2nd IWGoRS WorkShop

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Response of structures to the rocking motion including soil-strature interaction with an implication to design codes

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Considered Components of Ground Motion in Traditional Earthquake Engineering

- ✓ Horizontal components
- ✓ Vertivcal component: in some cases
- ✓ Ignoring of rotational (torsional & rocking) component

Reasons for Ignoring of Rotational Components in Dynamic Analysis

- ✓Lack of recorded rotational components of ground motions
- ✓Rotational components assumed small enough to neglected

Seismic Collapses and Damages Attributed to Rotational Components

- ✓ Tilt and relative land subsidence in Alska earthquake (1964).
- ✓ Large torsional responses of tall building in Los Angeles, during the San Fernando, California, earthquake in 1971 could attributed to torsioal motions .
- ✓ Collapse of bridges during San Fernando 1971, Miyagi-Ken-Oki 1978 and Northridge 1994 earthquakes.
- ✓ Earthquake damage to pipelines that is not associated with faulting or landslides

Studies on the Rotational Component of Strong Ground Motion can be Classified in to Two Parts:

1. Study on the Estimation and recording of rotational excitations,

2. Study on the Effect of those components on structural response and design criteria.

Estimation of torsional Components:

- ✓ Modeling of waves propagation modes using faulting mechanism in seismic source:

  (Bouchon & Aki, 1982; Castellani & Boffi, 1989; Lee & Trifunac, 1987; Zembaty, 2009; ...)

- ✓ Using of recorded translational data in dense arrays

  (Lee *et al*., 2004;Spudich and et.al (1995), Ghayamghamian and Nouri, 2007; Spudich and Fletcher, 2008; ...)

- ✓ Direct recording of rotational component using optical tools such as ring laser

  (Suryanto *et al*., 2006; Igel *et al*., 2007; Liu *et al*., 2009; Lin *et al*., 2009; ...)

Estimating of Rocking motions by Translational ones

1. Difference in the tilt sensitivity of the horizontal and vertical pendulums (introduced by Graizer,2006; used by kalkan and Graizer,2007)

2. Finite difference method (used by Ghayamghamian and Nouri, 2007)

3. Standard Geodetic method (introduced by Spudich *et al.*, 1995)

Objective of this Study

✓Estimation of rocking component using standard Geodetic Method applied to dense array data.

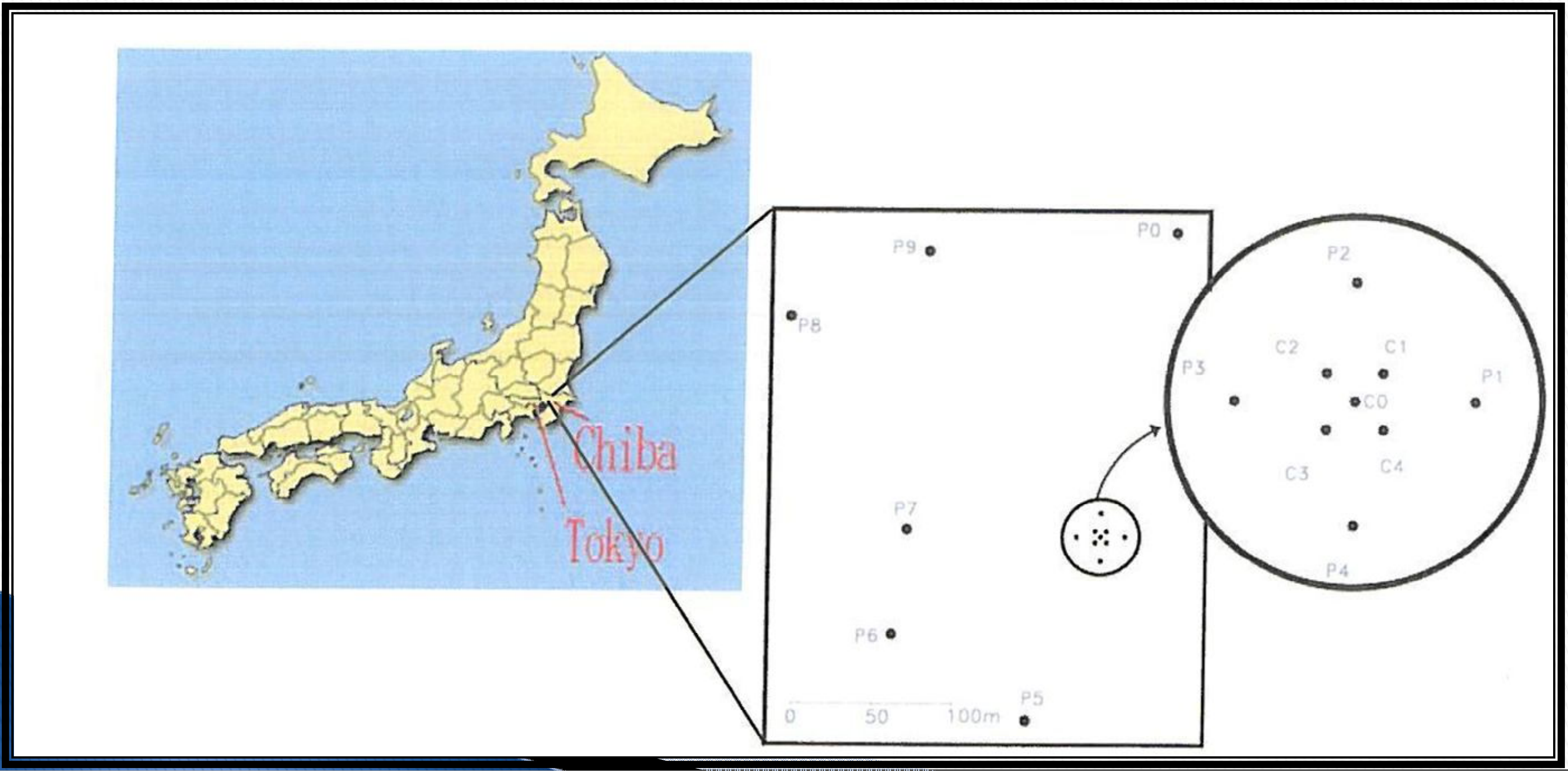
✓Study on the Effect of rocking component on linear and non-linear response of SDOF system (with and without considering soil-stracture interaction)

Chiba dense array

✓is located about 30 km East of Tokyo

✓seismometers and accelerometers are placed, with a minimum separation distance of 5 m, both on the ground surface and in boreholes

✓ The array system is composed of 15 boreholes with 44 three-component accelerometers, nine of them are densely arranged.



Estimation of Rocking Component Using Geodetic Method-Continued

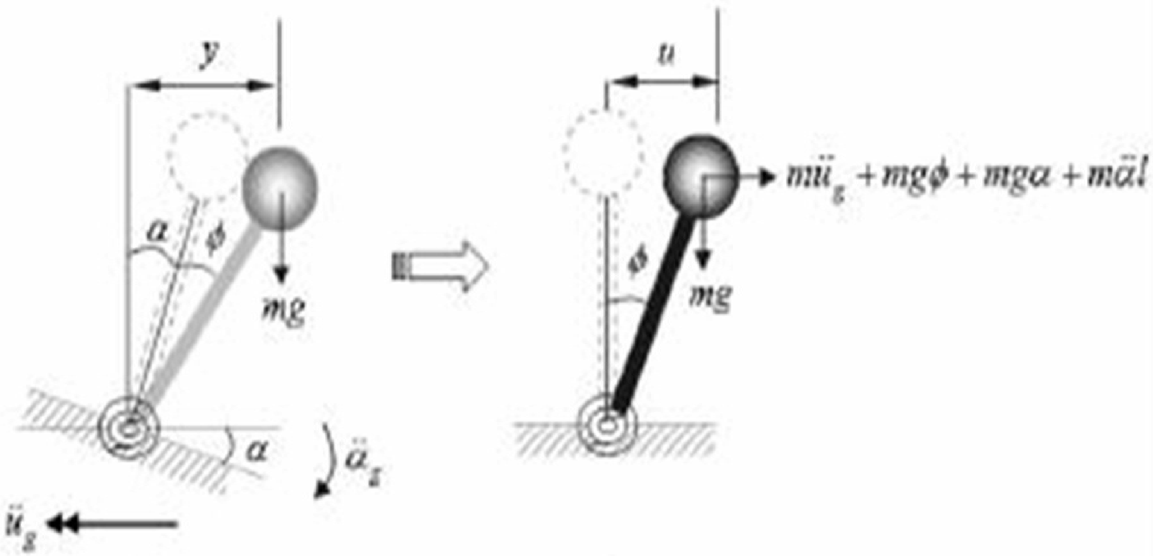
Data selection

From all 160 events that were recorded, Nine events with high signal-to-noise ratios and a wide range of magnitudes and peak ground accelerations (PGAs) were selected (Ghayamghamian & Nouri, 2007; Ghayamghamian,Nouri,Igel, Tobita, 2009)

Event No.	Distance (km)	PGA(cm/s/s)	M_{JMA}
#33	104.5	60	6.5
#37	44.7	400	6.7
#42	37.9	117	5.2
#46	47.7	71	5.6
#47	55.2	34	6.0
#81	42.2	86	6.0
#82	62.4	51	5.3
#84	40.2	121	5.4
#87	52.4	94	5.9

Linear and Non-Linear Response of SDOF System:

Equilibrium equation



(Kalkan & Graizer, 2007)

Rigid foundation slab supporting a one-dimensional set of lumped masses interconnected by massless spring, and with Dashpots were assumed to the stratural models.

Such models can be considered as an idealised form of the bridge pile, water storage tanks and etc

If the model is subjected to rocking and horizontal excitation the equilibrum equations can be written as :

Inertial force due to horizontal acceleration

Inertial force due to angular acceleration

$$m\ddot{u} + c\dot{u} + ku = -(m\ddot{u}_g + mg\varphi + mg\alpha_g + m\ddot{\alpha}_g l)$$

P-Δ effects

In this model effects of soil-structure interaction are neglected.

Linear and Non-Linear Response of SDOF System

Equilibrium equations and loading cases

The mentioned equations were solved in two cases:

1. translational ground motion acting alone:

$$\ddot{u} + 2\zeta\omega_n\dot{u} + (\omega_n^2 - g/l)u = -\ddot{u}_g$$

2. rocking and translational excitations acting simultaneously

$$\ddot{u} + 2\zeta\omega_n\dot{u} + (\omega_n^2 - g/l)u = -(\ddot{u}_g + g\alpha_g + \ddot{\alpha}_g l)$$

- ✓Horizontal component of ground acceleration ($\ddot{u}_g$)
- ✓Rocking component of ground acceleration ($\ddot{\alpha}_g$)
- ✓Rocking component of ground displacement (α_g)

- ✓Damping ratio of system (ζ)
- ✓Natural period of system (T_n)
- ✓Height of system (l)

The ratio between maximum responses in two loading cases (normalized response) provides a measure of the changes in the response due to rocking excitation.

Linear and Non-Linear Response of SDOF System:

Assumptions:

$$\ddot{u} + 2\zeta\omega_n\dot{u} + (\omega_n^{\;2} - g/l)u = -(\ddot{u}_g + g\alpha_g + \ddot{\alpha}_g l)$$

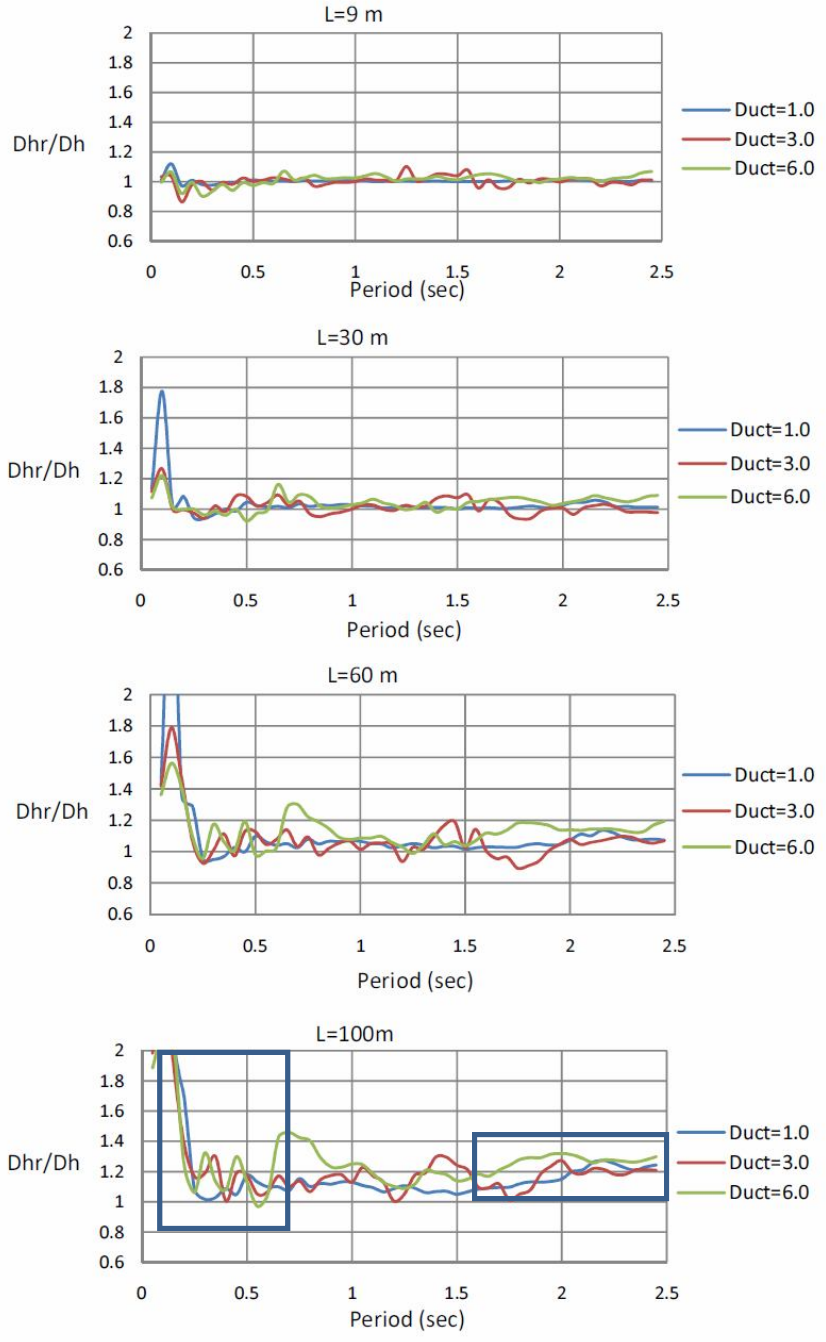
- ✓Damping ratio of system (ζ :5%)
- ✓Natural period of system (T_n : 0.05-2.5 sec)
- ✓Height of system (l : 9, 30, 60 & 100 meters)
- ✓Ductility (μ : 1, 3, 6)

Solving the equations using β Newmark Method by Programming in MATLAB software

- **Normalized spectral displacement (ratio of displacement) for each height of system and different ductility**
- **Response of 9 events are averaged.**

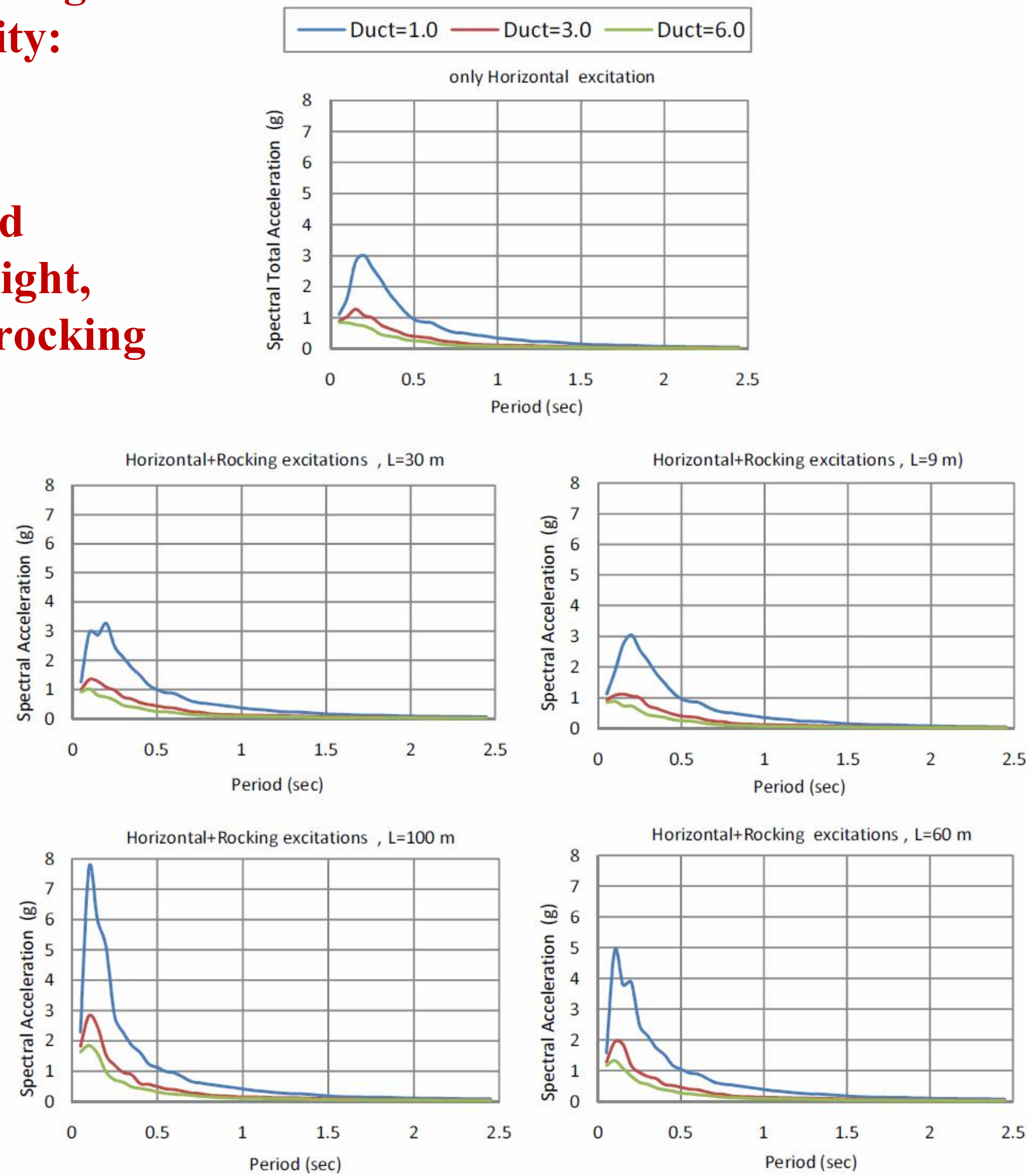
✓In this figure :
Dhr: spectral displacement of system with horizontal and rocking excitations
Dh: spectral dispalcement of system when excited by horizontal component

- **The results Shows that effect of rocking motion is considerable in low ductility and high buliding.**
- **With increasing of natural periods this effect going to be small.**

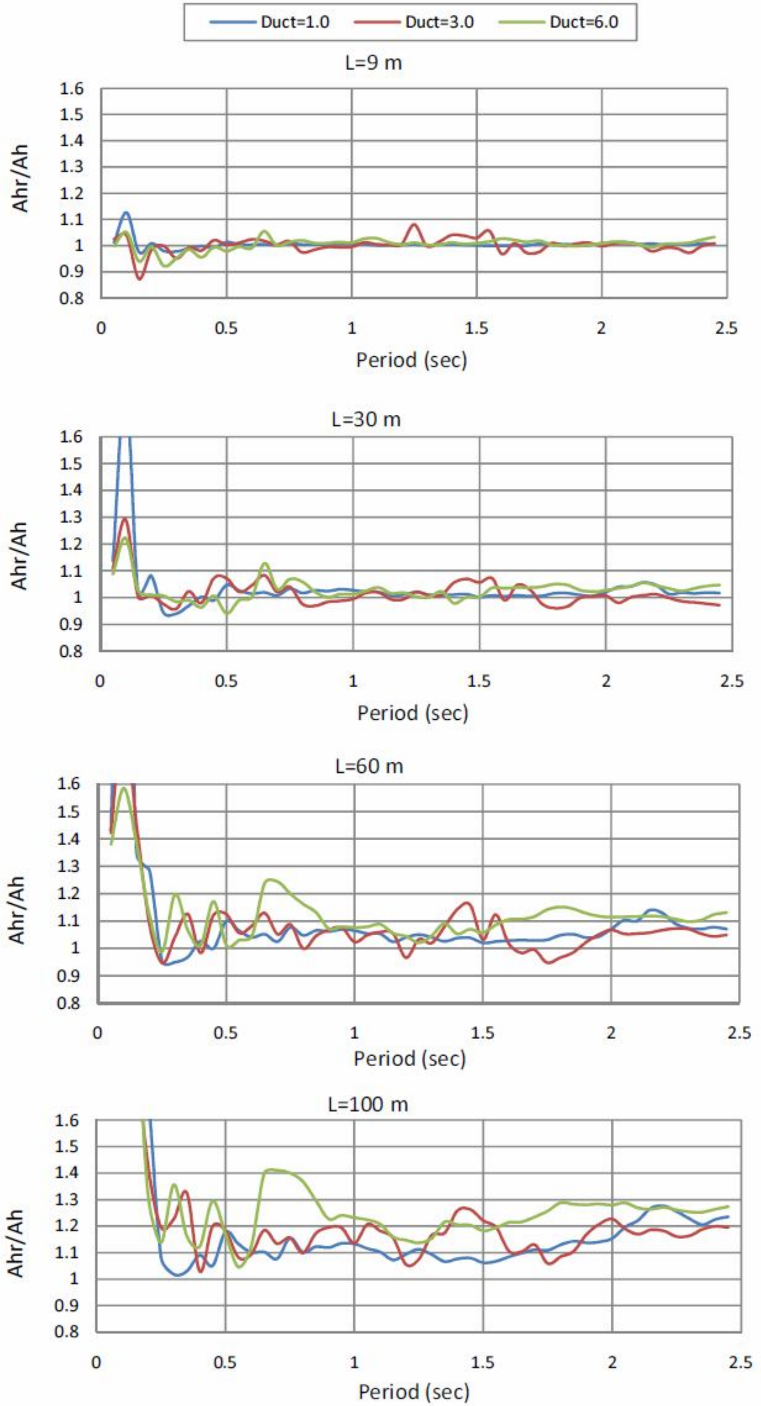


Spectral acceleration for each height of system and different ductility:

With decreasing of Periods and ductility and increasing of height, spectral acceleration effect of rocking motion going to be significant



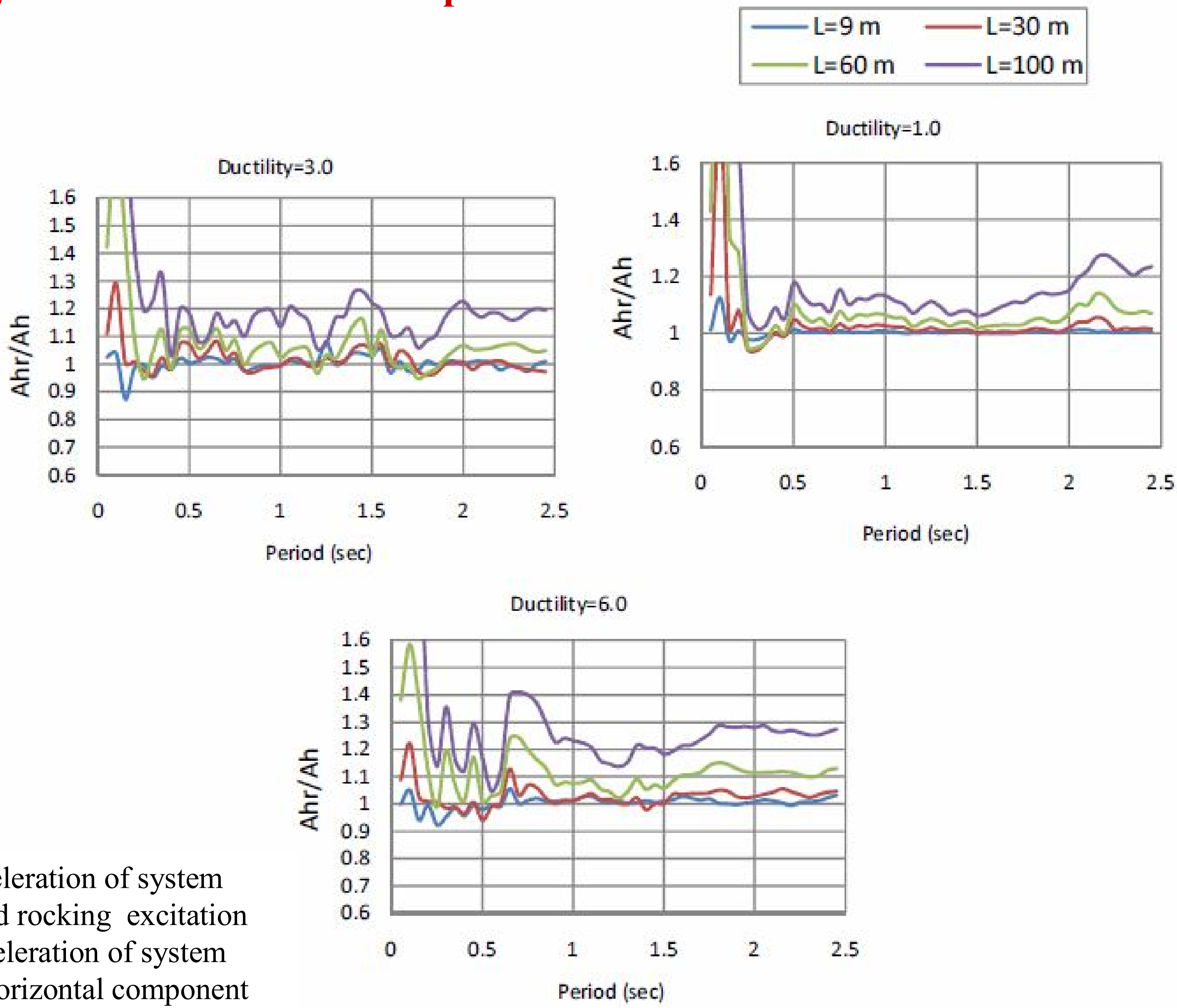
Normalized spectral acceleration for each height of system:



✓Ahr: spetral acceleration of system with horizontal and rocking excitation

✓Ah: spectral acceleration of system when excited by horizontal component

Effect of height on the acceleartion response

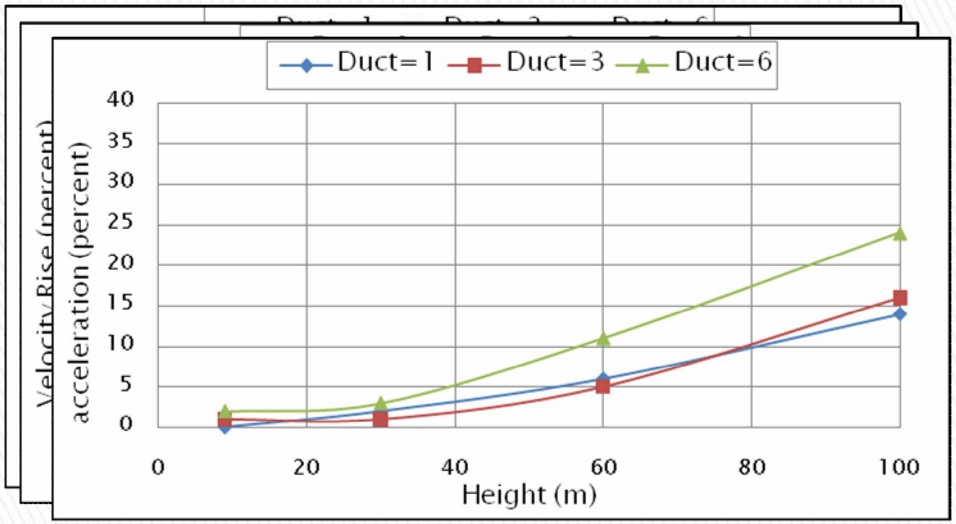


✓Ahr: spetral acceleration of system with horizontal and rocking excitation

✓Ah: spectral acceleration of system when excited by horizontal component

Linear and Non-Linear Response of SDOF System

✓ Approximate increase of response considering horizontal and rocking components simultaneously can be summerized:



Height (m)	Increase in Disp. (percent)	Increase in Vel.(percent)	Increase in Acc. (percent)
9	*0 – 3*	*0 – 1*	*0 – 2*
30	*2 – 5*	*1 – 2*	*2 – 3*
60	*6 – 12*	*7 – 12*	*6 – 11*
100	*13 - 24*	*21 - 36*	*14 - 24*

Codes Provisions About Rocking Component

Recommended relations (EC8.6, 2005)

$$R_x^{\theta}(T) = \frac{1.7\pi S_e(T)}{V_s T}$$

$$R_y^{\theta}(T) = \frac{1.7\pi S_e(T)}{V_s T}$$

$$R_z^{\theta}(T) = \frac{2.0\pi S_e(T)}{V_s T}$$

Se(T): elastic horizontal response spectrum

T: natural period

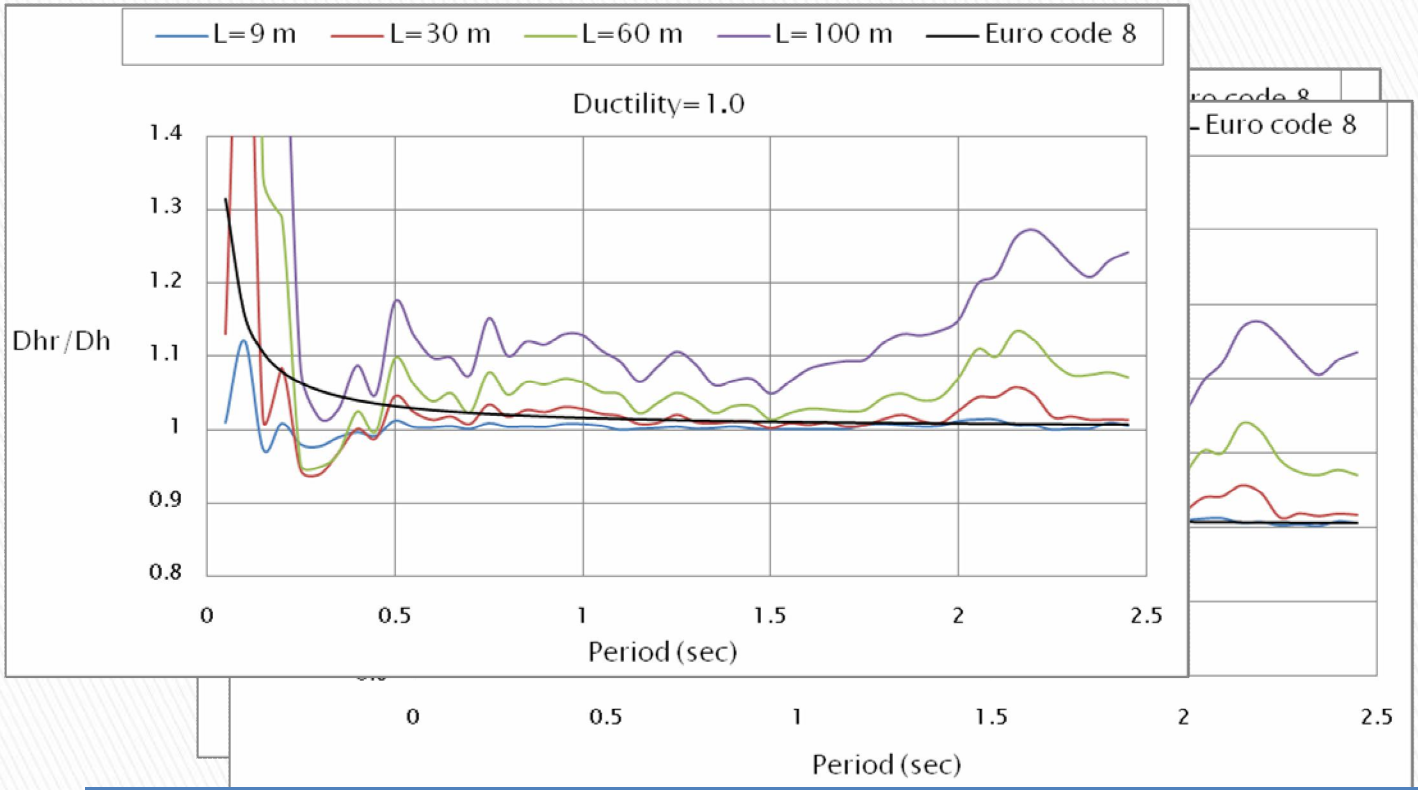
Vs: average S-wave velocity in the top 30 meters of the ground profile

For

- ✓Structures taller than 80 meters
- ✓Design acceleration higher than 0.25g

Linear and Non-Linear Response of SDOF System

- ✓Compareing the normalized responses obtained by dense array data and proposed relation of Eurocode 8

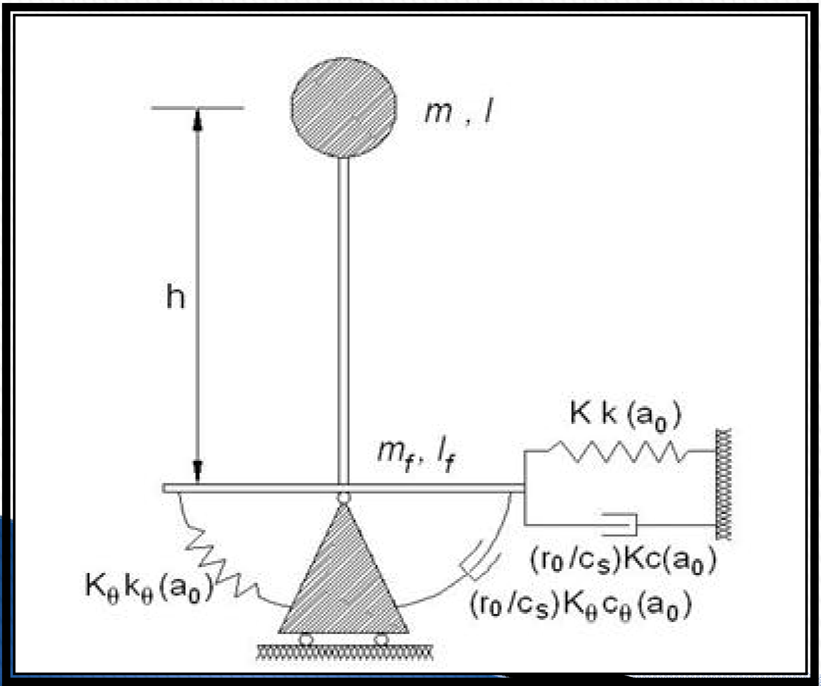


Comparision of results reveals that code values are very lowerestimated for high buildings

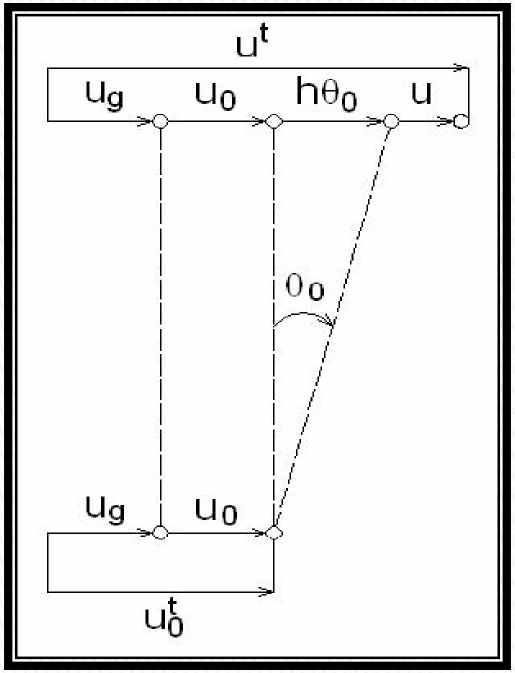
Linear Response of SDOF System with Considering SSI Effect

To include soil-strature interaction we assumed the below model:
For soil we have to degree of freedom : 1- rocking 2- sway, damipng of soil modeled by dashpot

Soil-structure model



Displacements of model



Linear Response of SDOF System with Considering SSI Effect

Steps for Analyzing of soil-structure model

- ✓Achievement of equilibrium equations in frequency domain
- ✓applying Fourier transform to the equations
- ✓convert to the time domain by inverse Fourier transform

$$[1+2\zeta i-\frac{\omega_s^2}{\omega^2}-\frac{(1+2\zeta i)}{\frac{S_{\zeta_g}}{m\omega^2}-m_f}-\frac{(1+2\zeta i)}{\frac{S_{\theta\zeta_g}}{m\omega^2}-\frac{m_f}{4}(\frac{r^2}{h^2})}]u(\omega)=$$

$$\frac{\omega_s^2}{\omega^2}[(\frac{m_f}{\frac{S_{\zeta_g}}{m\omega^2}-m_f})u_g(\omega)+(\frac{}{\frac{S_{\theta\zeta_g}}{m\omega^2}-\frac{m_f}{4}(\frac{r^2}{h^2})}+1)h\theta_g(\omega)]$$

$$u_0(\omega)=\frac{\omega^2(1+2\zeta i)}{S_{\zeta_g}-m_f\omega^2}u(\omega)+\frac{m_f\omega^2}{S_{\zeta_g}-m_f\omega^2}u_g(\omega)$$

$$h\theta_0(\omega)=\frac{\omega^2(1+2\zeta i)}{S_{\theta\zeta_g}-\frac{m_f r^2}{4h^2}\omega^2}u(\omega)+\frac{\frac{m_f r^2}{4h^2}\omega^2}{S_{\theta\zeta_g}-\frac{m_f r^2}{4h^2}\omega^2}h\theta_g(\omega)$$

Linear Response of SDOF System with Considering SSI Effect

assumptions :

1. A non-dimensional frequency as an index for the structure-to-soil stiffness ratio

$$\bar{S} = \frac{2\pi h}{Tc_s} \qquad \bar{S} = 0,\ 1,\ 2$$

2. Aspect ratio of the structure $\bar{h} = \frac{h}{r}$ $\quad \bar{h} = 3,\ 5,\ 8$

3. Structure-to-soil mass ratio index $\bar{m} = \frac{m}{\rho r^2 h}$ $\quad \bar{m} = 0.5$

4. The ratio of the mass of the foundation to that of the structure

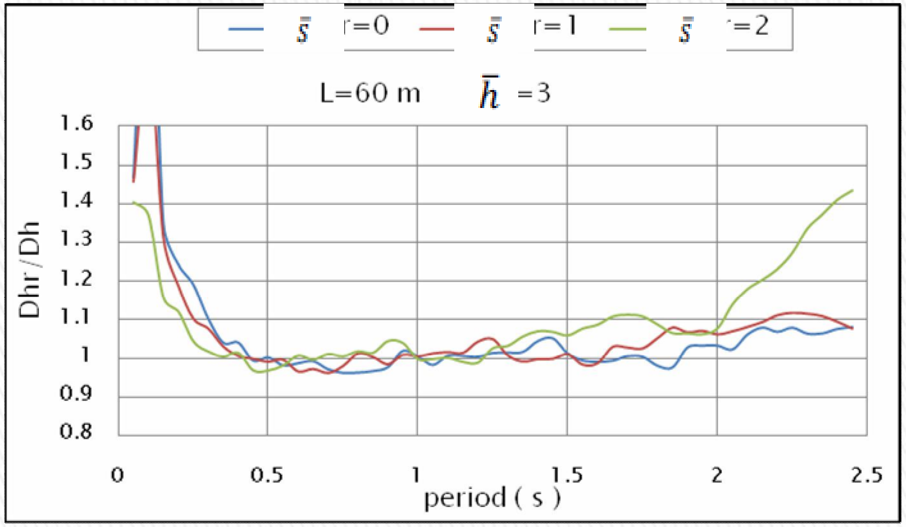
$$\bar{m}_f = \frac{m_f}{m} \qquad \bar{m}_f = 0.1$$

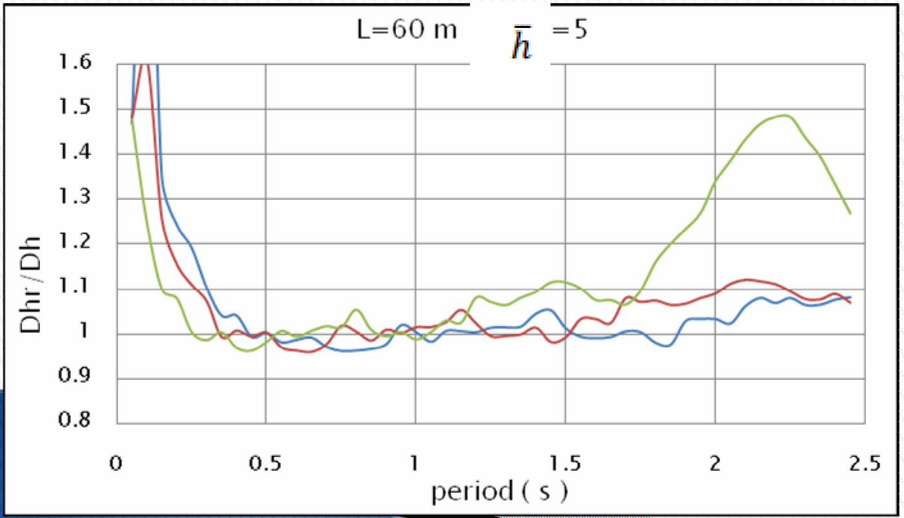
5. Poisson's ratio of the soil u = 0.33

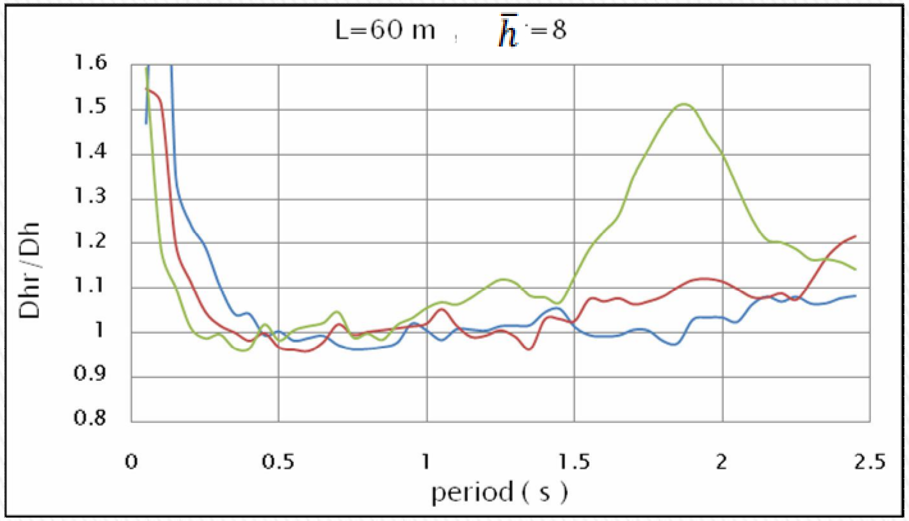
6. Material damping ratios of the soil and the structure ζ_g , ζ = 5%

Linear Response of SDOF System with Considering SSI Effect

Ratio of displacements with constant $\bar{h}$



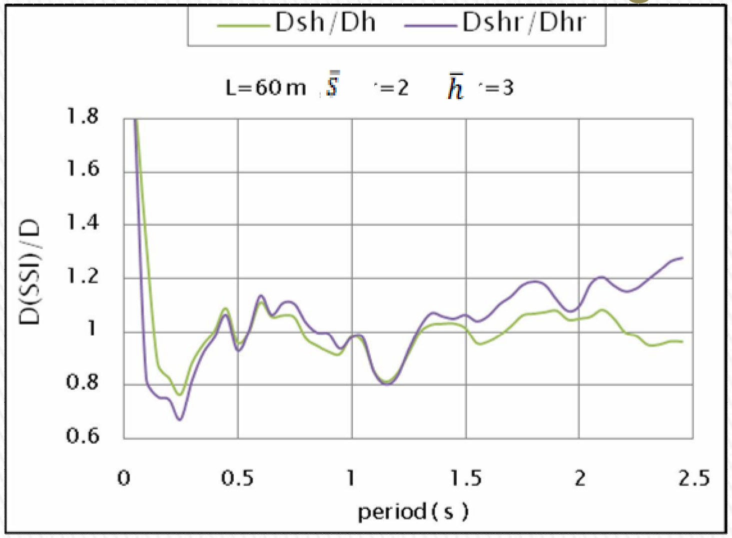


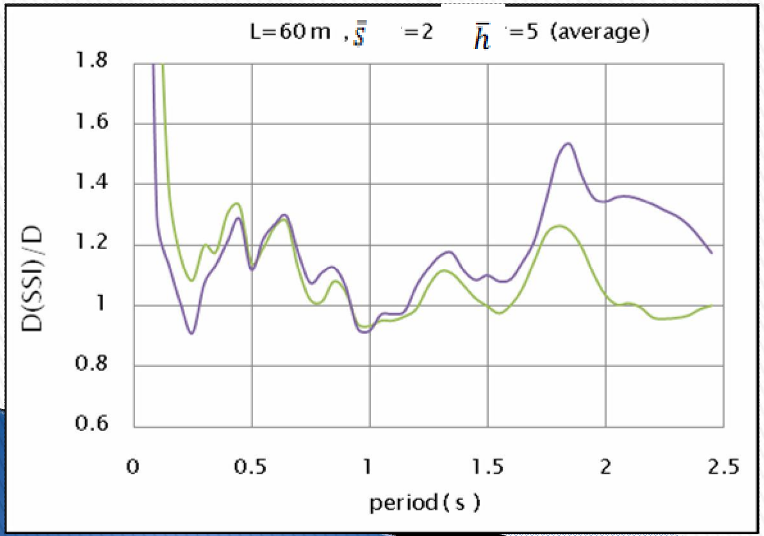


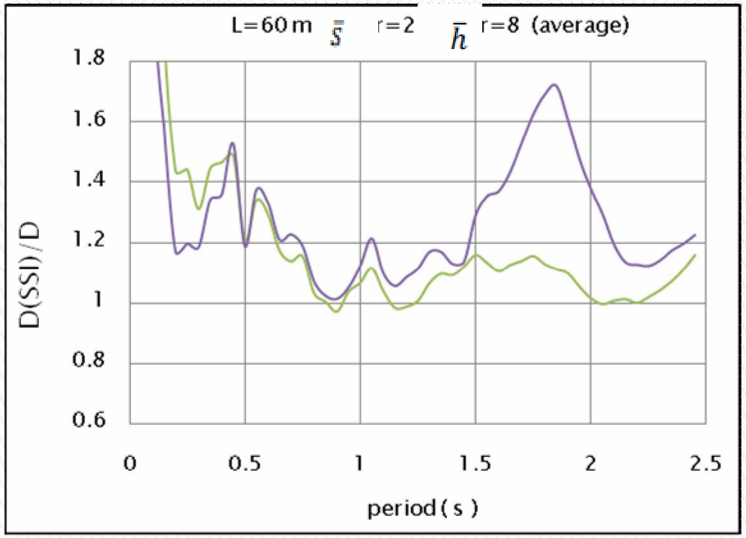
Thank you

Linear Response of SDOF System with Considering SSI Effect

SSI Effect with and without considering rocking component

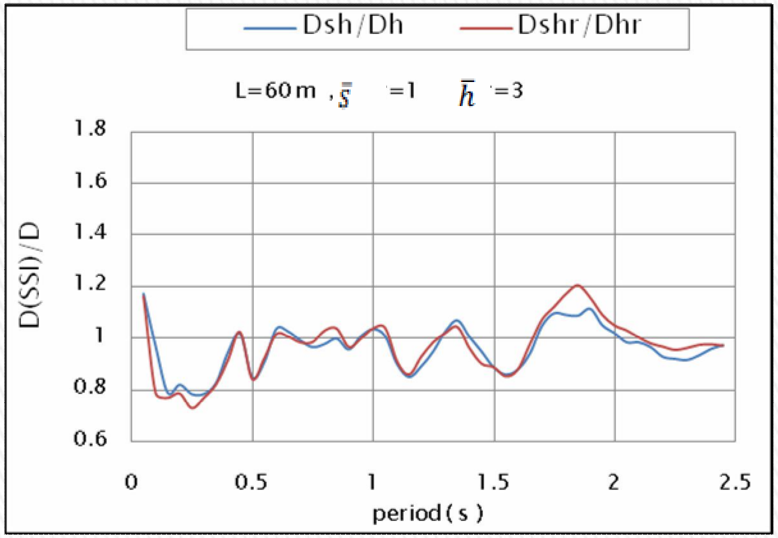


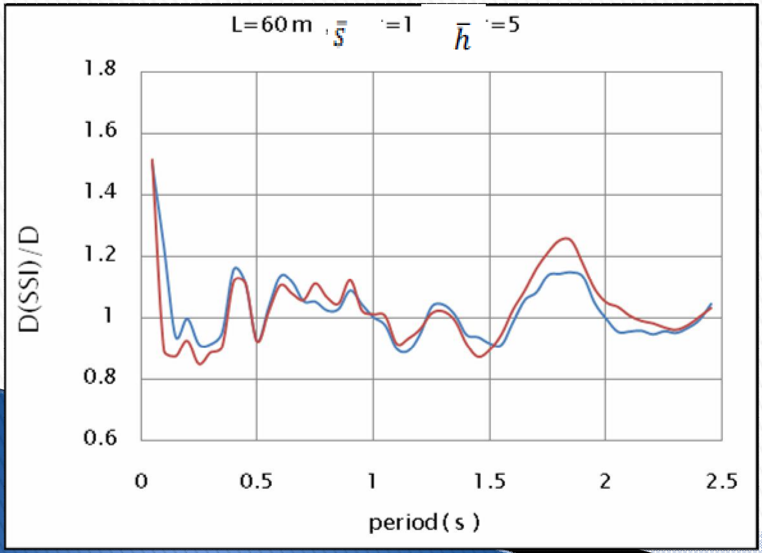


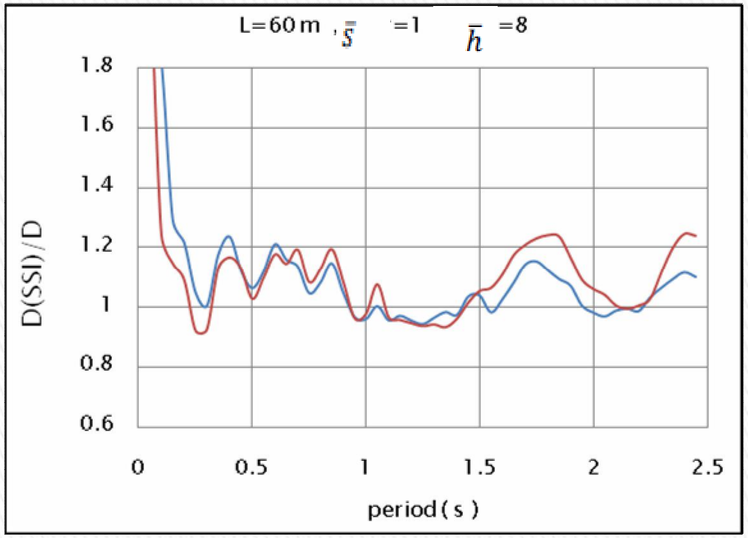


Linear Response of SDOF System with Considering SSI Effect

SSI Effect with and without considering rocking component







CONCLUSION

1. Rocking component influence the structural response and increases the response of structures.

2. Normalized responses is increased with increasing of ductility. Therefore, effect of rocking component in ductile structures is considerable. For example, in hieght of 100 m, for ductility of 1, 3 and 6, average increase of displacement is 13, 16 and 24 %.

3. Normalized responses are increased with increasing of hieght. For example, in ductility of 6, and height of 9, 30, 60 and 100 m, average increase of displacement is 3, 5, 12, 24 %.

4. Comparision of results relevant to proposed relations of Eurocode 8 with values of dense array data shows that, code values are very lowerestimated for high buildings and Based on the results, it can be concluded that effects of rocking component should be considered for structures taller than 30m.