Tsinghua University
Hydraulic engineering department

Real-time dynamic hybrid testing for soil-structure interaction analysis

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CONTENTS

1 Introduction of soil-structure interaction

Soil and structure should be considered as a whole system in dynamic analysis.

Direct method

- the structure and soil are treated as a whole system.
- The region of the soil adjacent to the structure-soil interface is also explicitly modeled.
- Artificial boundary must be introduced so as to cover the unbounded soil domain.

Substructure method

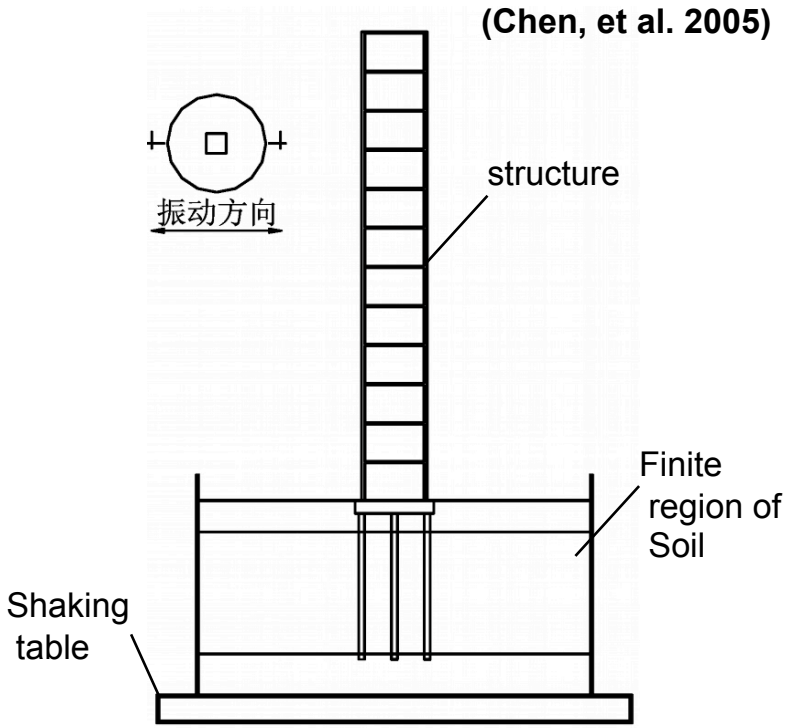
- the structure and the soil are treated as two different substructures.
- Each substructure can be analyzed using a best-suited computational technique.
- Combining the force-displacement relationship of the soil with the discretized motion equation of the structure, results in the final system of equation of the total dynamic system.

1 Introduction of soil-structure interaction

Considering SSI in shaking-table tests is still a problematic option.

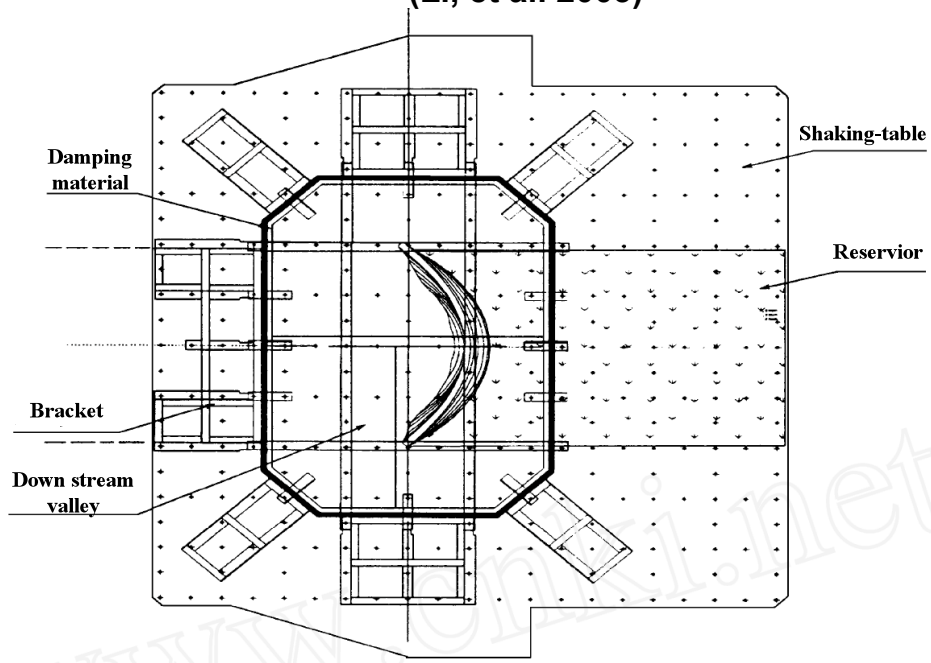
Model box with finite region of soil

(Chen, et al. 2005)



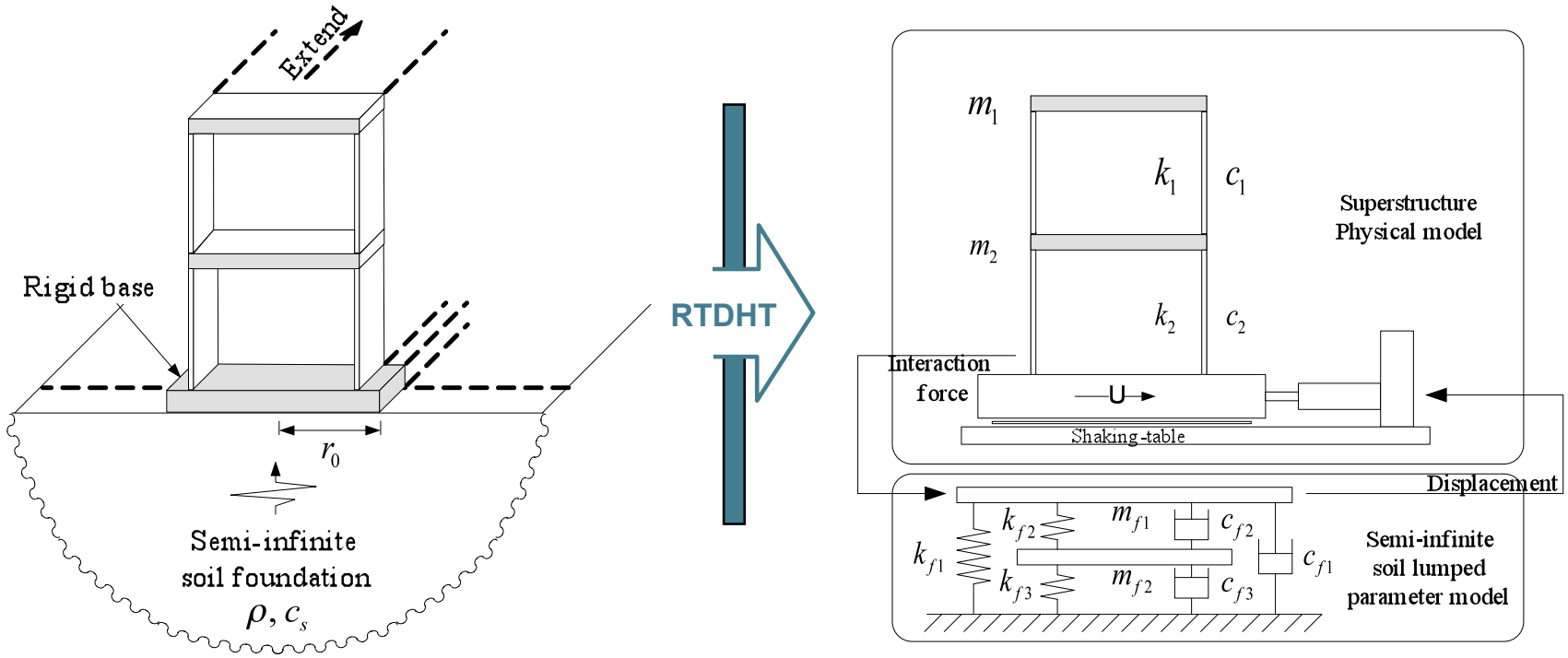
Model boundary with damping material

(Li, et al. 2003)

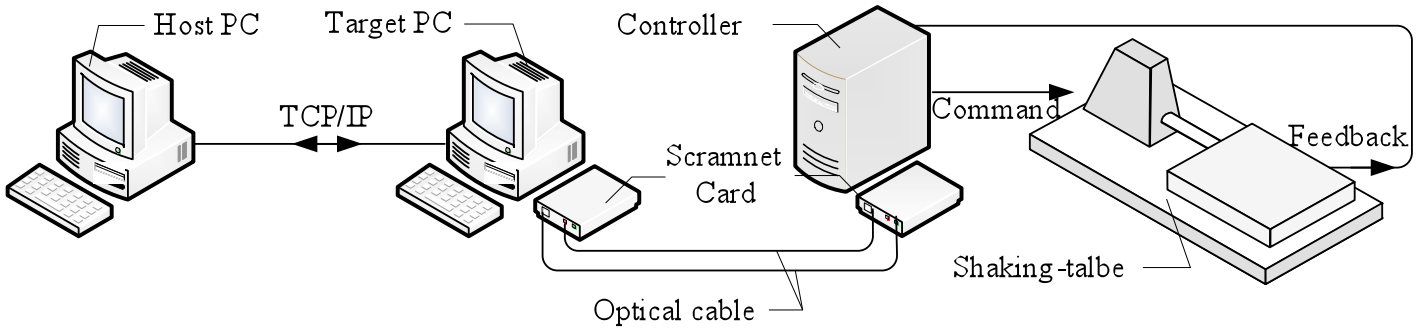


1 Introduction of soil-structure interaction

Combining the numerical calculations of semi-infinite soil together with superstructure large scale model testing.



2 RTDHT system in Tsinghua University



Distributed real-time calculation system

- Host PC – Ordinary computer with Windows operating system
- Target PC – Ordinary computer without Windows operating system (but xPC kernel)
- Software – Matlab, Simulink, Real-time workshop, xPC target

Shared common RAM network

- SCRAMNet card SC150
- Optical cable
- high-speed: 16.7 Mb/s
- ultra-low-latency: 250 ns

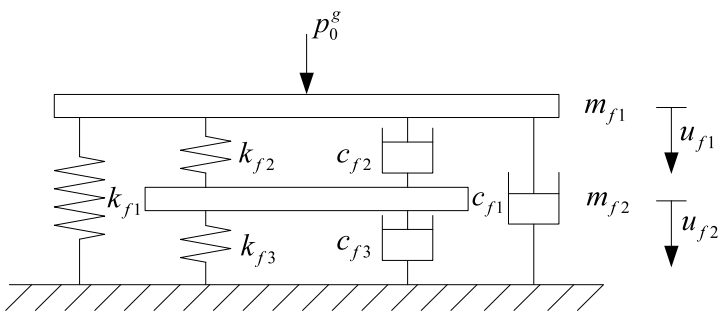
Shaking table loading system

- Area: 1.5m ×1.5 m
- Bearing capacity: 2 t
- Max acceleration: 3.6 g (bare table) 1.2 g (full loaded)
- Frequency: 0~50 Hz
- MTS 469D controller: Mathworks' Simulink is integrated into the controller platform

3 Soil-structure interaction model

Lumped parameter model used in this paper

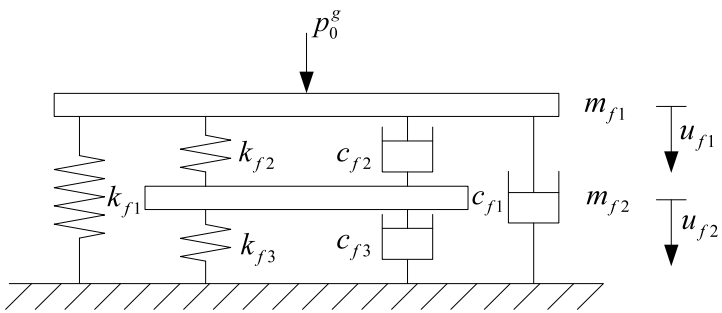
Luan Maotian & Lin Gao **1996**



$$M_f\ddot{U}_f + C_f\dot{U}_f + K_fU_f = P_f$$

3 Soil-structure interaction model

Lumped parameter model used in this paper



$$M_f \ddot{U}_f + C_f \dot{U}_f + K_f U_f = P_f$$

$$M_f = M_{fe} \begin{bmatrix} m_{f1}^* & \\ & m_{f2}^* \end{bmatrix} \Rightarrow M_{fe} = K_s \cdot \left(\frac{r_0}{c_s} \right)^2$$

$$C_f = C_{fe} \begin{bmatrix} c_{f1}^* + c_{f2}^* & -c_{f2}^* \\ -c_{f2}^* & c_{f2}^* + c_{f3}^* \end{bmatrix} \Rightarrow C_{fe} = K_s \cdot \frac{r_0}{c_s}$$

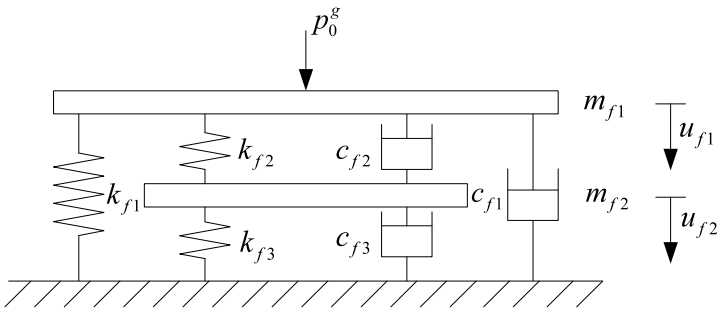
$$K_f = K_{fe} \begin{bmatrix} k_{f1}^* + k_{f2}^* & -k_{f2}^* \\ -k_{f2}^* & k_{f2}^* + k_{f3}^* \end{bmatrix} \Rightarrow K_{fe} = K_s = \pi \rho c_s^2$$

$$U_f = \begin{bmatrix} U_{f1} & U_{f2} \end{bmatrix}^T \qquad P_f = \begin{bmatrix} P_{f1} & P_{f2} \end{bmatrix}^T$$

3 Soil-structure interaction model

Dynamic stiffness coefficient

If the system is excited by harmonic force, the external force and displacement vector can be rewritten as follows:



$$P_f = \begin{bmatrix} P_{f0} & 0 \end{bmatrix}^T e^{i\omega t}$$

$$U_f = \begin{bmatrix} U_{f1,0} & U_{f2,0} \end{bmatrix}^T e^{i\omega t}$$

$$K(\omega) = P_{f0} / U_{f1,0}$$

$$K(a_0)/K_s = k(a_0) + i a_0 c(a_0)$$

$$= \left[k_{f1}^* + k_{f2}^* - a_0^2 m_{f1}^* - \frac{\left(k_{f2}^{*\,2} - a_0^2 c_{f2}^{*\,2}\right)\left(k_{f2}^* + k_{f3}^* - a_0^2 m_{f2}^*\right) + 2a_0^2 k_{f2}^* c_{f2}^* \left(c_{f2}^* + c_{f3}^*\right)}{\left(k_{f2}^* + k_{f3}^* - a_0^2 m_{f2}^*\right)^2 + a_0^2 \left(c_{f2}^* + c_{f3}^*\right)^2} \right]$$

$$+ i a_0 \left[c_{f1}^* + c_{f2}^* - \frac{2k_{f2}^* c_{f2}^* \left(k_{f2}^* + k_{f3}^* - a_0^2 m_{f2}^*\right) - \left(c_{f2}^* + c_{f3}^*\right)\left(k_{f2}^{*\,2} - a_0^2 c_{f2}^{*\,2}\right)}{\left(k_{f2}^* + k_{f3}^* - a_0^2 m_{f2}^*\right)^2 + a_0^2 \left(c_{f2}^* + c_{f3}^*\right)^2} \right]$$

3 Soil-structure interaction model

Dynamic stiffness coefficient

$$K(a_0)/K_s = k(a_0) + ia_0 c(a_0)$$

$$= \left[k_{f1}^* + k_{f2}^* - a_0^2 m_{f1}^* - \frac{\left(k_{f2}^{*\,2} - a_0^2 c_{f2}^{*\,2}\right)\left(k_{f2}^* + k_{f3}^* - a_0^2 m_{f2}^*\right) + 2a_0^2 k_{f2}^* c_{f2}^* \left(c_{f2}^* + c_{f3}^*\right)}{\left(k_{f2}^* + k_{f3}^* - a_0^2 m_{f2}^*\right)^2 + a_0^2 \left(c_{f2}^* + c_{f3}^*\right)^2} \right] + ia_0 \left[c_{f1}^* + c_{f2}^* - \frac{2k_{f2}^* c_{f2}^* \left(k_{f2}^* + k_{f3}^* - a_0^2 m_{f2}^*\right) - \left(c_{f2}^* + c_{f3}^*\right)\left(k_{f2}^{*\,2} - a_0^2 c_{f2}^{*\,2}\right)}{\left(k_{f2}^* + k_{f3}^* - a_0^2 m_{f2}^*\right)^2 + a_0^2 \left(c_{f2}^* + c_{f3}^*\right)^2} \right]$$

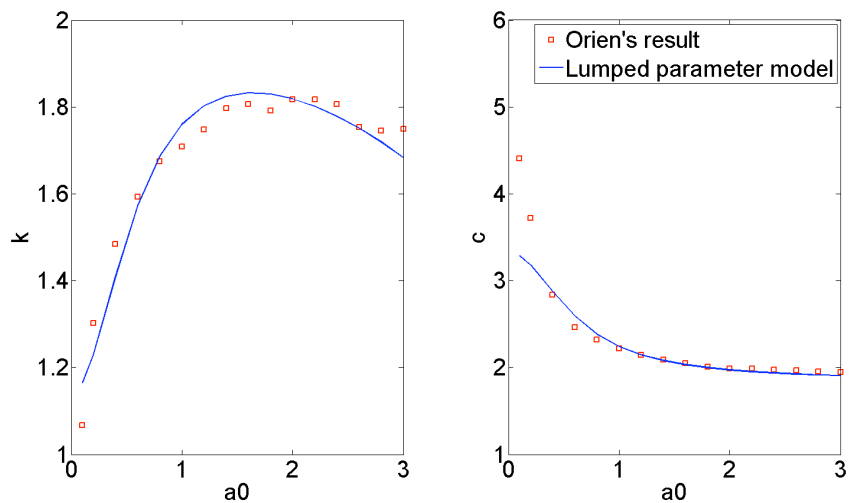
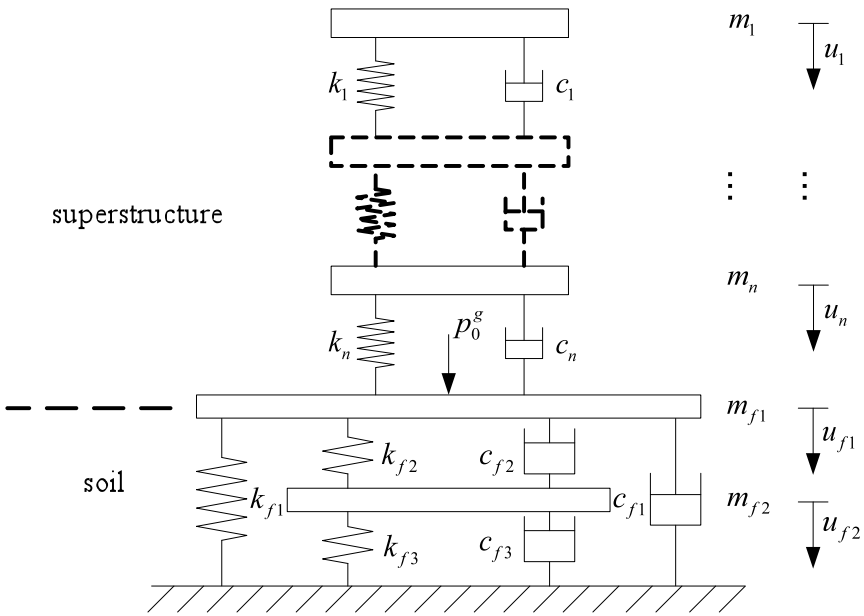


Table 1 Parameters of the lumped parameter model

m_{f1}^*	m_{f2}^*	k_{f1}^*	k_{f2}^*	k_{f3}^*	c_{f1}^*	c_{f2}^*	c_{f3}^*
0.035	0.150	1.423	0.716	-0.202	1.724	0.126	0.815

4 SSI-RTDHT test setup

1 Motion equation

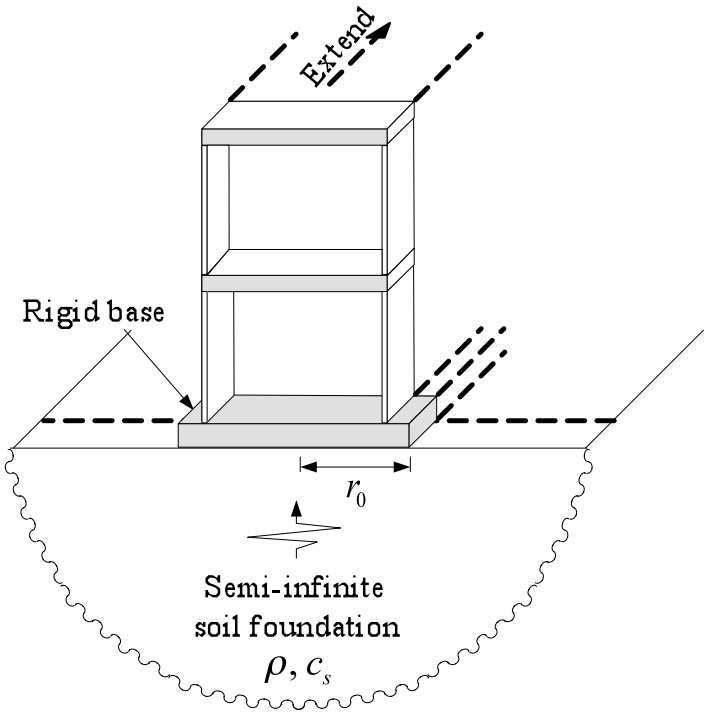


$$
\begin{bmatrix} m_1 & & & & \\ & \ddots & & & \\ & & m_n & & \\ & & & m_{f1} & \\ & & & & m_{f2} \end{bmatrix}
\begin{Bmatrix} \ddot{u}_1 \\ \vdots \\ \ddot{u}_n \\ \ddot{u}_{f1} \\ \ddot{u}_{f2} \end{Bmatrix}
+
\begin{bmatrix} c_1 & -c_1 & & & \\ -c_1 & \ddots & \ddots & & \\ & \ddots & c_{n-1}+c_n & -c_n & \\ & & -c_n & c_n+c_{f1}+c_{f2} & -c_{f2} \\ & & & -c_{f2} & c_{f2}+c_{f3} \end{bmatrix}
\begin{Bmatrix} \dot{u}_1 \\ \vdots \\ \dot{u}_n \\ \dot{u}_{f1} \\ \dot{u}_{f2} \end{Bmatrix}
+
$$

$$
\begin{bmatrix} k_1 & -k_1 & & & \\ -k_1 & \ddots & \ddots & & \\ & \ddots & k_{n-1}+k_n & -k_n & \\ & & -k_n & k_n+k_{f1}+k_{f2} & -k_{f2} \\ & & & -k_{f2} & k_{f2}+k_{f3} \end{bmatrix}
\begin{Bmatrix} u_1 \\ \vdots \\ u_n \\ u_{f1} \\ u_{f2} \end{Bmatrix}
=
\begin{Bmatrix} 0 \\ \vdots \\ 0 \\ p_0^g \\ 0 \end{Bmatrix}
$$

4 SSI-RTDHT test setup

2 Concretize



- Soil properties:
- Mass denscity $\rho=2000\ \mathrm{kg/m^3}$

- Soft Soil:

$c_s=200\ \mathrm{m/s}$

$K_{fe}=2.513\times10^8\ \mathrm{N/m}$

$C_{fe}=3.016\times10^7\ \mathrm{Ns/m}$

$M_{fe}=3.619\times10^6\ \mathrm{kg}$

- Hard Soil:

$c_s=800\ \mathrm{m/s}$

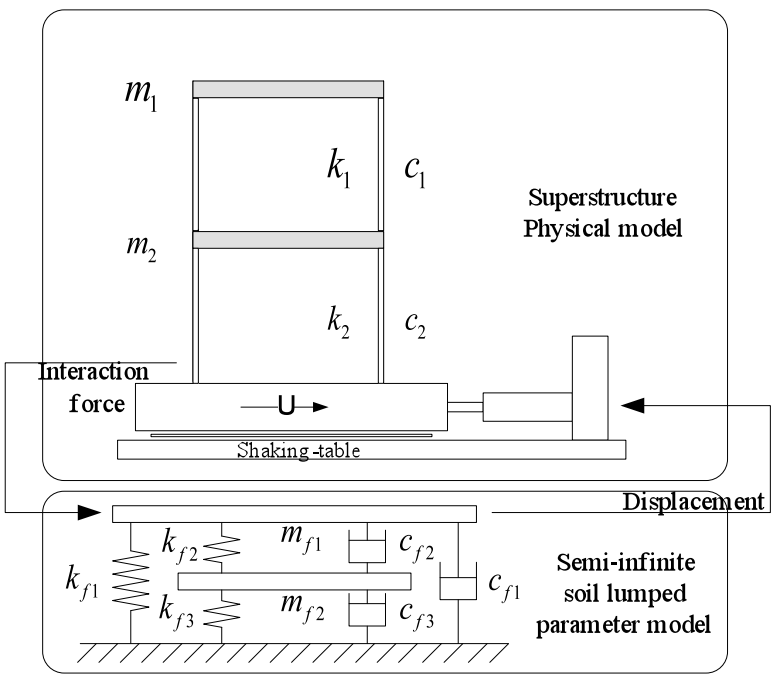
$K_{fe}=4.021\times10^9\ \mathrm{N/m}$

$C_{fe}=1.2064\times10^8\ \mathrm{Ns/m}$

$M_{fe}=3.619\times10^6\ \mathrm{kg}$

4 SSI-RTDHT test setup

3 Substructuring



1 Physical substructure

$$\begin{bmatrix} m_1 & \\ & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{Bmatrix}+\begin{bmatrix} c_1 & -c_1 \\ -c_1 & c_1 \end{bmatrix}\begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{Bmatrix}+\begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 \end{bmatrix}\begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix}=\begin{Bmatrix} 0 \\ -T \end{Bmatrix}$$

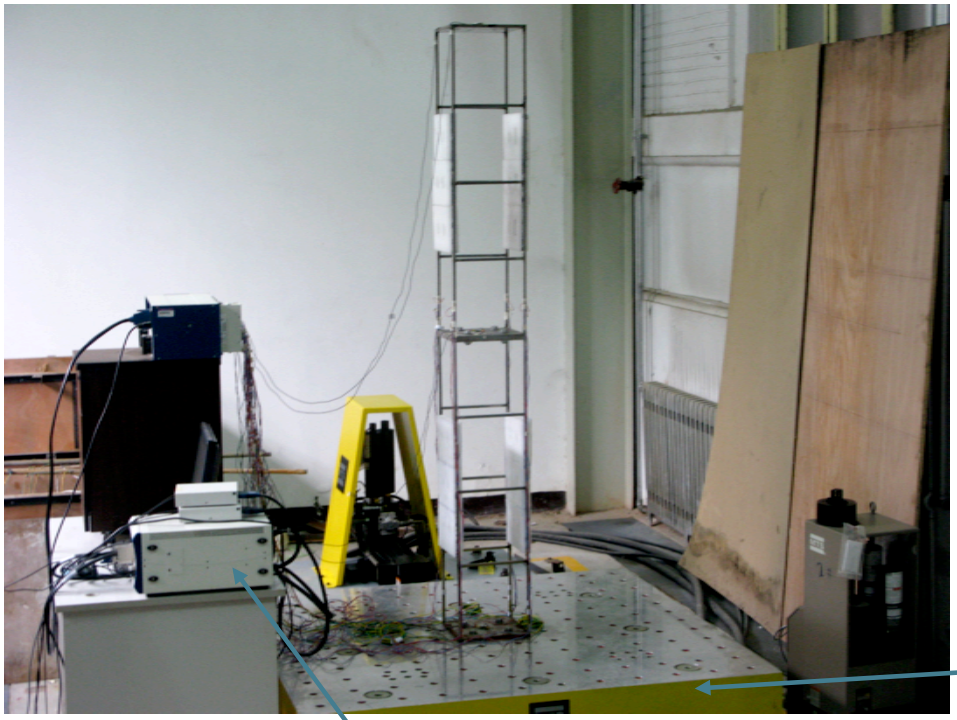
2 Numerical substructure

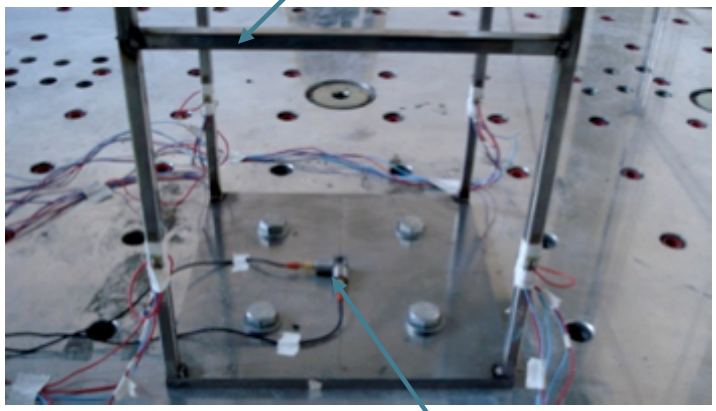
$$\begin{bmatrix} m_{f1} & \\ & m_{f2} \end{bmatrix}\begin{Bmatrix} \ddot{u}_{f1} \\ \ddot{u}_{f2} \end{Bmatrix}+\begin{bmatrix} c_{f1}+c_{f2} & -c_{f2} \\ -c_{f2} & c_{f2}+c_{f3} \end{bmatrix}\begin{Bmatrix} \dot{u}_{f1} \\ \dot{u}_{f2} \end{Bmatrix}+\begin{bmatrix} k_{f1}+k_{f2} & -k_{f2} \\ -k_{f2} & k_{f2}+k_{f3} \end{bmatrix}\begin{Bmatrix} u_{f1} \\ u_{f2} \end{Bmatrix}=\begin{Bmatrix} p_0^g+T \\ 0 \end{Bmatrix}$$

$$T=c_2\left(\dot{u}_2-\dot{u}_{f1}\right)+k_2\left(u_2-u_{f1}\right)$$

4 SSI-RTDHT test setup

4 Model and measurements





Strain gauges bridge
For shear force measurement

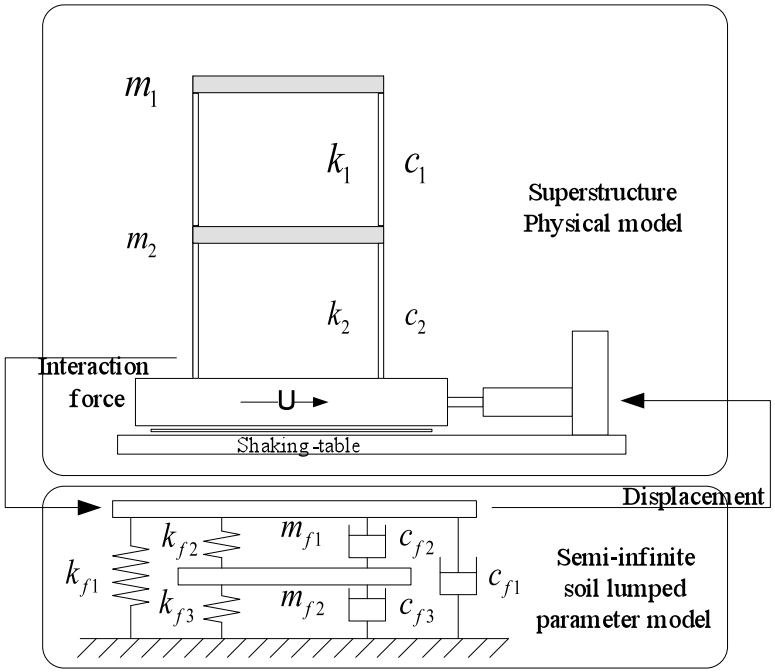
Accelerometer
For acceleration measurement

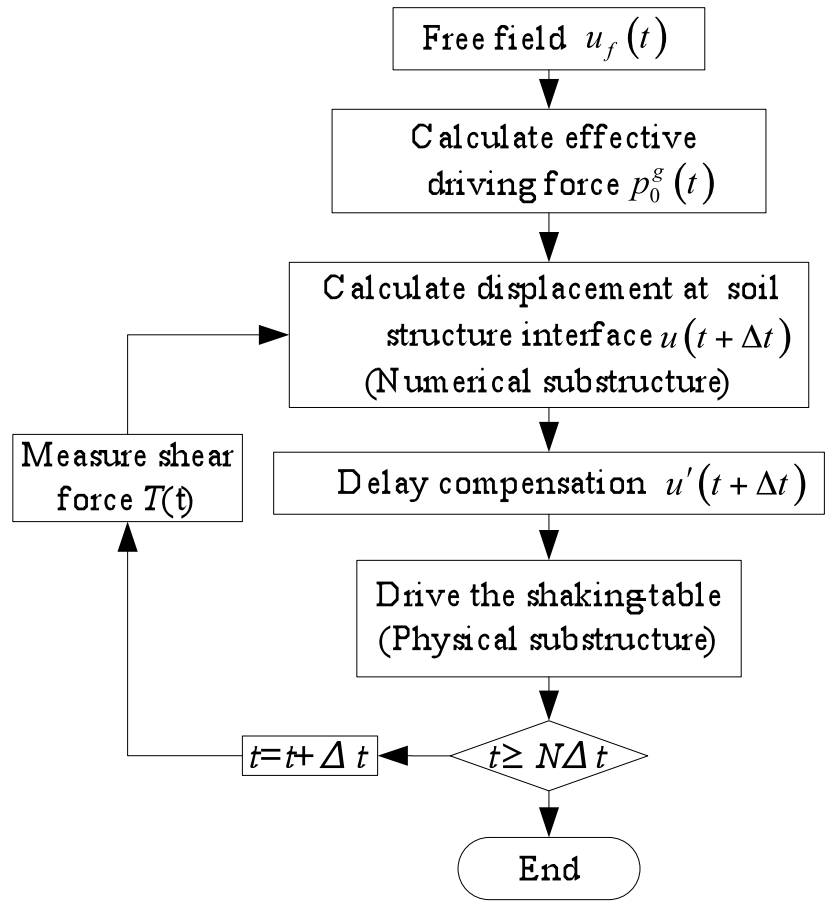
LVDT
For displacement measurement

NI DAQ
For data acquisition

4 SSI-RTDHT test setup

5 Procedure of SSI-RTDHT





5 SSI-RTDHT test results

1. Far boundary FEM

The mesh boundary is far enough so that the effect of the wave reflection and scattering from boundary on the structure-soil interface response can be avoided during the calculation duration.

$$D \geq \frac{cT}{2} \qquad L \geq 2D \qquad a \leq \frac{c}{10f}$$

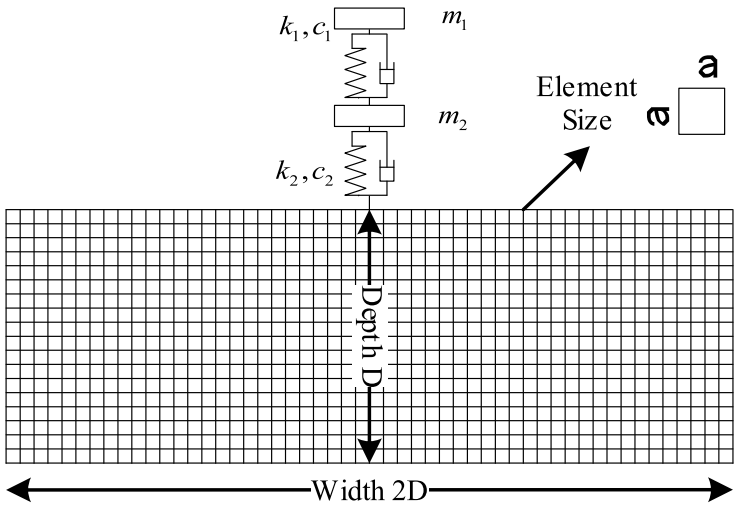
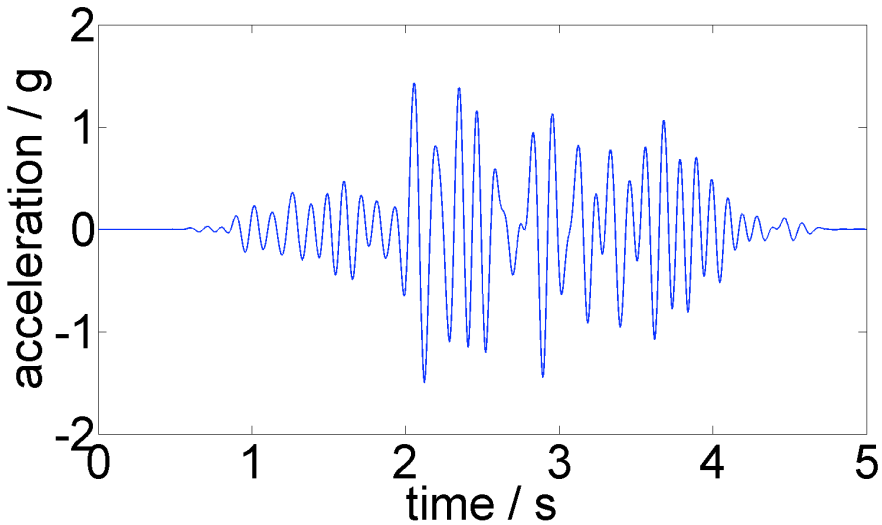


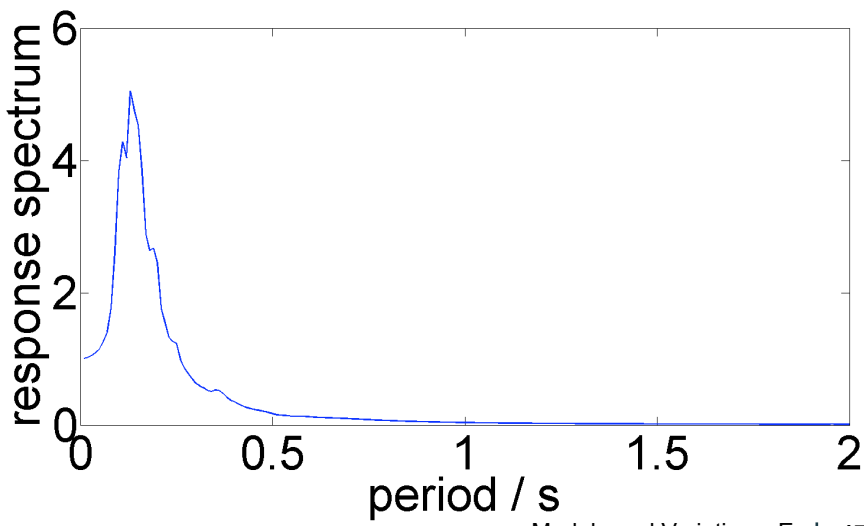
Table 3 Finite element analysis parameters

Wave velocity c_s/m·s-1	Calculation duration T /s	Highest frequency component / Hz	Depth D /m	Element size a /m	Node number
200	5	10	500	2	125751

5 SSI-RTDHT test results

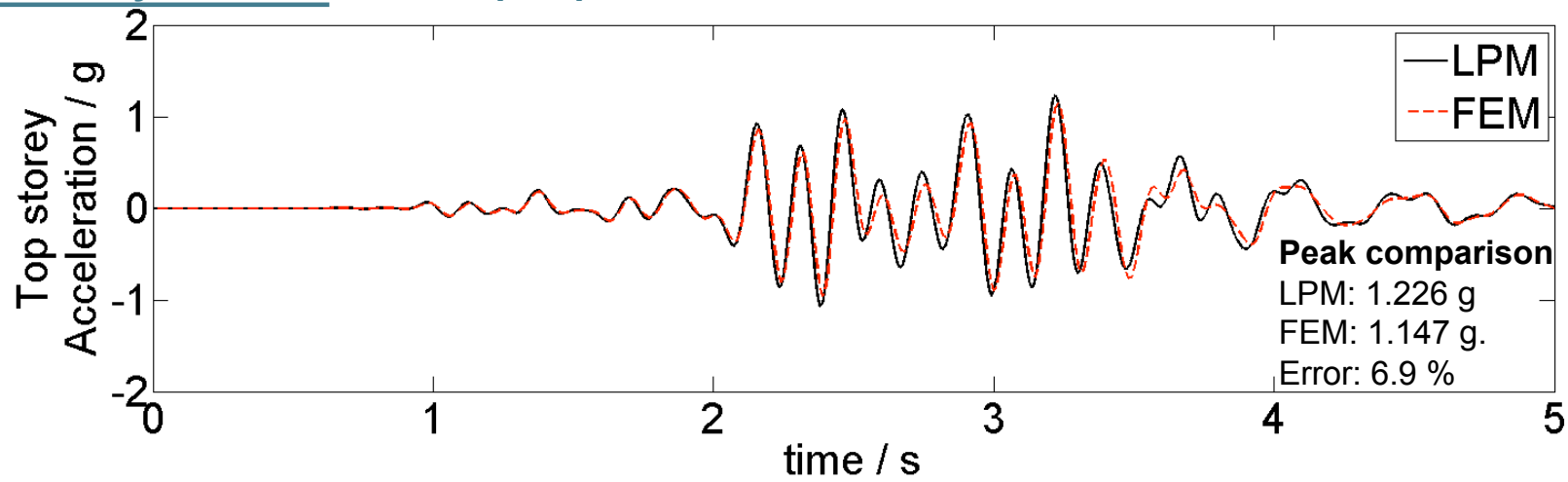
2. Artificial wave

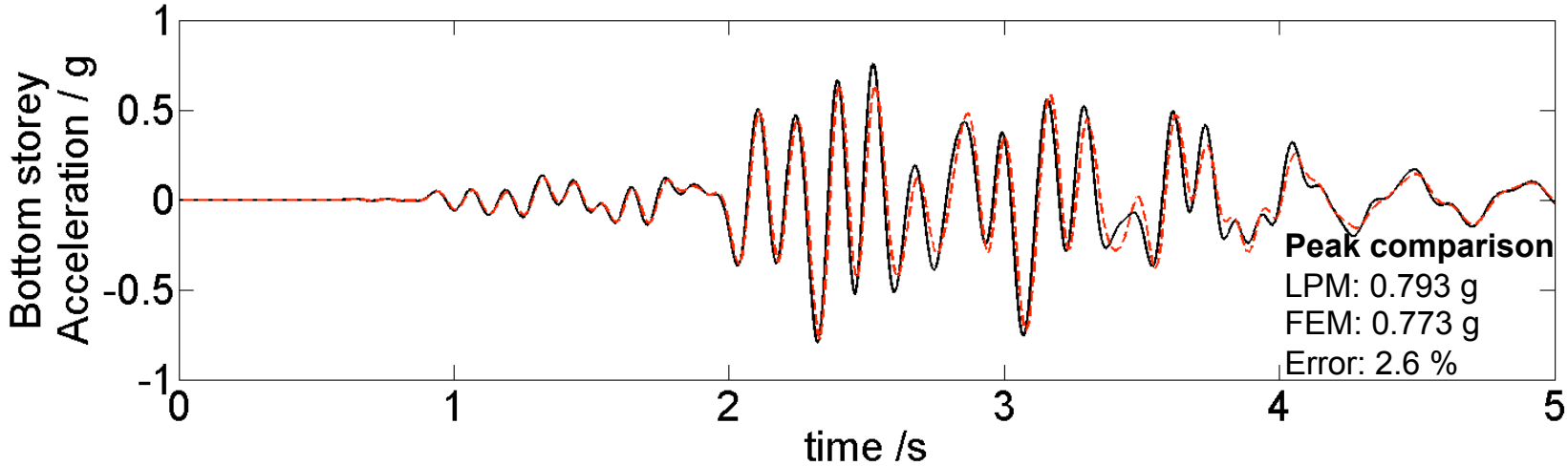




5 SSI-RTDHT test results

3. Accuracy verification of lumped paremeter model





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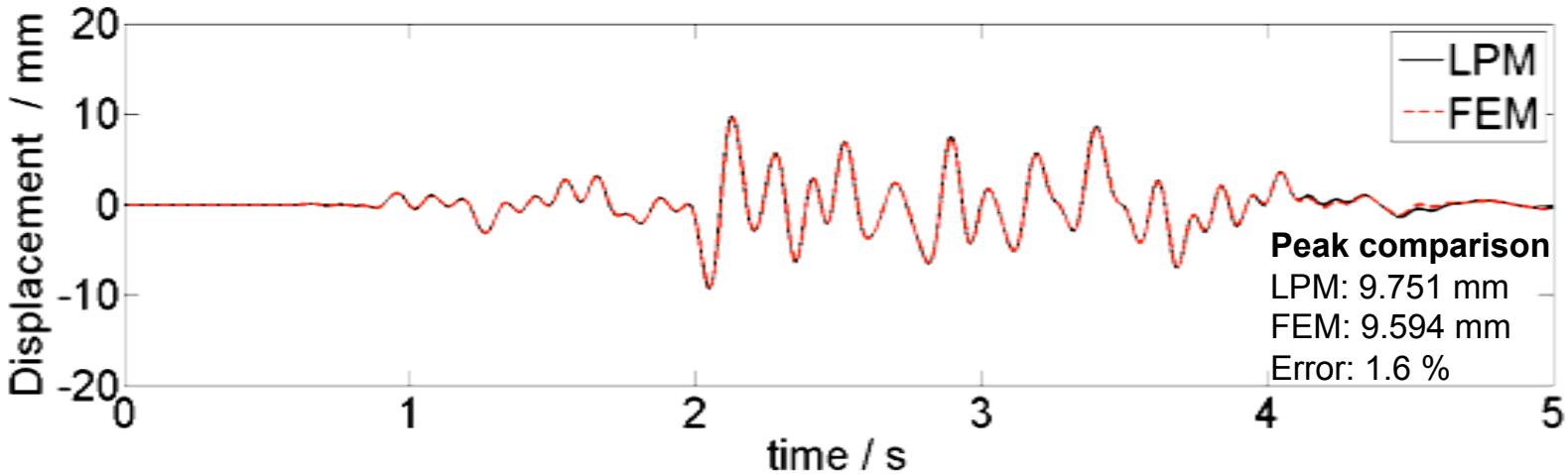

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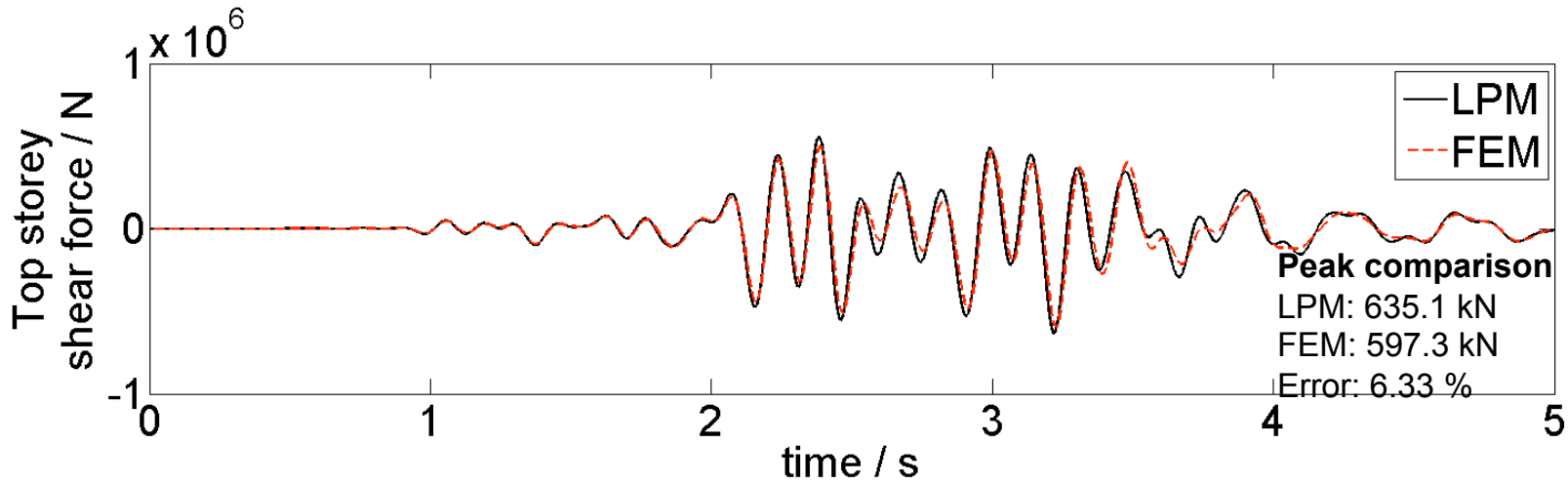

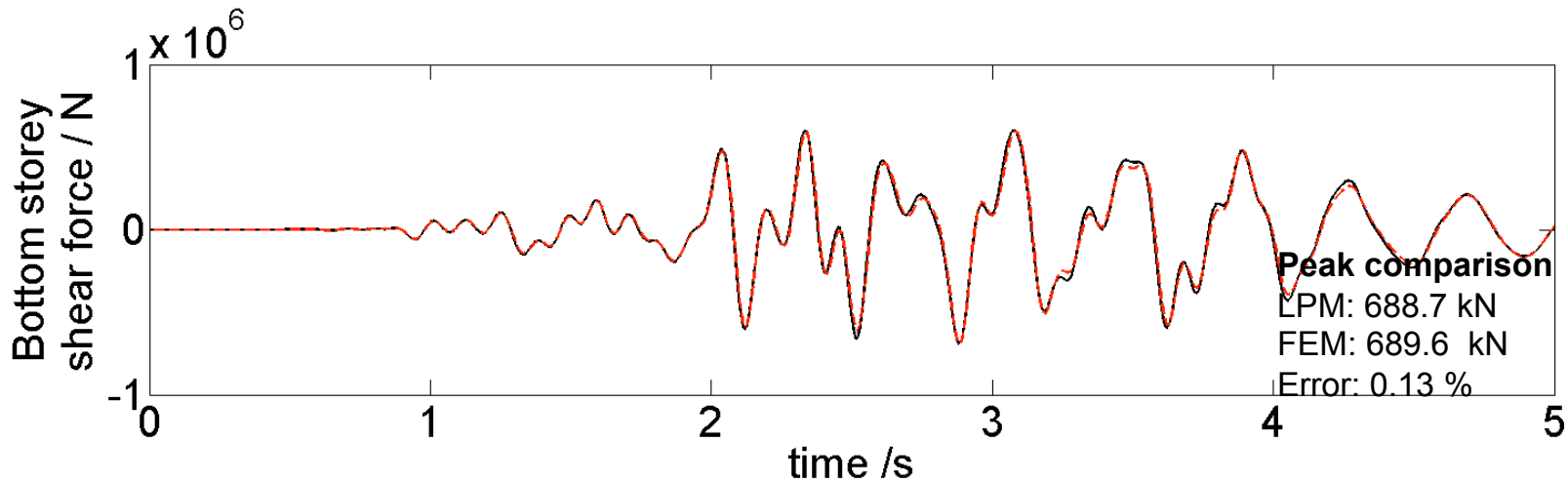

5 SSI-RTDHT test results

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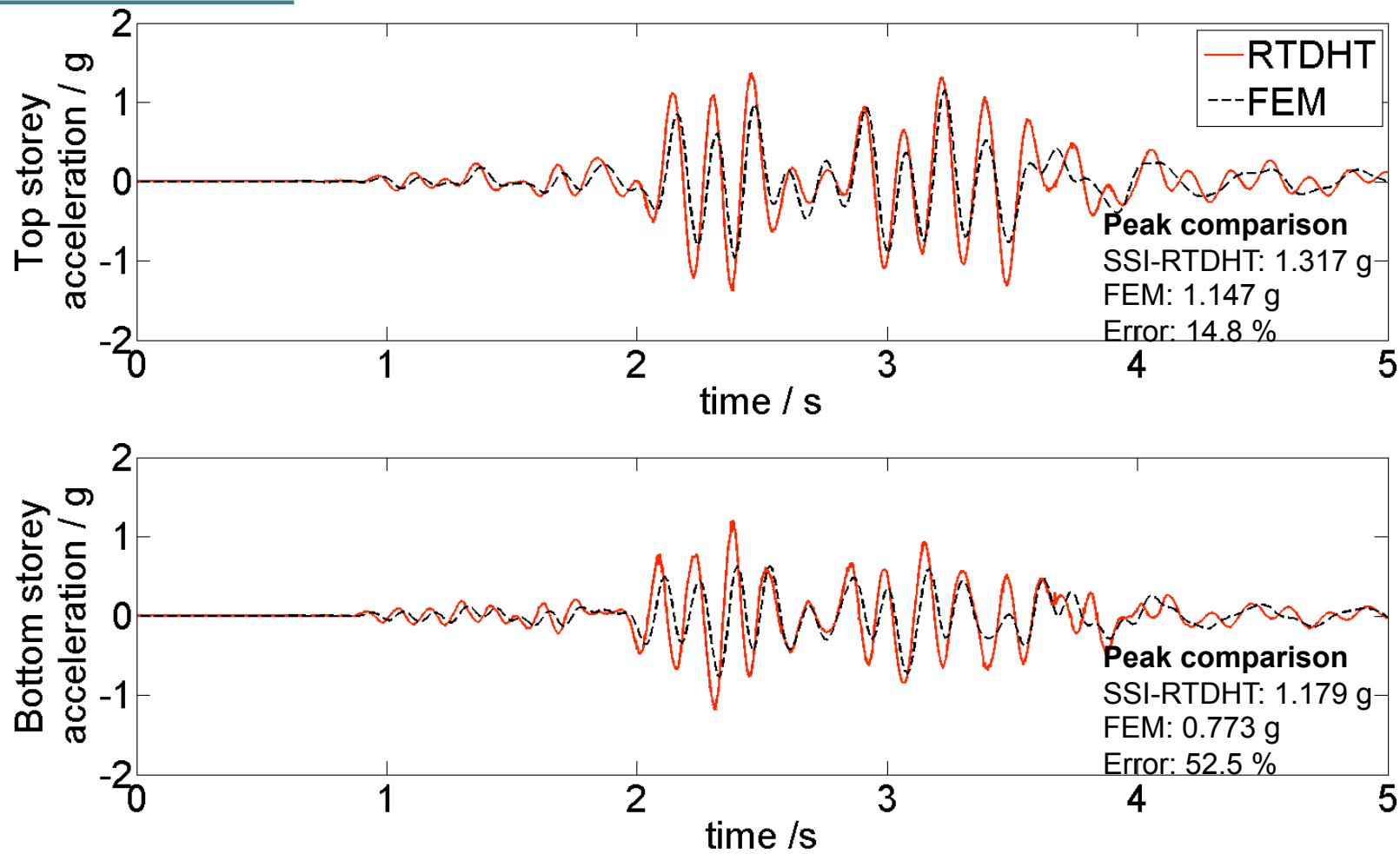

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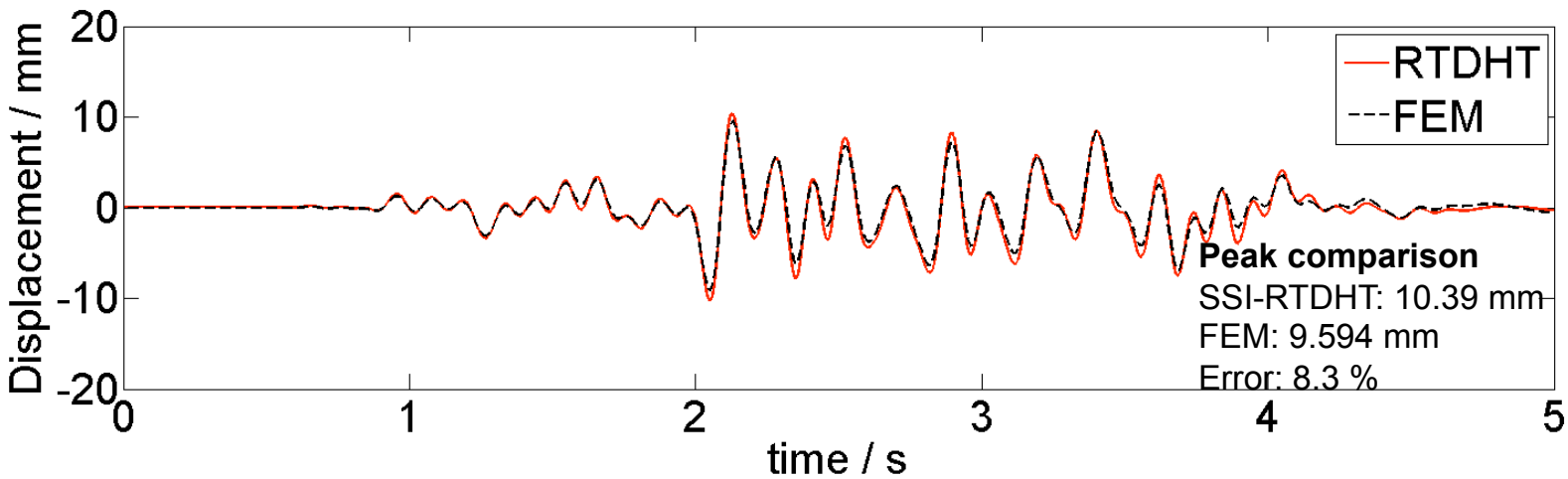

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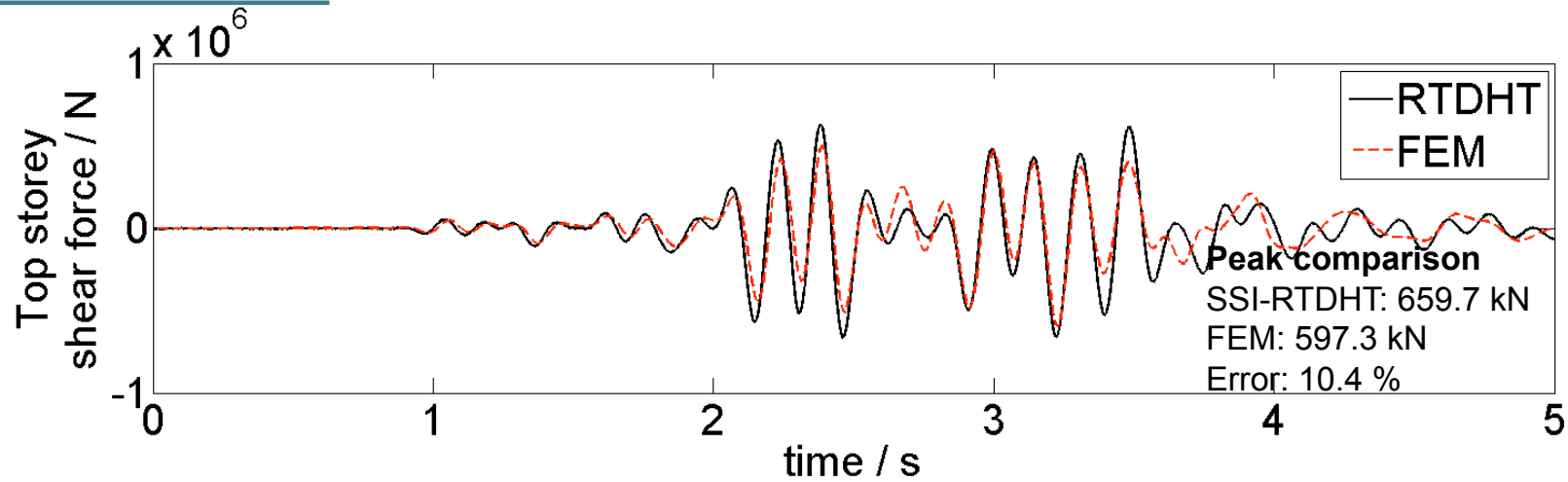
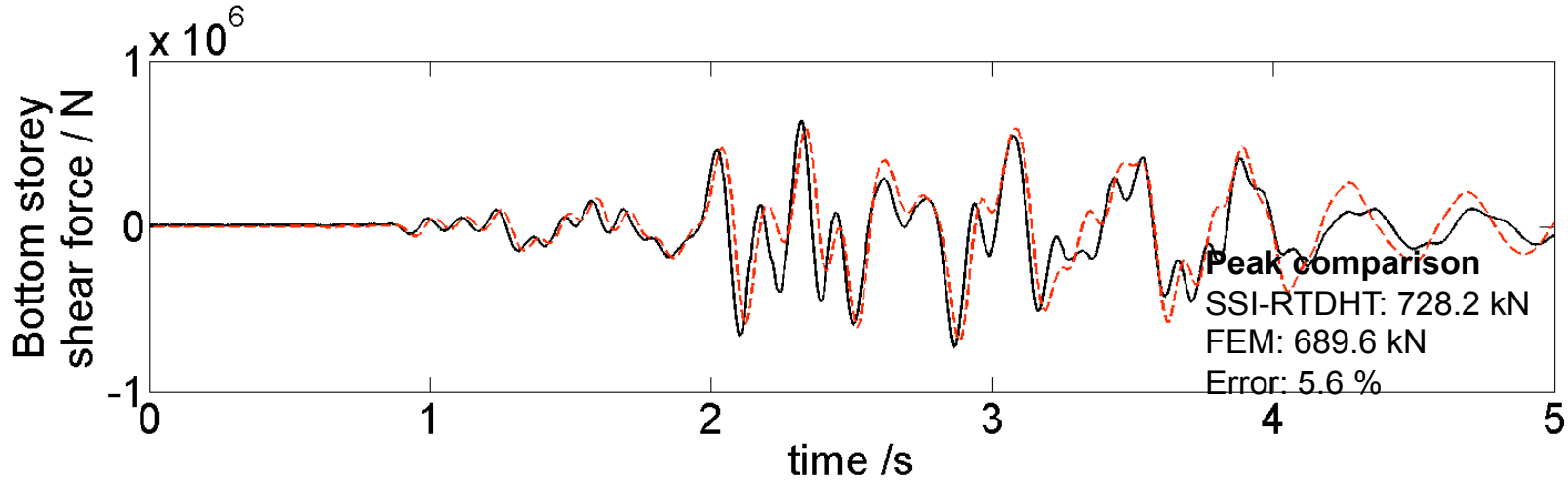
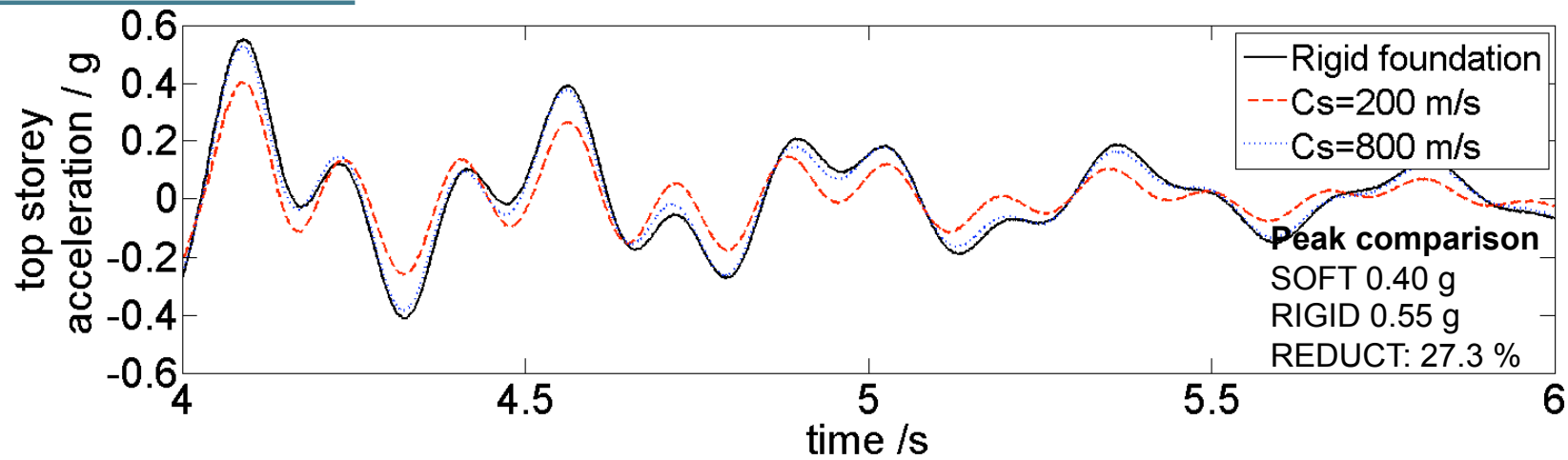
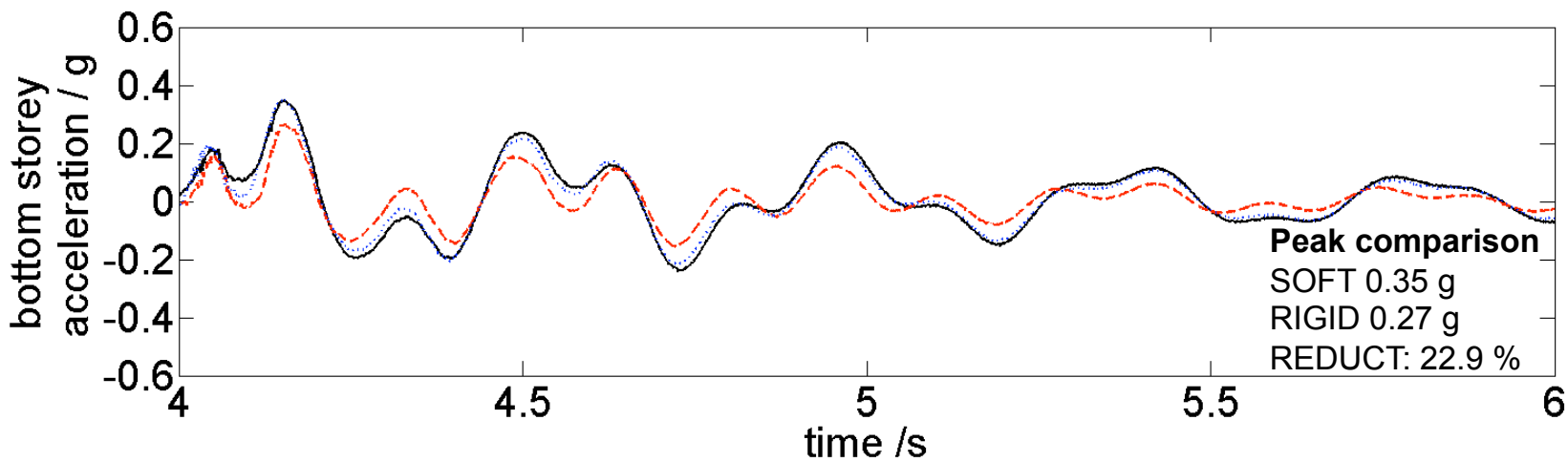




5 SSI-RTDHT test results

5. SSI effect of different types of soil





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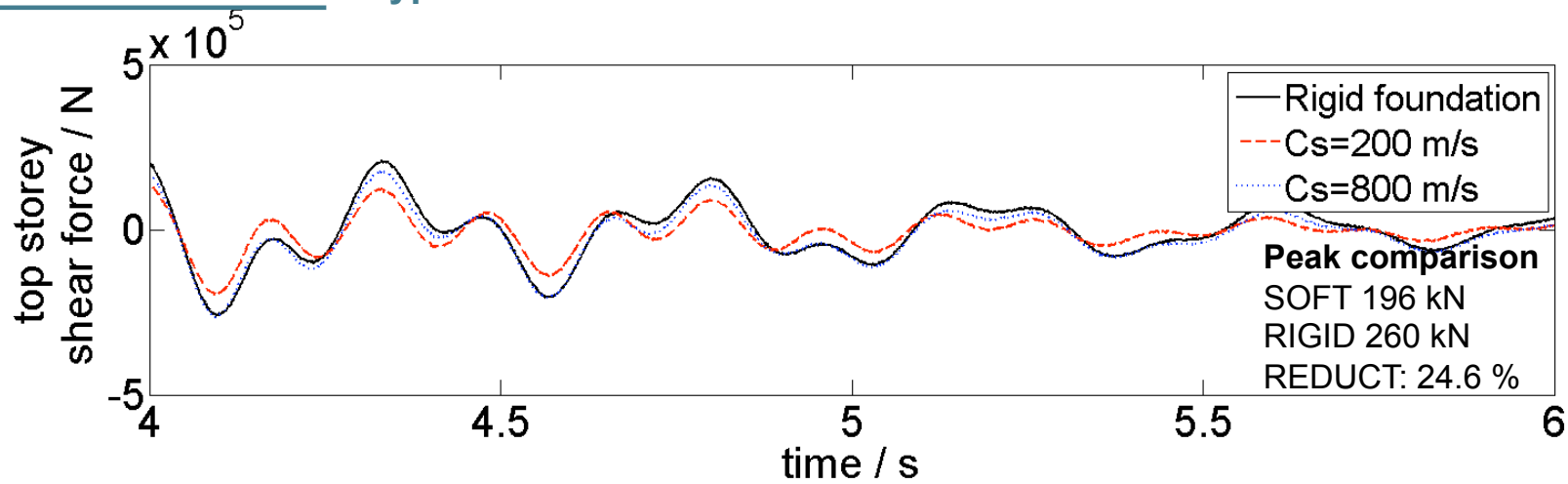

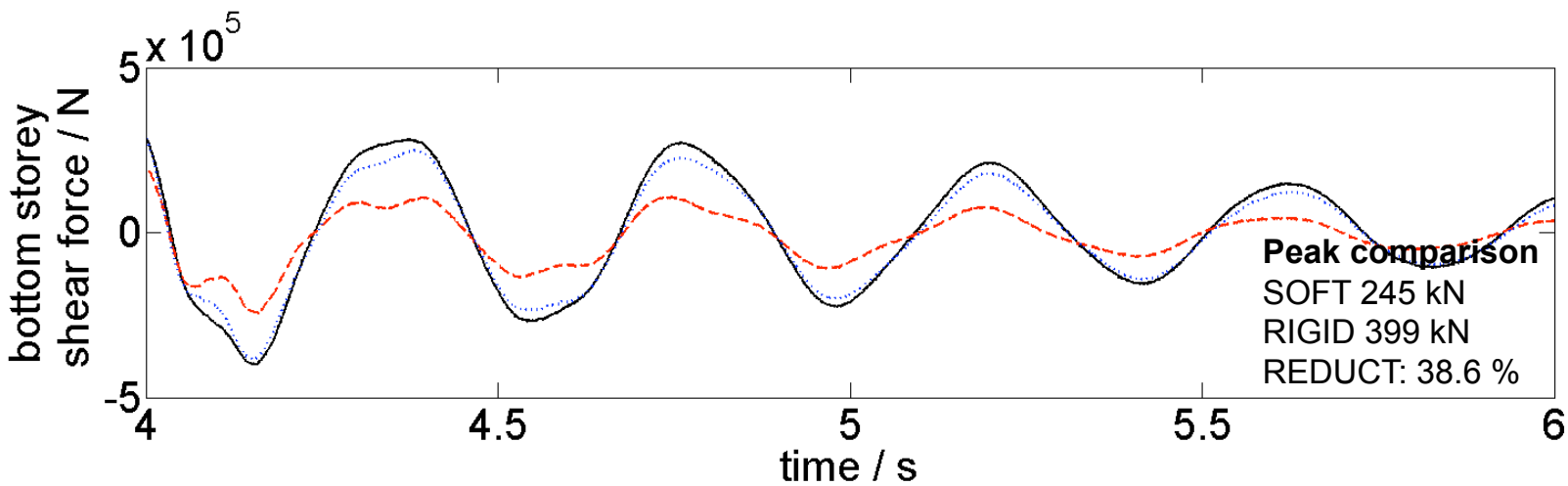

6 CONCLUSION

1. The lumped parameter model used in this paper can give a high accuracy approximation of the infinite half space elastic foundation.
2. Comparing the SSI-RTDHT test results with the FEM results shows that SSI -RTDHT can produce satisfying results in SSI analysis.
3. Comparing the tests results under rigid foundation, hard soil foundation, and soft soil foundation show that soil-structure interaction can affect the response of the structure: softer the soil is, more obvious the SSI effect becomes.

Using the idea of RTDHT, the infinite soil foundation model calculation and superstructure testing are combined together. Radiation damping of the infinite foundation can be included in shaking-table tests.

THE END