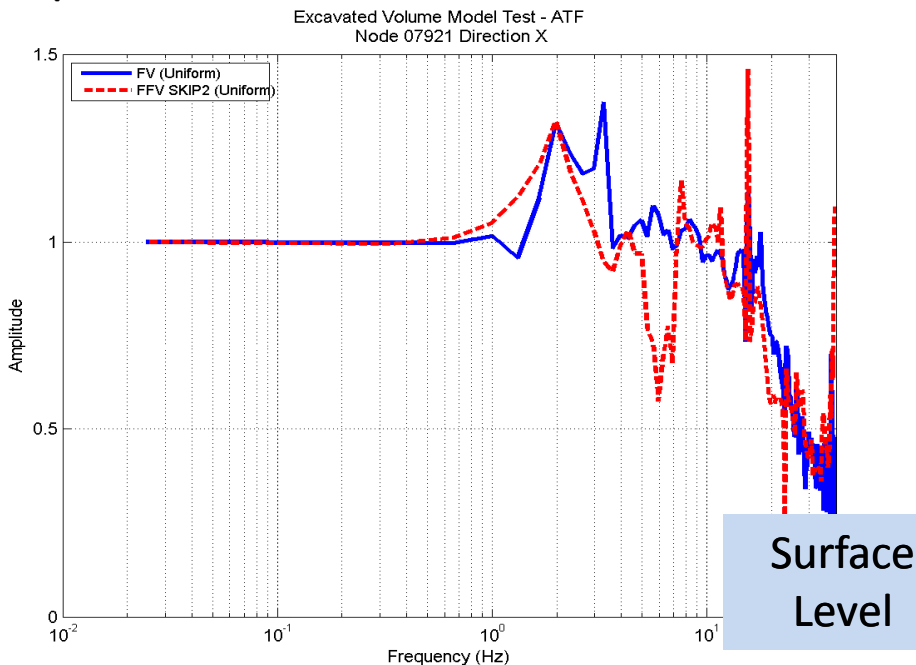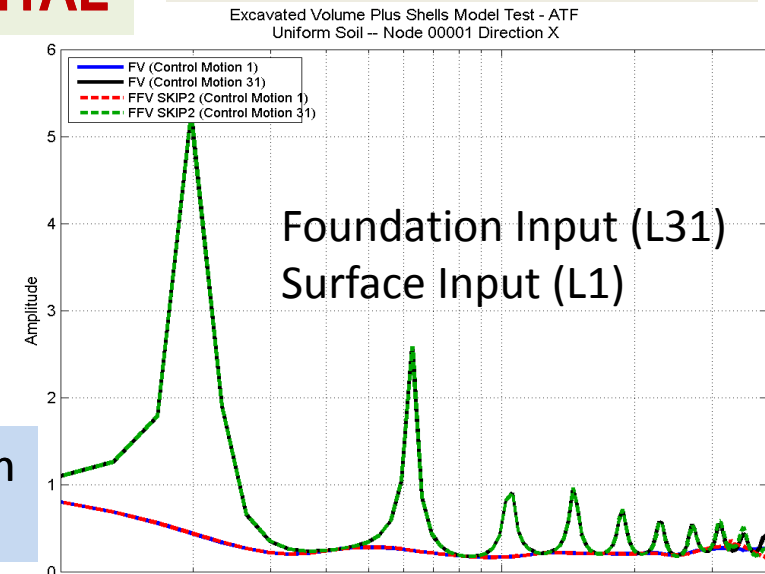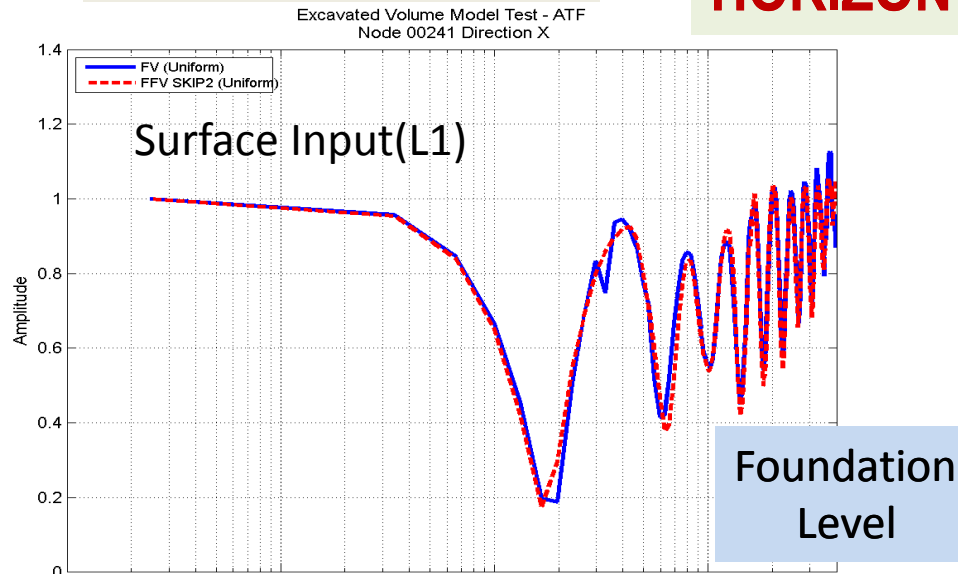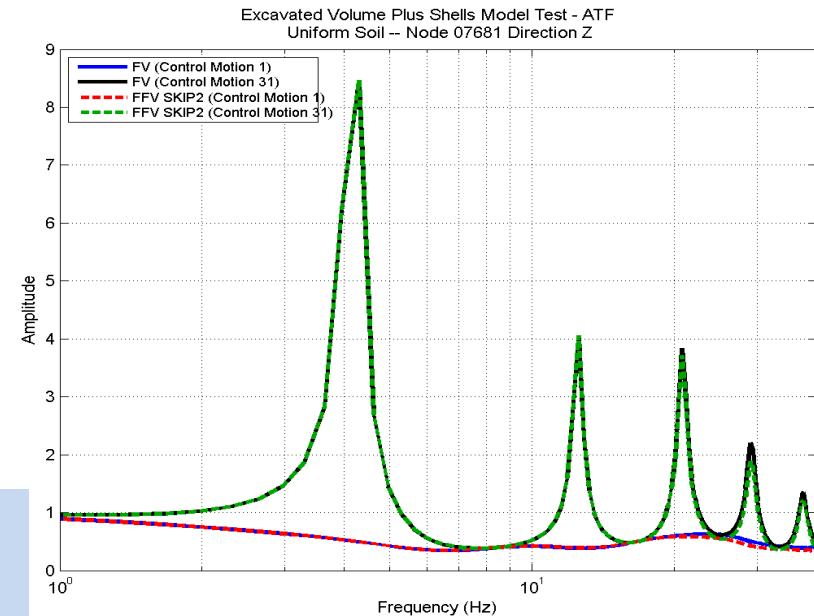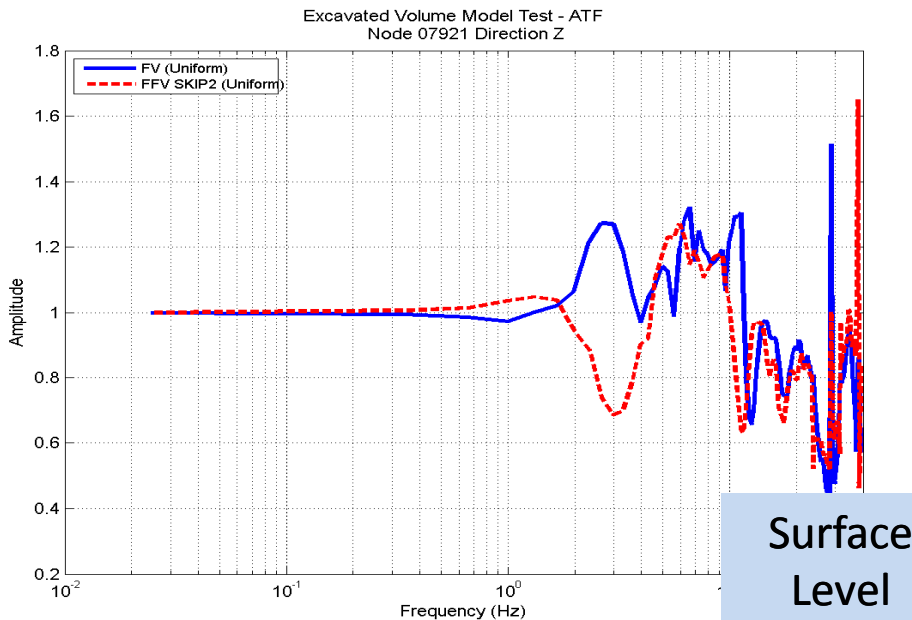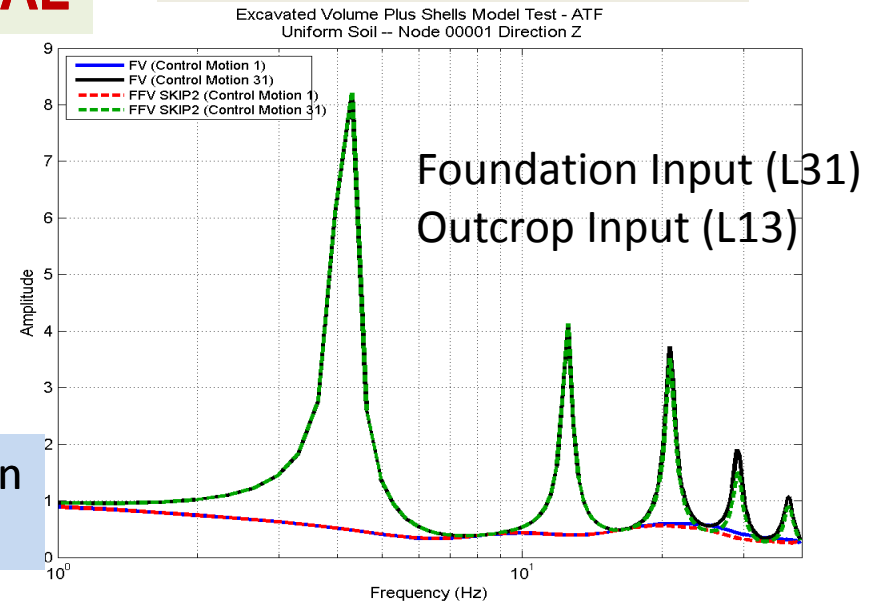-12, -24, -36, -48, -
60, -72, -84, -96, -
108, -120

FFV Skip 2

19

Excavation vs. Massless Foundation Models for Uniform Soil

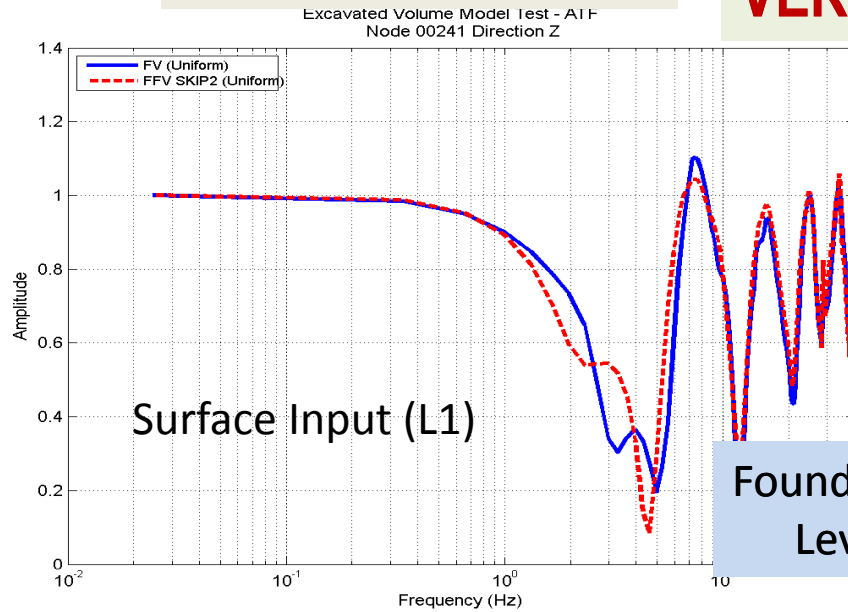Excavation Cavity Model

HORIZONTAL

Massless Foundation Model

Excavation vs. Massless Foundation Models for Uniform Soil

Excavation Cavity Model **VERTICAL** Massless Foundation Model
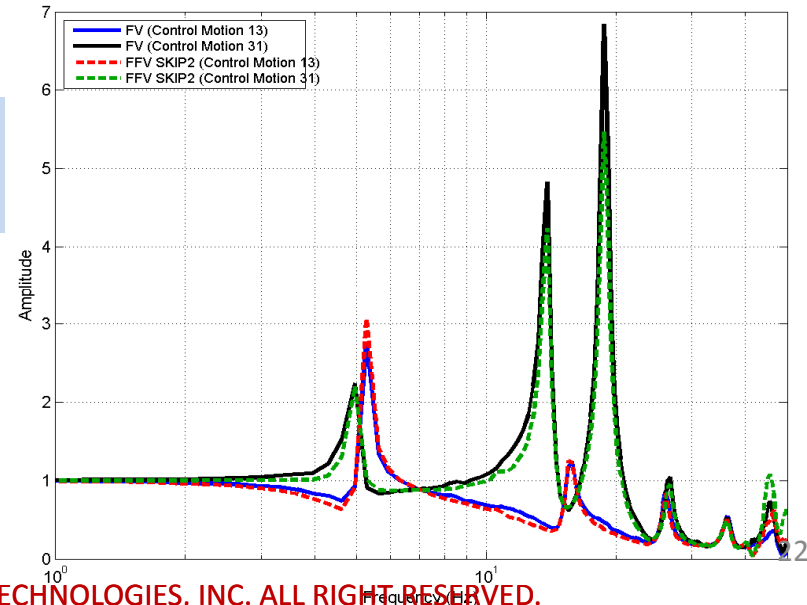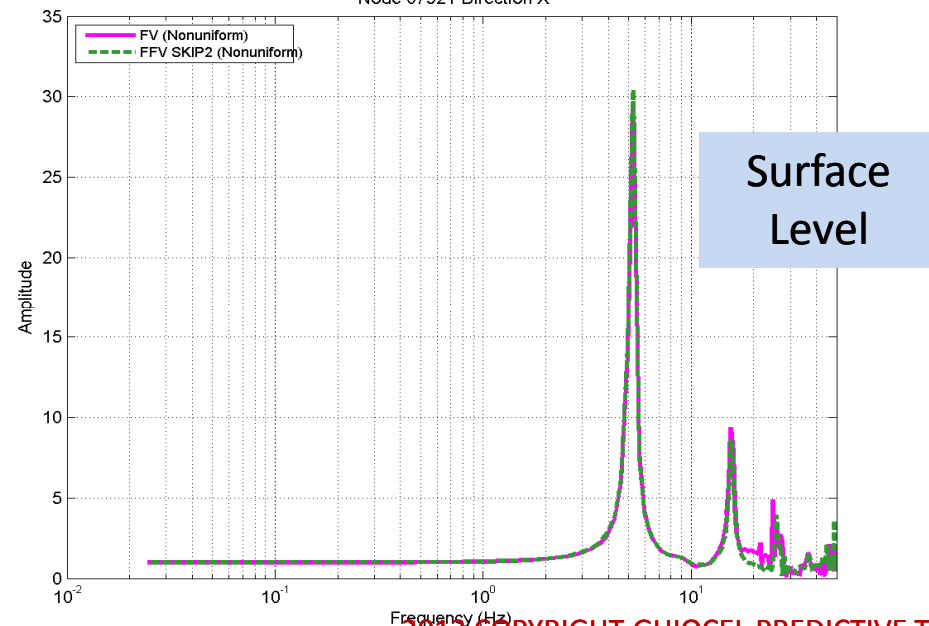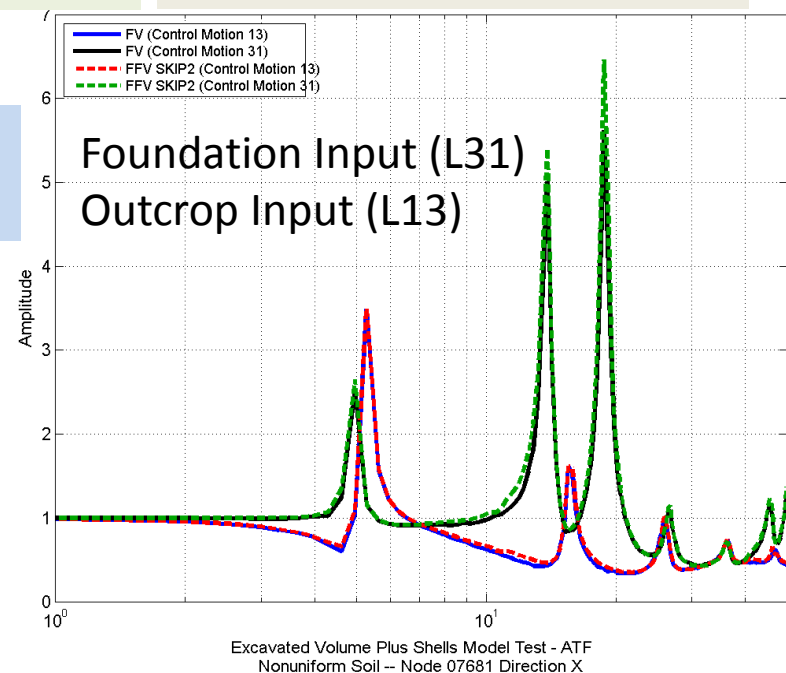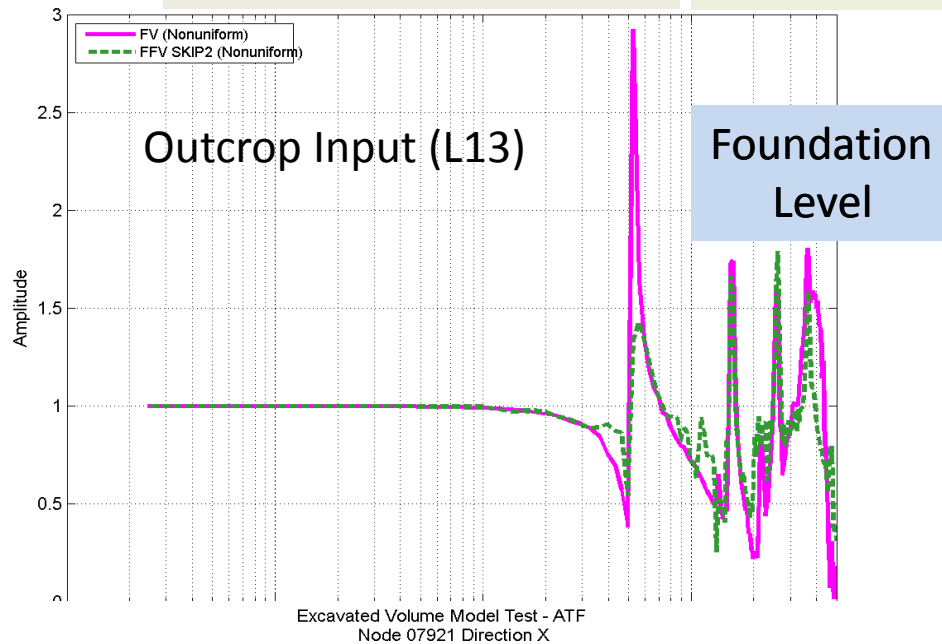
Excavation vs. Massless Foundation for Non-Uniform Soil

Excavation Cavity Model   **HORIZONTAL**   Massless Foundation Model

Outcrop Input (L13)   Foundation Level

Foundation Input (L31)
Outcrop Input (L13)

Surface Level

Excavated Volume Model Test - ATF
Node 07921 Direction X

Excavated Volume Plus Shells Model Test - ATF
Nonuniform Soil -- Node 07681 Direction X

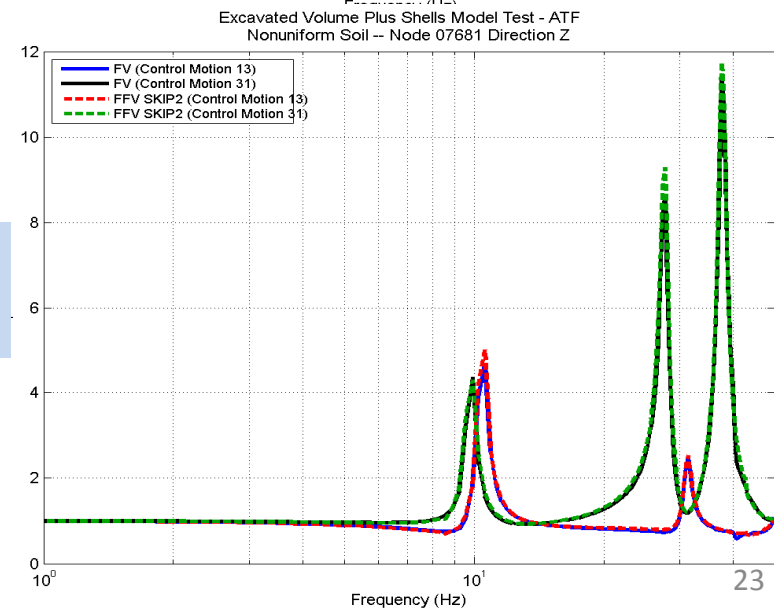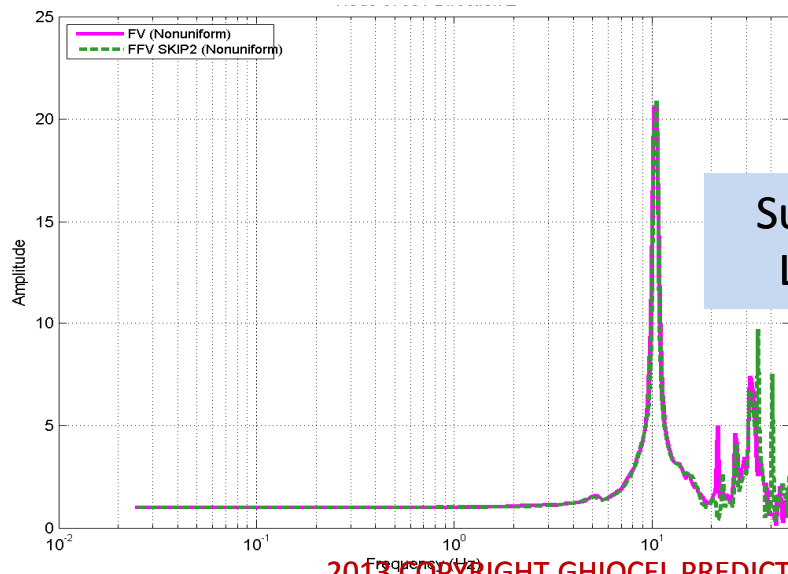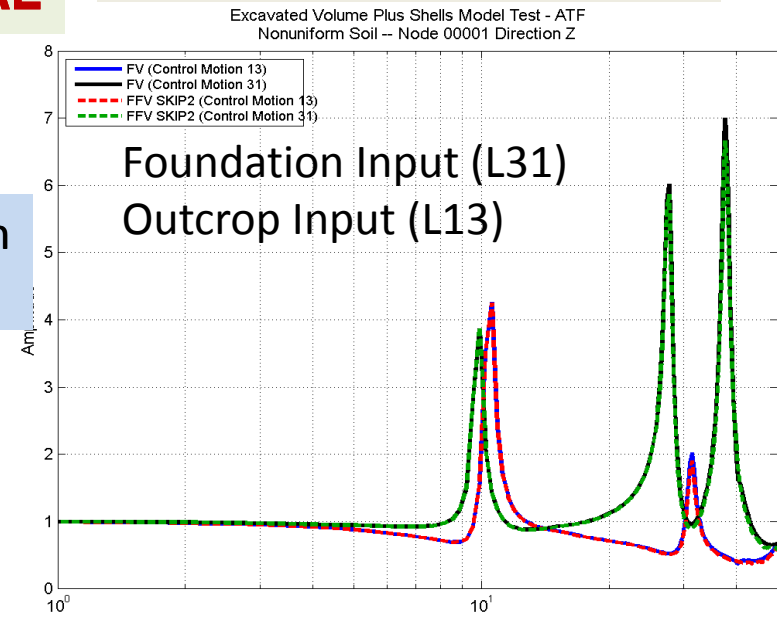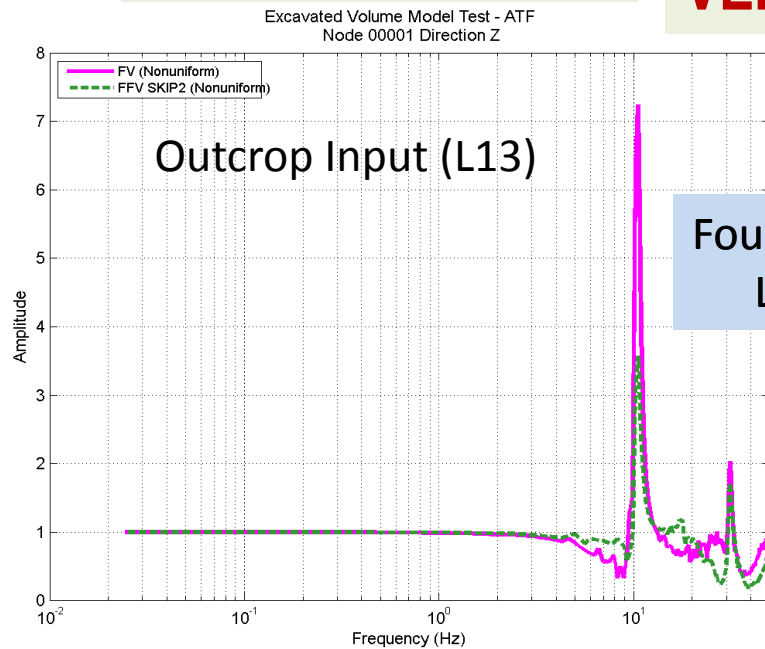# Excavation vs. Massless Foundation for Non-Uniform Soil

Excavation Cavity Model   **VERTICAL**   Massless Foundation Model

Conclusions

- MSM is a highly accurate and robust SSI approach for large-size embedded foundations, as nuclear island (NI) complex foundations. MSM is much more robust than SM.

- MSM could break down for deeply embedded foundations on a case-by-case basis.

- FV or FFV should be used for deeply embedded foundations, especially for soft soil layers above stiff soil or rock formations.

- The use of excavation cavity models to evaluate the accuracy of MSM or FFV for SSI analyses can be less practical, since they can provide "false alarms".